Towards a nature-based solution for the Brouwersdam beach in the Netherlands

Following the Building with Nature approach to counteract long-term erosion of a recreational beach as a consequence of large-scale morphological changes in a closed-off outer delta

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by

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to obtain the degree of Master of Science in Civil Engineering
at the Delft University of Technology

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An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

Cover: Brouwersdam beach. Photography by author.

Acknowledgements

Upon the completion of this thesis, I would like to express my gratitude to the people who supported and inspired me throughout the past nine months.

First of all, I want to thank the members of my graduation committee, without whom this report would not have been realised.
Peter van Sante, thank you for giving me the opportunity to work on this topic and being a supportive supervisor. Even though the pandemic prohibited to work and collaborate at the city hall in Zierikzee, I am very grateful for the opportunity to work on a thesis that is embedded in the real, complex world of coastal engineering.
Marian Lazar, thank you for having such a great passion for the beach, which has led to the formulation of this research. Your elaborate explanations on the past developments of the beach have led to a thorough understanding. Moreover, your ideas for nature-based solutions have contributed to the outcome of my thesis, for which I want to thank you especially.
Floortje d'Hont, thank you for thoroughly reading my report from cover to cover and for giving such good advice for improvement. Your reflections have encouraged me to look at the topic from a different perspective: a perspective that I would not have obtained without your analyses.
Stefan Aarninkhof, thank you for leading this graduation committee and thus giving me the opportunity to execute this research. Moreover, your critical questions during progress meetings have repetitively put me to thinking and your endless enthusiasm on nature-based coastal engineering fueled my passion for the field.
And finally, Martijn Onderwater, thank you for our many catch-up moments ('even bijpraten') in which you took the time to discuss my progress and issues with the topic. Your ideas and advice on the report were indispensable. Your unstoppable enthusiasm about coastal protection and your positive mindset were very welcome when I thought I had made some fatal mistakes. I pity that all of our meetings were bounded to the internet, but the more fun it is to meet in person during my final presentation.

Secondly, I would like to thank my predecessors in exploring the morphology of the Brouwersdam beach, Wilbert Huibregtse, Reinier Schrijvershof and Arthur de Boom. Mainly in the beginning of my research period, you have shared your thoughts and data with me, without which the start-up of this thesis would not have been so smoothly.

Thirdly, I want to express my gratefulness to marine ecologists Karin Didderen and Theo Prins, for taking the time to consult me - as a non-ecologically educated civil engineer to be - on the environmental aspects of the topic. Your insights and recommendations have brought the quality research to a higher level. Thereby, I would like to thank Dick van Aalsburg, for your time and consultation on the feasibility of brushwood in coastal groynes, based on years of experience of your family business.

Finally, I would like to express my gratitude towards my roommates in Rotterdam: you were the best company one can imagine while writing this thesis during the pandemic. Without your support, laughter and strong coffee during our daily breaks, this year would not have been the same. Thereby, gratitude to my friends from het Waterbouwdispuut, for the endless amount of hydraulic jokes, which have made the Master's course a *dam* good period. Moreover, Hoyte, thanks for being my rock in the surf zone. At last, but definitely not least, I want to express my gratefulness to my family, for being unconditionally supportive, motivating and proud during the past seven years.

Pauline Janssen
Delft, June 2021

Abstract

The Brouwersdam is a dam located in the provinces Zuid-Holland and Zeeland of the Netherlands. The dam was built in 1971 for flood safety of the hinterland as part of the Delta Plan. It connects the islands Goeree-Overflakkee and Schouwen-Duiveland and separates the North Sea from the former Grevelingen estuary. After the construction of the Brouwersdam, the shoals Middelplaat and Kabbelaarsbank merged and formed one large shoal located adjacent to the seaside of the dam. This is referred to as the the Brouwersdam beach.

The beach has been eroding and shifting towards the northeast ever since. The beach has no safety function, as the hinterland is protected from flooding by the Brouwersdam. However, the beach has a large recreational value, which will decrease if no human interventions are taken. Consequently, many stakeholders demand the preservation of the beach. For the Municipality of Schouwen-Duiveland, the loss of recreational value of the beach is estimated to decrease the yearly financial benefits by 0.8 to 5.4 million €. Hence, their interest in the preservation of the beach is large and therefore they have commissioned this study. Because the beach is located in a high-quality nature reserve (Natura2000), environmental regulations apply and many stakeholders are concerned about the ecological value of a potential measure. There is thus a need to take measures that mitigate the erosion while enhancing the ecosystem. Moreover, protecting and improving the natural environment in hydraulic engineering projects is an essential part of responding to the changing climate.

This study aims to design nature-based solutions for the ongoing erosion and coastline shift to which the Brouwersdam beach is subjected. The design approach of this research is based on the Building with Nature (BwN) design steps. A thorough analysis of the physical, ecological and social system is followed by the set-up of a Program of Requirements (PoR) for the design. Based on the PoR, designs are identified, evaluated and selected iteratively.

Data analysis and a modelling study in Delft3D-WAVE and UNIBEST-CL+, as part of the physical system study, show that 80% of the net longshore sediment transport occurs during high water conditions. Moreover, during high water, wind-generated waves with a mean significant wave height of approximately 0.8-1.2 m approaching the beach from the west (occurring 20 days per year on average) are responsible for approximately 65 % of the yearly net sediment transport in the southern edge of the beach, which experiences the most severe erosion. A validated forecasting UNIBEST-CL+ model shows that without intervention, the beach will erode at the same rate until 2030, after which these developments will proceed at a lower pace as the southern part will slowly reach the equilibrium coastline orientation. The surface area between 0 and +3 m NAP will decrease from 73 ha (2018) down to 57 ha (2030) and then further towards 42 ha (2050).
A literature study on the ecosystem of the Grevelingen outer delta suggests that minimal construction nuisance and bed disturbances are vital for the habitats of the main species. Moreover, from the consultation of two marine ecologists it is concluded the creation of a shellfish reef as part of the solution is realistic and would enhance the ecosystem.
Insights in the social system, substantiated by stakeholder consultations, reveals that the decision-making process is mainly complex because of the lack of stakeholders with both a high interest and high power. Moreover, the recreational demands for the solution differ per recreational function of the beach, i.e. water sports, beach sports and bathing. The division of the ecological interest into functions, i.e. the habitats of the main species, shows that recreational and ecological demands can be conflicting. Both the recreational and ecological demands are represented in the PoR.

The design iterations, based on the systems' insights and the PoR, led to the creation of three Nature-based Solutions. The alternative solutions include the creation of a shellfish habitat by making structures of layered brushwood fascine mattresses filled with shells or other hard substratum (an idea that was posed by Marian Lazar, after which it was examined and worked out in this thesis). The shellfish

reef, in which mainly Japanese oysters are expected to settle, provides ecosystem services such as the enhancement of biodiversity, water quality improvement through filtering nutrients and contaminants and the provision of shelter for other species. Moreover, the structures can be constructed CO_2-neutral and contribute to the goal of the Dutch government to the enhance return and recovery of shellfish reefs in the North Sea. The Brouwersdam beach is suitable to serve as a pilot location for the innovative application of these structures, because of its shallow foreshore (resulting in a small groyne height and costs) and the presence of a natural shellfish reef close by. The different configurations of the solutions, ensuring coastal protection, are:

- A groyne configuration, creating multiple pocket beaches, of 1 straight groyne and 4 L-shaped groynes with an orientation slightly tilted towards the west, i.e., the dominant wave direction (Solution A)
- A straight groyne with a west-east orientation, combined with a sediment beach fill between the current coastline and the groyne (Solution C)
- A fishtail groyne, which is a structure with a slightly curved, shore-normal groyne arm and a shore-parallel breakwater arm (Solution E)

These solutions were compared with frequent nourishing (solution F) and to the reference situation, i.e. taking no action. The assessment of the solutions by means of a Multi-Criteria Analysis (MCA), based on the categories functionality, costs, recreational value (water and beach recreation separately), ecological value and aesthetics, led to the conclusion that the designs are equally feasible but score differently on the categories. The results of the MCA thus illustrate that the conclusion on the most feasible solution depends on priority (e.g., solution A is the cheapest but decreases water recreational value, whereas solution E maintains this value but is more expensive).

The study concludes that preserving the Brouwersdam beach in a nature-based way is feasible. The MCA tool can potentially support future decision-making processes following this study by clarifying the trade-offs between the different designed solutions. Further exploring the economical benefits of recreational functions will contribute to validating the weight factors in these categories. The results of this study contribute to the discussion on the preservation of the Brouwersdam beach and to the strive for knowledge on ecosystem-based projects within the field of hydraulic engineering.

Contents

List of Acronyms

1D	One-dimensional
2DH	Two-dimensional horizontal
BKL	Basiskustlijn
BwN	Building with Nature
LAT	Lowest Astronomical Tide
MCA	Multi-Criteria Analysis
MHW	Mean High Water
MLW	Mean Low Water
MSL	Mean Sea Level
NAP	Normaal Amsterdams Peil
NCV	Natuurcompensatie Voordelta
NPV	Net Present Value
PGB	Project Group Brouwersdamstrand
PoR	Program of Requirements

1 Introduction

1.1. Context

The Brouwersdam is a dam located in the Dutch provinces Zuid-Holland and Zeeland. The dam was built in 1971 for flood safety of the hinterland as part of the Delta Plan. It connects the islands Goeree-Overflakkee and Schouwen-Duiveland and separates the North Sea from the former Grevelingen estuary (depicted in Figure 1.1). After the construction of the Brouwersdam, the morphological and hydrodynamic conditions in the former estuary changed significantly. The remaining parts of the shoals Middelplaat and Kabbelaarsbank merged and formed one large shoal located adjacent to the seaside of the dam. This is referred to as the the Brouwersdam beach, hereafter the beach (indicated by the close-up in Figure 1.1). The beach was thus created as part of a natural, morphodynamic response to a human-made structure.

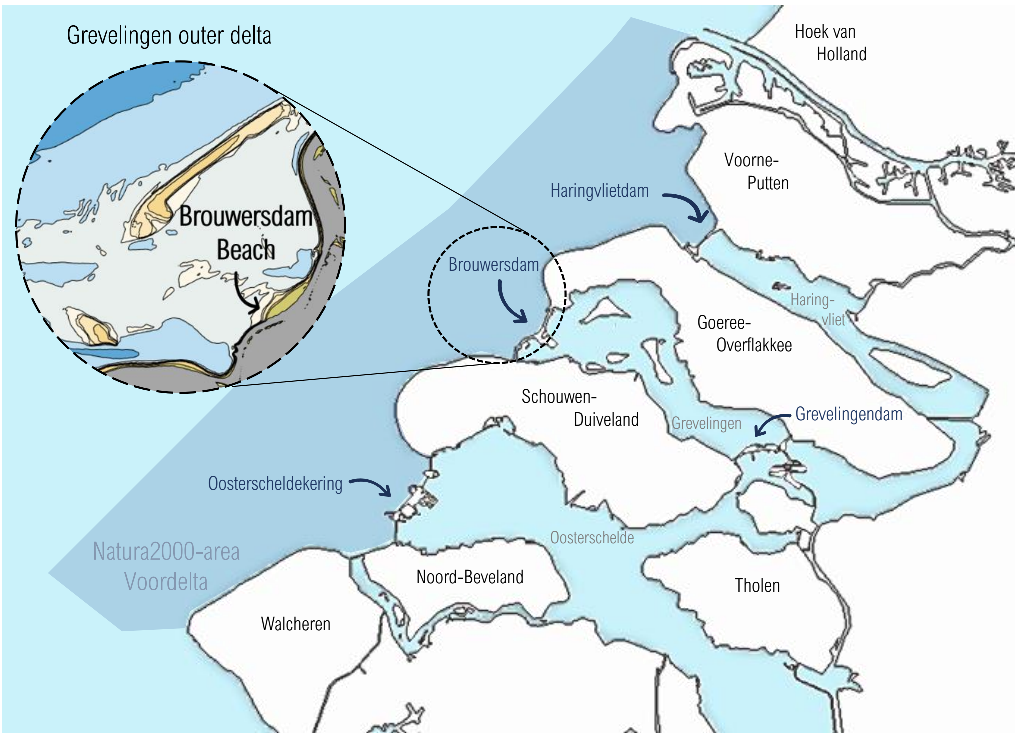


Figure 1.1: Overview of the study area in the Dutch provinces South-Holland and Zeeland: The southwestern Dutch delta with a close-up of the Grevelingen outer delta, in which the location of the Brouwersdam beach is pointed out. The Natura2000-area of the Voordelta is highlighted in darker blue.

The beach, depicted in Figure 1.2, has a significant recreational value. It is popular because of its suitability for activities like wind and kite surfing and kite buggying. The recreational activities are credited to support the local economy by 9 million €per year (Lazar & Elias, 2019).
Since the above described natural creation of the beach, it is shifting towards the northeast. In the past decades, the southern edge of the beach has shifted with 40 m per year in northeastern direction, and the beach surface area decreased with 1.5 ha per year. The shift to the northeast and the decreasing trend of the surface area is likely to continue in the future, and recreational values will be lost if no human interventions are taken. For Schouwen-Duiveland, the erosion of the beach has been estimated to have a negative economic effect of 0.8 to 5.4 million €/year (Arcadis, 2012).

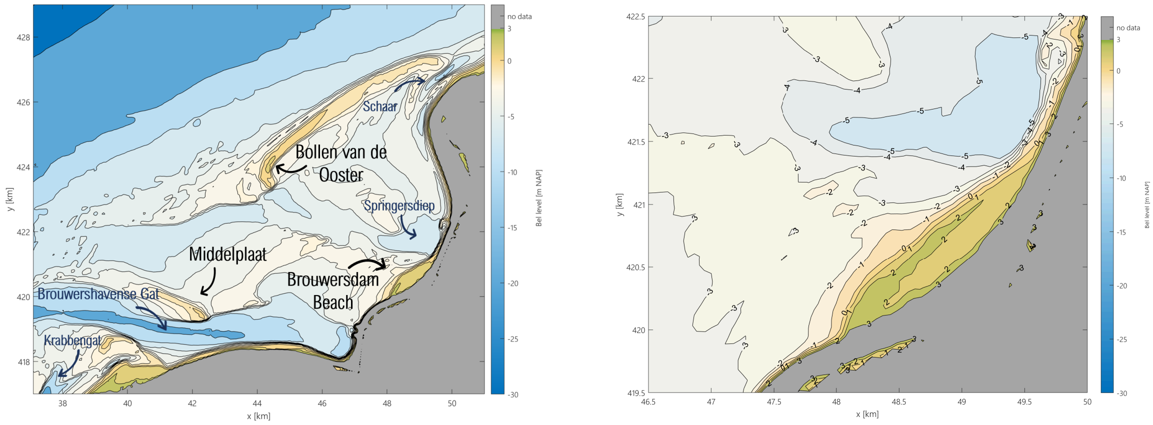
Figure 1.2: Aerial picture of the Brouwersdam and the adjacent beach. View is towards the coastline of Schouwen-Duiveland, i.e. the North Sea is depicted on the right side of the figure (photo made by Bram van de Biezen)

1.1.1. Study area

The beach currently has a length of approximately 2 km long, and the beach surface area (between 0 and +3 m NAP) covers approximately 66 hectares (Figure 1.3b). Aeolian transport in landward direction has led to the formation of an active dune row.

The beach is located in the Grevelingen outer delta, hereafter the outer delta (as shown in Figure 1.3a). The outer delta is the study area of this thesis. The outer delta's seaward boundary is located at the depth contour at -10 m NAP, which is approximately 8 km offshore of the Brouwersdam. The northern and southern boundaries are roughly situated in front of the coasts of Goeree-Overflakkee and Schouwen-Duiveland. The outer delta covers a surface area of approximately 100 km^2. The outer delta contains intertidal areas such as the Bollen van de Ooster and the Middelplaat and channels such as Brouwershavense Gat and the Springersdiep.

The study area is part of the Voordelta, which is the shallow coastal area with adjacent beaches in front of Zeeland and the southwestern part of Zuid-Holland, bounded by the continuous depth contour at -20 m NAP (Elias et al., 2016). The Voordelta is designated as Natura2000 area (as depicted in Figure 1.1). Natura2000 is a network of nature areas in Europe, in which certain plant and animal species and their natural habitats are protected with the aim of preserving biodiversity (European Commission, n.d.). Within Natura2000 areas, specific environmental regulations apply.



(a) Grevelingen outer delta

(b) Brouwersdam beach

Figure 1.3: Bathymetry of the Grevelingen outer delta and Brouwersdam beach, 2018-2019, derived from the Vaklodingen data set

1.1.2. Motivation

The loss of the beach and its recreational value is undesirable for many stakeholders, such as government agencies and local entrepreneurs; these stakeholders demand protective measures. The Municipality of Schouwen-Duiveland is one of these stakeholders and therefore commissioned this research. It is highlighted that frequent nourishments at the site would mitigate the erosion as long as the nourishing proceeds. However, in contrast to many other beaches in the Netherlands, the Brouwersdam beach does not fulfil a function for flood safety, as the hinterland is protected from flooding by the Brouwersdam. Therefore, it is not part of the Dynamic Coastal Preservation Program, meaning that the beach is not regularly nourished by Rijkswaterstaat. In 2016, the demand of the stakeholders for preservation of the beach resulted in a one-time beach nourishment of 500,000 m^3, as part of the pilot *Slimmer omgaan met zand op Schouwen*. The nourishment costs, paid by Rijkswaterstaat, were 4 million €, of which the regional stakeholders (Municipalities of Schouwen-Duiveland and Goeree-Overflakkee, Provinces of Zeeland and Zuid-Holland and local entrepreneurs) contributed 250,000 €(van den Heuvel & Rabelink, 2014). The need for preservation of the beach among stakeholders is thus large and ongoing. As nourishing is an expensive mitigation measure at this location, the Municipality of Schouwen-Duiveland is interested in cheaper solutions that increase the lifetime of a nourishment or even ensure that nourishing is not needed to preserve the beach.

In addition to stakeholders that demand the preservation of the recreational value, there are many stakeholders concerned about the environmental impact of a potential solution, especially because the beach is located in a high-quality nature reserve (Natura2000 area). The problem of the preservation of the beach is thus embedded in a complex social context, which complicates the decision-making process. Environmental legislation imposes certain requirements to a potential solution for the beach. Moreover, protecting and improving the natural environment in hydraulic engineering projects is an essential part of responding to the changing climate and, consequently, contributing to the achievement of the Sustainable Development Goals of the United Nations (van Eekelen & Bouw, 2020). Environmental enhancement is thus a necessary aspect in the design of a solution. In other words, a potential solution should be nature-based. nature-based solutions are, according to Cohen-Shacham et al. (2016), 'actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing well-being and biodiversity benefits'. An approach for the design of nature-based solutions for water-related infrastructure is the Building with Nature (BwN) approach (van Eekelen & Bouw, 2020). This five-step approach suits the design of a protective measure for the beach, as it uses natural forces to benefit economy, society and the environment and it is suitable for the design of coastal protection measures.

1.1.3. Knowledge gaps

Much research has been done in the past few decades regarding the morphodynamics in the Grevelingen outer delta. Among others, van der Spek & Elias (2021) conclude that the shift of the beach can be explained based on the distorted dynamic equilibrium of the former estuary. The morphological evolution of the shoreline has been simulated utilizing coastline models by Schrijvershof (2015) and Huibregtse (2013). However, the presence of complex flow patterns in front of the beach and the presence of a large active zone complicated the shoreline simulations with these models. Other model studies, such as Jansen et al. (2012) and de Boom (2016), have successfully simulated the current patterns and morphological developments in the outer delta. Still, the emphasis in these studies was not on coastline development: these coastal area models are therefore not applicable to predict the development of the beach. Moreover, despite several studies on the erosion of the Brouwersdam beach, an in-depth analysis of the sediment transports along the shoreline and the nearshore wave climate is lacking. Most important, a design study on possible solutions for the beach has not been conducted yet.

1.2. Research objective

This study aims to provide insight into the morphodynamics, social system and ecosystem in the vicinity of the Brouwersdam beach to design nature-based solutions for the ongoing erosion and shift to which it is subjected. The following research question is formulated:

What are alternative nature-based solutions to preserve the Brouwersdam beach?

To answer this question, six research sub-questions are formulated and two design phases are distinguished. These were established on the basis of the Building with Nature (BwN) design approach. The associated BwN design steps are depicted in Figure 1.4. The set-up of the sub-questions and design phases of this research is explained on the basis of the BwN design steps.

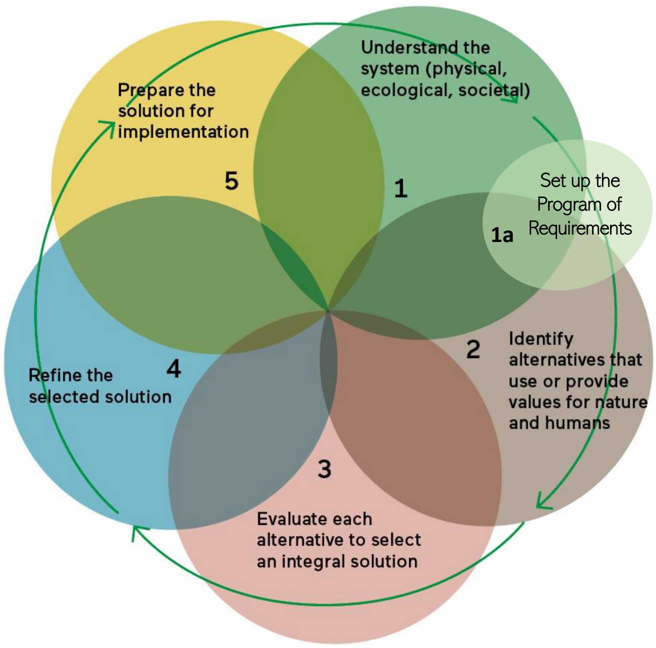


Figure 1.4: Building with Nature design steps, adapted from van Eekelen & Bouw (2020). The set up of the Program of Requirements is not included in the Building with Nature design steps, whereas this is an important step in the design process of this research. Hence, step 1a was added.

Research sub-questions

First of all, to be able to create nature-based solutions, the requirements that the solution must meet need to be determined. Hence, five sub-questions are formulated to understand the physical, social and ecological system (Sub-questions 1-5) and one to set up a Program of Requirements (Sub-question 6).

The answers to Sub-questions 1-5 are related to BwN design step 1 ('Understand the system (physical, ecological, societal)'). For this thesis, design step 1a is added to the BwN design approach. This extra step covers the set up of the Program of Requirements (PoR), relating to Sub-question 6. The research sub-questions are as follows:

1. What are the morphodynamic characteristics of the Grevelingen outer delta and the main morphological developments of the Brouwersdam beach?
2. Which features characterize the ecosystem of the Grevelingen outer delta and how can the solution potentially enhance the ecosystem?
3. Which stakeholders are engaged in taking a measure at the beach and which indicators reflect their goals and interests?
4. How are the longshore sediment transport rates temporally and spatially distributed along the shoreline, and which wave conditions have the largest contribution to the observed morphological evolution of the beach?
5. What is the expected future morphological evolution of the beach in the coming three decades?
6. Which requirements must a solution for the beach meet?

Design phases

Subsequently, the design process proceeds by identifying alternatives (BwN design step 2), evaluating each alternative to select an integral solution (BwN design step 3), and refining the selected solution (BwN design step 4). A remark is made on this linear appearance of the approach: in fact, the design process is performed iteratively. To report this iterative design process in an orderly manner, it is discussed in two design phases:

I. Identification, evaluation and selection - Identification of alternatives and evaluation to select the most feasible, integral solutions

II. Refinement and evaluation - Refinement and evaluation of the selected alternatives

The outcome of these design phases provides an answer to the main research question. The method applied to each of the sub-questions and design phases is discussed in Section 1.3. Note that the BwN design steps function as a basis for this research, but not all steps are taken. The identification of solutions for the beach is aimed to result in preliminary designs. In other words, the aim is to examine the possibilities, rather than providing designs that are ready for implementation. Hence, BwN step 5 ('Prepare the solution for implementation') is excluded from this research.

1.3. Methodology

Table 1.1 presents an overview of the sub-questions and design stages. The table includes the associated Building with Nature step, the main focus of the question or phase and the applied method. The content of this table is discussed below.

The aim of **Sub-question 1** is to get acquainted with the morphodynamic characteristics of the entire Grevelingen outer delta and the erosion and shift of the beach. To achieve this, a data analysis is performed. The most important sources of the examined data are the Jarkus data set (yearly measurements of the coastal profile), hydraulic data of nearby measurement stations and the existing Delft3D-FLOW model that was set up by Jansen et al. (2012).
Sub-question 2 focuses on the main features of the ecosystem, aiming to find ways in which the ecosystem can potentially be enhanced by the solution. This question is answered by means of a literature study and an expert judgement by two marine ecologists.
Sub-question 3 is associated with the analysis of the social system. The identification and categorization of the main stakeholders is established by means of a literature study, in partial collaboration with the Municipality of Schouwen-Duiveland. The main outcomes are discussed with the currently involved stakeholders.

Sub-question 4 and 5 relate to a modelling study, in which a Delft3D-WAVE model and a UNIBEST-CL+ coastline model is set up. This modelling study has three goals, namely: providing insight into the temporal and spatial distribution of the sediment transports and the contribution of different wave conditions (**Sub-question 4**), obtaining a sufficiently accurate prediction of the future shoreline development (**Sub-question 5**) and providing a tool that can be used to assess the (erosion mitigating) efficiency of different solutions (which is used for the evaluation in Design phase I).
Sub-question 6 focuses on the set-up of the Program of Requirements (PoR). The PoR can be seen as a summary of the main aspects of the system analyses.

Subsequently, as the system is sufficiently understood to be able to identify nature-based solutions, the research proceeds with **Design phase I**. Different erosion mitigation measures are investigated, which results in an overview of possible solutions. For each of these solutions, a first assessment of the feasibility is made. This assessment is done with a concise Multi-Criteria Analysis (MCA) based on the PoR. The functionality of the solutions is assessed based on shoreline simulations with the forecasting UNIBEST-CL+ coastline model. The most feasible solutions are selected. Subsequently, the selected solutions are refined in **Design phase II**. This includes the creation of more detailed designs. Then, these solutions are evaluated for a second time using an MCA, but now more extensively and based on the entire PoR.

Table 1.1: Method and focus of the research sub-questions and design phases, and the associated Building with Nature design step (indicated in the second column).

	BwN	**Focus**	**Method**
Sub-question			
1	1	**Physical system** Morphodynamic behaviour of beach and outer delta	**Data analysis** (Jarkus data, hydraulic measurement data, Delft3D-FLOW model results)
2	1	**Ecological system** Ecosystem characteristics, potential enhancement of ecosystem	**Literature study** || **Expert judgement**
3	1	**Social system** Stakeholder identification and categorization, translation of interest into indicators	**Literature study** || **Stakeholder sessions**
4	1	**Physical system** Longshore transport and nearshore wave climate	**Modelling study** (Delft3D-WAVE & UNIBEST-CL+ hindcast)
5	1	**Physical system** Expected future beach developments	**Modelling study** (UNIBEST-CL+ forecast)
6	1a	**Program of Requirements**	**Summarizing system analysis** || **Consultation** (Municipality of Schouwen-Duiveland) || **Stakeholder sessions**
Design phase			
I	2	**Identification of alternatives**	**Literature study**
	3	**Evaluation and selection**	**Modelling study** (UNIBEST-CL+ forecast model) ||**MCA** (concise, based on PoR)
II	4	**Refinement**	**Literature study** || **Expert judgement**
	3	**Evaluation**	**MCA** (extensive, based on PoR)

1.4. Scope

The research has several temporal and spatial delineations, which are discussed in this section.

The design period of this thesis is related to the period in which the feasibility of the designs can be ensured with sufficient certainty. As the beach is situated in a highly morphodynamic environment and spatial developments occur at a high pace, it is expected that after a certain period of time the demands on the preservation of the beach have changed or the preservation of the beach is no longer feasible. Moreover, the temporal horizon should be such that a reasonable prediction of the shoreline development can be made (i.e. a period in which the boundary conditions stay more or less equal to the present situation). Resulting from these two requirements, the temporal horizon of this thesis is up to 2050 (a period of 30 years). The solutions are thus designed for this period.

The spatial research domain is limited to the outer delta. The focus is, evidently, on the beach.
The social system is focused on the stakeholder analysis and is investigated in a descriptive manner. This means that the currently engaged stakeholders are examined and that the future developments in the social system are not examined. Moreover, direct interest and power of stakeholders with respect to decision-making on the preservation of the beach is investigated; a study on relations between stakeholders and the institutional context is not included in this research.

1.5. Thesis outline

This thesis is divided into twelve chapters. The structure of the report is represented in the flow diagram of Figure 1.5. The grey, rectangular boxes indicate a chapter, whereas the circled numbers refer to the associated chapter. The coloured boxes resemble the Building with Nature design steps as indicated in Figure 1.4.

The report starts with a literature study performed to get acquainted with the research area and present state of knowledge in Chapter 2. Chapter 2 up to 7 provide answers to the sub-questions (the flow diagram indicates which sub-question is discussed in which chapter). Subsequently, Chapter 8 and 9 present the findings of the design iterations in Design phase I and II. The methodology and interpretation of the results are discussed in Chapter 10. Thereafter, the answers to the sub-questions are summarized and conclusions are drawn (i.e. the answer to the main research question is given) in Chapter 11. The thesis is finalized with recommendations in Chapter 12.

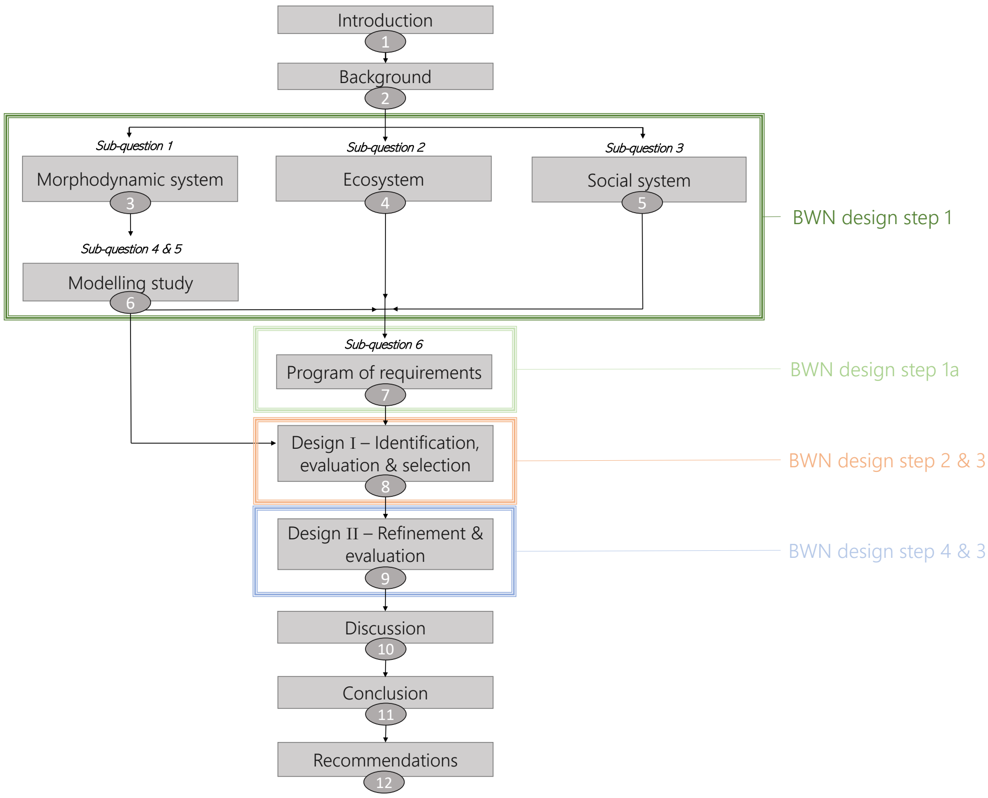


Figure 1.5: Flow diagram of methodology. The numbers indicate associated chapter. The colored boxes resemble the Building with Nature design steps as indicated in Figure 1.4

2

Background

This chapter provides the general background information that forms the basis for the study. The Building with Nature philosophy and approach are treated in Section 2.1. Section 2.2 and 2.3 respectively give the theoretical background on tidal inlets and the single line theory. Section 2.4 elaborates on the three-stage conceptual model of morphological developments in ebb-tidal deltas caused by damming of an estuary. Finally, the morphological history of the southwest Dutch Delta is discussed in Section 2.5.

2.1. Building with Nature

Building with Nature is, according to van Eekelen & Bouw (2020), 'a conceptual approach to creating, implementing and upscaling Nature-based Solutions for water-related infrastructure.' This implies working with nature, rather than against it. This section elaborates on the philosophy behind this approach and on the five steps that need to be taken when developing a Building with Nature design.

2.1.1. Building with Nature design steps

To generate a Building with Nature design, five steps are identified. These steps are depicted in Figure 1.4 and are explained in more detail below. Reference is made to Ecoshape (2020) and van Eekelen & Bouw (2020). The set up of the Program of Requirements is not included in the Building with Nature design steps, whereas this is an important step in the design process of this research. Hence, step 1a is added, in which the Program of Requirements is set up.

1. **Understand the system (physical, ecological and societal)**
   The approach starts from understanding the functioning of the system. This includes mapping the natural, physical and societal systems, together with the services they can provide for both humans and nature. The functions of a system determine the impact on the goal of the project.

2. **Identify alternatives that use or provide value for nature and humans**
   The solution should not only provide compensation and mitigation but should use the potential of the system as much as possible.

3. **Valuate each alternative to select an integral solution**
   This includes the determination of the qualities of the alternatives to create an optimal and integral solution. In this step, innovative ideas are tested and a comparison with traditional designs is being made. The uncertainties should be identified and a business case should be developed, including benefits to nature and humans. The involvement of stakeholders in the valuation and selection is necessary.

4. **Refine the selected solution**
   Conditions and restrictions follow from the societal and practical context should be considered before the implementation of the project.

5. **Prepare the solution for the implementation**
   On the way to realisation, the practical difficulties have to be handled to implement the solution in the next phase. This implies the preparation of action plans, risk analyses, contracts and other project-related documentation.

2.2. Classification of tidal inlets

Tidal inlets are openings in the shoreline connecting bays or lagoons to the open ocean (Bosboom & Stive, 2015). The classification of the tidal inlet is of importance for the Grevelingen outer delta, whose character changed due to the construction of the Brouwersdam.
A tidal inlet is influenced by both wave and tidal influences (Bosboom & Stive, 2015). Tidal currents maintain the inlets. In other words, tidal currents keep them from closing. The classification of Davis and Hayes (1984) distinguishes five tidal inlet classes, based on the relative influence of waves and the tide.

Generally, a wave climate is characterized by the mean significant wave height H_s (based on yearly average). Three classes can be distinguished: Low wave energy H_s < 0.6 m, medium wave energy 0.6 m < H_s < 1.5 m and high wave energy H_s > 1.5 m. With a value of $H_s = 1.1$ m at the seaward side of the inlet, (Chapter 3.2.2), the Grevelingen outer delta has a medium wave energy character.
Tidal environments are mostly distinguished on the basis of the magnitude of the tidal range and on the tidal character (dominance of the diurnal or semi-diurnal components). Davies (1980) distinguishes three tidal regimes, based on the mean spring tidal range R (MHWS-MLWS, i.e. Mean High Water Spring and Mean Low Water Spring). The mean spring tidal range is for a micro-tidal regime R < 2 m, a meso-tidal regime 2 < R < 4 m and a macro-tidal regime R > 4 m. The mean spring tidal range currently present in the Grevelingen outer delta is 2.90 m and is therefore characterized as a meso-tidal regime. Based on the combination of this value with wave energy characterized by a mean significant wave height of 1.1 m, the coastal system is classified as mixed-energy (tide-dominated), according to Figure 2.1.

Damming of an inlet leads to a shift of inlet class and therefore to major morphological changes. This is caused by a reduction of tidal energy whereas the mean wave energy is maintained. The reasoning behind this is further explained in Section 2.4 and the site-specific changes in the Grevelingen outer delta are discussed in Section 2.5.1.

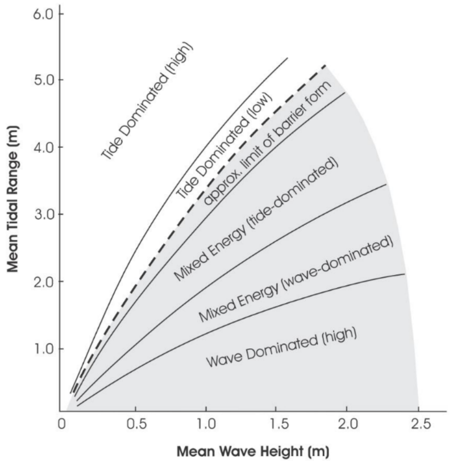


Figure 2.1: Tidal inlet classification based on the combination of the tidal range and wave energy based on the method of Davis and Hayes. Retrieved from Masselink and Hughes (2003)

2.3. Single line theory

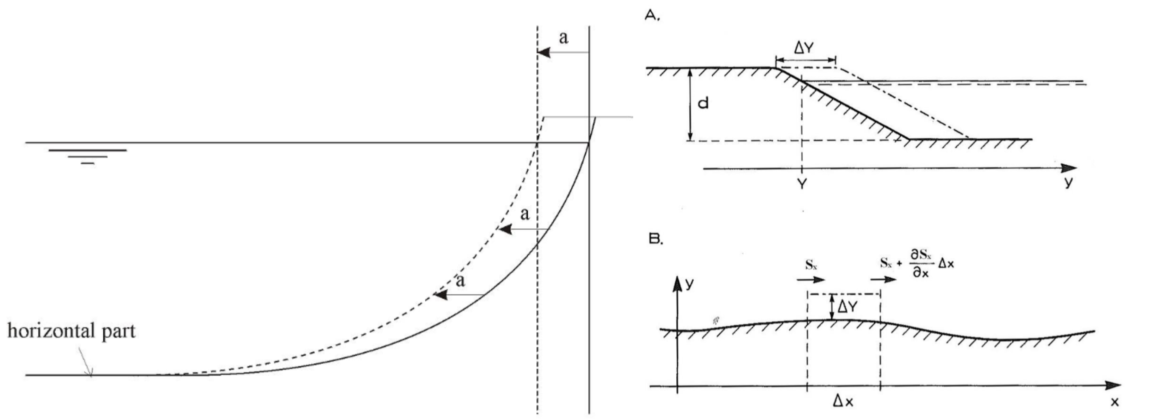
The single line theory is discussed in this section, because this theory is the basis of the 1D coastline model UNIBEST-CL+, which is used in the modelling study of this research.

Spatial and temporal fluctuations in sediment transport rates determine the morphological changes in coastal systems (Bosboom & Stive, 2015). This is expressed with the following sediment balance:

$$\frac{\delta z_b}{\delta t} + \frac{\delta S_x}{\delta x} + \frac{\delta S_y}{\delta y} = V \tag{2.1}$$

In Equation 2.1, $z_b(x, y, t)$ is the bed level above a certain horizontal level [m], $S_x(x, y, t)$ and $S_y(x, y, t)$ are the sediment transport rates per meter width of flow in the x- and y-direction (both horizontal) $[m^3/m/s]$ and $V(x, y, t)$ represents local gains or losses, also referred to as the sink or sources term per unit area $[m^3/m^2/s]$. For zero sinks or sources, it can be said that the coastline recedes in case of an increasing longshore sediment transport rate ($\frac{\delta S_x}{\delta x} > 0$) and vice-versa. To solve the coastal change from the sediment balance (Equation 2.1) for a coastline where wave-induced longshore transport is dominant, the problem can be solved by simplification. A coarse schematization of the coastline is made by the single line theory. The main assumption in this theory is that the shape of the coastal profile is constant along the coast or during a certain period of time, implying an equilibrium cross-shore profile. The coastline is thus a single line, moving seaward or landward, determined by the sediment balance. Another basic assumption is that there is a long-term trend in shoreline evolution. Both assumptions are reasonable in the case of the Brouwersdam beach.

The equilibrium profile is defined between a lower and an upper limit. For the lower limit, the closure depth [1] is usually taken, as bed level changes seaward of this point are assumed not to contribute to coastline dynamics. The upper limit depends on the sediment balance of the coast, more specifically: whether the coast erodes or not. The upper limit of an eroding coast should be the dune height to include volume changes of the dunes. For accreting coasts, the upper limit depends on the high water level in combination with a normative wave run-up.



(a) Schematized beach profile in single line theory

(b) Cross shore beach profile (A.) and top view (B.) with longshore transport S_x and coastline change ΔY in a coastline model.

Figure 2.2: Coastal schematization in single line theory (Bosboom & Stive, 2015)

An arbitrary coastal stretch is considered to elaborate on the governing equations of this theory. The y-axis is perpendicular to the coast, the x-axis is more or less parallel to the coastline (Figure 2.2b). The position of the coastline that is considered is at y = Y. To compute the shoreline changes, the wave conditions in the horizontal part of the profile are necessary, as the angle of wave incidence relative to

[1] The morphologically active zone extends (for coastal engineering practices) from the first dune to a short distance offshore of the breaker zone. The 'boundary' is set at the depth relative to MSL of about two times the extreme wave height (since breaking depth $h_b = \frac{H_b}{\gamma}$, with wave height H_b at which waves break and with breaker parameter γ being smaller than 1). The annual closure depth of Hallermeier defines extreme conditions as conditions that are exceeded for example twelve hours per year, similar to using the 1% wave height $H_{0.1\%}$ in the calculation.

the coastline ϕ is an important factor in determining the sediment transport S_x. In time interval δt the sediment balance can therefore be written as:

$$\frac{\delta Y}{\delta t} + \frac{1}{d}\frac{\delta S_x}{\delta \phi}\frac{\delta \phi}{\delta x} = 0 \tag{2.2}$$

The term $\frac{\delta S_x}{\delta \phi}$ can be determined with several sediment transport formulae. The term $\frac{\delta \phi}{\delta x}$ relates directly to the position of the shoreline Y. The position of the coastline changes in time due to gradients in sediment transport, and therefore the coastline rotates with an angle $\frac{\delta Y}{\delta x}$, implying a reduced angle of wave incidence ($\delta \phi = -\frac{\delta Y}{\delta x}$. Combining this with Equation 2.2 gives:

$$\frac{\delta Y}{\delta t} - \frac{1}{d}\frac{\delta S_x}{\delta \phi}\frac{\delta^2 Y}{\delta x^2} = 0 \tag{2.3}$$

This parabolic equation is, in general, solved numerically, for instance in coastline models such as UNIBEST-CL+. With this equation, the (S, ϕ)-curve can be constructed, by changing the wave angle with respect to the fixed coastline.

2.4. Conceptual model for ebb-tidal delta evolution after damming

There is a large volume of published studies describing the large-scale morphodynamic changes caused by blocking of the tidal flow in an estuary or tidal inlet. Among others, van der Spek & Elias (2021) analysed the morphological changes at the estuaries Brielse Maas, Haringvliet and Grevelingen in the Netherlands and summarized the observed development of the ebb-tidal deltas caused by damming of an estuary or tidal inlet in a three-stage conceptual model. This conceptual model is useful in the understanding of the current morphodynamic developments in the Grevelingen outer delta, including the development of the beach. The model consists of three stages. In each stage, the size of the ebb-tidal delta is further reduced. The model provides a first indication of the expected changes after interventions in estuary mouths and tidal inlets (van der Spek & Elias, 2021).

Phase 1: Open inlet - dynamic equilibrium (Figure 2.3, upper left panel)
The ebb-tidal currents (bringing sediment seaward, forming shoals) and waves (bringing sediment landward, breaking on the shoals) are in dynamic equilibrium. This implies a balance between the large-scale morphology and the forming physical processes.

Phase 2: Closed inlet - distorted state (Figure 2.3, upper right panel)
The dam causes the tidal prism to reduce significantly and a less abrupt reduction in ebb discharge. Hence, seaward directed transports in the main channels are reduced and thereby landward transport by waves is increased. The delta front erodes and shore-parallel intertidal shoals emerge, mainly due to wave-driven cross-shore transports. In the sheltered part of the outer delta, the (inter)tidal bars reduce in height. The seaward part of the tidal channels fill in with mainly mud, whereas the landward parts adjust to the new tidal flow pattern parallel to the shoreline.

Phase 3: Infilling basin (Figure 2.3, lower left panel)
The ebb-tidal delta is still undergoing changes and can be seen as a new, smaller tidal basin. A shore-parallel bar shelters the area. The erosion of the delta front and this bar continue. The basin morphology is not yet in equilibrium with the new, smaller tidal prism. The channels are still relatively deep and mud and sand is deposited at a high pace. The relief of the basin is gradually being levelled because the cross-shore tidal flow is too small to maintain the former bathymetry of channels and shoals. Wave action induces shoals and island beaches to erode and causes sediment deposition in the channels. Because the landward movement of the delta front slows down over time, the shore-parallel bar loses height, will breach and will eventually merge with the shallow shoals. The expectation is that sedimentation of the area continues up to the point that the deposits (which may be enhanced by an extra sediment import from adjacent areas) fill the basin entirely, merging it with the shoreline and thus building out the coastal plain.

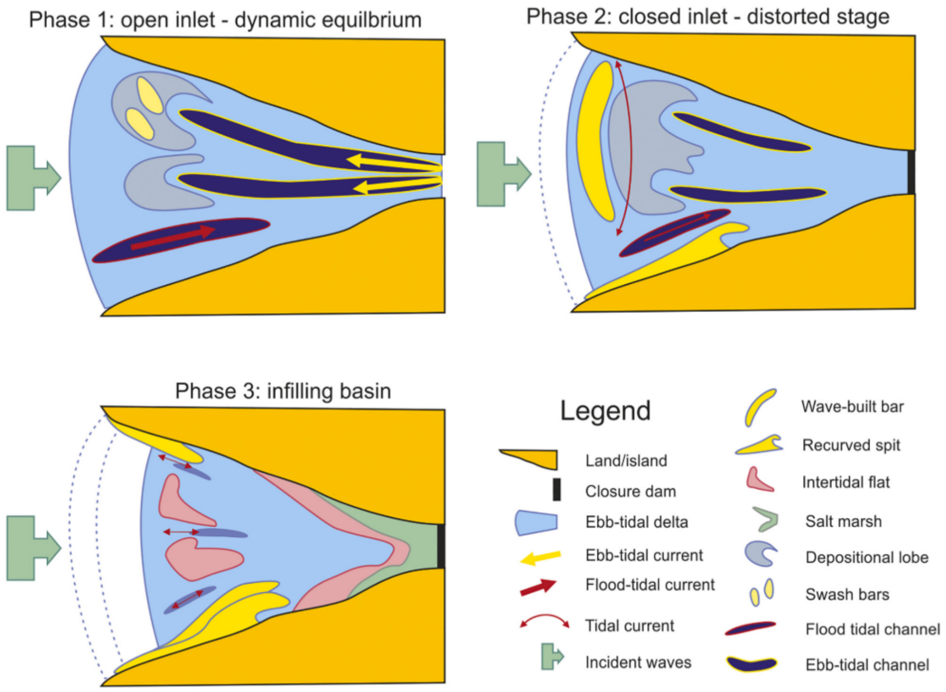


Figure 2.3: Conceptual model for ebb-tidal delta evolution after a significant reduction in cross-shore flow, based on the evolution of the Haringvliet and Grevelingen outer deltas between 1964 and 2015 van der Spek & Elias (2021).

The scale and speed of the changes in the model depend on local conditions such as the level of exposure, surface area and the amount of sediment supply. For example, the Grevelingen outer delta evolves slower than the Haringvliet outer delta, because large-scale import of sediment is absent and sediment is lost to the northeast due to wave-driven transport at the delta front. In addition, waves impact the Grevelingen outer delta from all directions, as well as north-south tide-induced currents at the seaward egde. Thus, reworking dominates over the landward transport of sand (van der Spek & Elias, 2021).

2.5. History of the southwest Dutch Delta

In the year 1953, a large part of the Dutch Delta was flooded during a storm surge event. This disaster led to the idea of the Delta Plan, a project which contains the closure of all tidal inlets in the South-West, except for the access channels in the to the ports of Rotterdam and Antwerp (the Waterweg and the Western Scheldt) (Nipius, 1998). The structures that have influenced and still influence the development of the Grevelingen outer delta are the Grevelingendam (1964), the Volkerakdam (1969), the Haringvlietsluizen (1971), the Brouwersdam (1971) and the Oosterscheldekering (1986) (Nipius, 1998). In 1962, the construction of the Brouwersdam in the Grevelingen estuary started. The construction started at the shoals Middelplaat and Kabbelaarsbank. Afterwards, the channel Springersdiep was closed with caissons and the Brouwershavense Gat was closed off with concrete elements. Construction was finished in 1974 (Aarninkhof & van Kessel, 1999). The (partial) damming of the estuaries led to the reduction of the tidal volumes of the estuaries, and thus changed the local tidal current patterns significantly. The Delta works therefore had a large impact on the morphology of the Voordelta, which already knew a large natural morphological activity (Stigter et al., 1990).

2.5.1. Morphological development of the Grevelingen outer delta

Two periods in the morphological development of the outer delta are distinguished: before and after the construction of the Brouwersdam. In other words, before and after closure of the Grevelingen estuary.

Before closure

Before the Grevelingen estuary was closed of, the largest channels in the ebb tidal delta were the southern, flood dominant Brouwershavense Gat channel (over 30 meters deep), and the northern, ebb dominant channel Springersdiep (Elias et al., 2016) (see Figure 2.4, upper panel). The latter confluences

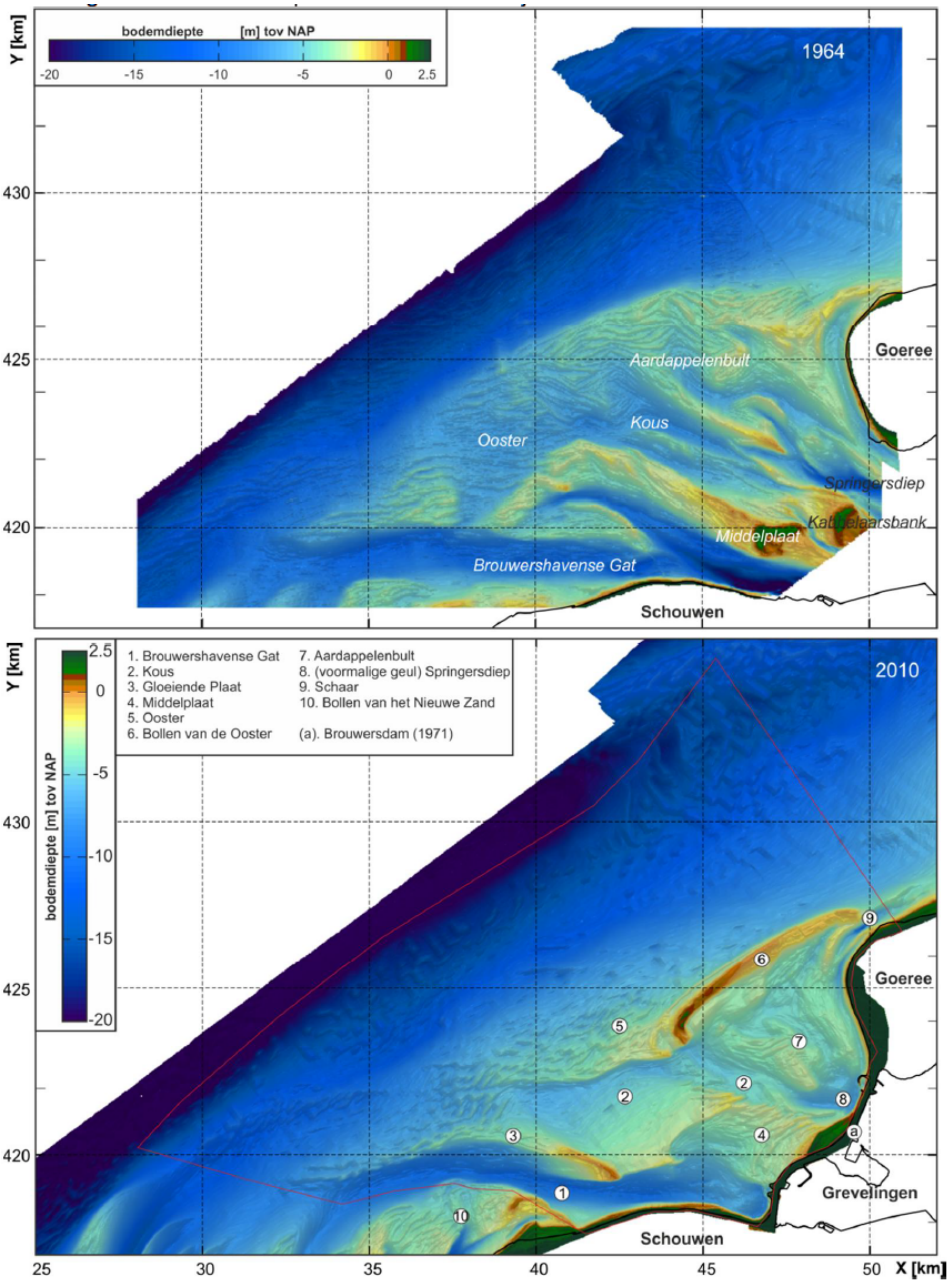
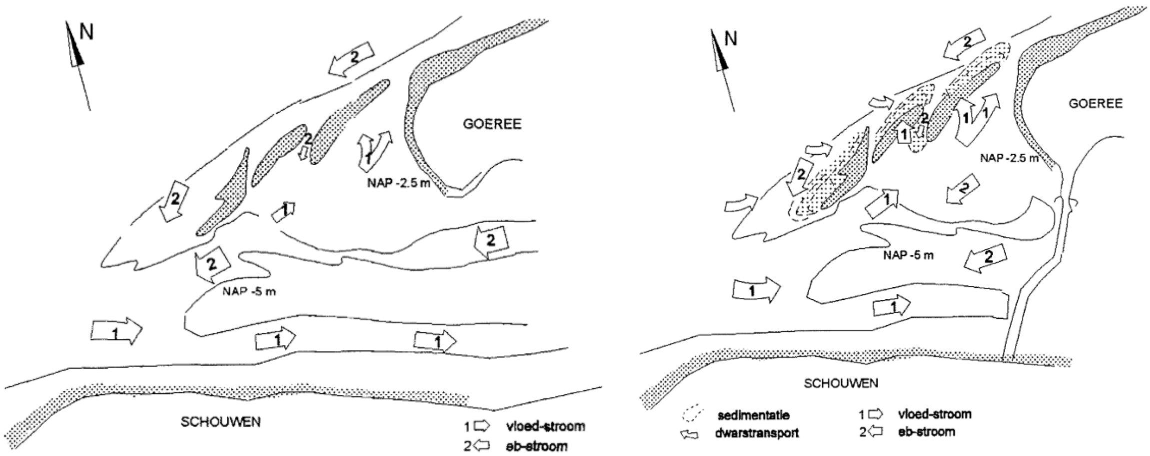


Figure 2.4: Overview of the bathymetry of the Grevelingen outer delta in 1965-1967 (upper panel) and in 2010-2011 (lower panel). Obtained from van der Spek & Elias (2021)

with the channel Kous, near Goeree. These channels, both orientated East-West, separated the shoals Kabbelaarsbank and Middelplaat (Elias et al., 2016). The water motion in the inlet was dominated by the cross-shore tidal current in and out the tidal inlet (Aarninkhof & van Kessel, 1999). The tidal flow direction was predominantly East-West (Nipius, 1998), depicted in Figure 2.5a. A dynamic equilibrium was present between the seaward force of the tidal current flowing in and out of the estuary and the landward, wave driven current and sediment transport (Phase 1 of the conceptual model of Section 2.4). The estuary had an approximate tidal prism of 360 million m^3 (Sha & van den Berg, 1993). Between 1933 and 1959, human interference induced a loss of tidal prism of the Grevelingen (while increasing the tidal prism of the Eastern Scheldt) (Elias et al., 2016).

In 1965 the construction of the Grevelingendam was finished, separating the Grevelingen estuary from the Eastern Scheldt (Elias et al., 2016). This turned the Grevelingen into an estuary without any connection to other estuaries and thereby the tidal prism was reduced by 14% (Elias et al. (2016); Cleveringa

(2008)).



(a) Before closure

(b) After closure

Figure 2.5: Current patterns in the Grevelingen outer delta before and after construction of the Brouwersdam (Nipius, 1998)

After closure

In 1971, the construction of the dam was almost finished and the Grevelingen and its ebb-tidal delta were separated (Phase 2 of the conceptual model of van der Spek & Elias (2021)). The Grevelingen estuary turned into a salt-water lake (Elias et al., 2016). The shore-normal, estuary-driven tidal current was reduced to zero (van der Spek & Elias, 2021). The influence of the northeast to southwest directed tidal flow (shore-parallel) on the outer delta increased (Nipius, 1998). In other words, tidal currents were still present, but these were now determined by the North-Sea tide instead of by the estuary. This induced a circular tidal flow pattern through the former tidal channels (van der Spek & Elias, 2021). The change in current pattern disrupted the balance between tidal versus wave-driven transport (Elias et al., 2016). The wave-induced erosion on the foreshore, which was compensated by tide-induced sedimentation before closure, now prevailed. In other words, the character of the coast has shifted from tide-dominated to wave-dominated (Figure 2.1). The wave climate and the tide started to change the form of the outer delta (Nipius (1998); Cleveringa (2008)). The current patterns and transport mechanisms before and after construction are depicted in Figure 2.5b.

In order to enhance the water quality of the Grevelingen lake, in 1978 the Brouwerssluis was constructed. This structure is used to flush the surface water of the lake and to let seawater in. It has a maximum discharge of 25 m^3/s and has a fish passage (Nipius, 1998). The discharge through this inlet did not have a significant influence on the morphodynamic changes in the outer delta.

In Figure 2.4, an overview of the bathymetry of the Grevelingen is depicted in the years 1964 and 2010. The morphological changes that took place between 1964 and 2010 are listed below (Phase 3 of the conceptual model of van der Spek & Elias (2021)). It must be highlighted that surface area of the ebb-tidal delta reduced, but the volume decrease was significantly smaller than would be expected based on existing relationships because the transport of eroded sediment towards the estuary is blocked by the dam (Elias et al., 2016). There is even a small net increase in the sediment budget. Part of this gained sediment must be eroded from the Banjaard shoal (which is part of the Eastern Scheldt ebb-tidal delta) (Elias et al., 2016).

- Erosion due to waves and landward movement of the ebb-tidal delta shoreface (down to -10 m NAP) (Elias et al., 2016). The northwestern side of the former shoal Ooster erodes. The sediment transport is onshore directed which forms an elongated, shallow shoal that shows a landward displacement (van der Spek & Elias, 2021). This north-south orientated shoal is called the Bollen van de Ooster. It took until 1999 to form a more or less continuous sand bar (van der Spek & Elias, 2021). The eroded sediment also partly filled in the former tidal channels (Cleveringa, 2008) and was transported towards the northeast along the coast of Goeree (Elias et al., 2016).

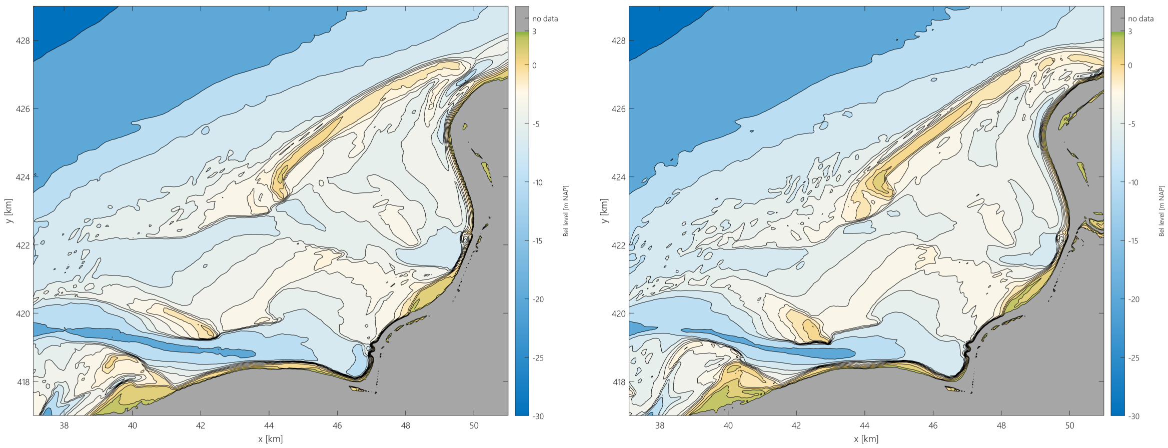
- A reduction of the total surface area and a change in the shape of the most seaward part of the ebb-tidal delta. The concave-up profile of the ebb-tidal delta changed into a convex profile (Cleveringa, 2008).

- Deposition takes place in channels Kous and Springersdiep, partly fed with sediment from the adjacent shoals (van der Spek & Elias, 2021).

- Deposition of mainly mud in the Brouwershavense Gat. Since 1998 the depth of the channel is more or less -10 m NAP (Aarninkhof & van Kessel, 1999). However, due to the offshore directed expansion of the Gloeiende Plaat, the volume of the gully has decreased.

- Erosion of the former shoals Middelplaat and Kabbelaarsbank, which are no longer maintained by tidal movement (Elias et al., 2016). Deposition of the eroded sediment takes place in front of the Brouwersdam, creating the beach. Aeolian transport in landward direction forms an active dune row.

Several of these morphological developments are still proceeding. The Grevelingen outer delta is still in phase 3 of the conceptual model of van der Spek & Elias (2021). The recent developments of the bed can be seen in Figure 2.6, in which an overview of the bathymetry in the years 2009-2010 and 2018-2019 is depicted.



(a) 2009-2010

(b) 2018-2019

Figure 2.6: Overview of the bathymetry of the Grevelingen outer delta in the years 2009-2010 and 2018-2019, derived from the Vaklodingen data set.

3 Data analysis

This chapter provides an answer to Sub-question 1: *What are the morphodynamic characteristics of the Grevelingen outer delta and the main morphological developments of the Brouwersdam beach?*

The first section gives an overview of the data used for this study (Section 3.1). Section 3.2 examines the hydrodynamic forcing mechanisms in the Grevelingen outer delta (tide, waves, wind). The bed composition in the study area is discussed in Section 3.3. Section 3.4 analyses the morphological evolution of the beach from 1990 up to the present state. The last section of this chapter (Section 3.5) provides a summary of the content of the chapter.

3.1. Data sources

The research data in this thesis are drawn from a couple of main sources. A distinction is made between hydraulic data and bed level data.

3.1.1. Hydraulic data

Hydraulic data (waves, tides, water levels, etc.) are collected using public online data, based on long-term measurements provided by Rijkswaterstaat. Rijkswaterstaat collects these data via Hydro Meteo Centra in the vicinity of the Grevelingen outer delta and provides them online from www.waterinfo.nl (Rijkswaterstaat, n.d.-b). The locations of the nearest stations to the beach are depicted in Figure 3.1. Per station, wave data (height, period, direction), wind data (speed, direction) or water level data (elevation) are collected.
The applicability of a data set depends, among others, on the size of the data set and the location of the data set relative to the study area. Therefore this research uses data from different measurement stations.

Waves

Locations Europlatform, Lichteiland Goeree, Schouwenbank provide complete wave data sets containing wave height, wave period and wave direction. The start of the observations, and therefore also the size of the data set, differs. The wave analysis in this research is based on Schouwenbank wave data because the wave modelling results showed that the existing reduced wave climate of this data set resulted in sufficient accurate nearshore wave conditions compared to hand calculations (see Section 6.2 for further elaboration). All relevant wave parameters are collected at Schouwenbank since 2002.

Wind

The closest station collecting wind data is Brouwershavense Gat 02. Besides its location, this station contains the most reliant wind data set with observations starting in 1982 and is therefore used for this research.

Figure 3.1: Hydrodynamic measurement stations Rijkswaterstaat near the Grevelingen outer delta (modified from www.waterinfo.rws.nl). A blue color means the station wave measurements are available, yellow indicates that water levels measurements are available.

Water level

The closest water level observations are collected at Brouwershavense Gat 08, located approximately 2 km south of the beach. Characteristic water level values relative to NAP are summarized in Appendix A.

Currents

Tidal current data are based on a numerical model, as current speed observations lack the Grevelingen outer delta. A recent Delft3D morphological and flow model was set up by Jansen et al. (2012) to assess the morphological effects of reintroducing the tide in Lake Grevelingen. This flow and morphological Delft3D-FLOW model, referred to as the Brouwersdam model, was set-up in this study for 2000-2010. This Brouwersdam model is calibrated with the larger scale Voordelta Delft3D flow model (validated for the Grevelingen outer delta by Delft Hydraulics (de Jongste et al., 2013)). This model's capability to simulate the morphodynamic behaviour of the outer delta is further verified by a comparison between the observed and simulated erosion-sedimentation patterns around the Bollen van de Ooster. This model can predict the morphological behaviour of the Grevelingen outer delta quite well (de Jongste et al., 2013). The tidal flow simulations of the Brouwersdam flow model serve therefore as a basis for this study. Therefore, it is important to underline the limited validation of the Brouwersdam flow model for the tidal current pattern near the beach. With a grid resolution of 50-80 m and without observations to validate the model, this flow model can be used to get insight into the current pattern, but the flow velocities near the beach are interpreted with caution.

3.1.2. Bed level data

Rijkswaterstaat measures regularly the development of the bed level. The two types of bed level measurements that are used in this thesis are:

- **Vaklodingen**
  Vaklodingen data are bed level measurements in certain compartments (*vakken*) executed once per 3 or 6 years. The measurements extend to approximately the -20 m depth contour and are interpolated and combined into a grid with a resolution of 20x20 m (Rijkswaterstaat, n.d.-a). Vaklodingen data of the Grevelingen outer delta are available from 1964 up to 2018-2019.

- **Jarkus**
  Jarkus measurements are yearly coastal measurements of Jarkus rays. Jarkus rays are imaginary cross-shore profiles with an intermediate distance of 200 to 250 m. These rays extend from prescribed locations along the coastal stretch (RSP-locations, *Rijksstrandpalen*) from the first dune

row to approximately NAP -13 m NAP. Jarkus is an abbreviation of *Jaarlijkse Kustmetingen* (Rijkswaterstaat, n.d.-a), i.e. yearly coastal measurements. The Jarkus rays covering the beach have an intermediate distance of 200 m (Figure 3.2). The Jarkus rays in which the beach is situated (or was situated since 1990) are rays 2020 to 2420.

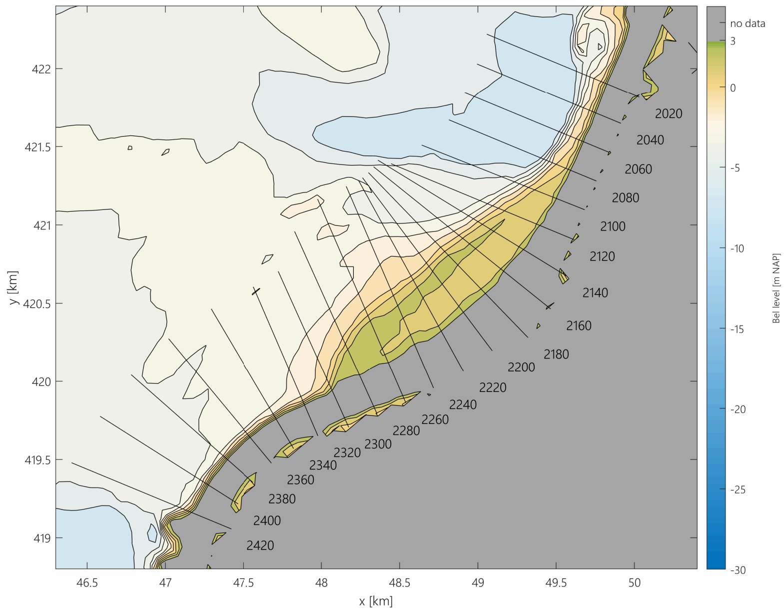


Figure 3.2: Overview of Jarkus rays covering the Brouwersdam beach, derived from the Jarkus data set (bathymetry 2019, derived from the Vaklodingen data set).

3.2. Hydrodynamic forcing

The local hydrodynamics mainly determines the morphological evolution of the Grevelingen outer delta. The three main driving forces that affect the water levels and flow patterns are the tide, the waves and the wind. These driving forces are discussed in this section.

3.2.1. Tidal regime

The tidal wave propagates from the Atlantic ocean to the Netherlands and crosses thereby the shallow North Sea basin. The tide travels in a counter-clockwise direction around the amphidromic point, which lies west of the Dutch coast (Bosboom & Stive, 2015). This induces a northern directed flood current and a southern directed ebb current, parallel to the Dutch coast. Flood and ebb velocities reach their maximum at respectively high and low water. A velocity and water level in phase is a characteristic of a progressive wave, occurring when a wave travels in relatively deep water, and friction has little effect on propagation.

Due to changes in the water depth and width during propagation, the tidal wave is distorted. For the non-dispersive tidal wave, the propagation speed is proportional to the square root of the water depth for the long tidal wave and, therefore, the wave length for alterations in the bathymetry. So, a reduction in water depth results in a concentration of energy, implying an increase of the tidal amplitude. As the North Sea basin's bathymetry is variable, the amplitude of the wave knows a large variability along the coast (Bosboom & Stive, 2015). The mean tidal range has a value of 3.86 m in Vlissingen (Western Scheldt) and decreases in northern direction to 1.74 m in Hoek van Holland (Elias et al., 2016). Note that these values apply at the mouth of estuaries and that the propagation of the tidal wave inside a basin can differ due to the basin geometry. The mean spring tidal range currently present in the Grevelingen outer delta of is 2.90 m.

Horizontal tide

The tidal wave enters the Grevelingen outer delta from the southwest. During flood (Figure 3.3), the velocities in the basin are directed in east to northern direction. Large flow velocities are present in the

flood channels such as the Brouwershavense Gat channel. Near the southwestern part of the beach, flow velocities reach up to 0.6 m/s. The flood velocities in the former tidal channel Springersdiep are very low, with a maximum flood velocity of about 0.2 m/s.
During ebb, the flow is directed in opposite direction. The largest ebb velocities occur in the Schaar channel (in between the coast of Goeree and the Bollen van de Ooster). Ebb velocities near the beach are lower than during flood, with values up to 0.3 m/s (Figure 3.3).
As the peak flood velocity is larger than the peak ebb velocity, the velocity signal has a positive skewed form, also referred to as a flood-dominant velocity signal. The velocity signal has a large impact on the net import or export of sediment: a larger flood velocity enhances landward near-bed transport and therefore a net import of sediment (reference is made to Bosboom & Stive (2015) for further elaboration on tidal asymmetry). Moreover, note that these ebb velocities are located seaward of the beach' coastline, whereas the higher flood velocities are also located landward of the coastline (due to the variations in water level). The residual current near the coastline of the beach is therefore dominant in the northeastern direction.

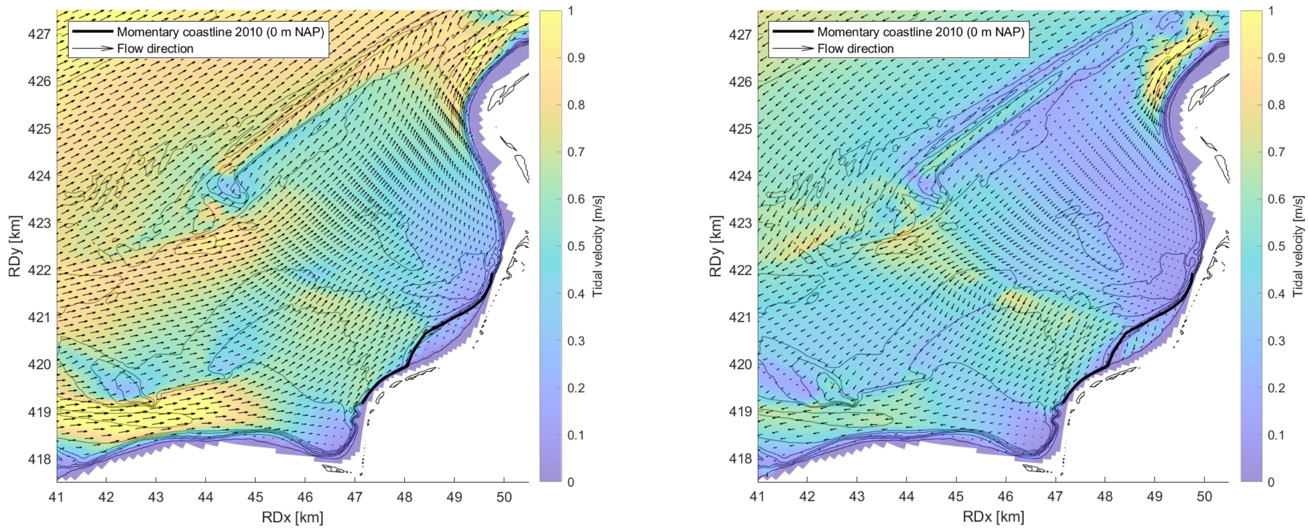


Figure 3.3: Simulated flood (left panel) and ebb (right panel) velocities in the Grevelingen outer delta in 2010, obtained from Brouwersdam flow model of Jansen et al. (2012). Depth contours are depicted to indicate the main morphological units' locations (Bathymetry 2010, derived from the Vaklodingen data set).

Vertical tide

The water level signal in the Grevelingen estuary from January up to March 2020 is depicted in Figure 3.4. This signal shows the spring-neap variations and a daily inequality in the vertical tide. The daily inequality is larger during spring-tide. The tidal levels at the right vertical axis indicate the tidal signal over a long period. For instance, characteristic values are Mean High Water (MHW) of +1.44 m NAP and Mean Low Water (MLW) of -1.06 m NAP. As the tide travels in shallower water in the outer delta than in the North Sea, the effect of friction is larger, and the wave's progressive character decreases. Near the beach, the velocity leads the elevation with approximately 1 to 2 hours during high and low water, respectively. In other words, the velocity peaks before the tidal elevation.

3.2.2. Wave climate

The offshore wave climate at Schouwenbank station is discussed in this section. The wave climate of the Grevelingen outer delta is simulated using numerical modelling and can therefore be found in Chapter 6. The Voordelta is characterized by a mixed-energy environment, influenced by both waves and tidal processes. The wave climate in the Voordelta is mainly composed of wind waves, generated in a shallow basin of the North Sea and directed from the west-southwest. Even though this wave direction prevails, northwesterly swell waves (low-frequency waves that originate from storms at the Atlantic ocean) are common. The wave rose for station Schouwenbank, located at a depth of 20 m (van den Boomgaard & Eikema, 2006), is depicted in Figure 3.5. The mean significant wave height at Schouwenbank is 1.1 m, and with a corresponding mean wave period of 4.05 s (van den Boomgaard & Eikema, 2006). During

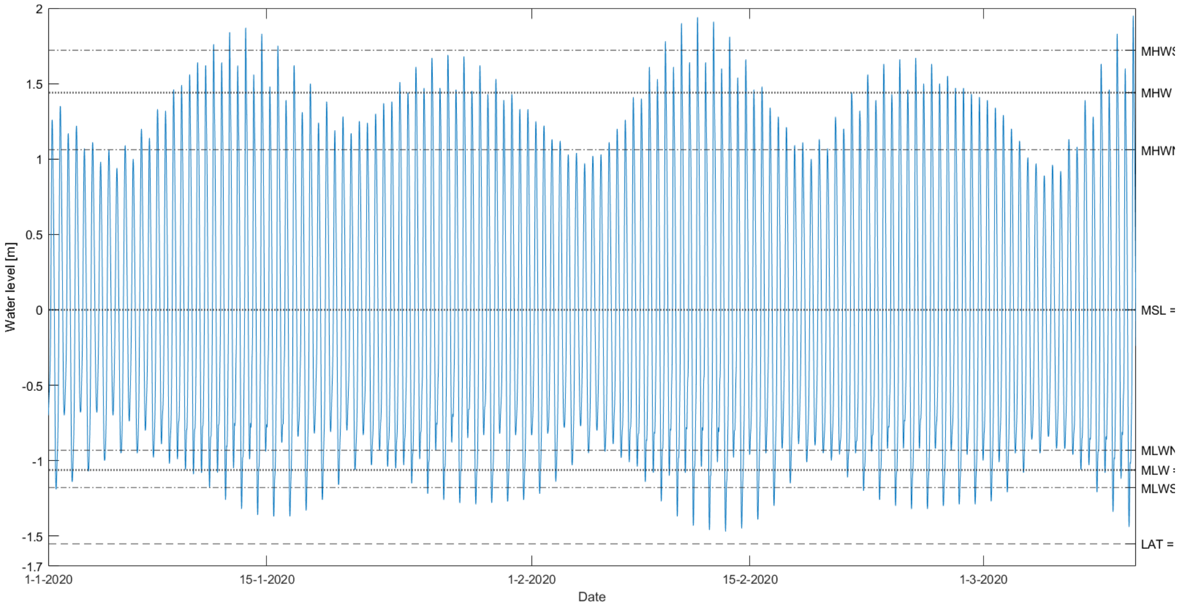


Figure 3.4: Tidal signal in the Grevelingen outer delta, containing four spring-neap tidal cycles (obtained from Rijkswaterstaat (n.d.-b), measuring station Brouwershavense Gat 08)

storms, the maximum wave height can reach up over 5 m (H_{max} = 5.15 m) with a corresponding wave period of T_{max} = 7.2 s. A significant wave height of 4.4 m is exceeded 0.1% per year ($H_{0.1\%}$ = 4.4 m, $T_{0.1\%}$ = 6.8m) (van den Boomgaard & Eikema, 2006). Additionally, storm surge levels of over 2 m have been measured (Elias et al., 2016).
Based on the combination of a mean tidal range of = 2.9 m and wave energy characterized by a mean significant wave height of 1.1 m, the tidal inlet is classified as mixed-energy (tide-dominated), according to Figure 2.1. Hence, this is in line with the conclusions of Elias et al. (2016).

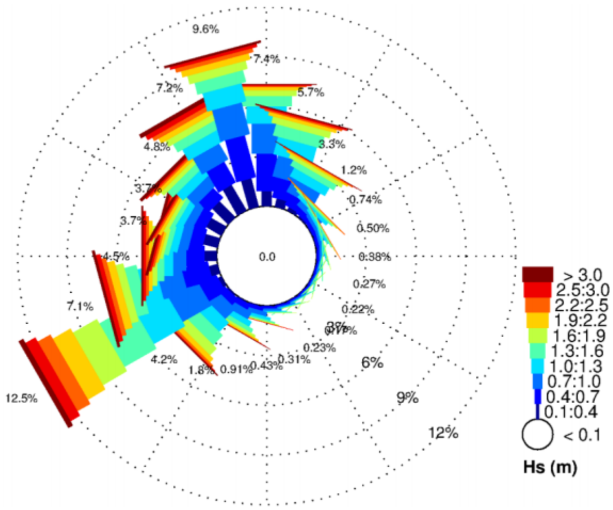
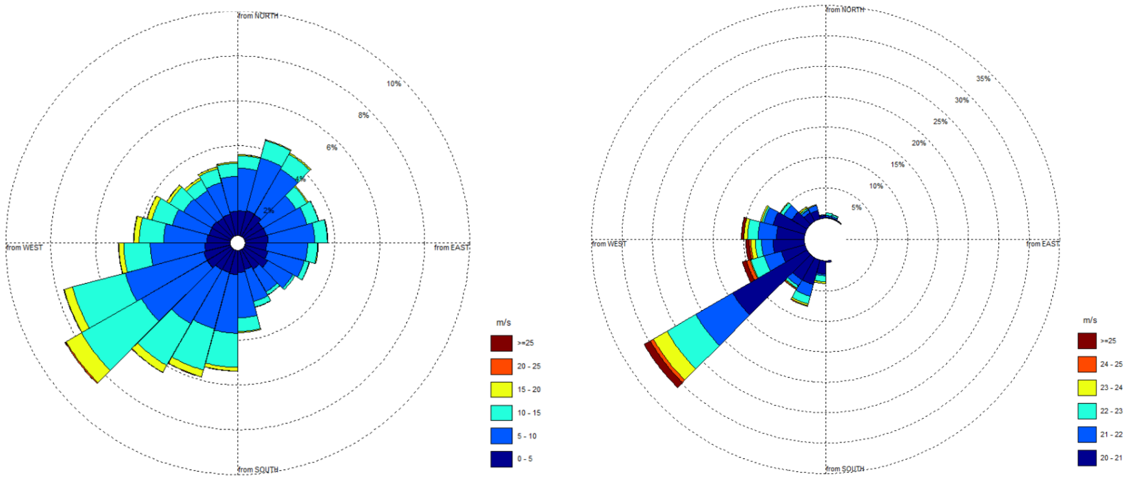


Figure 3.5: Wave rose for station Schouwenbank (2004-2014) (van der Wegen et al., 2017)

3.2.3. Wind forcing

The wind climate at the Brouwershavense Gat 02 station is depicted in Figure 3.6a. The prevailing wind directions are west to south. The most common wind speed is between 5 to 10 m/s. Storm conditions with wind speeds over 20 m/s (i.e.,9 Bft) are not uncommon. The predominant direction of these storms is southwest, shown in Figure 3.6b, which depicts the wave rose with wind speeds over 20 m/s.

This figure also shows that storms in the eastern to north-eastern direction are non-existent.



(a) Wind rose Brouwershavense Gat 02

(b) Wind rose Brouwershavense Gat 02, windspeed >= 20 m/s

Figure 3.6: Wind roses for Brouwershavense Gat 02 (1983-2021), obtained from Huibregtse (2013). Note the different scale and size of internal radius in both figures to enhance the visibility of the bins.

3.3. Bed composition

Since the damming of the southwestern estuaries, sediment exchange between the individual ebb-tidal deltas is enhanced due to an increased shore-parallel flow. The damming of the Grevelingen initially caused the sediment budget of the Grevelingen outer delta to increase (39 million m^3 between 1969 and 1989), where erosion followed until 2006 (-30 million m^3) (Elias et al., 2016). Sediment sinks and sources of the delta are sediment supply by the estuaries, sediment exchange with the North Sea, dredging and dumping and aeolian transport to the dunes. These mechanisms cause different sediment grain sizes to be deposited in the outer delta. Deposits from the North Sea, for instance, in the Brouwershavense Gat channel, consist predominantly of mud. Eroded sediment from the shoals that deposits in the channels consist, however, mainly of sand.
From 2007 up to 2010, the sediment volume increased again. This is due to reduced erosion of the shoreface (Bollen van de Ooster) and infilling of the Brouwershavense Gat Channel (Elias et al., 2016).

According to Prins et al. (2020) (Figure D.3), the median grain size (D_{50}) in the Grevelingen outer delta can be classified as fine sand (125-250 μm). Prins et al. (2020) also conclude that the silt content near the Bollen van de Ooster and the coast of Goeree increased in the past decade (2004-2019), whereas near the coast of Schouwen the sediment composition content got coarser. Recent modelling studies such as Schrijvershof (2015), Huibregtse (2013) and Jansen et al. (2012) have assumed a mean grain size of D_{50} = 210 μm. Local cone penetration tests near the beach, executed by Geological Service of the Netherlands (online available at Data and Information of the Dutch Soil (DINO), www.dinoloket.nl), show grain size values that are in line with this averaged value.

3.4. Morphological evolution of the beach

The analysis of the Grevelingen outer delta's bathymetry in Section 2.5.1 showed that the hydrodynamic changes induced morphological changes. Due to the delta's changed character, from mixed-energy (tide and wave)-dominated to wave-dominated, sediment was pushed onshore (Elias et al., 2016). An overview of the development of the beach from 1964 (before the construction of the Brouwersdam) up to 2010 is depicted in Figure 3.8. This figure shows that the shoals were merging between 1976 and 1998: the confluence happened in approximately 1990, and the beach got its convex shape. As discussed in Section 2.5.1, the ebb-tidal delta had reshaped (and was still reshaping) the beach, which started to erode in the southern part of the beach, and the beach shows a yearly shift towards the north-east (Lazar & Elias, 2019). Nowadays, the 'dry' part of the beach (Figure 1.3) between 0 and 3 m NAP

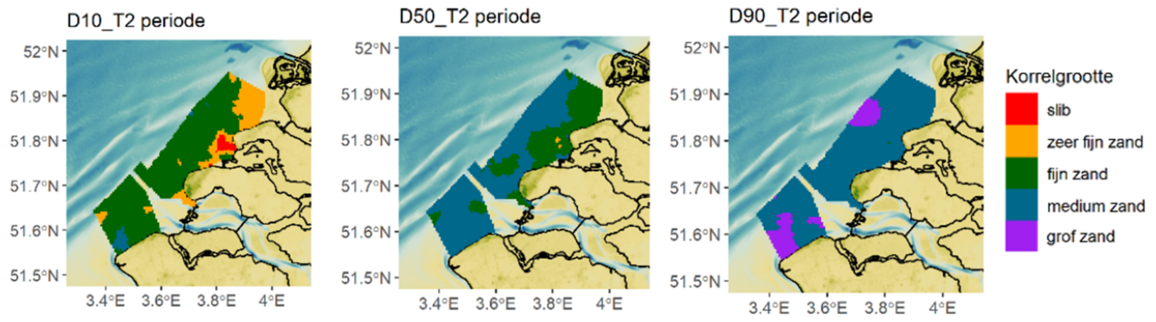


Figure 3.7: Sediment composition distribution in Voordelta, expressed in median grain size diameter (middle panel), and the 10th and 90th percentiles (left and right panel, respectively), in period 2016-2018. Maps are based on an interpolation of sediment data from benthos sampling. Silt: D < 63 μm, very fine sand: D = 125-250 μm, medium fine sand: D= 250-500 μm, coarse sand: D > 500 μm. Obtained from Prins et al. (2020)

covers approximately 66 hectares. Figure 1.3 shows that the beach slopes down towards the north-east, which causes the southwestern part to be situated higher than the northeastern part. In 2016, a beach nourishment was executed (which is elaborated in Appendix B). The nourishment induced a significant increase in the beach volume, and therefore, two periods are distinguished in the morphological analysis of the beach, namely period I (1990-2015) and II (2015-2020).

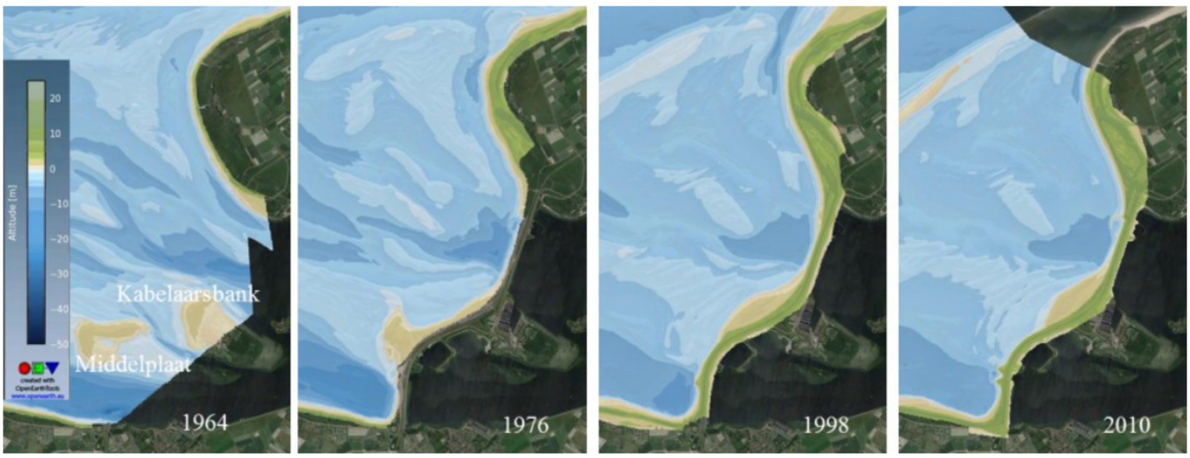


Figure 3.8: Development of the shoals Middelplaat and Kabbelaarsbank in the period 1964-2010 into the Brouwersdam beach (Lazar & Elias, 2019)

In the following sections, the morphological developments of the beach of the past couple of decades are analysed by means of Jarkus rays. This analysis is done for the years 1990 up to 2020 because the beach was formed in approximately 1990. It is more difficult to quantify the trends of period II because of the shorter duration of the period (5 years).
The use of Jarkus rays has flaws in both a temporary and a spatial sense. The spatial distance between Jarkus rays is 200 m. In between two rays the coastline is simplified as a straight line, not taking into account alongshore curvature. Alongshore volume differences between rays are therefore not detected. In temporal sense, the Jarkus data set lacks information, as it does not provide continuous data. The measurements are executed at a certain moment each year.

It is important to note that the Jarkus data in the sublittoral zone (deeper than approximately -1 m NAP) of the years 1990, 2005 and 2006 deviate from the observed trends, and the reliability of the measurements is unreliable. Therefore these values are left out of graphs and calculations.

3.4.1. Momentary coastline

The development of the momentary coastline (0 m NAP) between Jarkus rays 2020 and 2420 during period I is depicted in Figure 3.9. These figures show a trend of large regression rates in the south-west part and smaller but still significant transgression in the northwest. The alongshore coastal shift of the momentary coastline in the southwestern part is approximately 1 km in period I (approximately 42 m/year). The northwestern part shows a cross-shore transgression of 300 m, which implies an average accretion of 13 m/year. Generally, it can be stated that the retreat rates of the southwestern part are larger than the transgression rates of the northeastern part, indicating a trend of surface area loss. This finding is supported in the next section.

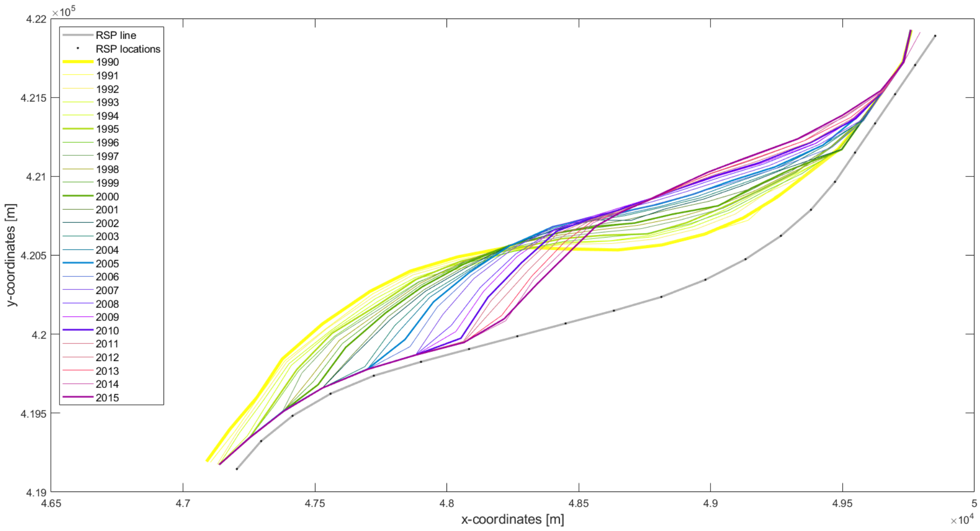


Figure 3.9: Momentary coastline of the coast between 1990 and 2015, derived from the Jarkus data set

3.4.2. Surface area

From the analysis of the momentary coastline, the conclusion can be drawn that the beach is shifting towards the northeast. When analysing the amount of surface area between 0 to 3 m NAP, a decreasing trend can be seen as well. This acreage is analyzed in this section because it is the most important part for recreational purposes: the acreage between the dune foot (+3 m NAP) and the MHW line (+ 1.4 m NAP) is particularly suitable for recreational activities such as sunbathing, whereas the zone between the coastline (0 m NAP) and the MHW line is suitable for sports like kite buggying (elaborated in Section 9.4). In period I (1990-2015), the beach surface area between 0 and 3 m NAP decreased by approximately 21 ha (from 83 ha in 1990 to 62 ha in 2015, Figure 3.10). Up to approximately 2005, a mean loss of 0.35 ha/year is detected. From 2005 to 2015, it decreases even faster with a mean yearly loss of 1.6 ha/year. Note that the recent surface area within the borders of Schouwen-Duiveland is a factor 20 smaller than in Goeree-Overflakkee: in 2020, the beach is located in such a way that the municipality of Goeree-Overflakkee owns 63 ha of beach (0 - +3 m NAP), whereas Schouwen-Duiveland owns only 3 ha (the border is approximately located at Jarkus ray 2300).
It is important to highlight that these amounts are calculated with Jarkus data, in which no distinction is made between sediment and revetment. It is, therefore, likely that part of the 'beach' in Schouwen-Duiveland is, in reality, the revetment of the dam. It is estimated that the revetment comprises is 2.5 ha.

3.4.3. Volume

The total volume of the beach (-3 to 3 m) since 1990 is depicted in Figure 3.11. The blue graph shows the volume of the total beach stretch: the total beach is not losing or gaining sediment up to 2015. However, the southern part loses sediment whereas the northern part gains sediment. The imaginary boundary between north and south is at ray 2240. This is because south of ray 2240, the nourishment was planned. Table 3.1 shows the values of the beach volume since 2010, in which a distinction is made

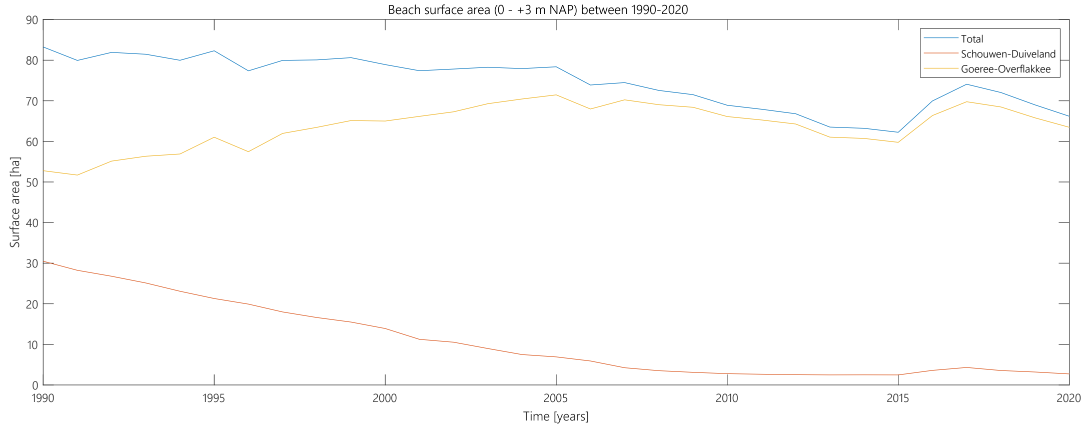


Figure 3.10: Surface area of beach (between 0 and +3 m NAP) in municipalities Schouwen Duiveland and Goeree-Overflakkee, derived from the Jarkus data set.

between several different periods. The most important features of the beach that can be deducted from this table are elaborated in the following paragraphs.

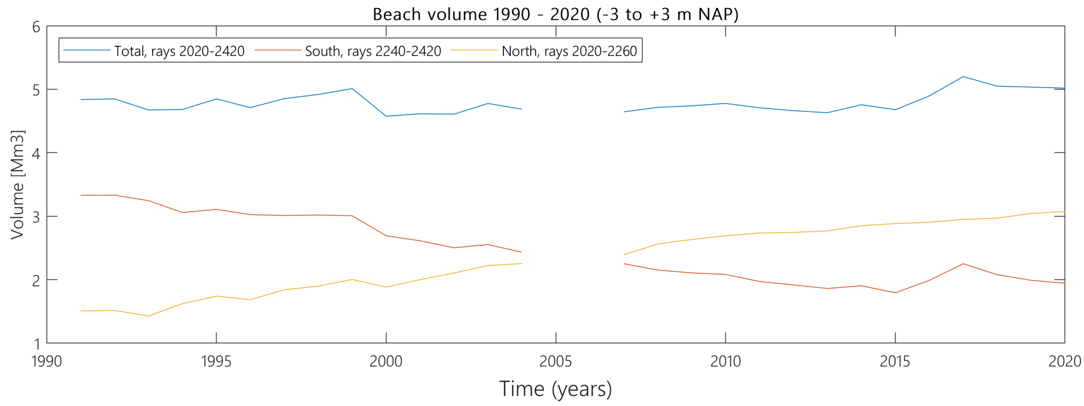


Figure 3.11: Beach volume between 1990-2020, for the total, northern (rays 2020-2240) and southern (rays 2240-2420) beach stretch, retrieved from the Jarkus data set (missing data below -1 m NAP for 1990, 2005 and 2006).

		2010-2015	2015-2017	2017-2018	2018-2020
Total beach	Absolute $[m^3]$	0	520,000	-150,000	-30,000
	Yearly average $[m^3/y]$	0	x	x	-15,000
South	Absolute $[m^3]$	-300,000	460,000	-170,000	-135,000
	Yearly average $[m^3/y]$	-60,000	x	x	-67,500
North	Absolute $[m^3]$	300,000	60,000	20,000	105,000
	Yearly average $[m^3/y]$	60,000	x	x	52,500

Table 3.1: Beach volume for total, southern and northern part between -3 and +3 m NAP, retrieved from Jarkus data set (Northern rays 2020-2220, Southern rays 2240-2420)

Cross-shore volume distribution

The total volume change of the beach can be subdivided into cross-shore zones in which different trends are detected. In Figure 3.12, the beach volumes between acreages -3 to 3 m NAP, -1 to 3 m NAP (total beach), -1 to 1.5 m NAP (foreshore) and 1.5 to 3 m NAP (dry beach) are depicted. Over the whole period between 1991 and 2015, a more or less stable situation is present for the acreage -3 to 3 m (black line). However, the cross-shore volume distribution is not stable. The sublittoral volume between -3 to -1 m NAP (blue line), shows a decrease up to 2003 (-430,000 m^3, -36,000 $m^3/year$) which stagnates and

then stays more or less equal up to 2015. The foreshore (-1 to + 1.5 m NAP, yellow line), is accreting up to 2003 (+ 310,000 m^3, +26,000 $m^3/year$) and then the volume decreases significantly (-790,000 m^3, -66,000 $m^3/year$). The dry beach volume (+1.5 to +3 m NAP, red line) stays approximately equal up to 2003 and then starts to increase up to 2015 (+ 640,000 m^3, +54,000 $m^3/year$).
So the conclusion on the recent situation (past decade) is that the biggest volume changes take place between -1 and +3 m NAP, in which the foreshore (-1 to +1.5 m NAP) erodes and the dry beach (+1.5 - 3 m NAP) accretes.
Another important note is that the sublittoral zone between -8 and -3 m NAP (not depicted) gained volume with a total increase of almost 1 Mm^3 in 25 years (+ 40,000 $m^3/year$). This can, most likely, be explained by the third phase of the conceptual model of van der Spek & Elias (2021), in which the sheltered back-barrier is filled in with sediment depositions.

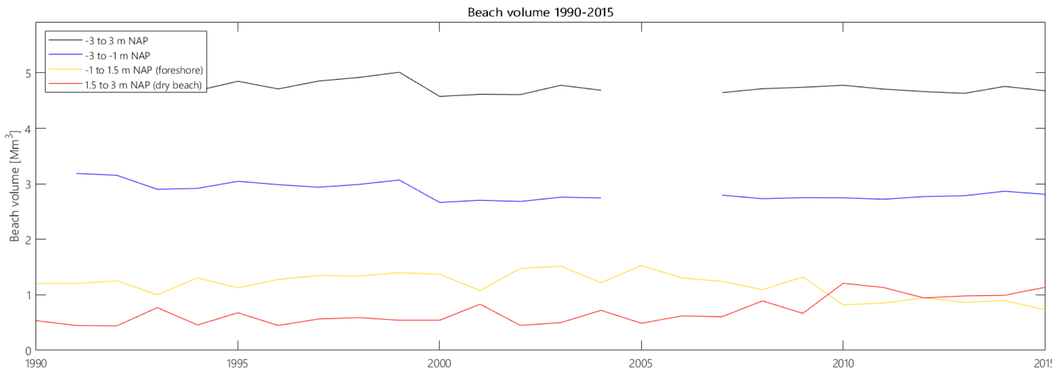


Figure 3.12: Total beach volume for different acreage between -3 and 3 m NAP for period I (1990-2015), derived from the Jarkus data set (missing data below -1 m NAP for 1990, 2005 and 2006)

Alongshore volume distribution

The changing position of the beach is also visible when plotting the yearly volumes per transect section (Figure 3.13). The ray that forms the imaginary boundary between erosion and accretion is shifting each year. Ray 2200 was in 2015 this 'boundary ray': rays 2420 - 2200 experience erosion, whereas ray 2180 to 2020 were accreting.

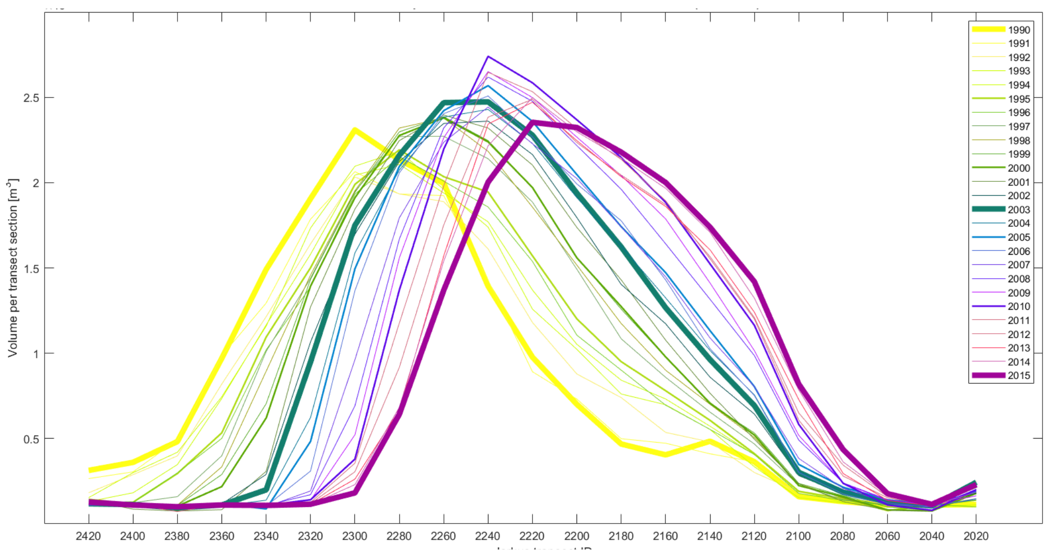


Figure 3.13: Beach volume per transect section between -1 and 3 m NAP (1990-2015), derived from the Jarkus data set

The findings in previous sections are evaluated by means of 3 cross-sectional profiles of the beach. The cross-sections of Jarkus rays 2300, 2200 and 2100 represent the southern, middle and northern part of the beach (Figure 3.14). In the southern part of the beach (transect 2300), the beach width got smaller (decrease in cross-shore width, i.e., retreat of the shoreline). The dune row in this cross-section decreased in height as well and disappeared between 2010 and 2015. The dune foot retreated for several meters. In this period, the erosion led to the total disappearance of beach in this transect (in other words, the revetment of the dam was reached before the year 2015). For transects 2200 and 2100, the opposite trend is observed: a growing dune in seaward direction and an increase in altitude and widening of the shallow part of the beach. The dune development is due to aeolian transport (Elias et al., 2016). The transgression of the intertidal area (foreshore) is most likely due to sediment deposits from the eroded sediment of the southern part.

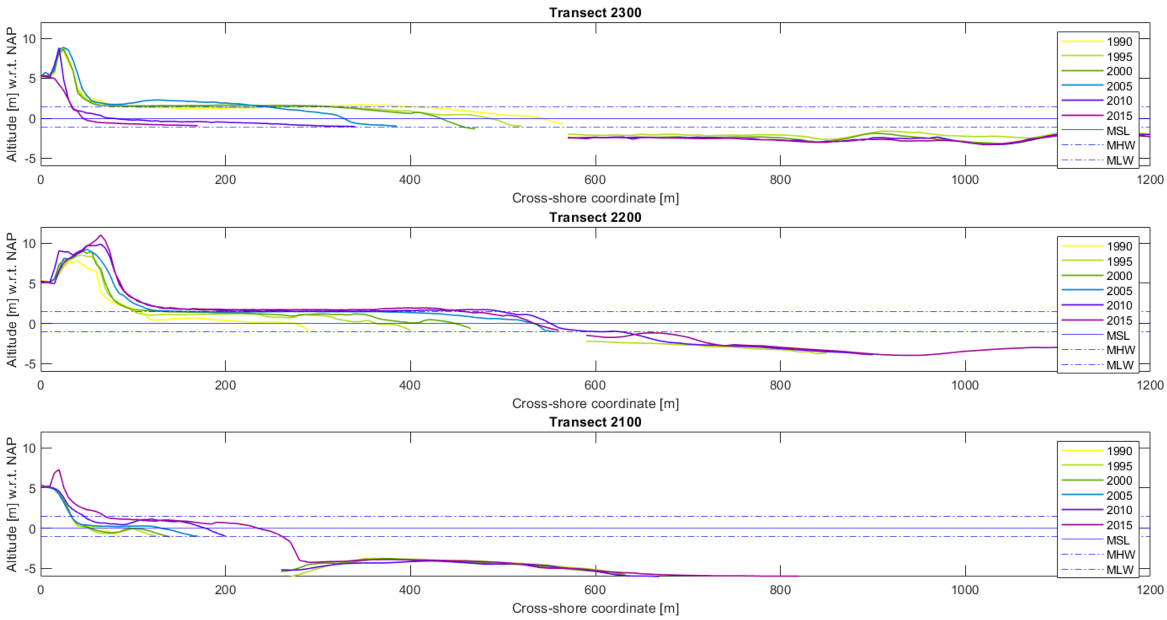
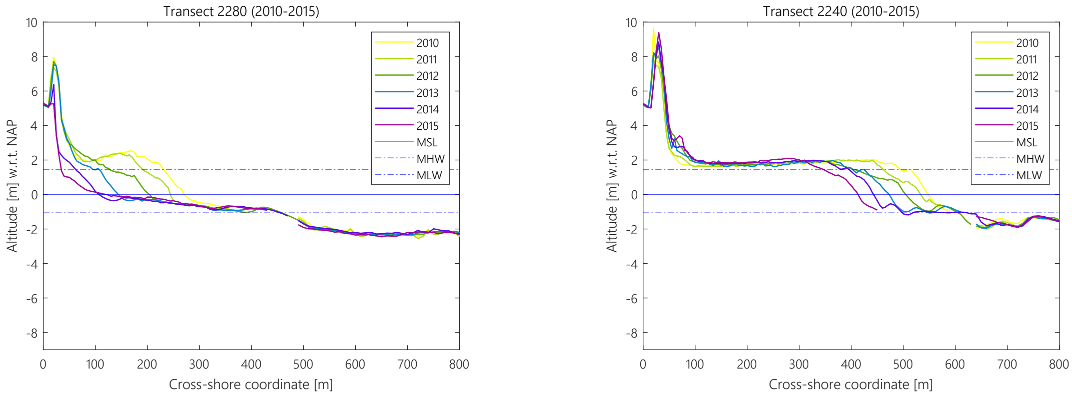


Figure 3.14: Cross-shore profiles of Jarkus transects 2300, 2200 and 2100, derived from the Jarkus data set

The above described developments may be even more clear in Figure 3.15, in which the cross-shore profile changes between 2010 and 2015 of transect 2280 and 2240 are depicted. What can be concluded from the comparison of the transects is that the most southern part (transect 2280) loses its dunes due to the erosion, whereas a transect 400 m more northward (transect 2240) shows an eroding intertidal area and a seaward displacement of the dune foot. This implies a slight steepening of the coast. To summarize, the most southern part of the beach experiences a decreasing cross-shore beach width, whereas the trend of the northern part is the other way around. The dune stretch at the whole beach is more or less moving seaward and increasing in height, except for the most southern rays in which the revetment of the dam is (almost) reached.



(a) Jarkus profile 2280 (south)

(b) Jarkus profile 2240 (south)

Figure 3.15: Development of southern transects of the beach between 2010 and 2015, derived from the Jarkus data set.

3.4.4. Average beach level

From the above reasoning, it follows that the intertidal acreages lose sediment and the dry beach gains sediment. The average height of the beach between 0 and 3 meters above NAP is calculated by dividing the yearly volume by the yearly surface area. A clear, increasing trend can be seen in the graph in Figure 3.16, in which the mean beach level is depicted. The beach gained 1 meter in height in 30 years.

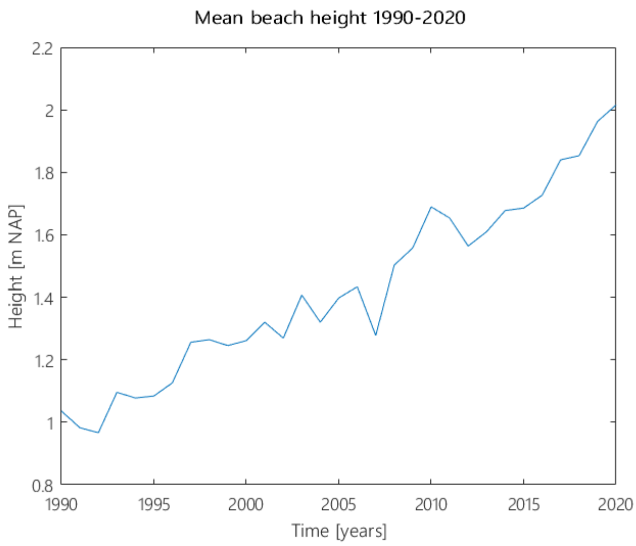


Figure 3.16: Mean beach height between 0 and 3 m NAP (1990-2020), derived from the Jarkus data set.

3.4.5. Nourishment and beach development afterwards

The nourishment was executed in two periods. The first part took place in the fall of 2015. Due to weather conditions, the activities were temporarily stopped during winter and resumed in spring 2016. The total volume of the nourishment was approximately 500,000 m^3 and was planned to be dumped in between transects 2360 and 2260. The longshore length of the nourishment was approximately 1 km. The purpose of the nourishment was to restore the beach profile to the profile it had in 2005. The properties of the preliminary design of the nourishment are listed in Rijkswaterstaat (2014a) and can be found in Table B.

Momentarily coastline

In period I, the alongshore position of the southern part of the beach (at a cross-shore distance of 200 m from the RSP line) shifted approximately 1 km towards the northeast. The nourishment induced a transgression of approximately 500 m in 2016 and 2017 (Figure 3.17), which partially restored the position of the coastline to its configuration in 2007. Thereafter, a retreat of approximately 300 m was detected. In 2020, the shoreline aligned partly with the coastline position of 2012.

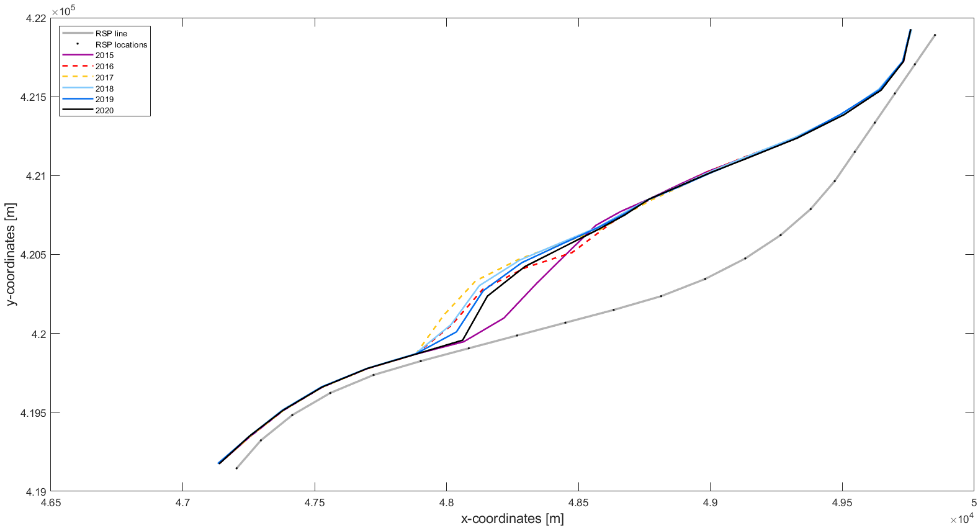


Figure 3.17: Momentarily coastline of the beach between 2016 and 2020, derived from the Jarkus data set

Surface area

The nourishment increased the total surface area of the beach by +12 ha (+20%), reclaiming the beach up to the amount of surface area in the year 2007 (a total area of 74 ha). In other words, 10 years of erosion were compensated by the nourishment. In the present situation (2020), only circa 4 ha of the reclaimed part is left (Figure 3.10). The total surface area of the beach is now 66 ha, which is equal to the surface area in the year 2012. This loss of 8 ha implies that since 2017, the beach loses more than 2.5 hectares per year. The surface area loss has thus been accelerated: before the nourishment, the loss was 1.6 ha/year. Between 2007 and 2012, the same amount of surface area was lost in as between 2017 and 2020.
Within the municipality of Schouwen-Duiveland, a total area of approximately 2 ha was gained by nourishing the beach (from 2.5 ha to 4.5 ha). The surface area in Schouwen-Duiveland decreased down to 2.7 ha in 2020. As most likely 2.5 ha of this area is in reality the revetment of the dam, the surface area in Schouwen-Duiveland is nearly zero in 2020.

Volume

The total volume of the nourishment was approximately 500,000 m^3 and was planned to be dumped in between transects 2360 and 2260. In Table B, the indicative volumes per ray field are given (Rijkswaterstaat, 2014a).
The cumulative volume of the southern part of the beach (between -3 and +3 m NAP, ray 2240 up to 2420) is depicted in Figure 3.11. This graph shows that the volume increases with 450,000 m^3 between 2015 and 2017 (this observed number is less than the nourished volume to shortcomings in the Jarkus data set, this is further explained in Appendix B). The volume graph shows a sharp decrease of 170,000 m^3 in the first year after the nourishment. Thereafter, this severe sediment loss in the south is reduced to a mean value of 70,000 $m^3/year$. Note that a part of this volume that is 'lost' in the south is transported towards other parts of the beach (in seaward or landward cross-shore direction, or in northward alongshore direction).
As was already concluded from the surface area analysis, the erosion in the south accelerated after the nourishment. From 2005 up to 2015, 60,000 $m^3/year$ was lost from the south, whereas this increased to 80,000 $m^3/year$ after the nourishment.
The conclusion that can be drawn from this volume data analysis is that, when these trends continue, the nourishment has a lifetime of approximately 6 years. The volume of the southern part of the beach will thus be equal to the state in 2015 in the year 2022.

3.5. Summary

The content of this chapter is summarized below, providing an answer to Sub-question 1: *What are the morphodynamic characteristics of the Grevelingen outer delta and the main morphological developments of the Brouwersdam beach?*

The tidal signal has a progressive character on the North Sea, where the water level and velocity signal are more or less in phase. The mean tidal range is 2.9 m. When the tidal wave enters the Grevelingen outer delta, the progressive character decreases. The maximum flood velocity is larger than the maximum ebb velocity, inducing a skewed velocity signal. This flood-dominant signal enhances coarse sand import. Moreover, the residual current at the beach is in the northeastern direction. The signal of the vertical tide has characteristic values of MHW = +1.44 m NAP and MLW = -1.06 m NAP.
The offshore wave climate is dominated by sea waves from the west-southwest and swell from the north-northwest. The mean significant wave height at Schouwenbank station is H_s = 1.1 m. Combined with the tidal range of 2.9 m, the coastal system can be classified with a mixed energy character.
The prevailing wind direction is south to west, with a dominant wind speed between 5 to 10 m/s. Storms, with speeds larger than 20 m/s, from the southwest are not uncommon.
The bed of the outer delta is composed of sediment that can be classified as fine sand (125-250 μm. On average, a grain size diameter of D_{50} = 210 μm suffices.

The development of the beach from 1990 up to 2020 is summarized in the following bullet points:

- The beach shows a spatial shift towards the northeast.
- The surface area of the beach decreases by 1.6 ha per year, and the average beach height increases with 3 cm per year.
- The total beach volume (-3 to +3 m NAP) stays more or less equal in the period before the nourishment, whereas it loses about 15,000 $m^3/year$ since the nourishment.
  This zone can be subdivided into 3 cross-shore zones, showing different types of behaviour. The sublittoral volume from -3 to -1 m NAP is more or less maintained. Erosion takes place in the foreshore (-1 to 1.5 m NAP) and accretion at the supralittoral part of the beach (1.5 to 3 m NAP). However, the beach shows alternating profile developments in longshore direction: the southern part has an eroding intertidal area, the northern intertidal area is accreting (hence, an increasing cross-shore beach width).
- The southern part of the beach (southward of ray 2240) has a net volume loss, showing a decreasing foreshore, dry beach and dune volume. The northern part shows opposite trends. The southern part loses 60,000 $m^3/year$ before the nourishment and 80,000 $m^3/year$ afterwards. The northern part gains 60,000 $m^3/year$ before the nourishment, down to 42,000 $m^3/year$ afterwards.
- It is likely that a part of the eroded sediment from the southern region of the beach is deposited partly at the dry beach and dunes (above 1.5 m NAP) and , partly in the intertidal area of the northern region of the beach. The remaining eroded volume is deposited elsewhere. Due to the fact that the volume changes of the beach are small compared to the morphological changes in the Grevelingen outer delta, it is hard to analyze towards which areas the eroded sediment is transported. Possibly, sediment exchange between the sublittoral zone and the zone between -8 and -3 m takes place (which is accreting, but this is most likely due to infilling of the outer delta as part of the large-scale morphological changes elaborated in Section 2.5.1), but sediment can also be deposited in the Springersdiep channel and maybe even northward of it. What can be concluded is that the morphological behaviour of the beach is in line with the formerly described developments of the Grevelingen outer delta: damming the estuary caused the building of shallow shoals showing increasing in heights and rapid displacements (Elias et al., 2016).
- The nourishment that was executed in 2016 increased the beach volume of the southern part between -3 and +3 m NAP with 450,000 m^3 according to Jarkus data, of which approximately 300,000 m^3 is lost in the period up to 2020 (3 years). Most of this volume loss took place in the first year after the nourishment (- 170,000 m^3), after which the southern part lost 70,000

$m^3/year$. This sediment is partly deposited in the northern area of the beach and partly lost from the system. The southern part of the beach will be at its pre-nourishment volume in 2022 if this trends continues.

- The nourishment increased the dry surface area (between 0 and +3 m NAP) of the whole beach by 12 ha (+20%), of which only 4 ha is left after 3 years. This implies a decrease of total beach surface area of 2.5 ha per year.

4 Ecological analysis

This chapter provides an overview of the main characteristics of the ecosystem of the Grevelingen outer delta. According to Slinger & Vreugdenhil (2020), the application of both ecological and engineering knowledge is required in nature-based hydraulic engineering. It is crucial for the design to obtain knowledge on the physical system (biotic and abiotic) to to explore the opportunities for nature development and the use of natural materials and dynamics and to be able to quantify the (positive or negative) impact of the solution on the ecosystem. The focus of the ecological analysis is thus on the link between the ecosystem and the physical aspects which a possible measure could affect (positively or negatively).

The ecosystem of the Grevelingen outer delta contains several habitat types and thus provides habitat for many species. The spatial variation of species depends, according to Bouma et al. (2005), predominantly on the abiotic conditions of an area. It is generally stated that a human intervention is likely to induce changes to an ecosystem. This can be explained by the fact that a human intervention often intervenes in the abiotic conditions and therefore causes habitats to shift or disappear. Consequently, the habitats are affected and thus the ecosystem is affected.
Another fact that can be derived from the relation between abiotic factors, habitats and ecosystems is that abiotic conditions of an area delimit the number of potentially occurring habitats. This implies that the possible Building with Nature designs are delimited by the abiotic factors.

This chapter provides an answer to Sub-question 2: *What are the features of the ecosystem of the Grevelingen outer delta and how can the solution potentially enhance the ecosystem?*
First of all, the necessary background information is given in Section 4.1. Section 4.2 discusses the abiotic conditions of the area. Section 4.3 discusses the main species of the area, their habitat requirements and the main habitat areas. These two sections are a summary of the full analysis, which is included Appendix D. Then, the possible enhancement of the ecosystem's functioning is discussed in Section 4.4. At last, in Section 4.5. Note that the ecological value of the Grevelingen outer delta is translated into measurable indicators in the next Chapter (in Section 5.6) as part of the social system analysis.

4.1. Background information

This section contains the necessary information which underlies the rest of the chapter.

4.1.1. Basic concepts

The definitions of the most important terms used in this chapter are listed below.

An ecosystem is 'a dynamic complex of plant, animal and microorganism communities and the non-living environment interacting as a functional unit', according to Milleninium Ecosystem Assessment (2005). For example, the Voordelta is a coastal ecosystem. The considered ecosystem in this research is the Grevelingen outer delta.

A habitat is, according to Dankers et al. (2012), 'the characteristic space occupied by an individual, an organism, a species, a community or a population. Populations, communities, or species occurring in the same geographic area often have clearly different habitats or parts of the environment in which they live. For sedentary organisms, the habitat is one specific place. In the case of organisms that are free to move, such as birds and fish, the habitat may be in very different locations depending on their life cycle or even time of day'. An ecosystem generally consists of multiple habitats.

Indicators are, according to Harrington et al. (2010), 'measurable and quantifiable characteristics that respond in a known and communicable way to either a changing condition in the environment, a changing ecological process or to a changing element of biodiversity'.

Ecosystem services represent, according to Costanza et al. (1998), the benefits that human populations derive, directly or indirectly, from ecosystem functioning.

4.1.2. Natura2000

Natura2000 is a network of nature areas in Europe, in which certain plant and animal species and their natural habitats are protected with the aim of preserving biodiversity (European Commission, n.d.). Within these areas, specific regulations apply. The areas that make up the Natura2000 network are designated by EU Member States, based on the European Birds Directive (*Vogelrichtlijn*) and Habitat Directive (*Habitatrichtlijn*). The purpose of the Birds Directive is to protect the 500 wild bird species that occur naturally in the European Union. The Habitat Directive aims to conserve specific animal and plant species, including the conservation of 200 rare habitat types (European Commission, n.d.). The Voordelta is one of these Natura2000 areas (Rijkswaterstaat & Royal HaskoningDHV, 2016). The boundary of the Natura2000 area Voordelta is depicted with a yellow line in Figure 4.1.

Because human activities take place in Natura 2000 areas, a management plan is set-up by the national government and local provinces. This plan states which measures are required and which activities are allowed. The goal of this plan is to realise the ecological goals while taking into account the needs of local private parties and entrepreneurs. This plan, *Beheerplan Natura2000 Voordelta*, is consulted for this research and can be seen as the basis for this chapter (Rijkswaterstaat & Royal HaskoningDHV, 2016).

Protected Seabed Areas and Resting Areas

Since the creation of Maasvlakte 2, the expansion of the port of Rotterdam, an important part of the nutrient-rich seabed of the Voordelta is lost, including more than 2000 hectares of the habitat type 'Permanently flooded sandbanks' (Rijkswaterstaat & Royal HaskoningDHV, 2016). This loss induced a large decrease in the foraging surface area and habitat of the protected bird types. Besides that, the seabed accommodates habitat for plants and animal species like shellfish, crabs and shrimps, which are the source of food for seals and birds. Because the Voordelta is protected natural area, this loss of seabed had to be compensated. The compensation consists mainly of two measures. To compensate the loss of habitat type 'Permanently flooded sandbanks', a total area of 24,550 ha is designated as Protected Seabed Area (*Bodembeschermingsgebied*) (Prins et al., 2020). To increase the utilization of the foraging areas for birds and other animal species, certain Resting Areas (*Rustgebieden*) are designated withing the Protected Seabed Areas. In the Protected Seabed Area certain rules are present for fishery and recreation so that nature at the seabed can recover. Activities that disturb the seabed are prohibited. This area is indicated by a pink line in figure 4.1. In Resting Areas, all activities can be prohibited during winter or year round, depending on the location (Rijkswaterstaat, n.d.-c). The designated Resting Areas are marked purple in the map. The effectiveness of the nature compensation is monitored by the project Nature Compensation Voordelta (*Natuurcompensatie Voordelta*, abbreviated as NCV), hereafter NCV (Prins et al., 2020).

4.2. Abiotic conditions

The assessment of the abiotic conditions in the Grevelingen outer delta is based on the ecotope system for coastal waters: the Salt Water Ecotope System (*Zoute wateren EcotopenStelsel*), abbreviated as ZES.1. For more details on this system and for the full assessment, reference is made to Appendix D.1.

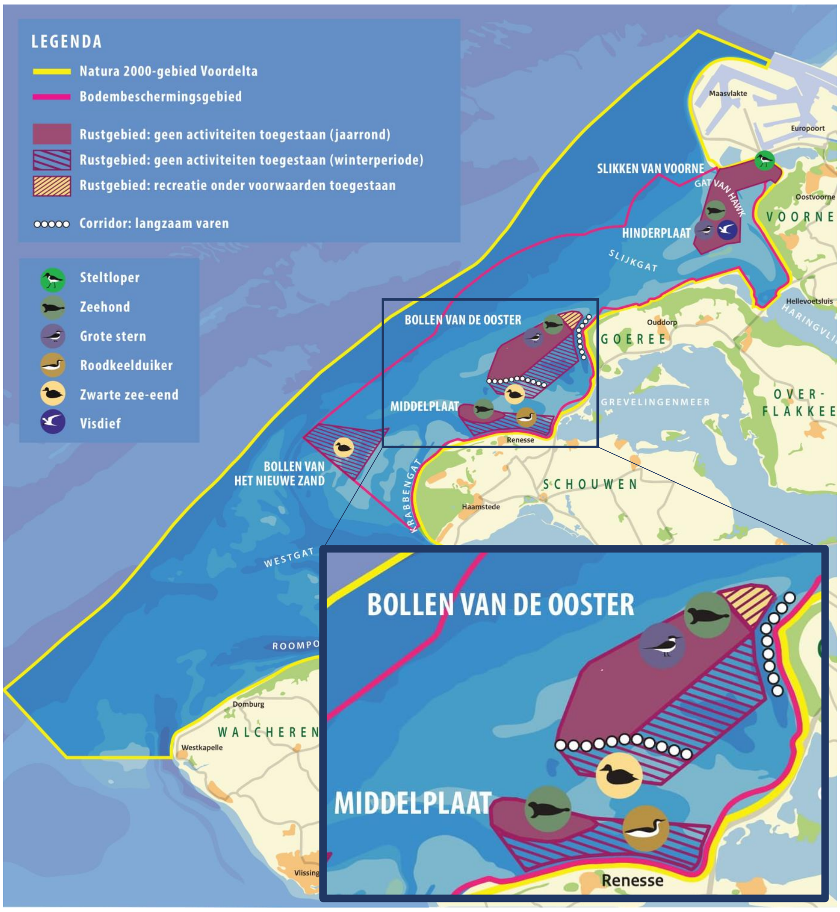


Figure 4.1: Map of Natura 2000 Management plan Voordelta (October 2014), with close-up of Grevelingen outer delta. Obtained and modified from Rijkswaterstaat & Royal HaskoningDHV (2016)

The main conclusions of this assessment are discussed in this section.

The most important physical processes that induce changes to an ecosystem are dominated by several abiotic factors. According to Bouma et al. (2005) the salinity, substratum type, water depth, hydrodynamics and sediment composition. This section covers the ecological importance and classification of each of these factors.

4.2.1. Salinity

Water salinity has a large influence on the existence of benthos (Wolff, 1973). There are no benthic species that can survive in fresh and salt water. The water of the Grevelingen outer delta has a mean salinity of more than 30 ppt (depicted in Figure D.1) and is therefore is classified as marine.

4.2.2. Substrate type

Hard substratum (stone, wood, etc) is discerned from soft substratum (sediment), among others because there is a clear difference between the flora and fauna that can live on hard and soft beds. There are few species that can live both on hard and soft substrate. Examples are mussels (Mytilus edulis) and the Japanese Oyster (Crassostrea gigas). In the Grevelingen outer delta, the only location with hard substrate is near the Blokkendam. Given the special features of this location, it is discussed separately in Section 4.3.2. The remaining part of the bottom in the delta is composed of sediment.

4.2.3. Water depth

There is a large difference between the occurrence of species in the sublittoral zone (permanently under water), the littoral zone (flooded each tide, also called intertidal zone) and the supralittoral zone (not

flooded). In the sublittoral zone the amount of sunlight that reaches the seabed is a determining factor for the occurrence of some plant species, which are present up to a depth of 5 m. Moreover, many juvenile and adult fish species find shelter and food in the shallow sublittoral zone.
Besides the water depth, also the exposure time (duration that a certain area is not inundated) is important for the littoral zone. The exposure time has a direct influence on the occurrence and growth of benthic animals. There is a distinct level above which benthic animals cannot survive, because the duration of submergence is too short (Reise, 1985). In the Grevelingen outer delta, there are only 2 offshore zones that are not sublittoral. These areas are the Bollen van de Ooster and the Middelplaat, both areas are littoral. Nearshore littoral and supralittoral zones are found along the whole coastline in the Grevelingen outer delta, including the Brouwersdam beach. The layout of the zones is depicted in Figure 4.2.

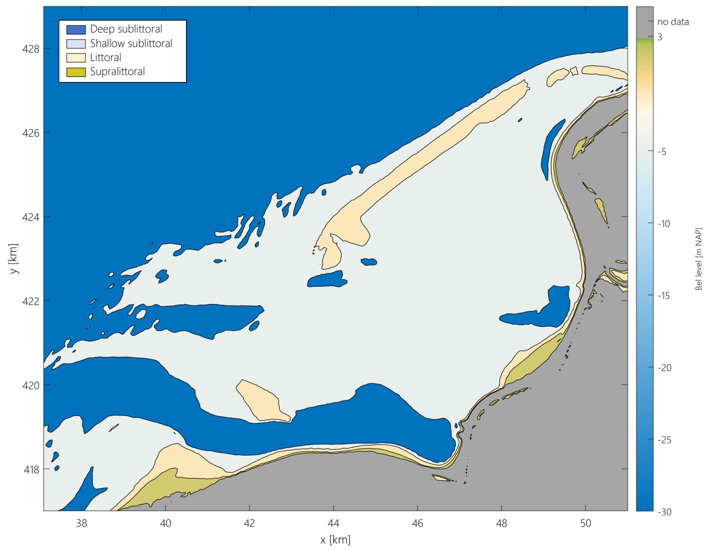


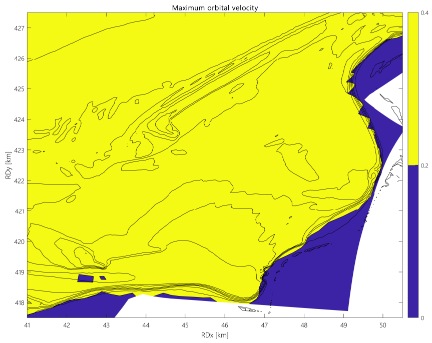
Figure 4.2: Spatial distribution of different depth zones, 2019, derived from the Vaklodingen data set.

4.2.4. Hydrodynamics

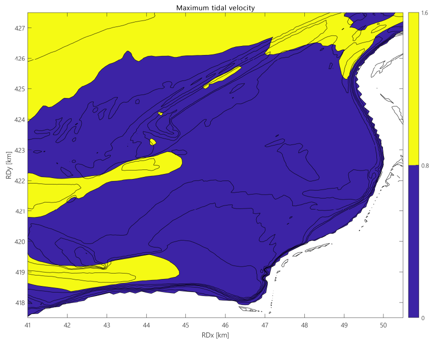
A distinction is made between high dynamic and low dynamic zones. Two factors are important in determining the level of dynamics, namely the maximum orbital velocity and the maximum current velocity. The influence of hydrodynamics on flora and fauna is diverse. When the current velocity or the wave action is able to move the sediment or bring it in suspension on a regular basis, benthic animals can hardly stay in place (Reise, 1985). To distinguish lowly and highly dynamic areas, Bouma et al. (2005) use a maximum orbital velocity of 0.2 m/s amd a maximum current velocity of 0.8 m/s. The distribution of both types of velocities over the outer delta is depicted in Figure 4.3a and 4.3b, in which a yellow color means the maximum velocity is above the distinguishing value (high dynamics) and purple indicates low dynamics. Taken these figures together, it can be said that the wave action is highly dynamic in the whole project area, whereas for the current velocities the area is sheltered and lowly dynamic.

4.2.5. Sediment decomposition

Next to salinity, the sediment decomposition is the most important factor in the spreading and existence of benthic animals in estuaries (Ysebaert & Herman, 2002). All benthic species have a range of sediment composition in which it can survive. Also foraging possibilities of certain waders (*steltlopers*) depend on the sediment composition. However, most of the benthic fauna species in the Grevelingen outer delta are able to survive in seabeds with a wide range of the sediment composition: the bottom shear stress is in general more determinant for benthic fauna than the sediment composition (T. Prins, personal communication, November 18, 2020). The median grain size (D_{50}) in the Grevelingen outer delta can be classified as fine sand (125-250 μm) and the silt fraction is not significant.



(a) Maximum orbital velocity in the Grevelingen outer delta, colors mark high and low dynamic zones



(b) Maximum depth averaged flow velocity in the Grevelingen outer delta, colors mark high and low dynamic zones

Figure 4.3: Depiction of maximum orbital velocity (a.) and maximum depth averaged flow velocity (b.) for the distinction between high and low dynamic zones. Yellow indicates high dynamics, purple indicates low dynamics. Based on the Delft3D-WAVE model that is set up for this research (a.) and the Delft3D-FLOW model of Jansen et al. (2012) (b.)

4.3. Species and habitat types

The abiotic conditions discussed in the previous section determine the possible presence certain habitat types. The Voordelta is designated for 6 habitat types, providing habitat for 6 species from the Habitats Directive and 30 bird species from the Birds Directive (Ministerie van Landbouw Natuur en Voedselkwaliteit, 2008). The habitat provided by the Grevelingen outer delta is not of equal importance for each of these fauna species. The focus is therefore on the habitat types and conservation conditions of the main species in the Grevelingen outer delta. or each of the habitat types and species, specific conservation goals are formulated. Once every few years, an evaluation is performed to assess whether the conservation targets have been achieved. The goals are reviewed and a new management plan set up. The most recent evaluation is documented in Kerngroep Handhaving Voordelta (2014), which also contains the new management plan. This document, *Handhavingsplan bij Natura2000 Beheerplan Voordelta 2015-2021*, is consulted for this thesis and can be seen as the basis for this section.

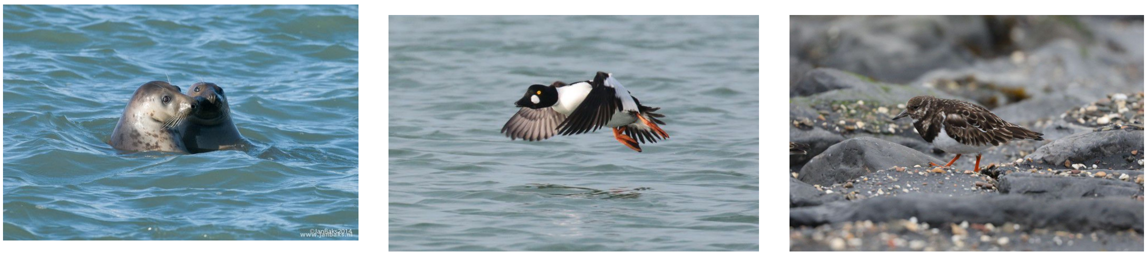
4.3.1. Species

The habitat species covered by the Habitats Directive are divided into two groups: marine mammals and migratory fish.

The marine mammals population in the Voordelta consists of the common and the grey seal. Seals require a calm sandy shoal as a habitat. The Voordelta provides several of these shoals and the preservation of these shoals and the rest is important for the continuity of the seal population (Kerngroep Handhaving Voordelta, 2014). A lack of rest is related to nuisance, for instance due to the presence of vessels and construction activities or water sport activities.

Four migratory fish species are present in the Voordelta. The Voordelta as habitat is sufficient for these species, but the increase of the population is impeded by the Haringvliet sluices and other upstream barriers. Extension of the population is only possible if the obstacles between the habitat in the Voordelta and the upstream located spawning and juvenile habitat are removed (Rijkswaterstaat & Royal HaskoningDHV, 2016).

Bird species can be classified into fish-eating birds, benthic fauna-eating birds at sea, benthic fauna-eating birds at tidal flats and herbivores and omnivores. The quality of the habitat for these species is determined by the availability of sufficient prey (fish or benthos) or the availability of nutrient-rich areas (for herbivores and omnivores) and sufficient rest at at sea, on the shoals and in the nearshore zone.



(a) Common seal in Grevelingen outer delta (Baks, 2020)

(b) Common Goldeneye (brilduiker)

(c) Ruddy Turnstone (steenloper)

Figure 4.4: Fauna species in the Grevelingen outer delta

4.3.2. Habitat types

Habitat types are categorised into marine habitat types and salt marshes and dunes. Marine habitat types are the sublittoral and littoral types of habitat. Within the Voordelta, two marine habitat types are present, according to the Rijkswaterstaat & Royal HaskoningDHV (2016), permanently flooded sandbanks (*permanent overstroomde zandbanken*, H1110) and silt and sandbanks (intertidal area) (*bij eb droogrvallende slikwadden en zandplaten*, 'H1140), after this intertidal flats.

Taken together, Rijkswaterstaat & Royal HaskoningDHV (2016) and van Moorsel et al. (2020) suggest an important role for the sandy shoals Middelplaat and the the Bollen van de Ooster, as these shoals provide habitat for seals and many bird species. The littoral zone of the Brouwersdam beach is an important habitat area for birds as well. The approximate amounts of different species foraging and living in these habitat areas are listed in Table 4.1. The hard substratum area (accommodating a shellfish reef) near the Blokkendam is not mentioned in the Management plan of the Voordelta (Rijkswaterstaat & Royal HaskoningDHV, 2016), because was discovered after the publication of it. However, the shellfish reef is considered to be an important habitat in this thesis. Moreover, since june 2021, the reef has a temporarily protected status with respect to fishing (Staatscourant, 2021). This holds that fishing activities are temporarily prohibited near the reef. It is expected that (existing and future) shellfish reefs will be protected by the EU Habitats Directive around 2021-2022, and that the flat oyster will be added as a typical species of protected habitats in the North Sea (*ARK Natuurontwikkeling*, n.d.).

The beach also contains the habitat type embryonic dunes. The quality of these dunes as a habitat is not optimal, due to a lack of rest (Rijkswaterstaat & Royal HaskoningDHV, 2016). These dunes do not have a protected status and therefore the focus is on the ecological value of the sublittoral and littoral part of the beach. Below, the main features of these habitats is discussed.

Brouwersdam beach

Table 4.1 shows that the Brouwersdam beach provides habitat for several bird species. However, human activities like marine navigation and kite surfing are disruptive for the required rest of bird species like the ruddy turnstone (*steenloper*).

Bollen van de Ooster

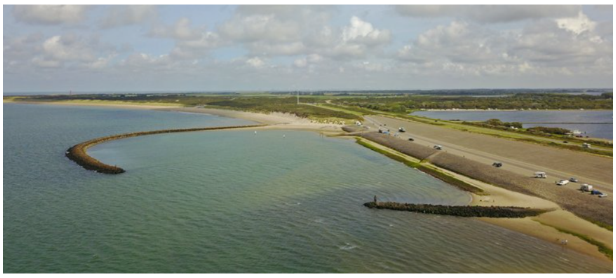
The Bollen van de Ooster is an intertidal shoal near the coast of Goeree-Overflakkee. It is an important area for seals and birds like the common scoter (*zwarte zee-eend*). Activities at this shoal are year-round prohibited. The Resting Area (depicted in Figure 4.1) is larger in winter, because the settling common scoters in nearshore areas during winter (Kerngroep Handhaving Voordelta, 2014). In addition to the habitat providing function for mammals and birds, a part of the Bollen van de Ooster serves as habitat for shellfish as well. In 2016 and 2017, multiple flay oysters, Japanese oysters and adult mussels were found at the southeastern side, the lee side (Sas et al., 2018). Subsequently, a shellfish pilot started, which implied the deployment of Pacific oyster shells, blue mussel shells and artificial structures (Didderen et al., 2019) (reference is made to Section D.2 for further explanation).

Middelplaat

The Middelplaat is an important habitat for seals and bird species. The intertidal flat is therefore year round a resting area (illustrated in Figure 4.1). Activities in the Brouwershavense Gat (the gully located southward of the shoal) are not allowed in winter (from November 1 up to April 1).

Blokkendam

The Blokkendam is the breakwater that provides shelter for the small port that is located at the northern part of the Brouwersdam. At the offshore side of the breakwater, a natural shellfish reefs is present (van Moorsel et al., 2020). This reef was discovered in 2016 (Didderen et al., 2019), which is estimated to originate from 2001-2002 (Staatscourant, 2021). The reef contains flat and Japanese oysters and is, as far is known, the only flat oyster reef in the Dutch North Sea. Flat oysters can be seen as key species and their reefs can accommodate a multitude of other species. Appendix D.2 elaborates on the importance of this reef. Furthermore, the ongoing shellfish pilot project in the Voordelta and the most important features for shellfish reef creation and conservation are discussed in this Appendix. The most important aspect is that the primary condition for reef conservation is, according to Sas et al. (2019), the total absence of seabed disturbance.



(a) Blokkendam, Grevelingen outer delta, obtained from Schrieken & Engelbos (2017)

(b) Shellfish reef near Blokkendam, obtained from Sas et al. (2016)

Figure 4.5: The natural shellfish reef near the Blokkendam in the Grevelingen outer delta

Species	Beach	BvO	Middelplaat
Marine mammals			
Grey seal	-	>100	< 7
Common seal	-	37-75	51-75
Fish eating bird species			
Terns & seagulls (sterns en meeuwen)	500-1000	-	-
Loons & grebes (duikers & futen)	>1000	>1000	250-500
Benthic fauna eating bird species (sea)			
Common Goldeneye & Greater Scaup (brilduiker en topper)	>1000	-	250-500
Common Eider (eidereend)	-	>1000	50-100
Common Scoter (zwarte zee-eend)	-	100-250	-
Benthic fauna eating bird species (intertidal flats)			
Ruddy Turnstone (steenloper)	>1000	-	-
Herbivores & omnivores	250-500	100-200	100-200

Table 4.1: Approximate amounts of species during one season (2011-2012) on habitat areas the beach, the Bollen van de Ooster and Middelplaat (Rijkswaterstaat & Royal HaskoningDHV, 2016)

4.4. Enhancement of the ecosystem's functioning

Nature-based designs are characterized by their use of the system's natural dynamics, their multi-functional and innovative design, and the fact that they are design in a specific context (van Eekelen

& Bouw, 2020). Furthermore, van Eekelen & Bouw (2020) elaborate on designing in sandy coastal ecosystems. In these ecosystems, the goals are the reduction of negative effects on natural features and the creation of new habitats that function well within the existing system. A healthy coastal system provides ecosystem services. As biodiversity is an important parameter for a healthy environment, Building with Nature solutions aim to enhance habitats and biodiversity by providing gradients along and across the shore. This differs from 'gray' infrastructure, that creates barriers and sharp divides between habitats (van Eekelen & Bouw, 2020).

The benefits of a project to the ecosystem can be related to the overall system in which it resides (the larger scale) or the project can be made more eco-friendly with small adaptations (the smaller scale). This section elaborates briefly on the larger scale benefits. The smaller scale benefits are examined in Chapter 9, in which the designs are refined. This section discusses two possible enhancements of the ecosystem, which hold the creation of two types of habitat. It should be noted that this study focuses on these two habitats, but there may be more possibilities to enhance the ecosystem on the larger scale. In other words, a more comprehensive study could indicate more enhancing features.

First of all, shoals are important habitats (Habitat type H1140), that could be created as part of the solution. The shallow area of the basin can be optimally used. As the foreshore is shallow, the construction of an artificial shoal does not require as much as sediment as in the case of a steeply sloping foreshore. An extra shoal could provide habitat for marine mammals and several types of birds. The habitat type currently functions well within the existing system and therefore it would enhance the ecosystem.

Secondly, an artificial shellfish reef could be constructed. The main ecosystem services of shellfish reefs are among others the mitigation of erosion by the retention of sediment and reducing wave energy, the improvement of the water quality by the filtration of sludge and algae from the water and the enhancement of biodiversity (Grabowski & Peterson, 2007). The latter can be explained by the fact that these reefs enhance the population of bird and other species through the provision of food and hard substrate. An example of a population of species that is possibly enhanced are benthic-fauna eating birds at tidal flats. The possibility of the creation of artificial reefs near the Brouwersdam beach as part of the project is discussed with Karin Didderen, marine ecologist. One of the main outcomes of this consultation is that the presence of Japanese oyster larvae in the Grevelingen outer delta is sufficient. In other words, if the solution creates one or more areas in which the habitat requirements of these oysters are met, these oysters will most likely settle and a reef will grow (K. Didderen, personal communication, May 16, 2021). Moreover, the creation of a shellfish reef as part of the project contributes to the commitment of the Dutch government to the return and recovery of biogenic reefs, such as shellfish reefs in the North Sea (Rijkswaterstaat, 2020).

4.5. Summary

This chapter provides an answer to Sub-question 2: *What are the features of the ecosystem of the Grevelingen outer delta and how can the solution potentially enhance the ecosystem*

First of all, the Natura2000 regulations are investigated. As part of these regulations, the Grevelingen outer delta is designated as Bed Protection area, in which several shoals are Resting Areas for seals and many types of birds.

Subsequently, the abiotic conditions of the area are examined. The outer delta can be characterized as a saline, mainly sublittoral area with two offshore littoral zones. It mainly consists of soft substratum, except for the natural oyster reef near the Blokkendam which contains hard substratum. The area is considered as highly dynamic with respect to the wave impact, but lowly dynamic with respect to the tidal current velocity. These characteristics are used in a later design stage to determine whether a structure can provide the necessary habitat requirements for oysters (Appendix D.6 and Chapter 8).

The enhancement of the ecosystem by the solution can be done by creating two habitat types. Firstly, the shallow area of the basin can be optimally used to create one or more shoals, which could provide habitat for, among others, seals and several types of birds. Secondly, the creation of a shellfish reef provides many ecosystem services such as the reduction of wave energy and the filtration of water, and enhances biodiversity as well. Moreover, the creation of a shellfish reef as part of the design contributes to the commitment of the Dutch government to the return and recovery of biogenic reefs, such as shellfish reefs in the North Sea (Rijkswaterstaat, 2020). A main outcome of the consultation with a marine ecologist is that, if the solution creates areas in which the habitat requirements of Japanses oysters are met, these oysters will most likely settle and a reef will grow.

5

Social system analysis

The preservation of the Brouwersdam beach is a complicated topic which encompasses a complex decision-making process. As the solution is ought to be nature-based, it should enhance nature restoration goals as well as addressing socio-economic needs (Slinger et al., 2021). To achieve such a solution, the actors are faced with making a trade-off between different functions of the solution and the beach (Janssen et al., 2020). This poses social dilemmas. A multi-functional nature-based solution can be attractive to certain stakeholders on the one hand, while it is not the most cost-effective solution for other stakeholders on the other hand (Janssen et al., 2020). Hence, the inclusion of multiple stakeholders in the design process is critical for the solution's success (van Eekelen & Bouw, 2020). To be able to include every relevant stakeholder in the design process, understanding of the social system is a main aspect in the Building with Nature design approach.

A distinction is made between stakeholders and actors. According to de Blois & De Coninck (2008), stakeholders, on the one hand, refer to the beneficiaries and the ones that have a specific stake in the project and are often not involved in the execution phase, whereas actors, on the other hand, are the directly involved ones in all phases of the project (from concept up to execution and operation). The actors interact in decision-making processes via institutions (Janssen et al., 2020). It is therefore useful to investigate the interactions between actors around NBS from an institutional perspective. However, an elaborate description of the institutional context is out of the scope of this thesis, just as the distinction between stakeholders and actors. Therefore, the currently involved actors and stakeholders are analysed in a descriptive manner and are referred to as stakeholders. Thus, the stakeholders are defined as individuals and organisations who are actively involved in the project or whose interests may be positively or negatively affected by the execution of the project (PMI Standards Committee, 2000).

The focus of the social system analysis of this thesis is on the link between the stakeholders' interests and the (physical) aspects which a nature-based solution could affect. These aspects can then be translated into specific requirements for the design of a measure.

The sub-question that is being answered in this section is Sub-question 3: *Which stakeholders are engaged in taking a measure at the beach and which indicators reflect their goals and interests?*. This question is being answered in this chapter. The first step is the identification of the main stakeholders and the assessment of their objectives and interests. This analysis is based on a literature study and meetings with the PGB (Project Groep Brouwersdamstrand), a specific collaboration between stakeholders. The stakeholders participating in the PGB and the stakeholders that were further identified by this group are considered to be the directly involved ones. The result is a descriptive list of involved stakeholders (Section 5.1), in which their interests are discussed. Besides, the recent, relevant developments concerning the beach are discussed. The second step involves the categorization of the stakeholders (Section 5.3). This results in an overview of the stakeholders' goals and interests in an objectives-interest table. Then, in Section 5.5 and 5.6, the main interests of the stakeholders (recreational and ecological value, respectively) are translated into indicators. This is done with the interest framework, explained in Section 5.4. The indicators are used in the Program of Requirements (in Chapter 7) to assess the positive or negative effect of a solution on the recreational and ecological value of the beach.

5.1. Stakeholder identification

In this section, the involved stakeholders and their role and interest are discussed. A list of stakeholders is established in collaboration with the Municipality of Schouwen-Duiveland (P. van Sante, personal communication, November 20, 2020), which is supported by literature review and consultations with the Project Groep Brouwersdam (PGB). The latter is a collaboration between directly involved stakeholders. This group aims to discuss developments concerning the Brouwersdam beach. The ultimate goal of this project group is to maintain a sustainable beach at the Brouwersdam (in Table 5.1, the column 'PGB' shows whether the stakeholder is involved in this group (V) or not (X)). The result of the stakeholder identification is the following list of stakeholders. The investigation shows that the main stakeholders can be divided into three types, namely government agencies, environmental NGOs and entrepreneurial collaborations. This list is then used in the next section to conclude on the main interests in the beach.

5.1.1. National, regional and local government stakeholders

The government agencies that have an interest at the beach are discussed below. Note that the beach is located at a domestic border and that, therefore, two municipalities and two provinces are involved.

- **Municipality of Schouwen-Duiveland and Goeree-Overflakkee**
  These municipalities are the landowners and, thereby, the terrain managers of the beach. The conservation of the beach is particularly important because the beach supports the local economy of both municipalities. The shift of the beach towards the northeast leads to a significant decrease of surface area within the borders of Schouwen-Duiveland. the urgency is therefore much larger for this municipality than for Goeree-Overflakkee. The beach surface area (between 0 and +3 m NAP) in Goeree-Overflakkee is approximately 63 ha against 3 ha in Schouwen-Duiveland (Jarkus data 2020, see Figure 3.10).
  However, when the erosion trend continues in the coming decades, the surface area of the beach in Goeree-Overflakkee will decline as well. Moreover, a decrease with of the beach (whether this is in Schouwen-Duiveland or Goeree-Overflakkee) will not benefit the recreational value of the beach and is therefore not desirable for both municipalities.
  In 2009, Ecorys provided a report in which the (direct and indirect) negative effects of the beach erosion are quantified (van den Heuvel & Rabelink, 2014). This investigation shows that in 2009, the erosion negatively affects the financial benefits with €0.8 million per year (gross). On the long term, if no human interventions are taken, this negative effect could increase up to €5.4 million per year (Arcadis, 2012).

- **Province of Zeeland and province of Zuid-Holland**
  The provinces are responsible for the sustainable spatial development of the area. Moreover, each province aims to increase the regional economy and to create new nature. Thereby is the province among other parties responsible for the monitoring of compliance with environmental (Natura2000) laws.The monitoring and licensing concerning natural legislation is done by a body of the province. The Omgevingsdienst of Zuid-Holland South (OZHZ) operates on behalf of the province of Zuid-Holland. The monitoring in Zeeland is done by the RUD (Regionale Uitvoeringsdienst), whereas the licensing is done by the Province itself. As there are many different enforcement agencies for the Natura2000 management plan, they collaborate in the monitoring organization, of which the Omgevingsdienst Zuid-Holland Zuid is the director.
  Finally, the province monitors the quality and the financial affairs of the municipalities. The interest for both provinces is therefore versatile: they have both economic and ecological stakes.

- **Rijkswaterstaat**
  Rijkswaterstaat is part of the Dutch Ministry of Infrastructure and Water Management and is the responsible party for the design, construction, management and maintenance of the main Dutch infrastructure facilities. To prevent the Netherlands from flooding, like in 1953, Rijkswaterstaat made a plan to ensure flood safety called the national Dynamic Coastal Preservation Program.

To maintain a flood-proof coast, Rijkswaterstaat established the Basic Coastline (Basiskustlijn, BKL) in 1990: the amount of sediment in the coastal zone must be equal to the amount in 1990. When the yearly coastal assessment shows that a coastal stretch contains less sediment, Rijkswaterstaat nourishes the considered stretch. Thus, Rijkswaterstaat only nourishes beaches that fulfil a function for flood safety. As the beach is located in front of the Brouwersdam, which protects the hinterland from flooding, the beach is not part of the Dynamic Coastal Preservation Program. The preservation of the recreational beach is not the responsibility of Rijkswaterstaat.
Moreover, Rijkswaterstaat is, as the coordinating manager of the North Sea, responsible for the monitoring and maintenance of the Natura2000 values. The interest of Rijkswaterstaat is therefore only ecological.

- **Ministry of Economic Affairs and Climate Policy (EZK), Ministry of Infrastructure and Water Management (IenW), Ministry of Agriculture, Nature and Food Quality (LNV)**
  At a ministry, the government policy is prepared and implemented. In case of plans for a new construction or project in the Grevelingen outer delta, the ministry of IenW approve. This ministry has almost no interest in the preservation of the beach. The Ministry of LNV is accountable for the protection of nature. Nature conservation laws (such as Natura2000 legislation) will be decisive whether a solution at the beach can be achieved. Hence, the interest of this ministry is to ensure that the solution complies with nature legislation. The Ministry of EZK is, in the context of the beach, concerned with climate change and to a lesser extent the recreational activities that enhance the (local) economy. The compliance with environmental legislation is monitored by EZK. Their (small) interest is in the preservation and growth of the coastal tourism due to the economical benefits.
  Moreover, the budget for the construction of a tidal inlet in the Brouwersdam (reference is made to Section 5.1.4) is made available by the Ministries of IenW and LVN. If, after further research, the inlet is thought to harm the beach, these ministries may support a solution for the beach financially.

- **Staatsbosbeheer**
  Staatsbosbeheer is a national public body that operates on behalf of the Dutch government, aiming to strengthen the natural value of the Netherlands. It is the land owner and manager of many nature reserves, among others the lake Grevelingen and parts of the Brouwersdam. The (construction) activities at the seaside of the Brouwersdam may affect these areas. Hence, the stake of Staatsbosbeheer is to ensure that a solution has a minimal impact on the natural value of the surroundings of the Brouwersdam.

5.1.2. Environmental NGOs

Several non-governmental organizations (NGOs) are involved with the natural and environmental value of the Brouwersdam beach and its surrounding area. It must be highlighted that it is without of the scope of this thesis to perform an elaborate analysis on all NGOs that are engaged with the Grevelingen outer delta. Hence, only four stake holding NGOs that are considered to be most important are listed. NGOs with a possible stake, which are not included in the analysis, are for example Stichting Noordzee and Stichting Anemoon. Another notion should be made on the interest of the environmental NGOs. From the ecosystem analysis in Chapter 4, it is concluded that recreational activities disturb the habitats of many species by causing nuisance. The interest of the environmental NGOs is thus further specified: there is no interest in preserving the beach for recreational activities, but as the decision-making process for a possible solution (which may affect the ecosystem) is ongoing, there is an interest of the environmental NGOs to protect the ecological value of the area and possibly create nature enhancing solutions.

- **Zeeuwse Natuur- en Milieufederatie (ZMF)**
  The ZMF (Nature and Environment Federation of Zeeland) is an umbrella organization that operates on behalf of their members, which are regional nature organizations. The aim is to protect the nature and environment of Zeeland. Moreover, the ZMF drives initiatives that contribute to a sustainable society.

- **ARK Natuurontwikkeling**
ARK Natuurontwikkeling (ARK Nature Development) is a Dutch private nature organization. It carries out research and takes initiatives for nature conservation and management, both inside and outside the Netherlands (*ARK Natuurontwikkeling*, n.d.). ARK Natuurontwikkeling makes efforts to combine nature conservation with other social objectives such as water safety, landscape development, recreation and water or raw material extraction. Together with the WNF (Wereld Natuur Fonds), it commissioned several shellfish reef restoration pilots in the Voordelta (Sas et al., 2018).

- **Wereld Natuurfonds (WNF)**
The Wereld Natuur Fonds (WNF) is the Dutch branch of the World Wide Fund for Nature (WWF), which is one of the world's largest nature conservation organizations (WWF-NL, n.d.). WWF focuses on the preservation of biodiversity, responsible use of renewable raw materials and reduction of pollution (WWF-NL, n.d.). Together with ARK Natuurontwikkeling, it commissioned several shellfish reef restoration pilots in the Voordelta (Sas et al., 2018). Since the discovery of the shellfish reef near the Blokkendam in 2016, WNF and ARK Nature Development have asked for additional protection of this habitat.

- **Stichting De Noordzee** Stichting de Noordzee (the North Sea Foundation) is a Dutch environmental organization that is committed to the protection and sustainable use of the North Sea. Activities that concern the outer delta hold the protection of seabed areas (including the ecological friendly ways of dredging), shellfish reef restoration and the reduction of waste in sea and at beaches.

5.1.3. Entrepreneurial collaborations
The two main entrepreneurial collaborations that are engaged with the beach are:

- **Platform Pioniers Brouwersdamstrand (PPB)**
The PPB (Platform Pioneers Brouwersdamstrand) is a partnership between fifteen entrepreneurs that join forces by acting as a partner for public and government agencies. The platform aims to contribute to the further development of the Brouwersdam as a recreational hot-spot from an entrepreneurial perspective. The urgency of resolving the situation at the beach is high for some members of this platform: the beach restaurant of one of the entrepreneurs is located at the southern part of the beach, which experiences large erosion rates (Figure 5.1 shows the state of the restaurant during MSL). The structure experiences a lot of damage, and the bottom of the foundation piles are inundated most of the tidal cycle (L. Traa, personal communication, Augst 31, 2020)). The other beach clubs are not located as close to the eroding part of the shoreline. However, the owners of these are concerned about the erosion as well, because the shifting coastline will also reach these beach clubs in the future. Thereby, they have an economical stake: if the recreational value of the beach decreases due to the eroding beach, their turnover will decrease as well.
Thereby, a recent goal of the platform is to make the Brouwersdam Beach the most sustainable beach in the Netherlands. The interpretation of this is still unknown, but a high natural value of the environment is also important for this party.

- **Toeristisch Ondernemend Zeeland (TOZ)**
The TOZ (Tourism Entrepreneurship Zeeland) is the umbrella organization of the Zeeland parts of among others the Koninklijke Horeca Nederland (KHN) and the foundation Day-trips Zeeland (stichting Dagattracties Zeeland). The partnership aims to create and maintain an attractive environment and a sustainable recreational sector. It thus benefits from sustainably maintaining the beach.

5.1.4. Recent developments
Several developments concerning the beach have taken place over the last decade. The main developments are discussed in this section.

Figure 5.1: Strandclub Zee at the Brouwersdam beach, photo taken at approximately MWL (mean water level) (photo taken at 31-08-2020)

Beach nourishment 2016

The urgency to preserve the beach led in 2015 to the following. The Province of Zeeland requested Rijkswaterstaat to skip a regular nourishment on the Kop van Schouwen to stimulate the natural dynamics of the dunes. This was a quantity 400,000 m^3 sand. The regional parties, such as the involved municipalities, suggested to Rijkswaterstaat to nourish that amount of sand at the Brouwersdam beach. Rijkswaterstaat initially did not agree to this plan as it would be a recreational nourishment, and the sand could be used elsewhere within the Dynamic Coastal Preservation Program. After the regional parties proposed co-financing the nourishment, Rijkswaterstaat agreed to the plan (M. Lazar, personal communication, October 4, 2020). The Municipalities of Schouwen-Duiveland and Goeree-Overflakkee, Provinces of Zeeland and Zuid-Holland and local entrepreneurs contributed financially with €250,000 (van den Heuvel & Rabelink, 2014). Consequently, a total amount of 500,000 m^3 was nourished in 2016 (see Section 3.4).

Project Getij Grevelingen

In 2012, a vision for the area around the Brouwersdam was developed: the Rijkstructuurvisie Grevelingen Volkerak Zoommeer (RGV). One of the goals was to recover the oxygen level of the water in Lake Grevelingen by constructing an inlet in the Brouwersdam. Therefore the Project Getij Grevelingen (Tidal Project Grevelingen) was set up. All above mentioned governmental agencies are involved in this project. Appendix C elaborates on the tidal inlet. In principle, a connection between the Grevelingen and the North Sea increases the opportunities for ecological benefits, but morphological changes will occur in the Grevelingen outer delta, especially at the Bollen van de Ooster and the Brouwersdam beach (Jansen et al. (2012); Rijkswaterstaat & Royal HaskoningDHV (2016)). The morphodynamic effects depend partly on the location of the tidal inlet, which are depicted in Figure C.1. These morphodynamic changes mainly relate to the migration of sandy shoals and the beach.
The balance between the disappearance and development of sandy shoals and the beach is difficult to predict. The nature of the changes depends partly on whether a tidal power station is placed in the Brouwersdam. Many researches have been done concerning these changes, and these conclude that the tidal inlet is expected to affect the hydrodynamics and morphology of the beach (Jansen et al. (2012); Wang (2010)). Further research should be carried out into the extent to which these effects are assessed as negative for preserving the beach. During this research, a simultaneous investigation is conducted to determine the location of the inlet. In the Program of Requirements of this project, the beach's preservation is stated as a wish (M. Lazar, personal communication, March 26, 2021).

Zeeuwse Kustvisie and the Recreational BKL

The Province of Zeeland created the Zeeuwse Kustvisie in collaboration with the North Sea coastal municipalities, environmental organizations (NGOs), recreational interest groups, the ZLTO (an organization for farmers and gardeners), Rijkswaterstaat and the water boards (de Waterschappen). As part of this collaboration, which was signed by all parties in 2017, agreements are made about possibilities

and restrictions on the Zeeland coast .
In the Zeeuwse Kustvisie, the desire to arrive at a recreational BKL was expressed. The Dynamic Coastal Preservation Program has supported the parties involved in assessing the consequences of a recreational BKL. Based on these consequences, the municipalities have gained insight into the costs associated with introducing a recreational BKL. The parties concerned have decided to set up a recreational sand fund for this purpose. The current capacity and working methods of the Dynamic Coastal Preservation Program are tailored to the current program. They cannot include recreational nourishments until it is clear whether there is sufficient support for a recreational sand fund and whether a recreational BKL is feasible (Rijkswaterstaat, 2019). After it is clear whether the recreational sand fund has sufficient support, in consultation with the Ministry of Infrastructure and Water Management (I&W), it must be clarified how a recreational BKL can be implemented (Rijkswaterstaat, 2019).
In 2011, the four coastal provinces of Zeeland, Zuid-Holland, Noord-Holland and Fryslân commissioned an external party to investigate the possibilities for defining and mapping a recreational BKL (Basis Kustlijn) (Broer et al., 2011). The recreational BKL should indicate how wide the beach should be to provide sufficient space for the recreational functions of the coastal stretch. In this assessment, the Brouwersdam beach is categorized as a sports and events beach that is used intensively, which requires a minimum beach width of 100 m (from the dune foot to the mean high water level line) (Broer et al., 2011).

5.2. Main interests

Based on the stakeholder identification of the previous section, the interests concerning the beach preservation can be divided into two main categories, namely recreation and ecology. In this section, the main interests of the stakeholders are discussed.

Recreation

From the stakeholder identification, it can be concluded that the economic interest in the beach is mainly including recreation. Entrepreneurs profit from recreation and therefore the entrepreneurial collaborations have a high stake in the preservation of the recreational value. For local government stakeholders, the recreation the beach is important as well: the recreational activities are credited to support the local economy by approximately 9 million euros per year (Lazar & Elias, 2019). The main stakes of environmental NGOs are not concerning recreation.

Ecology

The preservation and development of nature is the main stake of the environmental NGOs. However, the government stakeholders and entrepreneurial collaborations have a stake in ecology as well. The beach is part of a larger Natura2000 area (which is elaborated in Section 4.1). This means that the state of nature defined in the Natura2000 Management plan has to be maintained by several government stakeholders. Part of this plan includes the assignment of resting and foraging areas for different species and thereby limiting the recreational area. For entrepreneurial collaborations, the aim of preserving the ecological value of the area can conflict with their aim of increasing or maintaining its recreational value (Rijkswaterstaat & Royal HaskoningDHV, 2016). To conclude, preserving and increasing the ecological value is not only an interest of environmental NGOs: the sense of responsibility and appreciation for nature and landscape is increasing among all stakeholders.

5.3. Stakeholder categorization

In Section 5.1, the stakeholders are identified, and their tasks, interest and role concerning the beach are analyzed. In this section, the stakeholders are categorized. This is done by means of an objectives-interest table and a power-interest matrix.

5.3.1. Categorization of stakeholders' objectives

For a case with a clear problem that requires a solution, an objectives-interest table (introduced by Hermans & Cunningham (2018)) is suitable. Whether this research concerns a clear problem is arguable, but nevertheless, the table is a convenient anyway of schematizing the stakeholders and their stakes. The table distinguishes between stakeholders' strategic objectives (related to the general situation) and problem-specific objectives (related to the issue) (Ecoshape, n.d.-b). The combination of these two objectives indicates the level of interest that each party has in the problem-related situation (Hermans & Cunningham, 2018). Thus, the stakeholders that are listed in Section 5.1 are categorized in Table 5.1. For completeness, the level of interest and power of each of the stakeholders is indicated in Table 5.1. The reasoning behind the assignment of these levels is elaborated in Section 5.3.2.

Table 5.1: Stakeholders' objectives with respect to recreation and ecology and level of interest in the problem. PGB stands for Project Groep Brouwersdam, a V meaning the stakeholder is involved in the project group and vice-versa for an X.

Stakeholder	PGB	Strategic objective: Recreation	Strategic objective: Ecology	Problem specific objective	Power	Interest
Municipality of Schouwen-Duiveland (problem-owner)	V	Room for recreation and attractive beaches for tourism	Room for nature with a high ecological value	An innovative and cost-efficient solution for the erosion of the beach, which mainly enlarges the beach on territory of Schouwen-Duiveland	Medium	High
Municipality of Zuid-Holland	V	Room for recreation and attractive beaches for tourism	Room for nature with a high ecological value	An innovative and cost-efficient solution for the erosion of the beach	Medium	High
Province of Zeeland (the Regionale Uitvoeringsdienst)	V	Growth of the recreational economy of the province	Monitoring of compliance with natural (Natura2000) legislation and licensing	Preservation and growth of the coastal tourism in a sustainable way	Medium	Medium
Province of Zuid-Holland (Omgevingsdienst Zuid-Holland Zuid)	V	Growth of the recreational economy of the province	Monitoring of compliance with natural (Natura2000) legislation and licensing	Preservation and growth of the coastal tourism in a sustainable way	Medium	Medium
Rijkswaterstaat Zee en Delta	V	Facilitating Dutch infrastructure, among others with the aim to enhance economical activities	Coordinating manager of the North Sea and reviewing the effects of the existing use on Natura2000 conservation goals	Management of the Brouwersdam and its near surroundings, executing party of Ministry of IenW	High	Low
Ministry of Infrastructure and Environment (IenW)	X	Safe, effective and efficient use of Dutch North Sea zone	Monitoring of compliance with environmental (Natura2000) laws and decision-maker and payer of Project Getij Grevelingen	Decision-making	High	Low
Ministry of Agriculture, Nature and Food Quality (LNV)	X	Safe, effective and efficient use of Dutch North Sea zone	Monitoring of compliance with environmental (Natura2000) laws	Ensuring that the solution complies with nature legislation	High	Low
Ministry of Economic Affairs and Climate Policy (EZK)	X	Strong Dutch economy	Review the effects of the existing use on Natura2000 conservation goals	Preservation and growth of the coastal tourism in a sustainable way	High	Low
Zeeuwse Milieufederatie (MDF)	X	-	Preserving and enhancing the environment of Zeeland	Protection and possible enhancement of biodiversity and nature values of the beach	Low	Medium
Staatsbosbeheer	X	-	Owner of the nature areas on the Grevelingen side of the Brouwersdam	Ensuring that a solution has minimal impact on the natural value of the Brouwersdam	Medium	Medium
ARK Natuurontwikkeling	X	-	Nature conservation and management	Protection of present and development of new (shellfish) habitats in the Voordelta	Low	Low
Wereld Natuurfonds (WNF)	X	-	Preservation and enhancement of biodiversity, the use of renewable materials and the reduction of pollution	Protection of present and development of new (shellfish) habitats in the Voordelta	Low	Low
Platform Pioniers Brouwersdamstrand (PPB)	V	Development of Brouwersdam beach as recreational hotspot	The preservation of a natural attractive environment	An innovative and cost-efficient solution for the erosion of the beach, which mainly enlarges the beach on the territory of Schouwen-Duiveland	Medium	High
Toeristisch Ondernemend Zeeland (TOZ)	X	A sustainable recreational sector	The preservation of a natural attractive environment	Preservation of the coastal tourism in a sustainable way	Low	Medium

5.3.2. Power-interest matrix

According to Persson & Olander (2004), it is not enough to just identify the demands and needs of the stakeholders to effectively manage their interests. To do so, the relative power of different stakeholders on the implementation of the project must be identified. Power refers to the ability to influence the design process and final project outcomes. A commonly used method to establish this is the Power-Interest matrix. This matrix groups stakeholders based on their interest and power (Ackermann & Eden, 2011). It is a tool to map how interested each stakeholder is in the project decisions and how much power they have to incorporate their demands in the decision-making process (Persson & Olander, 2004).

A power-interest matrix is established for the stakeholders of the beach, as depicted in Figure 5.2. In the context of the beach, power relates to a key position in the decision-making process regarding the approval of implementing certain designs and possibly also providing budget for the solution. The interest relates to the preservation of the beach. The position of the stakeholders in the matrix relative to each other is explained from high to low power.

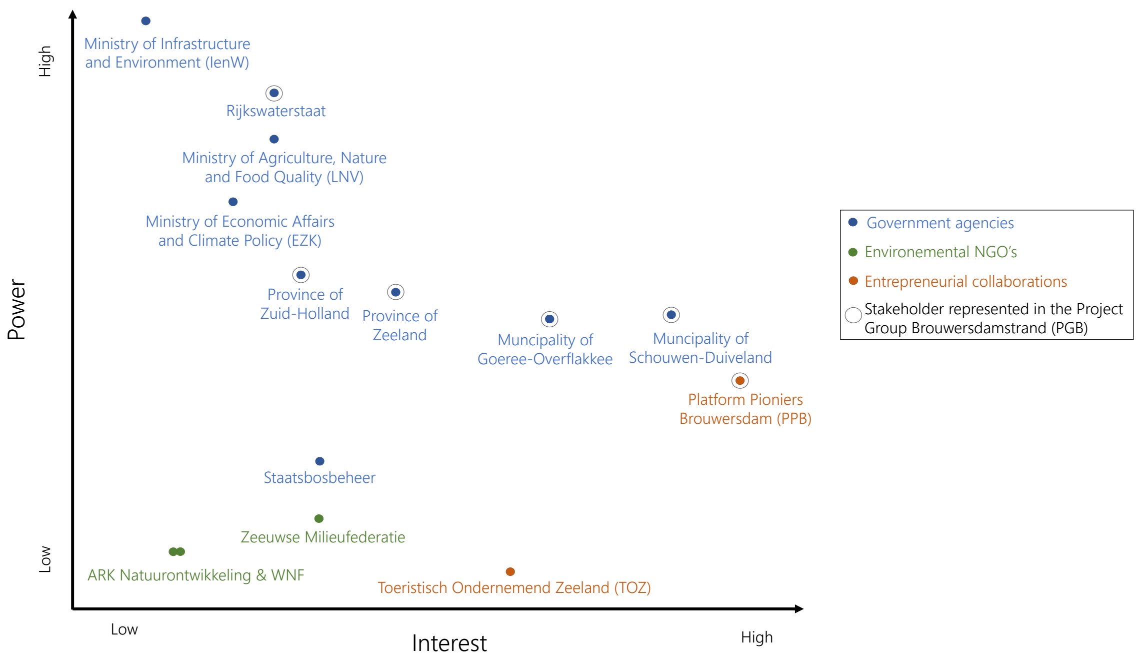


Figure 5.2: Power-interest matrix of stakeholders of the Brouwersdam beach. Note that these are the stakeholders that are currently engaged in the project (descriptive analysis), whereas more groups of individuals or organisations may have a stake in the project. Moreover the main engaged environmental NGOs are analyzed, whereas more NGOs could have been identified.

High power

The ministries have a lot of power as they may provide budget for the solution. This, and the approval of a solution, makes the ministries to be involved at the last part of the decision-making process.

The Ministry of IenW has no interest and the largest power, as this stakeholder has the authority to approve or reject the design. Moreover, it may provide budget for the solution if it considers the problem to be large enough that action is required. Because Rijkswaterstaat operates on behalf of IenW, its power is high as well, but somewhat lower than the power of IenW. Rijkswaterstaat has more interest than IenW, as they are the managers of the Brouwersdam. The Ministry of LNV monitors the compliance with environmental legislation and can therefore approve or reject designs as well, giving it a lot of power. Its little interest covers the support of nature-enhancing solutions. The Ministry of EZK has similar power in approving or rejecting designs, but as environmental legislation is considered to be more important at the beach, the power of EZK is less than LNV.

Medium power
The provinces have medium interest and medium power. Their interest in recreation is less than the interest of the municipalities. Their power is higher than the power of municipalities, as they are closer involved in decision-making processes of the ministries. The municipality of Zuid-Holland has slightly more power than the municipality of Zeeland, because it is a larger organization with more connections to the national government. The municipality of Schouwen-Duiveland is the government agency with the highest interest, followed by the municipality of Goeree-Overflakkee. Their power is equal. Lastly, the stakeholder with the largest interest is the PPB (Platform Pioniers Brouwersdam), as it represents individuals of which the turnover of their businesses is directly related to the recreational value of the beach. Its power is medium, as it may contribute financially to a solution.

Low power
TOZ (Toeristisch Ondernemend Zeeland) is the stakeholder with the least power. With its focus on recreation, the interest is medium. The environmental NGOs ARK Natuurontwikkeling and WNF have slightly more power, as they could pose objections and cause delay or rejection of the project if they consider a solution to have a negative effect on nature. The same holds for the Zeeuwse Milieufederatie, but as this stakeholder operates on behalf of many regional organizations, their stake and power is higher. Staatsbosbeheer has the same level of interest as the Zeeuwse Milieufederatie, as it operates on behalf of the national government.

Conclusions on power and interest
The main conclusion is drawn on the power-interest matrix represented in Figure 5.2, is that there are no stakeholders with high power as well as high interest. This complicates the decision-making process significantly, as the stakeholders with the power to make decisions have a small stake. To increase the likelihood on the implementation of a nature-based solution for the beach, several actions can be taken. First of all, the stakeholders with a medium power and medium to high interest, can collaborate to form one large stakeholder with high power. The Project Group Brouwersdam (PBG) is a similar concept, but there is no clear consensus on the best approach to preserving the beach among the stakeholders within this group. The provinces, municipalities and the PPB could, if they reach this consensus, can form a coalition. This coalition can be seen as a 'new' stakeholder, which has high interest and high power, and may convince the ministry of IenW to support a nature-based solution for the Brouwersdam.
Secondly, the interest of the Ministry of LNV could be increased by pointing out the nature enhancing benefits of a nature-based solution. If this stakeholder has a larger interest, it may collaborate in convincing other stakeholders with high power to take action. Further recommendations on the decision-making process in the social context are elaborated in Chapter 12.

5.4. Interest framework

To translate the stakeholders' interests into a program of requirements for a solution, a framework is established. The framework is based on the process-based framework developed by Van der Moolen (2015), which was used and adapted by Smit (2020) as well. The components of the framework used in this research are depicted in Figure 5.3. The first component is the interest of the stakeholders. The interest is subdivided into functions. To satisfy the stakeholders, the functions must be preserved. For the provision of the function, several indicators are formulated. Each indicator is a measurable parameter and is critical for the existence of the specific function. The indicators are measurable parameters and can thus be used to assess the impact of an erosion mitigating measure on the stakeholders' interest.
For example, extreme water sport is a function of recreation. To ensure that extreme sports can be carried out, the water depth must not significantly be affected by the measure. Therefore water depth is an indicator for recreation.

As elaborated on in Section 5.2, the main interests in the area are recreation and ecology. The indicators for the recreation are discussed in the next section, whereas the indicators for the ecology are discussed in Section 5.6.

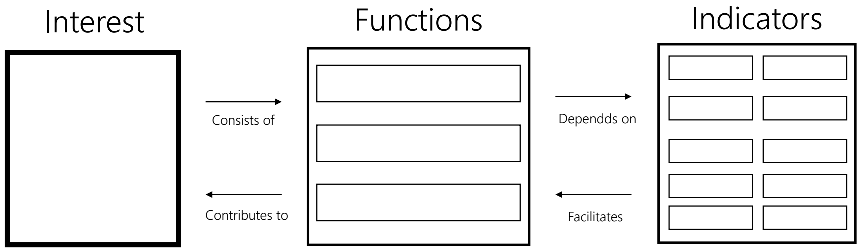


Figure 5.3: Interest framework

5.5. Indicators for recreational value

The solution for the beach should focus on the recreational potential of the beach. The recreational potential of an area depends, according to Williams & Micallef (2009), on three aspects: (1) physical aspects (morphology, waves, currents etc.), (2) socioeconomic aspects (access, safety, landscape, cultural interests etc.), (3) and biological aspects (flora and fauna). The socioeconomic aspects (2) of the Brouwersdam beach are assumed not to be influenced by an erosion mitigating measure. The biological aspects (3) are evaluated in the next section. Hence, this section focuses on the physical aspects (1) that may impact the recreational function of the beach.

The main functions of the beach related to recreation are divided into three categories: extreme water sports, extreme beach sports and more quiet beach activities such as sunbathing (including swimming) and strolling. These functions are depicted in Figure 5.5, in which the indicators are depicted as well. Each function and its associated indicators are discussed in the paragraphs below. In Chapter 7, these indicators are made more concrete and the criteria for the indicators are elaborated.

5.5.1. Water sports

The Brouwersdam beach is the most crowded place for kitsurfing in Europe (Broer et al., 2011), and is used windsurfing as well. A sheltered, shallow area like the Grevelingen outer delta is very suitable for these sports because of the stable wind sea climate.

The beach width is important for all recreation activities. For the surfing community, the beach width is (above MSL) important as this is the area where the preparation of the kites is being done. This requires a wide beach (in cross-shore direction) because of the length of the gear. A wide beach in longshore direction is convenient as well, because of the downdrift movement that kite surfers make when surfing in this area: in the southwestern corner of the beach, the surfers enter the water. Due to the predominant wind direction from the southwest, the surfers enter the beach again in the northwestern part (J. Bosboom, personal communication, May 4, 2021). The accessibility of the water in the southern and the northern part of the beach is thus important.

Lastly, the water depth is important for the performance of these sports. According to Van Zanten (2015), a large water depth can be regarded as pleasant for the surfer. Still, a too shallow area with sandbanks can lead to the surfers' obstruction, especially because of the large variations in the exposed area during the tidal cycle.

5.5.2. Beach sports

The beach is suitable for beach sailing and kite buggying, mainly because a large part of the beach is inundated during high tide, creating a solid surface of the sandy beach. The dry part of the beach (above MHW) is suitable for preparing the kiting and sailing gear. A wide (intertidal and supratidal) beach is therefore important.

A small sediment size could cause high rates of blowing and drifting sediment, disturbing the sports exercises on the beach. Moreover, a small grain size of the beach sediment reduces the strength of the sedimentary bed of the beach, which can cause the wheels to sink into the sediment, which is also disturbing. Hence, the sediment size of the beach should not be much smaller than it currently is. The effect of a different grain size elsewhere near the beach is investigated if this applies to a solution.

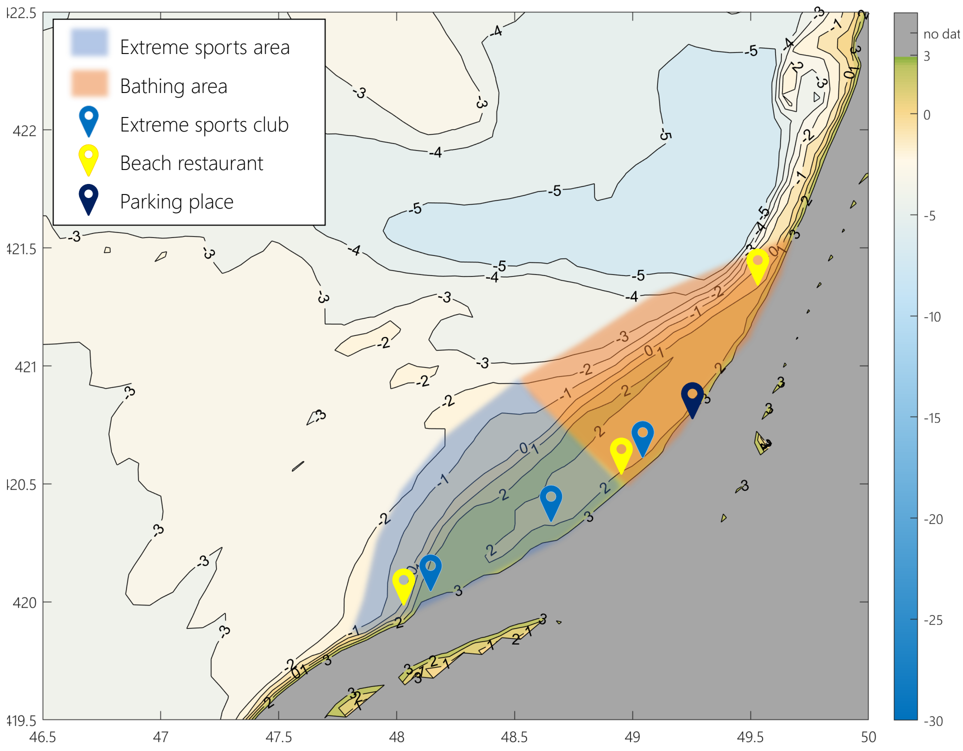


Figure 5.4: Layout of the beach surface area in relation to recreational purposes (J. Eichler, personal communication, February 1, 2021). Locations of beach restaurants, sports clubs and the parking place based on Google Maps (5-2-2021). Bathymetry (2019) retrieved from the Vaklodingen data set.

5.5.3. Sunbathing, strolling and other beach activities

Next to sports, recreational activities such as sunbathing (including swimming) and strolling make the beach a popular place. Thus, the beach has a lot of potential for entrepreneurs. To provide sufficient space for beach restaurants and the different types of beach users, a wide beach is required. Moreover, when extreme sports activities are taking place near the beach and hard wind is present, this can result in unsafe situations for walkers on the beach. Therefore, the beach is divided into a bathing zone and an extreme sports zone. The border between those is the beach entrance (*strandopgang*) 'the Kous' near beach restaurant Brouw (Figure 5.4. Northeast of this border is the bathing beach, and southwest of it is the extreme sports beach (J. Eichler, personal communication, February 1, 2021). However, a conversation about this topic with the entrepreneurs of the beach (Meeting Projectgroep Brouwersdam at 4-5-2021) shows that in practice, the whole beach is used by kite surfers and other extreme sporters. The fact that the beach is used by many different recreational users underlines the importance of a wide beach.
A small sediment size can cause a nuisance in the case of blowing and drifting sediment and is thus inconvenient. As aeolian transport of sediment depends on many other factors as well (such as wind speed, wind direction, soil moisture content, vegetation, beach width), a change in the median grain size at the beach will not necessarily lead to nuisance. Hence, indicator is therefore only of significant importance if major differences in the beach sediment size are expected.
With respect to swimming activities (as part of sunbathing), several factors concerning safety play a role. The flow velocity near the beach is important. In rip currents, flow velocities can be over 1 m/s, which is unsafe for swimmers (Verbeek, n.d.). Experiments in which swimmers of different ages and physical conditions were tested showed that swimming in water with a flow velocity of 0.7 m/s is difficult for a fit person, even without accounting for waves and panic (Verbeek, n.d.). Therefore 0.7 m/s is taken as the maximum allowed flow velocity. Thereby, also the water depth is important: sudden, large gradients in the water depth can lead to unsafe situations for swimmers. At last, the turbidity of the water should be not increase significantly because that reduces the pleasure of swimming.

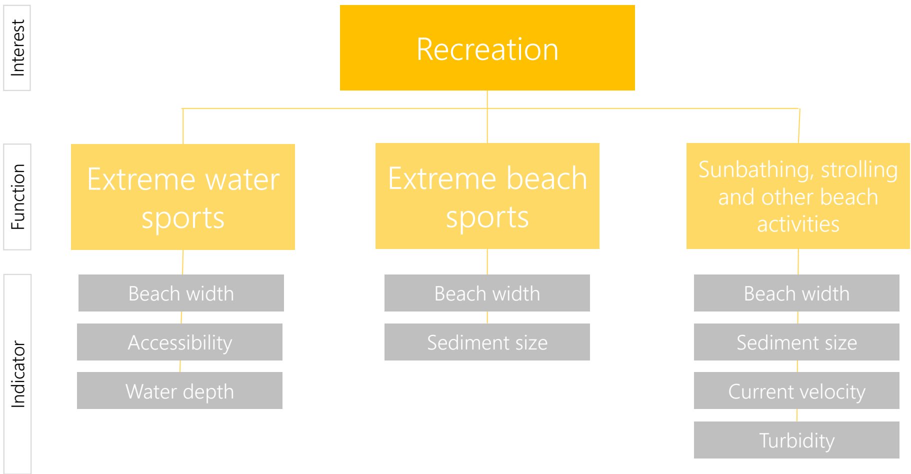


Figure 5.5: Interest framework for recreation

5.6. Indicators for ecological value

To be able to evaluate and test certain design alternatives with respect to ecology, the changes in abiotic conditions have to be assessed. To be able to do this, the interest framework as discussed in 5.4 is applied. The main interest is the value of the ecosystem of the Grevelingen outer delta. The functions that contribute to the ecological value can be seen as the functioning of different species. Therefore the functions in the framework are the habitat types for the most important species that live and forage in the research area. The indicators are mainly abiotic conditions, as habitats of species are changed by a change in abiotic conditions.The (abiotic) factors that indicate the potential state of a function are depicted in Figure 5.6. In Chapter 7, these indicators are made more concrete and the criteria for the indicators are elaborated. Note that salinity is not included in the diagram, even though this is an important factor for many species. The reason that this abiotic factor is left out is that the proposed solution is not expected to cause any changes in the salinity of the project area.

In addition to the abiotic conditions, another indicator is important for the preservation of certain habitat types, which is rest. This indicator holds that the seabed disturbance and nuisance in the outer delta should be minimal. The presence of vessels and construction activities causes harm to the habitats of nearly all species. The presence of vessels and construction activities cause nuisance and possibly also disturb the bed. Hence, the frequency of construction works and the amount of seabed that is disturbed has to be minimized.
The size and amount of shoals are a determining factor as well: they comprise the main habitat area of seals and birds. However, the latter is not included in the diagram, as the proposed solution is not expected to affect the main shoals in the area (the Bollen van de Ooster and the Middelplaat).
It is important to highlight that the potential of a function is assessed with this framework, not the actual functioning. The quality of a function depends on several factors (such as biotic conditions). Therefore the change of an indicator implies the change of the potential of a function. Hence, an increase or decrease of a function is likely occur when the value of the indicator changes.

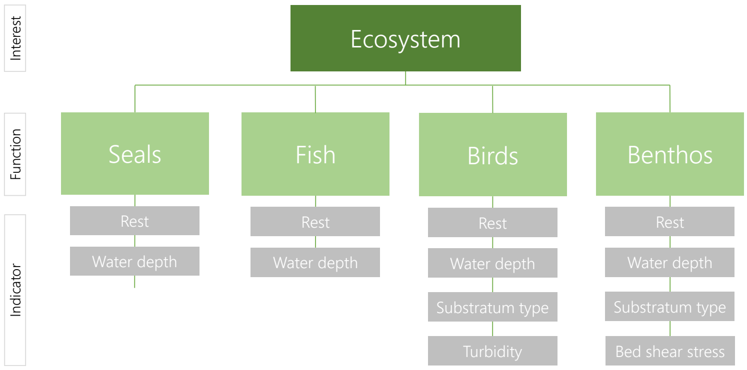


Figure 5.6: Interest framework for ecology

5.7. Summary

The sub-question that is answered in this section is sub-question 3: *Which stakeholders are engaged in taking a measure at the beach and which indicators reflect their goals and interests?*.

First of all, the stakeholders are divided into government agencies, environmental NGOs and entrepreneurial collaborations. Five governmental agencies and one entrepreneurial collaboration are represented in the Project Group Brouwersdam (PGB), a cooperation between directly involved stakeholders aiming to preserve the beach. The main interests among the stakeholders regarding the beach are recreation and ecology.

The visualisation of the relative power and interest of the stakeholder by means of a power-interest matrix clarifies one of the main problems in the decision-making process: there are no stakeholders with both high power and high interest. The stakeholder with the largest power, the Ministry of Infrastructure and Environment (IenW), has only little interest in the beach. The stakeholder with the most interest is the Platform Pioniers Brouwersdam, followed by the Municipality of Schouwen-Duiveland. Recent developments near the beach such as the recreative nourishment of 2016 and the development of the concept of a recreational BKL (*Basiskustlijn*) show that stakeholders are willing to take action and to contribute (financially) to the preservation of the beach.

Lastly, the main interests of the area (recreation and ecology) are translated into indicators by means of an interest framework. The interest recreation is subdivided into the functions of water sports, beach sports and sunbathing, strolling and other beach activities. The indicators that facilitate these functions concern the beach width, the sediment size, the accessibility of the shoreline, the water depth, the maximum current velocities and the turbidity of the water. These outcomes were discussed during two meetings with the PGB.
The interest ecology is subdivided into the habitats of the main species, of which the habitat requirements were examined in the previous chapter. The main species are seals, birds, fish and benthos. Their habitat requirements were translated into indicators. Rest (relating to the disturbance of the bed and other types of nuisance) is the most important indicator for the ecological value of the area, as the main species require a habitat with minimal disturbances. Furthermore, the abiotic conditions that indicate the ecological value of the area are the water depth, substratum type, turbidity and bed shear stress.

6
Modelling study

The literature review of Chapter 2 and data analysis of Chapter 3 provide insight into the driving processes behind the emergence, development and erosion of the beach. However, to be able to counteract the erosion and displacement of the beach, insight in the temporal and spatial distribution of the longshore sediment transport and the relative relative importance of different wave conditions to the observed erosion is needed. A modelling study is performed to obtain these insights. Moreover, an prediction of the future development of the beach without any human interference in the system is needed, as this is the reference situation. In other words, the coastline development with a certain solution must be compared to the situation without any solutions to be able to conclude on the efficiency. A quantitative method like a modelling study offers an effective way to provide insight into this future development.
Hence, the modelling study has three goals, namely (a) providing insight in the cross-shore and longshore distribution of longshore sediment transports and the contribution of different wave conditions, (b) obtaining a sufficiently accurate prediction of the future shoreline development and (c) providing a tool which can be used to assess the efficiency of different alternatives. The latter, goal (c), is discussed in Chapter 8. Goals (a) and (b) relate to Sub-questions 4 and 5, of which the answers are given in this chapter:

- Sub-question 4: *How are the longshore sediment transport rates temporally and spatially distributed along the shoreline and which wave conditions have the largest contribution to the observed morphological evolution of the beach?*
- Sub-question 5: *What is the expected future morphological evolution of the beach in the coming three decades?*

In the first section of this chapter, Section 6.1, the methodology leading to these sub-questions' answers is explained. Section 6.2 elaborates on the wave model set-up, after which the results of this wave model are discussed in Section 6.3. Then, Section 6.4 discusses the set-up of the coastline model. Thereafter, Section 6.5 elaborates on the calibration of the hindcast model. Section 6.6 elaborates on the results of the hindcast model and an answer is provided to Sub-question 4. Section 6.7 includes the validation of the model. Lastly, the forecast model results are discussed in Section 6.8, providing an answer to Sub-question 5.

It is highlighted that, along with the temporal horizon of this thesis up to 2050, a simplification is made. That is, sea level rise is not taken into account in the modelling study and in the design of the solutions. The highly morphodynamic character of the Grevelingen outer delta is assumed to have much larger impact on the developments of the beach than the rise of the sea level in this 30 year period of time. According to Haasnoot et al. (2018), the sea level rise in 2018 along the Dutch coast was about 2 mm per year. In this report, the expected sea level rise in 2050 is about 20-40 cm compared to 1995. This implies, when converted on the basis of the accelerated annual rise, than the sea level at the Dutch coast is expected to rise approximately 10-30 cm in the period 2020-2050. Moreover, the increasing height of the beach in the past 30 years was 3 mm/year, i.e. the beach increased 1 meter in this period (as depicted in Figure 3.16). Compared to the sea level rise in this period, which is about 10-15 cm, the heightening of the beach is much larger. Hence, the morphological changes as part of the large-scale morphological changes of the outer delta due to damming are likely to be the dominant mechanisms.

6.1. Modelling methodology

A 1D UNIBEST-CL+ model is used to achieve the two goals specified in the paragraph above. This section begins with discussing the choice of the model, after which the steps of the methodology are explained.

6.1.1. Model choice

The numerical model UNIBEST-CL+ is based on the the single line theory, which is discussed in Section 2.2. The main assumption on which this model is based is that the shape of the cross-shore profile does not change in time, implying an equilibrium profile. This means that cross-shore transports are not taken into account. Moreover, the implementation of nearshore tidal current patterns is rather simple in UNIBEST-CL+ (the velocity is extrapolated over the depth of the profile with the square root of the set velocity). The complex flow patterns in the Grevelingen outer delta, which vary significantly with spatial location and tide, cannot be implemented in the model. Hence, UNIBEST-CL+ is mainly applicable at shorelines with mainly wave-driven sediment transports (which is the case at the Brouwersdam beach). This makes UNIBEST-CL+ a fast model allowing for the application of a (nearly) full wave climate , but it is less suitable for the investigation of detailed morphology (Tonnon et al., 2018). A 2DH morphological model (a coastal area model) such as Delft3D has the advantage to simulate detailed sediment transport patterns and morphology and the inclusion of tidal forcing. This model is able to simulate the cross-shore transport and the flow patterns in the vicinity of the beach. However, the incorporation of tidal current patterns combined with a large amount of offshore wave conditions requires a lot of computational power and time. This would not fit within the time frame of this research. To reduce the computational demand, it is required to reduce the forcing conditions. Hence, this implies that the wave climate should be schematized down to several (e.g. 6) wave conditions. As insight in the contribution of wave conditions is one of the goals of this thesis, the use of a coastal area model such as Delft3D is not convenient.

6.1.2. Implications of 1D coastline model

The assumption of an equilibrium beach shape implies that the impact of storms cannot be examined by using a 1D model, as storms mainly induce gradients in the cross-shore transports. However, as storms are in general not the main cause of structural erosion (Bosboom & Stive, 2015), this implication is not expected to reduce the quality of the model simulations significantly. The assumption also implies that the build up of dunes by aeolian transport is a very slow process. However, in the case of the beach, the growth of the dunes and the heightening of the beach profile is quite significant. Hence, the net yearly longshore sediment transport rates at eroding parts are slightly overestimated by the model. This is induced by the fact that cross-shore transports are not taken into account: the yearly shoreline retreat that is simulated is assumed only to be caused by gradients in the longshore transport, whereas in real life sediment is also transported towards higher parts of beach and to the dunes (which is concluded in Chapter 3, and visualised in Figures 3.14 and 3.15). Hence, in real life this cross-shore redistributed sediment is not lost from the system, whereas the model simulates as if it is. For the model simulations this implies that the sediment balances should be interpreted with caution.

6.1.3. Method

To provide insight in the sediment transports and the contribution of different wave conditions, a hindcast model is being set up. This model simulates the morphological development of the coastline between 2010 and 2015. This period is chosen because it is a sufficiently long period in which no beach nourishments have been executed and therefore the undisturbed coastline development can be evaluated. Moreover, as the morphology near the beach is characterized as dynamic, it is convenient that this period is close to the current situation.
The hindcast model is calibrated by comparing the simulated and the observed coastline development. It provides insight into the cross-shore distribution of longshore transport, the relation between longshore transport and coastline orientation and most important, in the contribution of different wave

conditions to the erosion.

Then, the model is validated. This is done by simulating the shoreline development between 2018 and 2020 with the same settings as in the hindcast model. These results are compared to observed data of this period. If the modelled and observed coastline correspond, then the model can be considered to simulate the beach development sufficiently and a forecast can be done on the future coastline development. The forecast model is set up to achieve the second goal: this model gives a prediction of the future coastline development beyond 2020.

For both the hindcast and the forecast model, several boundary conditions are required. The simulations of a Delft3D-WAVE model (which is set up in this research) and a hydrodynamic Delft3D-FLOW model (which was set up by Jansen et al. (2012)) function as boundary conditions. The flow simulations are discussed in Chapter 3, whereas Section 6.2 elaborates on the set-up and results of the wave model. Together with bed level data, these simulations form the input for the coastline model (Section 6.4). The relation between the model input, output and the sub-questions is visualized in a flow diagram in Figure 6.1.

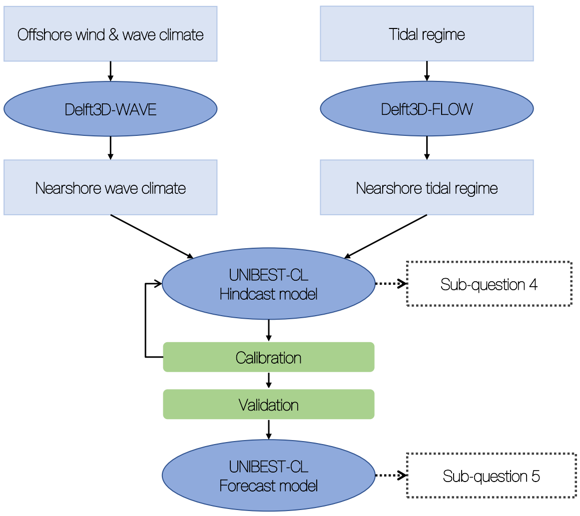


Figure 6.1: Flow diagram of modelling study. Rectangles include input and output values, ellipses indicate model tools.

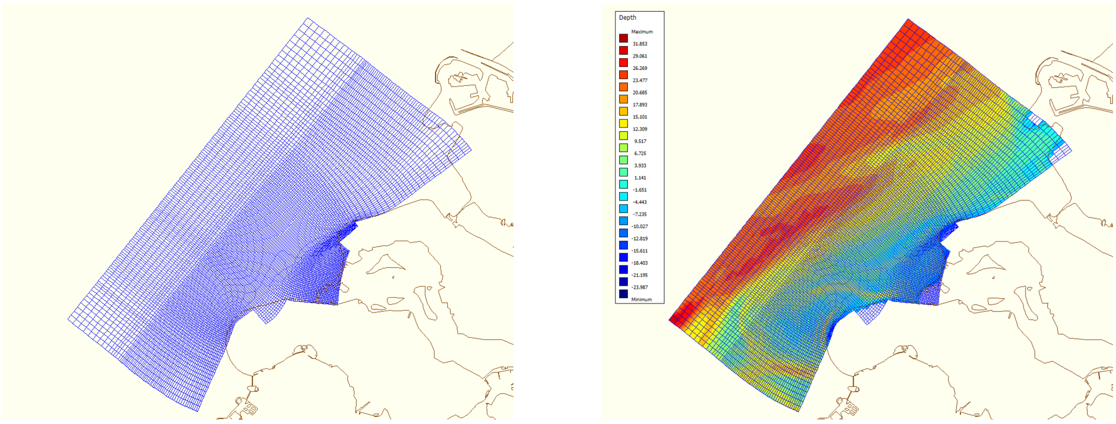
6.2. Wave model set-up

Delft3D-WAVE is a 2DH wave propagation model suite that runs the SWAN model (Simulating WAves Nearshore) (Deltares, 2014). SWAN is an open-source, third-generation model that is developed at the TU Delft (Deltares, 2014) in which waves are described by the 2D wave action density spectrum. It requires user-defined input data for offshore wave data and calculates wave propagation, generation by wind, non-linear wave-wave interactions, and wave dissipation for a given bathymetry.

6.2.1. Grid and bathymetry schematisation

SWAN uses a computational grid and an associated bathymetry grid to perform the wave transformation. The computational grid is a spatial grid on which the wave action balance equation is solved. This can either be a rectangular or a curvilinear grid, but there are some main requirements. First of all, the resolution of the grid should be high in the area of interest. Secondly, the computational grid must be large enough to avoid disturbances at the boundary to affect computations in the area of interest. However, computational time increases with the number of grid points, so it is preferable to limit the number of grid points. A curvilinear computational grid that takes these requirements into account has been constructed by Jansen et al. (2012) and is used by the wave model (Figure 6.2). The grid covers part of the Voordelta, with an offshore resolution of 250 to 750 m. In landward direction, the resolution increases up to 50 to 80 m in the area of interest. The location of the offshore boundary of the grid is representative for the location of Schouwenbank station, the data source for the offshore wave boundary conditions.

The bed level geometry is schematized by means of Vaklodingen data. These observation points are available at a grid of 20x20 m and are therefore grid-cell averaged to the curvilinear grid. The hindcast model computations are executed with Vaklodingen data from 2009-2010, whereas the forecast simulation makes use of the most recent data available, which are Vaklodingen from 2018-2019 (Figure 6.2b).



(a) Computational grid

(b) Bathymetry grid 2018-2019

Figure 6.2: Delft3D-WAVE computational grid and associated bathymetry grid (2018-2019)

6.2.2. Wave boundary conditions

A necessary boundary condition for the wave model is the offshore wind and wave climate. Simulating wave propagation towards the coast over a long period of time is too time-consuming, and therefore the wave data is schematized. This holds the transformation of a time series of wave conditions into a number of typical conditions which represent the full-time series. The schematized offshore wave climate applied is the wave climate from Huibregtse (2013). The reduced wave conditions are derived from the Schouwenbank wave data set (1980-2012), obtained approximately 30 km seaward off the beach, whereas wind data observations of the Brouwerhavense Gat 02 station are used (1982-2012) (see Chapter 3 for the motivation of using these data).

The reduced climate was obtained Huibregtse (2013) as follows. First, the useless data was filtered out of the data set, for instance, wind data without directional information.
Secondly, the waves were classified into sea and swell waves. This separation was done with the use of the following relation:

$$H_s = (\frac{1}{4.5}T_p)^B + C \tag{6.1}$$

In this equation, H_s is the significant wave height and T_p the peak period. The relation in Equation 6.1 has been established based on a relationship for the maximum steepness of wind-sea waves, which was found in the Joint North Sea Wave Project (JONSWAP). In this project, values of 'B'=2 and 'C'=0 were found for the maximum steepness of wind-sea waves. For the Schouwenbank data, a nearly similar shaped line was used for the distinction between sea and swell waves, using 'B' = 1.65 and C = -0.7. Additionally, the peak wave period (T_p) for swell is constrained with a minimum value of 5 seconds. Figure 6.3 shows a scatter plot of the reduced wave climate and the line that is applied to distinguish swell from sea waves.
Thirdly, the data from the two separated parts were divided into multiple bins for different wind directions and wave heights. This process holds splitting the data per wind direction class, after which these are split per wave height class. Table 6.1 shows the different classes. This classification led to wave observations that are bundled into different conditions. In total, 108 conditions were made, consisting of 63 wind sea conditions and 45 swell conditions (listed in Table E.1). Per condition, the wind direction,

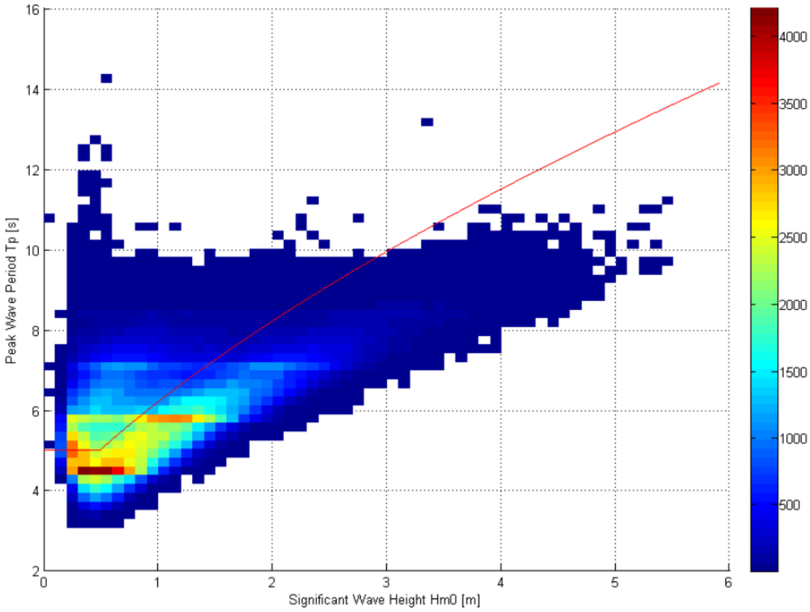


Figure 6.3: Distribution of significant wave height versus peak wave period. Red line represents splitting criterion between sea and swell waves (beneath and above the line, respectively), obtained from (Huibregtse, 2013).

wind speed, significant wave height, peak wave period and wave direction are averaged. This averaged value represents a number of observations. This number is translated into a duration in days per year.

Class		I	II	III	IV	V	VI	VI	IIX	IX	X	XI	XII
Wave direction	θ [°N]	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	270-300	300-330	330-360
Significant wave height	H_s [m]	< 0.5	0.5-1	1-2	2-3	3-4	4-5						

Table 6.1: Classification of normal wave conditions at Schouwenbank (after Huibregtse (2013))

The incident wave conditions need to be prescribed at the boundaries of the computational grid. In the Delft3D-WAVE model, each condition is computed as if it lasts for one minute. The scaled duration of each condition is added in the UNIBEST-CL+ model to account for different probabilities of occurrence. This is further explained in Section 6.4. Furthermore, the model requires some parameters for computational and physical processes. The input parameters are listed in Table E.2.

The Grevelingen outer delta is a shallow area. Near the beach, the water level can vary from 0 m (e.g. emergence of the sea bed) to over 2.5 m water depth. The stage within the tidal cycle is therefore, an important factor in determining the height and period of nearshore waves. Ideally, all wave conditions are simulated during a full spring-neap tidal cycle. This requires however, a large amount of computational power and time. Therefore the vertical tide (water level elevation) is reduced to three water levels: MHW (+1.44 m NAP), MSL (0 m NAP) and MLW (-1.06 m NAP). The simulations are executed for the 2010 and 2018 bathymetry (as explained in Section 6.1).

6.3. Wave model results

The offshore wave climate is transformed to the nearshore by the wave model. This has resulted in a nearshore wave climate consisting of 324 wave conditions (an offshore wave climate of 108 conditions calculated during high, mean and low water conditions). The simulated nearshore wave climate is analysed in this section. First of all, three wind-generated (sea) conditions are discussed. Then, 2 swell conditions are examined.

6.3.1. Wave transformation to the nearshore

Travelling from offshore in a seaward direction, the height, period and direction of a wave changes. Focusing on individual wave conditions results in a few remarkable outcomes. In view of the scope of this study, the transformation to the nearshore of only a few conditions is analysed. The considered conditions are 33, 39, 55, 63 and 81, which are depicted in Figure 6.4.

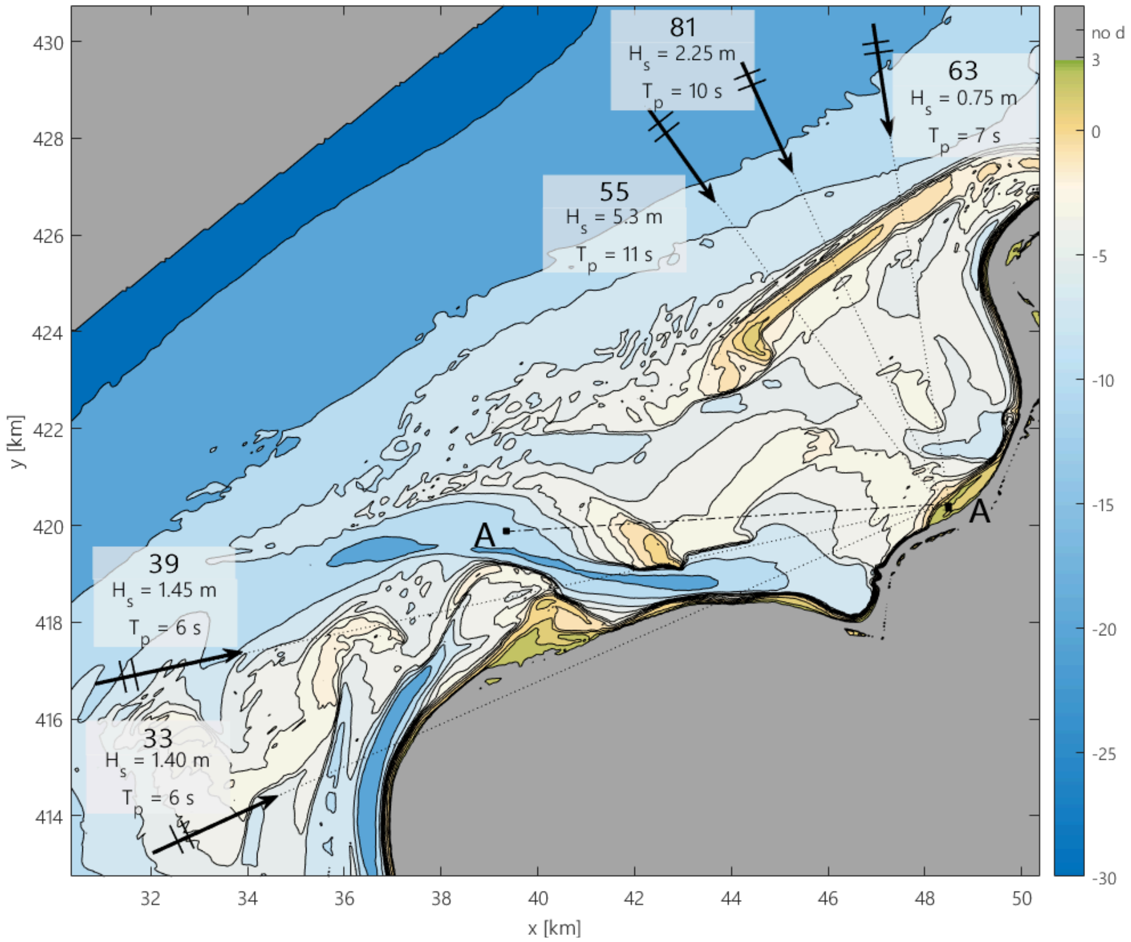


Figure 6.4: Overview of the Grevelingen outer delta. Five typical wave conditions are represented by a black arrow with its condition number, significant wave height and peak wave period. Note that the wave characteristics at each wave condition represent the offshore wave condition at the Schouwenbank station. Cross-section A-A is marked with a dash-dotted line.

Main sea waves

The most common wind-generated sea is condition 33, approaching from the southwest ($H_{s,0}$ = 1.4 m, $T_{p,0}$ = 6 s, θ_0 = 243 ^oN), with a moderate wind (U_{wind} = 11 m/s) from approximately the same direction. This condition represents 21 days of the full year wave climate.

Condition 39 is a fairly common sea condition (representing 17 days) and is responsible for the largest sediment transport rates at the beach (as examined in Section 6.6). The wind and wave characteristics of this condition are similar to those of condition 33, except for a larger wave angle of incidence: θ_0 = 255 ^oN. As this wave condition is an important factor in causing the beach to erode, the wave transformation to the coastline is analysed over cross-section A-A (dash-dotted line in Figure 6.4). The analysis shows the effect of the Middelplaat shoal, where the orbital velocity locally increases, and the wave energy (expressed in H_s) is dissipated. After passing this shoal, the wave height and peak period stay more or less equal for several kilometres until the wave reaches the beach. Near the beach, a high orbital velocity of over 0.5 m/s is observed, simultaneously with a sharp decay of wave height and period. The mean wave angle of this condition along the outer delta gives the pattern depicted in Figure 6.6. The refraction in the shallow outer delta results in waves approaching the beach from the west. This refraction pattern is observed for other south-western wave conditions as well (such as condition 33). This causes the wave angle of incidence at the closure depth of the active beach profile to be very large, which is further discussed in Section 6.6.

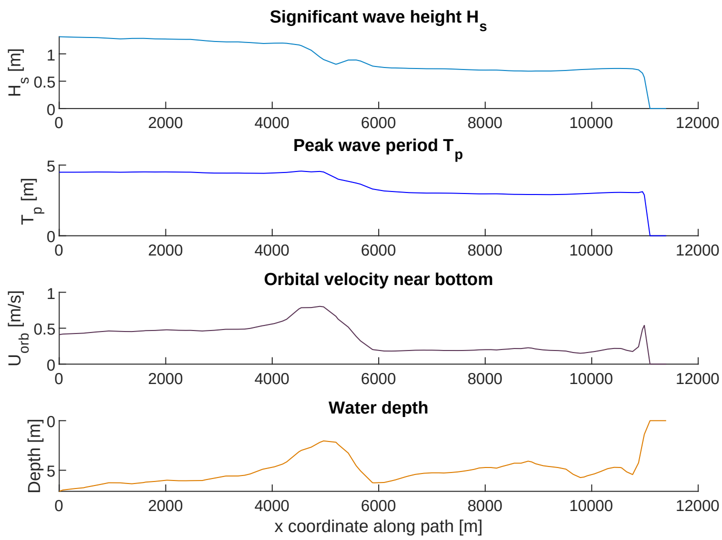


Figure 6.5: Wave transformation of condition 39 over cross-section A-A, with x in landward direction (see Figure 6.4)

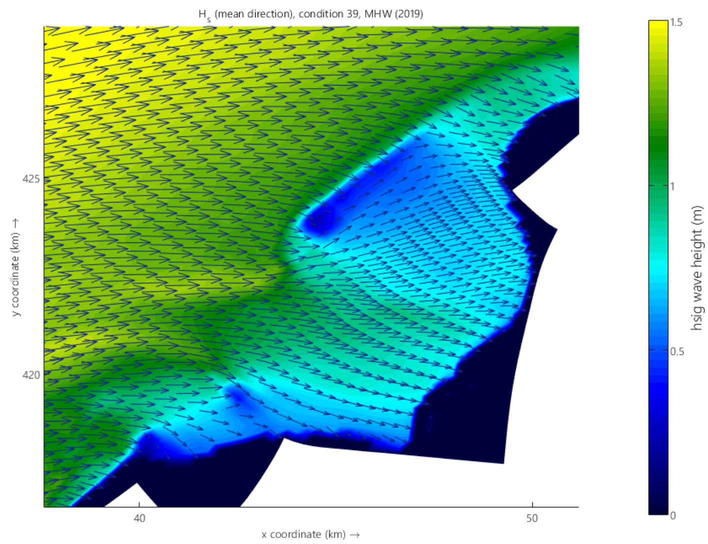


Figure 6.6: Distribution of significant wave height and mean wave angle of condition 39 along the outer delta during high water conditions (Delft3D-WAVE model, 2019).

The third sea state is condition 55, directed from the northwest. It represents the heaviest storm conditions (approximately occurring 30 minutes per year). Figure 6.7 shows the wave height distribution along the outer delta for both years (2010 and 2019) and for all tidal conditions. What stands out when analyzing this figure is the effect of the Bollen van de Ooster, which functions as a natural breakwater for this condition (and other waves coming from the northwest). For both years, it can be seen that the wave height (and energy) is reduced significantly at this shoal. During low water conditions in 2010, the wave height reduces by approximately 60 %, whereas during high tide, the reduction is about 30%. Thereby, the increase of the Bollen van de Ooster between these years is also observed: the same wave experiences more dissipation at the shoal in 2019 than in 2010.

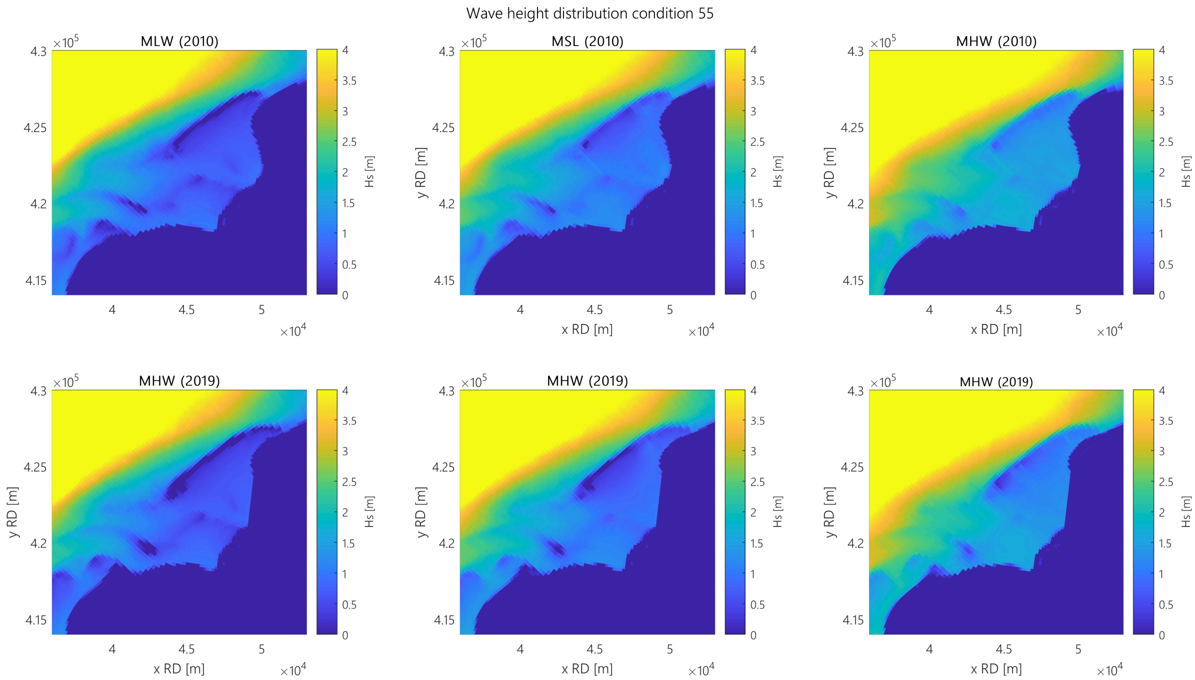


Figure 6.7: Wave height distribution of condition 55 ($H_{s,0}$ = 5.3 m, $T_{p,0}$ = 11 s, θ_0 = 326 ^oN), for low, mean and high water conditions in the years 2010 and 2019 (Delft3D-WAVE model)

Main swell waves

The mean direction of swell waves is north to the northwest (see Chapter 2). These waves are characterized by a high ratio between period and wave height. The most common swell condition (81) travels from the north and is characterized by $H_{s,0}$ = 0.75 m, $T_{p,0}$ = 7 s. The highest swell waves (condition 63) are characterized by values of $H_{s,0}$ = 2.25 m, $T_{p,0}$ = 10 s. When these waves travel towards the beach, the Bollen van de Ooster reduces the wave energy and wave height with the same ratio that was seen with condition 55 (having the same direction).

6.3.2. Wave climate near the beach

The wave conditions in the vicinity of the Brouwersdam beach are discussed below.

Mean significant wave height

The nearshore significant wave height is much smaller than offshore due to the reduced wave energy. At ray 2400 (approximately 500 m south of the beach, see Figure 3.2), the mean significant wave height is H_s = 0.43 m. When travelling across the coastline from ray 2400 up to the northern part of the beach, the mean H_s is more or less the same (decreasing to H_s = 0.39 m at ray 2080). The difference between the stages of the tidal cycle are larger: at ray 2400 during high water the mean H_s = 0.56 m whereas this is H_s = 0.41 m and H_s = 0.31 m during mean and low water conditions respectively.

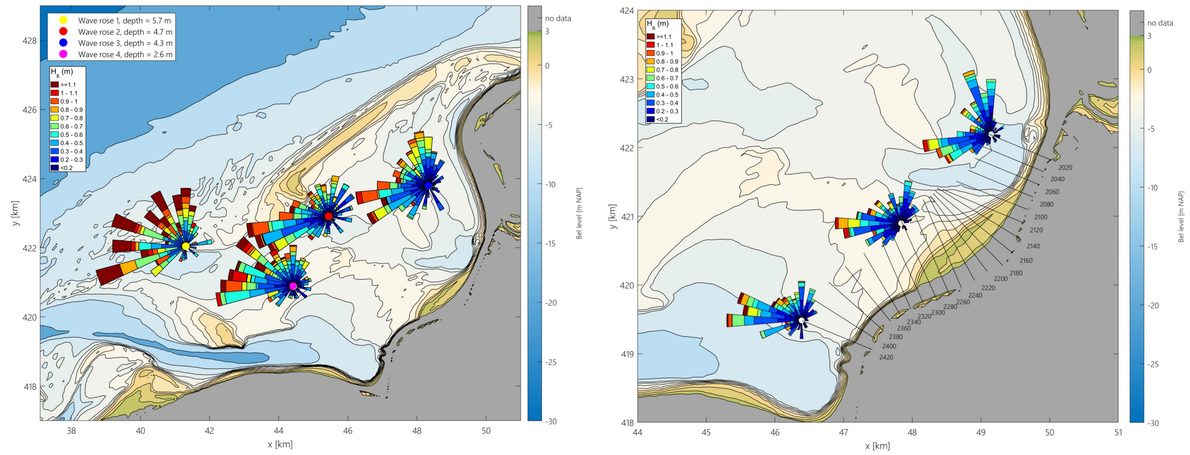
Wave direction

The effect of refraction through the delta is visible when considering the wave roses in Figure 6.8a. The wave roses in the lee side of the Bollen van de Ooster show a dominance of south-westerly and northern waves, whereas at the more exposed locations are also dominated by westerly waves and northwesterly waves.

When comparing the wave roses of ray 2400 up to ray 2020, the effect of refraction is visible as well (Figure 6.8a). Note that in the southern part, the wave angle of incidence of the dominant wave direction (west) to the shoreline normal of the beach is quite large at the end of the transects.

Maximum orbital velocity near bottom

In shallow and intermediate water, waves induce an orbital motion near the bed. This orbital motion contributes to the stirring of sediment. In combination with a current, this leads to sediment transport.



(a) Nearshore wave roses in the Grevelingen outer delta. Waveroses constructed with simulated nearshore conditions, by means of a transformation of Schouwenbank wavedata to nearshore.

(b) Nearshore wave roses at the end of Jarkus transects 2020, 2300 and 2420. Wave roses constructed with simulated nearshore conditions, by means of a transformation of Schouwenbank wave data to nearshore.

Figure 6.8: Nearshore wave roses in the Grevelingen outer delta (a.) and near the Brouwersdam Beach (b.), simulated with SWAN model 2018-2019. Bathymetry, 2018-2018, retrieved from the Vaklodingen data set 2018-2019.

The simulated maximum orbital motion near the bed is depicted in Figure 6.9. The maximum orbital velocities offshore of the shoals Bollen van de Ooster and Middelplaat are much larger than landward of these shoals. Their dissipating effect is again visible. What also stands out is that the orbital velocities are much higher (up to 0.8 m/s) near the southern part of the beach, whereas the orbital velocity in the northern part (near the Springersdiep channel) has a maximum of 0.3-0.4 m/s. This underlines the large impact of the Bollen van de Ooster and the Middelplaat on the nearshore wave climate, as they function as a natural breakwater.

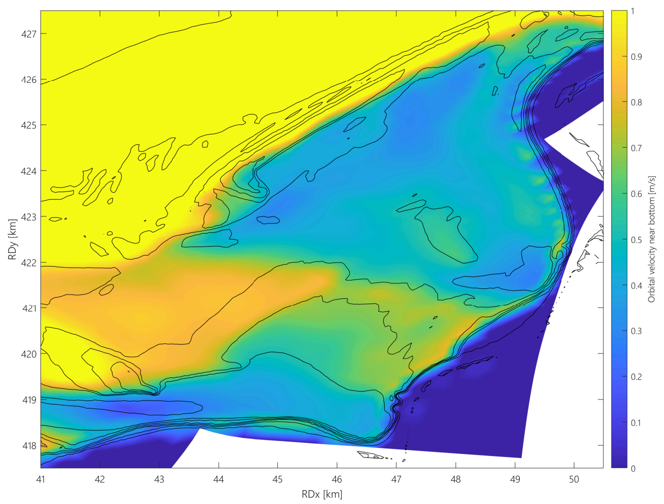


Figure 6.9: Maximum orbital velocity near the bed of all wave conditions (Delft3D-Wave model, bathymetry 2019). Depth contours are depicted to distinguish the different morphological units.

6.3.3. Summary

The findings of this section are summarized in this section.

The most common sea waves approach from the southwest. A significant part of the energy of these waves is dissipated at the Middelplaat. These waves are refracted in the shallow area and approach the beach, therefore from the west. A large part of the energy of stormy (sea) waves, directed from the north-northwest, is dissipated at the Bollen van de Ooster (a decrease of 30-60% of the H_s during high

and low water respectively). The increased elevation of this shoal between 2010 and 2019 enhances this effect.
The dominant swell waves are directed from the north-northwest and experience the same energy reduction at the Bollen van de Ooster.

The mean significant wave height at the end of the transects ranges from H_s = 0.3 m during low water to H_s = 0.55 m during high water. The yearly average significant wave height along the beach (at the closure depth) is H_s = 0.43 m. Thereby, the southern part of the beach experiences mostly western waves, whereas waves approaching from the north are dominantly present in the northern part as well. Lastly, the maximum orbital velocity is much larger in the southern part of the beach (up to 0.8 m/s), whereas this is 0.3 - 0.4 m/s at the northern edge of the beach.

6.4. Coastline model set-up

UNIBEST CL+ is commercial software that is used for the modelling of longshore sediment transport and morphodynamic development of coastlines (Deltares, 2011). This coastline model is applicable for coasts spatially varying from 1-1000 km, and for time scales from years to centuries. The model is based on the single line theory, which is explained in Section 2.2.

The first step in the simulation contains the calculation of the longshore transport (LT). This is done on the basis of the wave data, profile characteristics, sediment characteristics and the longshore currents (wind, tide and wave generated). In this study, the wave climates were extracted from the Delft3D wave output at user-defined nearshore points. These points should be chosen at the seaward boundary of the active profile. The transport is a function of the coastline orientation and is each time-step calculated per user-defined ray. This results in an (S,ϕ)-curve, describing the relation between coastline orientation and sediment transport rate. Note that the coastline orientation is defined as the line perpendicular to the coastline.

Secondly, the coastline evolution is computed in the CL-module. This is done by means of the LT output and the initial coastline profile, type of coastline, structures and sources or sinks. The CL-module is based on the single line theory (Section 2.3), which describes the position of the coastline as a single line (the red line in Figures 6.10c and 6.10d). The underlying assumption is that the cross-shore beach profile has a constant shape. The change of the line is only a function of the gradients in longshore transport. This holds that cross-shore transports and the seasonal variation of the profile is ignored. For further elaboration on the model specifications, reference is made to the UNIBEST-CL+ User Manual (Deltares, 2011).

6.4.1. Input parameters for LT-model

In the LT-module, the sediment balance (Equation 2.3) is solved numerically and (S-ϕ)-curves are constructed for each cross-shore ray. The cross-shore rays are defined by several input parameters: a schematic cross-shore profile, the coastline orientation, the active profile height, a schematic wave climate and tidal signal and finally, the input for morphological and wave parameters (Deltares, 2011).

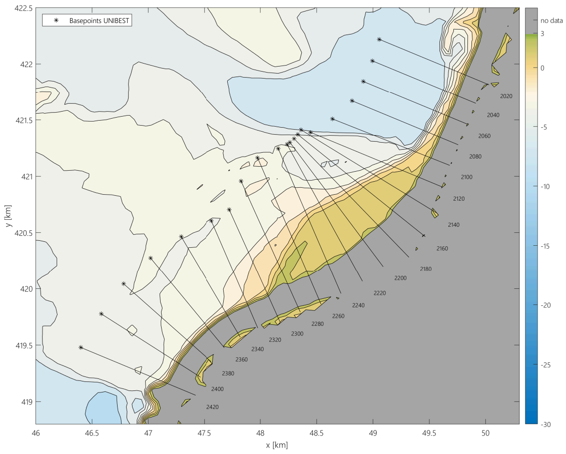
- The cross-shore profiles should reach far enough in seaward direction so that all longshore transport in the active zone can be simulated. The active profile is determined by analysing Jarkus data of consecutive years to see which part of the profile shows morphological activity. Moreover, the depth of closure is determined by the 0.1% wave height $H_{0.1\%}$ (Chapter 2), which is approximately 4.4 m offshore (van den Boomgaard & Eikema, 2006) and approximately 1.5 m nearshore. From the definition of Hallermeijer in Section 2.3 and a nearshore wave height of $H_{0.1\%}$ = 1.5 m, the closure depth is approximately 3 m. This implies an active coastal zone reaching approximately 800 m seaward of the coastline. The cross-shore profiles are therefore derived using Jarkus data supplemented with Vaklodingen data from the closest year, as the Jarkus data set does not contain the data to construct the required length of the cross-sections. The wave climate and tidal signal are imposed at the end of the transects, called base points. The location of the rays and base points are depicted in Figure 6.10a and 6.10b. The hindcast and forecast model uses Jarkus data of 2010 and 2018, respectively.

- The coastline orientation is based on Jarkus data.
- The wave characteristics are extracted from the nearshore wave results at the base points. This is in line with Equation 2.3, in which ϕ represents the wave angle of incidence at the closure depth. The 2010 wave model provides boundary conditions for the hindcast model, whereas the forecast model uses the nearshore waves of the 2019 wave model.
- The tidal signal at each base point is extracted from the Delft3D-FLOW model and is simplified to a single value per water level condition (MHW, MSL and MLW). For each of these three tidal stages, a characteristic value for the tidal flow velocity is obtained. The vertical tide (water level) follows the horizontal tide (current), with approximately one hour, and therefore the flow velocity at MHW is approximately equal to the mean maximum flow velocity (in northeasterly direction). For MLW, the same holds for the mean minimum flow velocity (in southwesterly direction). The most recent simulations that the Delft3D-FLOW model provides are for the year 2010; these data are thus used for both the hindcast and the forecast model.
- The wave and transport parameters are listed in Table E.3. All parameters are equal for both the hindcast and forecast model, except for the mean grain size. The median sediment diameter of the forecast model is larger compared to the hindcast model because the beach nourishment was executed with sediment with a larger grain size than the original D_{50} of the beach sand. The data of the sieve curve analysis of the nourished sediment could not be obtained. Therefore an average diameter of D_{50} = 220 μm was assumed for the forecast model, instead of D_{50} = 210 μm in the hindcast model.

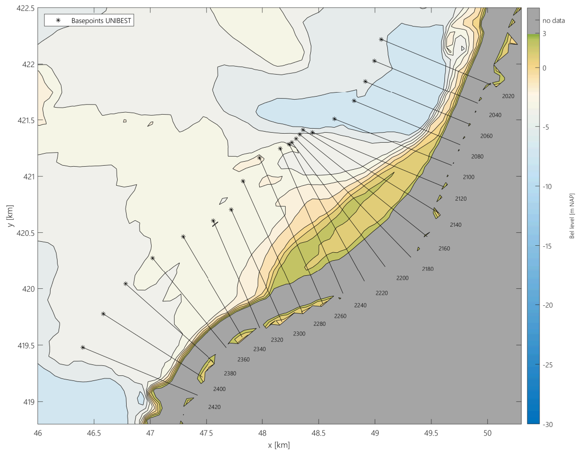
6.4.2. Input parameters for CL-model

To set up a UNIBEST-CL model, the following data are required: the shape of the coastline, the longshore transport computations (relations between coast orientation and sediment transport following from the LT-module), the dimensions and specifications of coastal structures and a user-defined time frame and output frequency (Deltares, 2011).

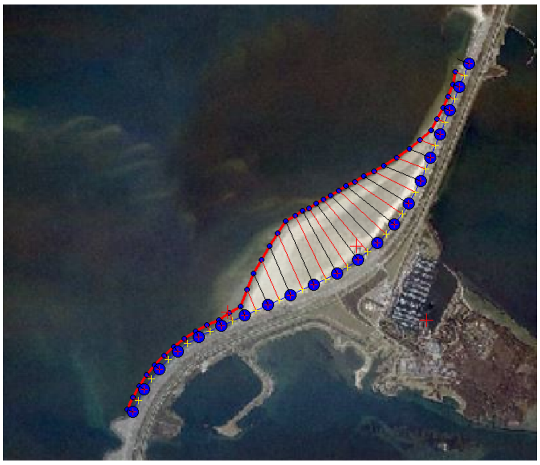
- The shape of the coastline follows from the 0 m NAP point at each transect, retrieved from the Jarkus data set of the considered year. The simulated coastline is depicted in Figure 6.10c and 6.10d, in which aerial photographs of the relevant years are added for clarity.
- The defined time frame differs per model. The hindcast model simulates the coastline between 2010 and 2015 (calibration). The validation is done with a simulation of the coastline between 2018 and 2020. The forecast model predicts the coastline evolution between 2020 and 2030.
- Each simulated year consists of three different periods, in which each period represents a tidal condition. The duration of the periods with MHW and MSL forcing conditions is 3.5 months, whereas MLW forcing conditions are simulated during 5 months (resembling the duration of the phases of a tidal cycle). Hence, a simulated year in UNIBEST starts with 3.5 months of MHW conditions, followed by 5 months of MSL and 3.5 of MLW conditions. Each month consists of 100 time steps.
- The boundary condition at both edges of the beach is a constant coastline position ($\frac{\delta y}{\delta t} = 0$, which implies $\frac{\delta Q_s}{\delta x} = 0$). This condition is considered to be valid, as the coastline positions of ray 2020 (north) and ray 2420 (south) did not change significantly in the past two decades. Moreover, the coastline at both locations is not expected to build out or move landward in the coming decade. At the southern boundary, the coast has receded up to the revetment. The northern boundary is located at the Springersdiep channel of 6 m deep, which can be seen as a sediment sink. Changes in transport quantities near the boundary are therefore not expected to induce significant coastline change in the coming three decades.



(a) Bed level of the Brouwersdam beach in 2009-2010, derived from Vaklodingen dataset. The considered rays in UNIBEST are depicted as black lines, with basepoints at end of each transect to mark the input points for the UNIBEST hindcast model (2010).



(b) Bed level of the Brouwersdam beach in 2018-2019, derived from Vaklodingen data set. The considered rays in UNIBEST are depicted as black lines, with basepoints at end of each transect to mark the input points for the UNIBEST forecast model (2018).



(c) Aerial photograph of the beach in 2010 and schematisation of the coastline in the CL-module of UNIBEST (2010, hindcast)

(d) Aerial photograph of the beach in 2018 and schematisation of the coastline in the CL-module of UNIBEST (2018, forecast)

Figure 6.10: Bed level of the beach with considered Jarkus rays (upper panels, a. and b.) and schematized coastline in the CL-module (lower panels, c. and d.). Left panels relate to the hindcast model, right panels the forecast model.

6.5. Calibration

The hindcast model is calibrated with the use of Jarkusdata. The simulated coastline is compared with the observed coastline changes. The transport depends, among others, on the chosen sediment transport formula, wave-current interaction model, wave parameters, wind drag coefficient and sediment characteristics. These were changed in the hindcast model until the simulated coastline position was nearly equal to the observed coastline after 5 years. The sensitivity of the model to these factors differs. A sensitive input factor is, among others, the sediment transport formula. Van Rijn (2004) turned out to give the most stable results and the best simulations. The same holds for the wave-current interaction model of Fredsøe. The optimal values for the parameters can be found in Table E.3.
The hindcast model simulates the observed coastline change sufficiently well. In Figure 6.11 it can be seen that the receding and accreting coastline trends are reproduced by the model. The large correlation between observed and simulated changes is quantified by a value for the coefficient of determination of $r^2 = 0.88$.
Further analysis of the agreement between observed and simulated coastline change is done using the bar chart in Figure 6.12. The modelled retreat in the southern rays 2320 - 2280 is in line with observations, whereas rays 2240-2200 show a small underestimation of the erosion. The accreting trend of the northern part of the beach is simulated correctly as well. A small underestimation and overestimation

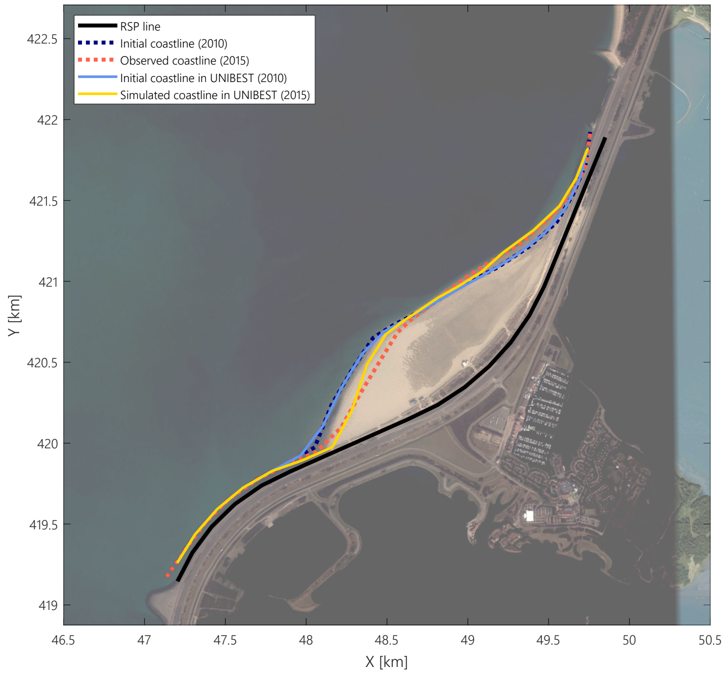


Figure 6.11: Top view of the observed and simulated coastline evolution between 2010-2015, obtained from the hindcast model.

of accretion are seen in the middle and northern part, respectively.

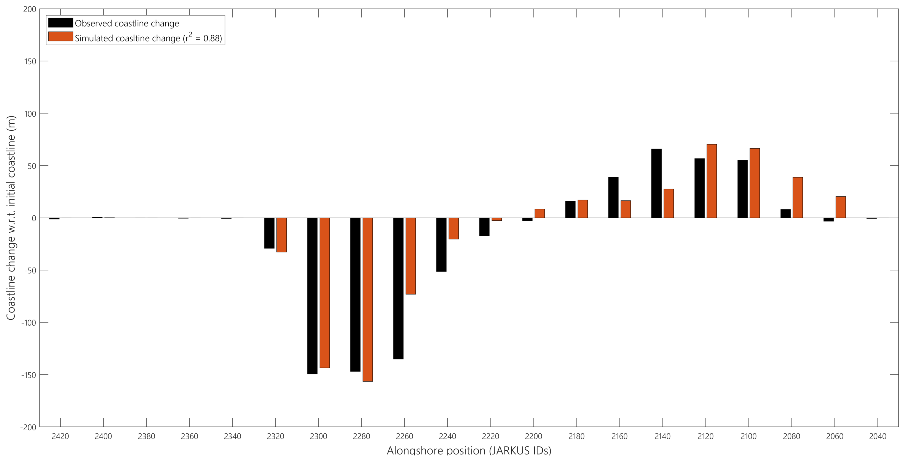


Figure 6.12: Bar chart of observed coastline evolution (black) and simulated coastline evolution (red) between 2010-2015.

6.6. Hindcast model results

The hindcast model provides insight into the temporal and spatial distribution of the transport and the contribution of different wave conditions to the observed coastal change. The most important conclusions are discussed in this section, providing an answer to Sub-question 4: *How are the sediment transport rates temporally and spatially distributed and which wave conditions have the largest contribution to the observed morphological evolution of the beach?*

6.6.1. Temporal distribution of sediment transport rates

The temporal distribution of the transport rates is evaluated using the constructed (S, ϕ)-curves in the LT-model. The first thing that stands out when comparing the curves is that the sediment transport rates during MHW are significantly larger than during MSL and MLW. This can be seen when comparing the (S, ϕ)-curves of ray 2280 in Figure 6.13. The sediment transport at this ray is eight times higher during high water conditions than during mean water level conditions. This can be explained by the fact that during high tide, the wave impact is larger, the submerged part of the beach is the largest (therefore, the active zone is larger), and the tidal current velocity is at its maximum.

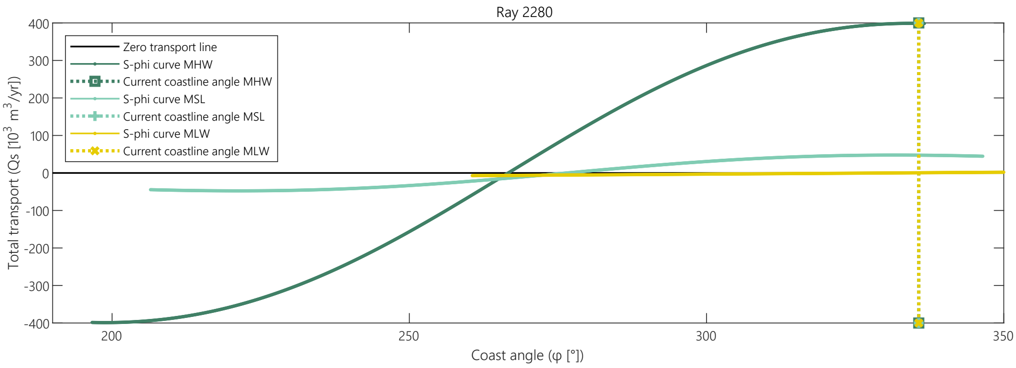


Figure 6.13: (S, ϕ)-curves of ray 2280 during MHW (dark green), MSL (light blue) and MLW (yellow)

6.6.2. Alongshore distribution of longshore sediment transport

The second thing that stands out is a decreasing height of the (S, ϕ)-curve when travelling from south to north. Figure 6.14 present the (S, ϕ)-curves of the southern, middle and northern part of the beach at high tide. According to those curves, the maximum sediment transport in the south (ray 2280) is 400 $10^3 m^3/y$, whereas this is approximately 250 $10^3 m^3/y$ in the middle of the beach (ray 2180) and about 150 $10^3 m^3/y$ in the north (2080). These results are in line with the observed receding coastline in the southern part and an accreting coastline in the northern part. Moreover, this pattern can be explained by the fact that the wave angle of incidence is large in the southern rays (ranging up to 65 ^{o}) and the fact that the maximum flood velocities are present in this area.

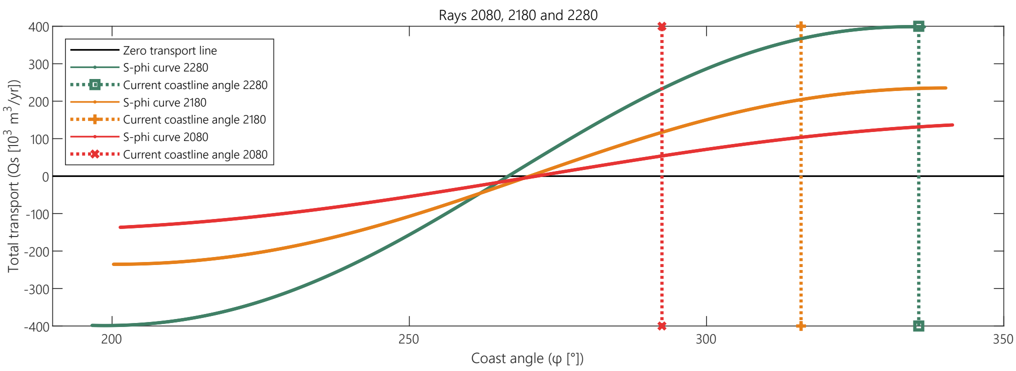


Figure 6.14: (S, ϕ)-curves of rays 2280 in the south (dark green), 2180 in the middle (orange) and 2080 in the north (red) (high water conditions).

So far, the conclusion can be drawn that the model shows that the highest transport rates are found in the southern rays during high tide, induced by the simultaneous presence of waves and currents. As the high water conditions induce the largest net transports, the cross-shore distribution of the alongshore transport rate during high tide is analysed in the next paragraph.

6.6.3. Cross-shore distribution of longhore sediment transport

Figure 6.15 shows the cross-shore distribution of gross transports simulations in UNIBEST for rays 2080, 2180 and 2280 representing the northern, middle and southern part of the beach, respectively. The net transports are depicted in Figure 6.16. Note the different magnitudes at the y-axis. In both figures, positive transports indicate transport parallel to the beach in north-eastern direction, and vice-versa.

First of all, the gross transport rates are discussed. From the figures below can be concluded that the magnitude of the gross transport is for all rays more or less stable when moving offshore up to approximately a 100 m seaward of the coastline (x = -100 m). An exception is the transport peak at x = -600 m at ray 2280. This distinct peak in transport can be explained by the fact that a sand bar is located at this cross-shore location. Turning to the nearshore transport rates, the peaks in the middle and southern rays stand out, with gQ_s > 3000 $m^3/m/year$ between x = -30 m and x = +40 m. At both rays, this indicates peak transports in northern direction between -0.5 m NAP and + 1.5 m NAP. What also stands out in this figure is the difference between the magnitudes of the southward and northward directed transports along the coast. In the north (ray 2080), the peak negative transport is larger than the peak positive transport (+ 1300 $m^3/m/year$ v.s. - 1400 $m^3/m/year$). In the middle part (ray 2180), the magnitude of the positive transport is larger than the negative (+ 3300 $m^3/m/year$ v.s. - 1400 $m^3/m/year$). In the southern part, the negative transport is even smaller: + 3300 $m^3/m/year$ v.s. - 800 $m^3/m/year$.

When analysing the net transport rates, a maximum longshore transport of ca. 2500 $m^3/m/year$ in the southern part can be concluded, at x = 25 m. Peak transport at ray 2180 (middle) is somewhat smaller (2250 $m^3/m/year$), nearly at the coastline. Peak net transport at ray 2080 in the north is around 300 $m^3/m/year$ and occurs between x = -60 and x = 14 m. Note a negative net transport in a small part of the cross-section of ray 2080 at x = 30 m.

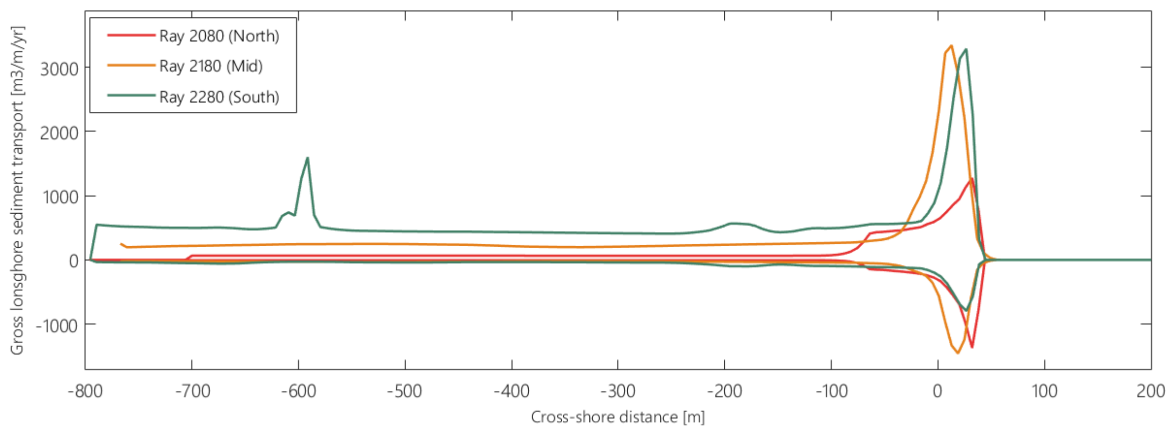


Figure 6.15: Cross-shore distribution of gross alongshore transport (gQ_s [$m^3/m/year$]) during high water conditions for northern, middle and southern located rays

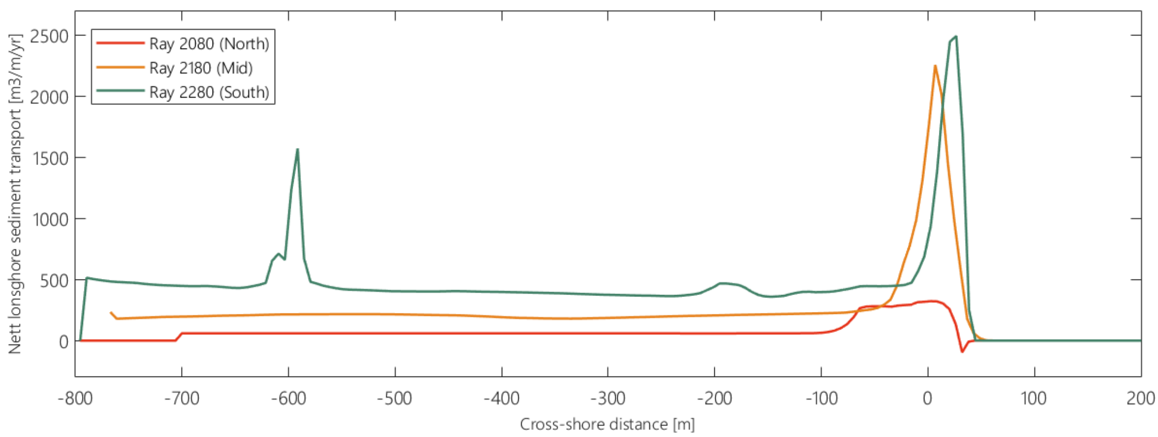


Figure 6.16: Cross-shore distribution of net alongshore transport (nQ_s [$m^3/m/year$]) during high water conditions for northern, middle and southern located rays

6.6.4. Contribution of different wave conditions to coastal change

Taking a closer look at the contribution of each wave condition to the sediment transport in the southern rays (2300-2240), a few conclusions can be drawn.

The first thing to notice is the minor impact of swell wave conditions on sediment transport rates. The low-frequency waves cause 3% of the total net transport at ray 2280.

Secondly, there are six wind-generated (sea) wave conditions (out of 108 wave conditions) responsible for more than 80% of the total net sediment transport during high water in the southern side of the beach (2240 - 2260). These wave conditions are condition number 33, 34, 39, 40, 45 and 46. These wave conditions have minor differences in wave characteristics, their characteristics are in the following range: 1.4 < $H_{s,0}$ < 2.4 m, 5.9 < $T_{p,0}$ < 7.4 s, 240 < θ_0 < 290 ^oN. Thereby, they are characterized by moderate breeze to strong wind conditions directed from southwest to west (10 < U_{wind} < 15 m/s, 225 < θ_{wind} < 285 ^oN). These conditions are all common, together they represent 63 days of a full year (17%). As high water is present at ca. 30% of the time, these nearshore high water conditions are present during ca. 20 days per year. Moreover, as ca. 80% of the total yearly longshore transport occurs during high water, of which 80% is induced by the above described wave conditions, this means that 80%x80% $\simeq$ 65 % of the total yearly transport in the southern stretch is caused by these waves. Their nearshore wave heights vary from 0.8 < $H_{s,n}$ < 1.2 m during high water, the nearshore peak period is between 5.5 < $T_{p,n}$ < 7.5 s and the wave angle of incidence at the closure depth is -35 < ϕ < -55 ^{o} with respect to the coast normal. Note that that the coastline is oriented south-west to north-east at this point and that these waves are all directed from the west (southwest-west to northwest-west). The above described 6 conditions are the only conditions with sediment transport rates during high water above 15 10^3 $m^3/m/year$ at ray 2280. The magnitudes of these six range from 39 10^3 $m^3/m/year$ (condition 46) to 68 10^3 $m^3/m/year$ (condition 39). The other 104 conditions have transport rates of -10 to +15 10^3 $m^3/m/year$, with 0.7 10^3 $m^3/m/year$ on average.

6.6.5. Sediment balance

The description of the morphodynamic system is concluded with a sediment balance in which the sediment transport rates at the boundaries of the system are considered, as well as the transport gradients along the coastal stretch. It is also examined whether the coastal system gains or looses sediment.
The yearly sediment transport rates Q_s [10^3 $m^3/year$] along the beach, resulting from the hindcast model, are depicted in Figure 6.17. A few conclusions can be drawn from this figure. The sediment balances for high, mean and low water are included in Appendix F.

First of all, the alongshore shifting trend of the beach is visible when comparing the yearly sediment transport rates between x = 1.2 - 2 km, the southern part of the beach. The value of Q_s is decreasing over time and shifting towards the north.
The second main conclusion concerns the transport rates at the boundaries. At the southern boundary (x = 0 km), zero sediment enters the system. The northern boundary (x = 4 km) shows a mean sediment export of Q_s = 20,000 $m^3/year$. Notice a significantly lower export during the first simulated year (2010), this is probably due to the spin-up time of the model. This means that, according to the model, the system loses 20,000 $m^3/year$. This implies that the system has lost ca. 100,000 m^3 from 2010 up to 2015. This number is compared to observed data. Figure 3.11, which is constructed with Jarkus data, shows no volume loss or gain in this period (for the acreage between -3 and +3 m NAP). When considering the gradients over the coastal stretch, the data matches the observed data better. The beach is divided into a southern and northern part, of which ray 2240 is the boundary. The southern part loses according to observed data 300,000 m^3 to the northern part in this period. The model simulates a loss in the south of 400,000 m^3, of which 300,000 m^3 is deposited in the south and 100,000 m^3 is lost. A possible explanation for the overestimation of the model is that the model does not take into account cross-shore volume changes, but simulates the same shoreline evolution. Thus, in reality, the sediment that is deposited on the higher parts of the beach (ca. +2 m NAP) contributes to shoreline retreat, whereas this retreat is simulated by the model as longshore transport losses. Taking this into account, the model provides sufficient insight in the sediment distribution.

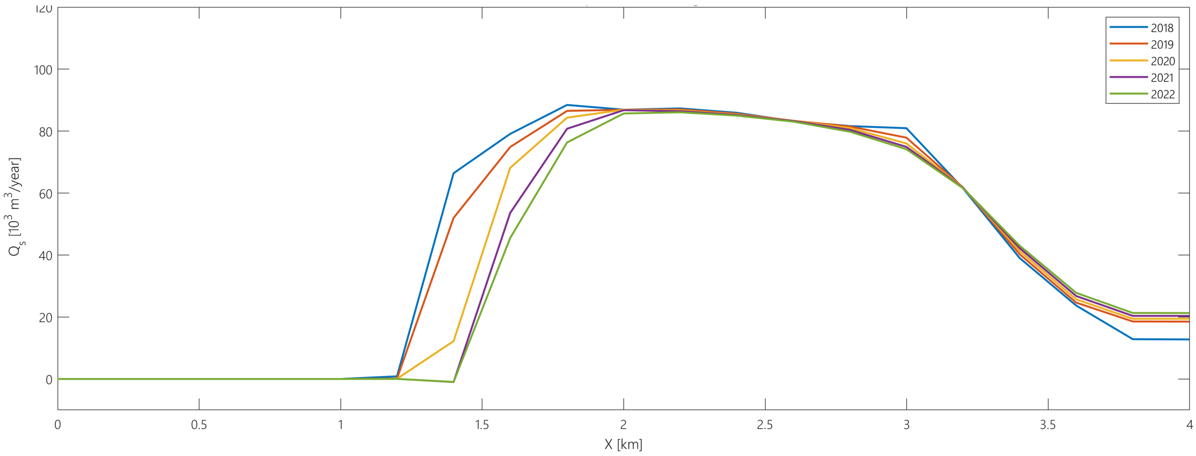


Figure 6.17: Simulated yearly sediment transport rates, tide averaged, hindcast model (2010-2015)

6.6.6. Summary

The main conclusions that can be drawn from the hindcast model results are listed below. This list provides an answer to Sub-question 4: *How are the sediment transport rates temporally and spatially distributed and which wave conditions have the largest contribution to the observed morphological evolution of the beach?*

Temporal distribution The highest longshore transport rates to the north occur during high water (up to 8 times more transport than during mean water conditions). In total, ca. 80% of the sediment transport over a tidal cycle occurs during high water. This can be explained by three mechanisms. Firstly, the larger wave attack: as waves are depth-limited in the shallow outer delta, their wave energy is much higher during high water. The mean significant wave height ranges from H_s - 0.3 m during low water to H_s = 0.55 m during high water. Another reason for a higher wave attack during high tide is that the offshore shoals (mainly the Bollen van de Ooster) function as a natural breakwater. During low tide, 60 % of the wave energy of waves approaching from the northwest is dissipated at this shoal, whereas during high tide this is only 30 %.
Secondly, during high water, the beach has a large inundated, active zone, in which a lot of sediment transport can take place.
Thirdly, the flood tidal current velocity, which maximum is ca. 0.6 m/s in northeastern direction during high tide against 0.3 m/s in southwestern direction during low tide, enhances a tide-induces current in the same direction as the predominant wave-induced current. Hence, larger sediment transport rates towards the northeast occur during high water.

Spatial distribution alongshore The alongshore transport to the north is maximum in the southern part (up to 3 times larger than in the north). This is due to a larger wave angle of incidence at the closure depth, a larger water depth in front of the southern part of the coastline and therefore less wave energy reduction and the higher flood velocities occurring in the south.

Spatial distribution cross-shore The highest transport rates are located between - 0.5 and + 1 m NAP. This is due to large orbital velocities (inducing the stirring of sediment) in combination with the alongshore current in this intertidal zone.

Dominant conditions The waves are dominant in causing the erosion and displacement of the beach. Six wind-generated (sea) wave conditions during high water are responsible for more than 65% of the total net longshore sediment transport in the southern stretch. These wave conditions occur ca. 20 days/year. The nearshore characteristics of these waves are a significant wave height from 0.8 < $H_{s,n}$ < 1.2 m, a peak wave period of 5.5 < $T_{p,n}$ < 7.5 s and a wave angle of incidence at the closure depth of -35 < ϕ < -55 ^{o} with respect to the coast normal (waves directed from the southwest-west to northwest-west). Hence, the dominant wave direction near the beach is West.

6.7. Validation

The validation is intended to check if the model is a good representation of reality, and that the hindcast model did not model the shoreline evolution coincidentally well. The simulated coastline development between 2018 and 2020 is compared to the observed changes in this period, see Figure 6.18. The first thing that can be concluded from this figure is that the coastline retreat in the south is simulated very well. However, a small coastline advance is simulated in the middle part of the beach, wherein real-life, the coastline is more or less stable at this point. The difference is however a coastline retreat of approximately 50 m in 2 years, which is not considered as a problem for the quality of the model. Furthermore, the northern part of the beach, which is stable, is simulated according to observations. As the validation gives a good result, it can be concluded that the prediction of the forecast model is sufficiently accurate.

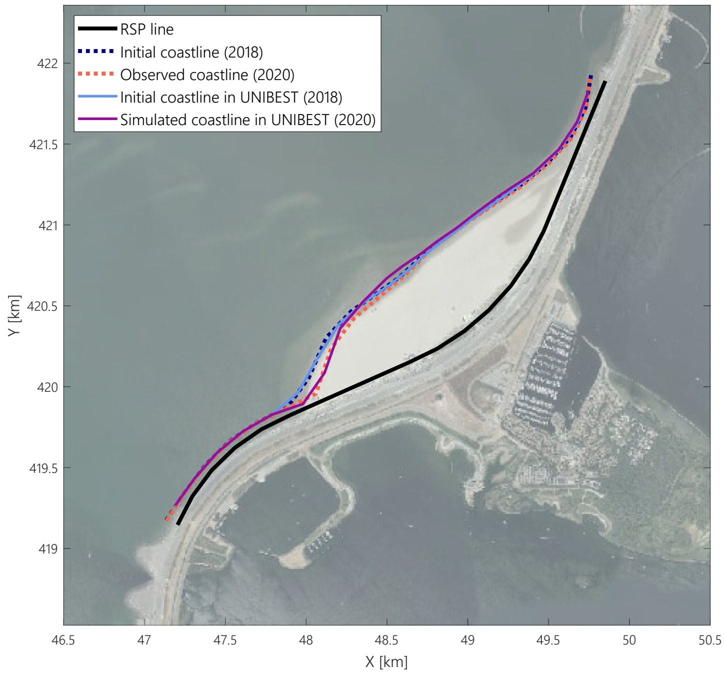


Figure 6.18: Top view of the observed and simulated coastline evolution 2018-2020.

Furthermore, the simulated volume changes are compared to observed volume changes. The distinction between south and north is relevant. Table 6.2 shows the absolute and yearly averaged volume changes in two periods: 5 years before the nourishment (2010-2015) and right after the nourishment (2018-2020). As was also concluded from the Section 6.6, the model simulates more sediment export compared to observed data (-30,000 $m^3/year$ instead of -15,000 $m^3/year$).
The main conclusion with respect to the design of a nourishment is as follows. The data analysis of Section 3.4 showed that in the year following the nourishment, the southern part of the beach loses 170,000 m^3 (of which 150,000 m^3 is lost as only 20,000 m^3 is gained in the north). The years afterwards, this severe sediment loss in the south is reduced to a mean value of 70,000 $m^3/year$ (simulated by the model as 100,000 $m^3/year$), and a gain in the north of 55,000 $m^3/year$ (simulated by the model as 70,000 $m^3/year$). Hence, the volume of a nourishment in the south is initially reduced with ca. 1/3 (170,000 of 500,000 m^3), after which its annual loss was 70,000 $m^3/year$. Hence, the nourishment of 500,000 m^3 has a lifetime of ca. 6 years. Averaging these numbers gives a net loss of sediment in the south of 80,000 $m^3/year$ after a nourishment. When the beach is evolving towards its original shape again, this loss will reduce to 60,000 $m^3/year$ (similar to the situation before a nourishment). Then, after a decade or so, the beach reaches its equilibrium shape more and more, and the sediment loss in the south (and gain in the north) will reduce even further (Figure 6.21).

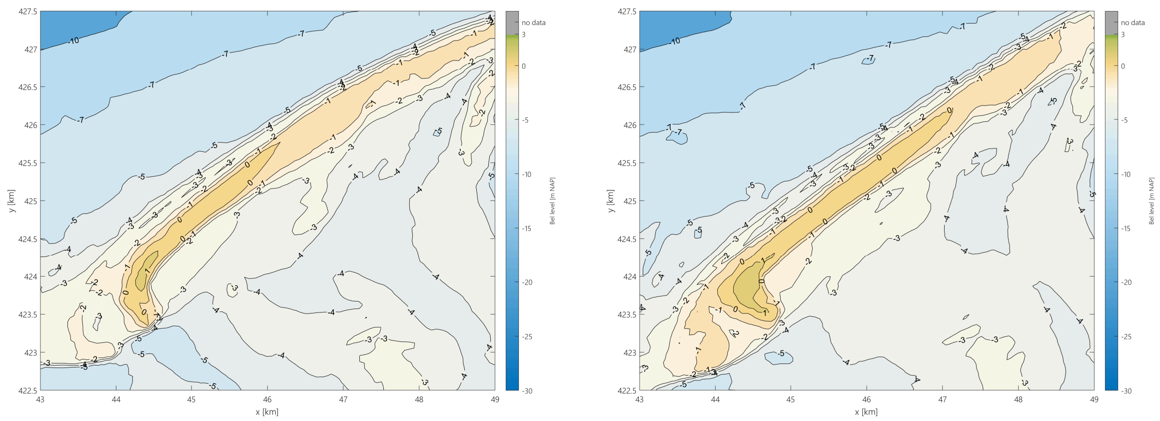
		2010-2015		2018-2020	
	Change in volume	Jarkus	Model	Jarkus	Model
Total beach	Absolute $[m^3]$	0	-100,000	-30,000	-60,000
	Yearly average $[m^3/y]$	0	-20,000	-15,000	-30,000
South	Absolute $[m^3]$	-300,000	-400,000	-160,000 *	-200,000
	Yearly average $[m^3/y]$	-60,000	-80,000	-80,000 *	-100,000
North	Absolute $[m^3]$	300,000	300,000	130,000	140,000
	Yearly average $[m^3/y]$	60,000	60,000	65,000	70,000

Table 6.2: Mean changes in beach volume for total, southern and northern part between -3 and +3 m NAP, retrieved from Jarkus data set and UNIBEST hindcast and forecast model (Northern rays 2020-2260, Southern rays 2240-2420). ** These values are averaged with the data of 2017-2018: the southern part lost ca. 300,000 m^3 between 2017 and 2020, of which more than half in between 2017-2018. In 2018-2020, the mean loss was 70,000 $m^3/year$, but to account for a larger initial loss, the value is set to 80,000 $m^3/year$ (hence, an absolute value of 160,000 m^3 in 2018-2020).*

6.7.1. Implications of stationary wave climate

The simulated shoreline migration is based on the notion that the hydrodynamic boundary conditions in the Grevelingen outer delta stay more or less equal in the coming three decades. This is, however, an uncertain assumption as the outer delta is not in dynamic equilibrium. The large-scale morphodynamic changes (elaborated in Section 2.4) are still taking place. As the sediment transport is mainly wave-driven along the beach, a change in the wave climate can induce significant changes in the shoreline development. Hence, the assumption of a stationary wave climate may decrease the quality of the forecast the model results.

To what extent the wave climate will change in the future depends mainly on the development of the shore-parallel bar the Bollen van de Ooster. According to the conceptual model of van der Spek & Elias (2021), the shoreward migration and increase in height of the shore-parallel bar (the Bollen van de Ooster in this case) is followed by a decrease in height and eventually a breach and erosion of this bar. The wave analysis of Section 6.3 has shown that the Bollen van de Ooster is responsible for the dissipation of 30 to 60 % of wave energy of north-westerly waves (during high and low water respectively). Northwesterly waves originate mostly from nearby storms or are swell waves from the Atlantic ocean, and represent ca. 30% of the annual wave climate (as can be deduced from the offshore wave rose depicted in 3.5). The influence of this shoal on the wave climate near the beach is thus significant (this is visualized in Figure 6.8a, which shows the wave roses in the outer delta).



(a) Bollen van de Ooster 2009-2010

(b) Bollen van de Ooster 2018-2019

Figure 6.19: Bathymetry of the Bollen van de Ooster, the shore-parallel bar at the front of the Grevelingen outer delta, derived from the Vaklodingen data set.

Two scenarios are distinguished to analyse the implications of the above described assumption for the beach development forecast. That is, the scenario in which it does not breach and the scenario in which the bar breaches and erodes within in the period up to 2050:

- The first scenario (no breach) covers the situation in which the bar keeps increasing in height and migrating shoreward. Hence, the amount of wave dissipation at the outer delta front increases. To a lesser extent, this also applies to the Middelplaat shoal. So, the average wave energy along the beach will decrease. However, that does not imply less erosion of the beach: near the shoreline, wave energy of north-western waves is decreased, which relatively increases the amount of western wave energy. As these western waves are responsible for the largest part of the longshore sediment transport in northeastern direction (reference is made to Section 6.6), the net sediment transport to the northeast will be enhanced. Consequently, erosion of the southern part of the beach will increase over the years. However, when assuming that the pace of the morphological developments is similar to the small changes of the past decade (depicted in Figure 6.19), the enhancement of the erosion will not be significant. This means that the simulated shoreline development up to 2050 is reasonable in this scenario.
- In the second scenario (breach), the Bollen van de Ooster will breach in the period up to 2050. If it breaches, then northwesterly wave energy reaching the beach will increase significantly (as 30-60% of this wave energy is not dissipated at the bar anymore). Hence, the increase of wave energy along the shoreline will be significant (note that the eroded sediment of the bar will be deposited in deeper parts of the outer delta, so the whole area will become shallower, which induces wave energy reduction as well). Moreover, the dominant wave direction near the southern edge of the beach will rotate several degrees towards the northwest. This can be visualized by looking at the lower two nearshore wave roses of Figure 6.8b: these will show more northwestern waves in this scenario.

  With respect to the longshore sediment transport rate: the mean wave angle of incidence on the southern part of the shoreline will be reduced, which reduces gradients in the yearly net longshore transport. In other words, the gross longshore transports towards the southwest will increase as the southwestern directed wave-induced current will be larger. Hence, the erosion due to longshore transport of the southern part will reduce.
  However, large wave impact can result in a significant redistribution of the sediment in the cross-shore profile. Mainly during storm conditions, the waves reach the dunes due to higher water levels and higher waves, and hence the upper part of the cross-section is part of the active profile. This results in an offshore directed sediment transport from the dunes towards deeper parts of the profile. In the general case of a stable beach situation (no structural erosion), this storm-induced erosion is temporary. However, in the case of structural erosion, which applies to the beach, the the sediment will not return to the higher parts of the profile as it will be removed in alongshore direction. Hence, when considering the changes in cross-shore sediment transport, the increase of northwestern wave energy along the beach due to a breach of the Bollen van de Ooster will probably result in larger erosion rates, mainly during the storm season (winter).

  Hence, the above reasoning on the changing longshore and cross-shore transports are not conclusive on the net effect of a breach of the Bollen van de Ooster on the nearshore wave climate. The UNIBEST-CL+ forecast model may overestimate or underestimate the erosion and displacement of the beach, dependent on the relative contribution of the both described mechanisms.

It is hard to determine the likelihood of a bar breach in the coming three decades. van der Spek & Elias (2021) elaborate on the development of the Grevelingen outer delta as a response to damming of the former estuary. Moreover, the developments in the Grevelingen outer delta are compared to the evolution of the Haringvliet outer delta in which a similar reduction of the cross-shore tidal flow was caused by damming. In the Haringvliet ebb tidal delta, this led to breaching and erosion of the shore-parallel bar. As the Grevelingen outer delta has a more exposed position and a smaller sediment supply, this outer delta has not reached the stage of bar breaching yet. A prediction on when the bar is expected to breach is not elaborated in this article. However, it is discussed that breaching is preceded by losing height of the bar. As this is not the case for the Bollen van de Ooster (which gained height in the past 10 years, as can be seen when comparing the bathymetry between 2009 and 2019 in Figure 6.19), a breach is not expected to happen in the near feature (e.g., the coming decade). An elaborate examination on the future developments of the Bollen van de Ooster and the consequences for the hydrodynamic conditions near the beach could is not within the scope of this research. Hence, to be able to simulate the future morphological developments of the beach, it is assumed that the bar is not breaching up to 2050. Nevertheless, the above explained implications for the interpretations of the results should be kept in mind.

6.8. Forecast model results

This section begins by elaborating on the simulations from 2020 up to 2050 and will then provide an answer to Sub-question 5: *What is the expected future morphological evolution of the beach in the coming three decades?*

The forecast model is used to substantiate the prediction of future coastline development. The simulation between 2018 and 2030 is depicted in Figure 6.20. The trend of retreat in the south and accretion in the north is continued according to the model.

Looking at the simulation up to 2025, the erosion rates are according to the expected value. As was concluded from the data analysis in Section 3.4, the southern part of the beach shows a mean alongshore shift (parallel to the Brouwersdam) of ca. 42 m/year. The simulated shift is ca. 280 m in an alongshore direction in 7 years, which corresponds to a mean value of 40 m/year. Hence, the erosion of the southern edge of the beach is assumed to be simulated sufficiently.

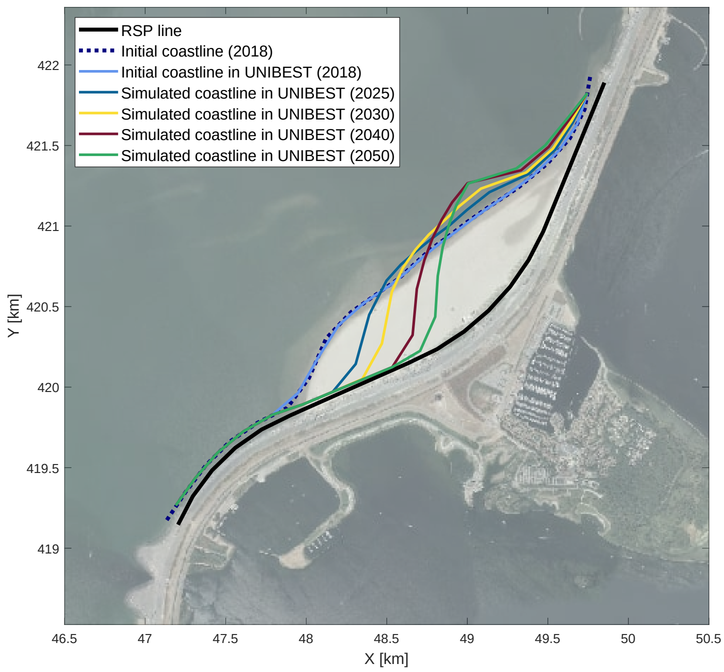


Figure 6.20: Top view of the simulated coastline development of 2025, 2030, 2040 and 2050 (forecast model UNIBEST)

The northern part of the simulated coastline of 2025 a mean coastline advance of ca. 70 m in 7 years, corresponding to 10 m/year. This result can be considered in two ways. On the one hand, if the morphological development of the beach from before the nourishment is taken as a basis, this simulation is quite accurate (as an advance of the northern part of 13 m/year was concluded in Section 3.4). If, on the other hand, the coastline development of 2016-2020 is considered (Figure 3.17), a different result would be expected. The seaward movement of the coastline is nearly zero in those years after the nourishment. If this trend will be continued in the coming decade, the forecast model is overestimating the coastline advance in the north. A possible explanation for the overestimation of accretion is the fact that UNIBEST-CL+ does not simulate cross-shore transport: the redistribution of sediment over the cross-section during a storm event contributes to the structural erosion of a beach stretch (Bosboom

& Stive, 2015). However, when examining the sediment balance of the forecast model (Figure 6.21), a stable and reasonable transport gradient is simulated in the northern area, which supports the thought that the model is a good representation of reality.
Now turning to the simulation up to 2030 and on, the conclusion can be drawn that the model simulates a slower coastline evolution between 2025-2030 than in the 5 years prior to these (2020-2025). The southern shift in the longshore direction of 40 m/year reduces to ca. 25 m/year. The accretion in the north continuous at approximately the same rate, but the accreting coastline stretch gets smaller. This can be linked to the fact that the whole beach area reduces and therefore also the eroding and accreting stretches. The surface area between 0 and +3 m NAP decreases from 73 ha in 2018 down to ca. 57 ha in 2030 (-16 ha in 12 years). Beyond 2030, the shoreline will develop with a slower pace. The surface area decreases further towards ca. 42 ha in 2050.
Beyond 2030, shoreline development slow down. The southern part of the beach develops towards a coastline position perpendicular to the dominant wave direction (west). The surface area between 0 and +3 m NAP reduces further towards ca. 42 ha in 2030 (-15 ha in 30 years).

Sediment balance
When considering at the sediment balance of the forecast model (i.e. after the beach nourishment) several conclusions can be drawn. The yearly sediment transport rates (tide-averaged) along the coastal stretch up to 2050 are depicted in Figure 6.21.

The first thing that stands out is the high sediment transport rate in the southern stretch of the beach, mainly during the first years of the simulation (2018-2020). This difference can be explained by the fact that the beach nourishment changed the shape of the southern part of the beach significantly, inducing higher wave angles of incidence and therefore high transport rates. The peak transport value decreases over the years, from 100,000 $m^3/year$ down to a maximum transport rate of 50,000 $m^3/year$ in 2050. This decreasing trend is due to the fact that the beach shape adapts to the forcing mechanisms: the shoreline develops towards its equilibrium coastline orientation.

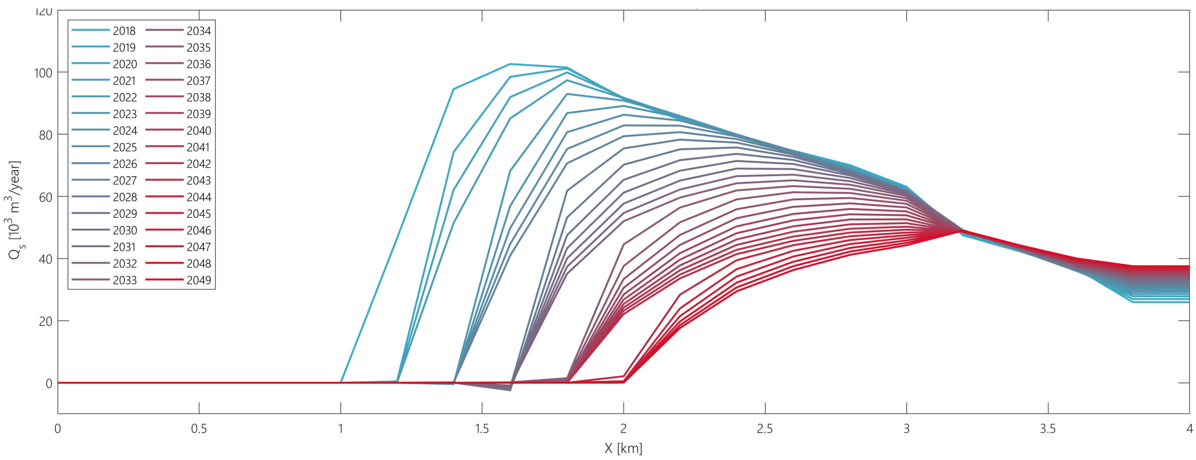


Figure 6.21: Simulated yearly sediment transport rates, tide averaged, forecast model (2018-2050)

Secondly, the transport gradients are discussed. The alongshore transport gradients of the forecast model differ from the hindcast gradients. The yearly transport rates of both models are shown in Figure 6.22, aiming to ease the comparison between the hindcast and forecast results. Note that only the sediment balance up to 2030 is shown in this figure.
The gradients in the southern stretch (positive gradients, so erosion), are quite similar for both periods. However, the negative gradients (inducing accretion) differ along the beach. Consider the stretch from x = 2 km up to x = 3.5 km: from x = 2 km moving upward, the hindcast model shows a small slope (ΔQ_s = -40 $m^3/m/year$ at x = 2 - 3 km), and then a larger slope (ΔQ_s = -260 $m^3/m/year$ at x = 3 - 3.5 km). This leads, respectively, to small and large accretion values.
The forecast model shows a large difference in gradient between the start (2018) and end (2030) of the simulation. For x = 2 - 2.5 km, the slope starts at ΔQ_s = -160 $m^3/m/year$ in 2018, decreasing down to ΔQ_s = -18 $m^3/m/year$ in 2029. For x = 2.5 - 3.5 km, the slope is constant with a value of ΔQ_s = -100

$m^3/m/year$. This means that right after the nourishment, a lot of accretion takes place in x = 2 - 2.5 km. The more northern part, in x = 2.5 - 3.5 km, is accreting constantly in time and space, which is different from the (spatially varying) situation before the nourishment.
However, after 10 years of simulation, the shape of the beach is similar to the shape before the nourishment. This can be seen when comparing the transport graphs of the hindcast model and the graph of, for example, 2028: the graph of 2028 takes the same form as before the nourishment. In other words, the transport gradients are similar in the situations before and 10 to 15 years after the nourishment.

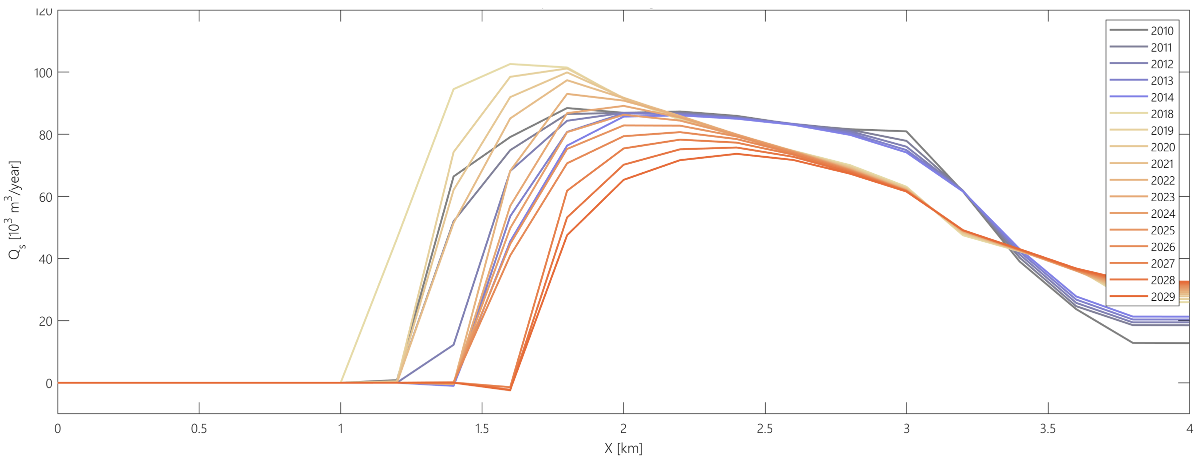


Figure 6.22: Comparison between the simulated tide-averaged sediment transport rates per year for the hindcast (bluish colors) and forecast model (yellowish to reddish colors), 2010-2015 and 2018-2029 respectively

Now turning to the sediment transport rates at the boundaries, again a zero sediment influx at the southern boundary is simulated. The mean export of the system is 30,000 $m^3/year$, which is 1.5 times larger than in the hindcast model. Hence, due to the fact that the system had gained volume during the nourishment, the amount of sediment that yearly leaves the system is 50 % larger. Still, the net export of sediment is not large with respect to the total volume of the beach.

6.8.1. Summary

The main conclusions that can be drawn from the forecast model results are listed below. This list provides an answer to Sub-question 5: *What is the expected future morphological evolution of the beach in the coming three decades?*

Based on the simulations with the UNIBEST-CL+ coastline model (2018-2050) it can be concluded that from 2020 up to 2030 the simulated shoreline develops similarly to the observed shift of the decade before the beach was nourished. This means that up to 2030, the shoreline retreat goes on and the surface area (0 to +3 m NAP) decreases from 73 ha (2018) towards ca. 57 ha (-16 ha in 12 years). Beyond 2030, the shoreline will develop with a slower pace. The surface area decreases further towards ca. 42 ha in 2050 (- 15 ha in 30 years). The southern part of the beach develops towards a a coastline position perpendicular to the dominant wave direction (west). The sediment balance of this simulation suggests that the beach will not reach an equilibrium within the coming three decades.
It must be highlighted that the simulated shoreline migration is based on the notion that the hydrodynamic boundary conditions in the Grevelingen outer delta stay more or less equal in the coming three decades. This is a reasonable assumption, provided that the Bollen van de Ooster do not breach before 2050.

7

Program of Requirements

This chapter provides an answer to Sub-question 6: *Which requirements must a solution for the beach meet?*

The Program of Requirements (PoR) is divided into functional, ecological, recreational and aesthetic requirements. The PoR can be seen as a summary of the interest frameworks of Chapter 5, supplemented by several requirements from the municipality of Schouwen-Duiveland. Afterwards, the PoR is discussed with the stakeholders represented in the PGB (Project Group Brouwersdamstrand). Some defined requirements are bounded by specific values that led from the social system or ecosystem analysis. For other requirements, there are no concrete limits specified. This is because some criteria cannot be expressed in numbers and because several physical conditions vary significantly from location to location. In that case, it is not practical to set specific limits for the entire project area. Moreover, limiting factors (such as the spatial domain of the coastline model) make it difficult to assess the effect of a solution on certain physical factors. Hence, for each of the criteria discussed below, it will be addressed whether limits have been set and how the assessment will be done (qualitatively or quantitatively).

This chapter begins by laying out the functional requirements in Section 7.1. The requirements for rectional and ecological value are discussed in Section 7.2 and 7.3 respectively. The requirements for aesthetics are elaborated in Section 7.4. Subsequently, the Program of Requirements is summarized in Table 7.1 as part of Section 7.5.

7.1. Functional requirements

First of all, to ensure a certain degree of effectiveness, there are several functional criteria.

7.1.1. Beach surface area

The solution's main goal is to maintain and increase the area of the Brouwersdam beach, thereby extending its lifespan. Therefore the main requirements concern the surface area and the width of the beach. The **surface area of the beach (1)** (area between 0 and +3 m NAP) is chosen as an indicator for useful recreational area. A minimum surface beach surface area of 70 ha between 0 and +3 m NAP is taken as a minimum. This value is taken because it provides sufficient space for the recreational activities (it equals the surface area of 2009, in which the beach was considered to provide sufficient space).

An additional requirement is formulated to guarantee that the solution ensures a sufficient **beach area within the borders of Schouwen-Duiveland (2)**. This criterion states that there should be a minimum of 4 hectares of beach within the borders of Schouwen-Duiveland. For the amount of hectares located in Schouwen-Duiveland, the position of the beach as in 2017 is taken as a starting point (after the beach was nourished, see Figure 3.10). In that year, the beach provided sufficient space for the recreational activities within the borders of Schouwen-Duiveland (more than 4 ha).

Broer et al. (2011) categorize the Brouwersdam beach as a sports and events beach that is used intensively and requires a large beach area. The minimum necessary beach width, according to this research, is 100 m from the dune foot (+3 m) to the high water line. However, for kite buggying and beach sailing activities, the intertidal part between 0 m NAP and the high water line is essential. It is estimated that to execute these activities, a **minimum beach width (3)** of 200 m is needed. As the beach has a convex shape, this requirement can not be fulfilled at the edges. The edges are therefore excluded from this requirement. The edges are considered to have a longshore distance of ca. 200 m.
The beach surface and width will be assessed quantitatively with the use of the forecast coastline model.

7.1.2. Adaptivity

The solution must be adaptive in multiple ways. To ensure that the solution is feasible in different future scenarios concerning Getij Grevelingen, the following two criteria are formulated: the solution must be **effective in combination with a tidal inlet located north (4) or south (5) of the beach**. As the coastline model has not been set-up to simulate a tidal inlet in the dam, this criterion is assessed qualitatively.
Thereby, it must be possible to **combine** the solution **with a beach nourishment (6)**. If several parties contribute to the payment or other developments that induce an increase in the budget, then a beach nourishment may be executed. It is therefore required that this is possible in combination with the solution. This requirement is assessed qualitatively.

7.1.3. Costs

The benefits of the solution must be offset against **construction costs (7)** and the **maintenance costs (8)**. There is no concrete budget for the solution; the available budget will depend on which parties are involved. It is expected that if several parties contribute to the payment, the contribution of the municipality of Schouwen-Duiveland will be higher (P. van Sante, personal communication, January 29, 2021). The costs of each solution are calculated and assessed quantitatively.

7.2. Recreational requirements

From Chapter 5 it can be concluded that several physical conditions can be used as indicators for the recreational and ecological value of the area. These indicators translate the impact on the physical system into a value increase or decrease. Reference is made to Section 5.5 for the background of the following requirements.

It is important to highlight that most of these indicators will only be assessed if the solution is expected to cause significant changes to the indicator. For example, if an alternative does not include a nourishment, the sediment size is not expected to change significantly, and it is then assumed that the requirement of a suitable sediment grain size will be met. Moreover, if the solution is expected to impact only a part of the project area, only the change of the (ecological or recreational) value of that specific location is assessed.

7.2.1. Requirements for water recreation

The **water depth (10)** is important for extreme water sports. As the intervention is likely to be located in the extreme sports area near the beach (depicted in Figure 5.4), it is important to pay attention to the effect on the water depth in this area. There are no specific limits for this criterion. If the assessment of a particular solution shows that the water depth will be affected significantly, the effect on water sports will have to be examined on a site-by-site basis. The assessment will be done qualitatively.

Another important indicator for extreme water sports is the **accessibility (11)** of the water from the beach: for example surfing is prevented when a certain (non-accessible) structure is made at the shoreline.
Thereby, **safety** includes the minimal risk of extreme water sporters to clash with certain **structures (12)**. When a kite surfer loses control, it takes several seconds to be transported over a few hundreds meters, and thus every structure that is built at the shoreline could be a potential danger.

7.2.2. Requirements for beach recreation

The **type of substratum (13)** can have a large influence on recreation. Hard substratum is on the beach is not desired for recreational purposes. The impact will be investigated qualitatively site-by-site.

The **sediment size at the beach (14)** is important for extreme beach sports. The sediment should not be finer than it currently is ($D_{50} = 210\mu m$). This limit is not hard; it gives an indication for which sediment size the level of nuisance is low. Morerover, this requirement is only assessed if major differences in the beach sediment size are induced by the solution.

As aeolian transport of sediment depends on many other factors as well (such as windspeed, wind direction, soil moisture content, vegetation, beach width), a change in the median grain size at the beach will not necessarily lead to nuisance. Hence, indicator is therefore only of significant importance if major differences in the beach sediment size are expected.

The **turbidity (15)** should not cause hindrance to the recreational activities. A qualitative assessment will be performed to examine the impact of the solution on turbidity.

The **safety** comprises the maximum **current velocity (16)**, which is restricted to 0.7 m/s to maintain a safe swimming environment and the level of obstructions.

7.3. Ecological requirements

Following from Chapter 5 and 4, it can be concluded that several physical conditions can be used as indicators for the ecological value of the area. These indicators translate the impact on the physical system into a value increase or decrease. Reference is made to Section 5.6 for the background of the following requirements.

The change of a soft **substratum type (17)** into a hard one has a positive impact on the ecosystem, as this creates habitat for benthos and birds. Large **turbidity (18)** can cause changes to the ecosystem as well (as less sunlight reaches the bottom in turbid water). There is no strict maximum to the level of turbidity; it should be minimized. Turbidity is assessed qualitatively by assessing whether the wave impact or current velocity increases (at similar depths), as larger hydrodynamic impact causes more turbidity.
A large **bed shear stress (19)** can impact several habitats types. For instance, an increase in bed shear stress near the shellfish reef should be restricted. However, an increasing bed shear stress in the deep sublittoral is accepted. Thus, the change in bed shear stress (caused by waves and currents) must be considered per location. This assessment will be done qualitatively. The last key indicator concerning ecology is **rest (20)** in main habitat areas. This indicator holds that the seabed disturbance and nuisance in the outer delta should be minimal. The presence of vessels and construction activities causes harm to the habitats of nearly all species. Hence, the frequency of construction works and the amount of seabed that is disturbed is assessed.

Note that the water depth is excluded from these indicators, even though this abiotic condition has impact on the type of habitat that can occur. The reason for the exclusion is because the determination of water depth changes on the ecological value of the area requires a full ecological assessment of the area (Bouma et al., 2005), which is outside the scope of this thesis.

7.4. Aesthetics

The last requirements encompass the aesthetic value of the design. Even though aesthetics are non-functional and subjective, it can play a large role in the acceptance of the design by stakeholders. According to Boelskifte (2014), the involvement of aesthetics in the design process is vital for the success of the project.
According to Boelskifte (2014), aesthetics have to do with overall human perceptions of quality. This means that aesthetics are associated with how things feel, taste, smell, as well as their appearance. Hence, most engineering decisions may affect the aesthetic value of a solution. Aesthetics are governed by subjective criteria (Boelskifte, 2014). This thesis aims to describe the aesthetic value of the solutions

based on four aspects. These aspects are chosen such that their assessment is tot completely subjective (e.g. the amount of structures near the shoreline is partly a quantitative assessment). Note that the score given to a certain aspect in the MCA (Chapter 9), is a subjective score assigned by the writer of this thesis. To obtain a more reliable decision on the score of the aesthetics, for example a survey could be held among the stakeholders of the beach. In that way, multiple opinions and interests will then be reflected in the score. However, as aesthetics associated with a perception and feeling of humans, the aesthetic value can only be truly assessed when the solution is executed. But, this applies ofcourse to several aspects of the multi criteria analysis: the scores are an estimate based on the expected outcome. This is further elaborated in Chapter 12 (Recommendations).

The first aspect relates to the **view over the North Sea (21)** from the perspective of someone standing on the beach. This view is considered to enhance a positive perception on the beach, and therefore the obstruction of the view is considered as a deterioration of the aesthetics. This aspect is assessed based on the rate of obstruction of this view. The second aspect relates to the amount of **structures on the beach (22)**. A structure forms an obstacle and therefore negatively affects the feeling of a wide and boundless area. This aspect is assessed based on the level of obstruction at the beach. The third aspect relates to the **shape of the shoreline (23)**. A natural appearing, gradual curvature of the shoreline is desired. Sharp angles and straight lines in the shoreline appear artificial and may reduce the perspective of humans to be in a high quality natural area. Lastly, the feeling of **innovation (24)** affects the human perception. A creative, innovative solution is unexpected and original (Faste, 1995), which supports the human perception of quality, in opposition to conventional ideas (Boelskifte, 2014). Hence, the more innovative a solution is, the higher the aesthetic value.

7.5. Summary

The Program of Requirements (PoR) is summarized in Table 7.1. It consists of requirements that are subdivided in the following categories: functionality, recreational value (water), recreational value (beach), ecological value and aesthetics. The way of assessing the requirement (qualitatively or quantitatively) in the following stage of the research is indicated in the column 'Assessment' with a 'V'.

Table 7.1: The Program of Requirements (PoR), including criteria for evaluation of alternatives. The most right columns indicate whether the requirement will be assessed quantitatively or qualitatively. The 'V' indicates which of these two applies for a certain requirement.

	Nr.	Requirement	Criterion	Assessment	
				Quant.	Qual.
Functionality	1	Total beach surface area	>74 ha	V	
	2	Beach surface area in S-D	>4 ha	V	
	3	Minimum beach width	>200 m	V	
	4	Combi inlet North	n/a		V
	5	Combi inlet South	n/a		V
	6	Combi nourishment	n/a		V
	7	Construction costs	n/a	V	
	8	Maintenance costs	n/a	V	
	9	Certainty	n/a		V
Recreational value (water)	10	Water depth	Minimal changes and gradients		V
	11	Accessibility	Sea accessible from beach		V
	12	Safety (structures)	n/a		V
Recreational value (beach)	13	Substratum type	Soft		V
	14	Sediment size	>210 μm	V	
	15	Turbidity	Miminal disturbance		V
	16	Safety (current vel.)	<0.7 m/s	V	
Ecological value	17	Substratum type	Hard is desired		V
	18	Turbidity	Minimal disturbance		V
	19	Bed shear stress	Minimal		V
	20	Rest	Minimal disturbance		V
Aesthetics	21	View over North Sea	Minimal obstruction		V
	22	Structures on the beach	Minimum amount of obstacles		V
	23	Shoreline shape	Smooth, natural appearance		V
	24	Innovation	Innovative design and appearance		V

8
Design I: Identification, evaluation and selection

The main goal of this section is the identification of different realistic alternatives providing win-win situations. This holds that the alternative mitigates and compensates for the beach erosion and enhances the ecological value of the area. The chapter relates to Design phase I.

This chapter is divided into four parts. The first part, Section 8.1 is concerned with the erosion causing mechanisms and the possible features a solution can contain to mitigate the effect of these mechanisms. Secondly, Section 8.2 discusses the possible effective measures to counteract, mitigate or compensate for the erosion. Each of these alternatives were simulated in the forecast model (the set-up and results of these simulations are discussed in Appendix G). Thirdly, Section 8.3 elaborates on the technical feasibility of each of the solutions, by assessing the structure on the two main failure mechanisms. Subsequently, in Section 8.4, a first estimate of the feasibility and efficiency of each alternative is made. The most feasible alternatives are selected to be refined and evaluated in the next chapter.

Note that the chapter is related to the second and third BwN design steps. Section 8.2 is related to the second step 2 ('Identify alternatives that use or provide value for nature and humans') whereas Section 8.4 is related to the third step 3 ('Evaluate each alternative to select an integral solution').

In this chapter, reference is often made to the 'southern part' and the 'northern part' of the beach. These terms refer respectively to the (eroding) part south of ray 2240 and the (accreting) part north of it. Thereby, the term reference situation is used to refer to the situation in which no measures are taken. In other words, that is the situation in which the shoreline will develop similarly to the coastline development as depicted in Figure 6.20.

8.1. Mitigation

This section begins by listing the main mechanisms that contribute to erosion. It will then go on to the examination of different ways to mitigate the effects of these mechanisms.

8.1.1. Main erosion causing mechanisms

The structural erosion of the southern part of the beach is caused by a gradient in longshore sediment transport towards the northeast. Concerning the causes of the erosion, the main conclusions from Section 6.3 (Wave model results) and Section 6.6 (Coastline model results) are listed below:

Temporal distribution The highest longshore transport rates to the north occur during high water (up to 8 times more transport than during mean water conditions). In total, ca. 80% of the sediment transport over a tidal cycle occurs during high water.

Spatial distribution alongshore The alongshore transport to the north is maximum in the southern part (up to 3 times larger than in the north). This is due to a larger wave angle of incidence at the closure depth, a larger water depth in front of the southern part of the coastline and therefore less wave energy reduction and the higher flood velocities occurring in the south.

Spatial distribution cross-shore The highest transport rates are located between - 0.5 and + 1 m NAP. This is due to large orbital velocities (inducing the stirring of sediment) in combination with the alongshore current in this intertidal zone.

Dominant conditions The waves are dominant in causing the erosion and displacement of the beach. Six wind-generated (sea) wave conditions during high water are responsible for more than 65% of the total net longshore sediment transport in the southern stretch. These wave conditions occur ca. 20 days/year. The nearshore characteristics of these waves are a significant wave height from 0.8 < $H_{s,n}$ < 1.2 m, a peak wave period of 5.5 < $T_{p,n}$ < 7.5 s and a wave angle of incidence at the closure depth of -35 < ϕ < -55 ^{o} with respect to the coast normal (waves directed from the southwest-west to northwest-west). Hence, the dominant wave direction near the beach is West.

Structures or soft measures that counteract this erosion are designed to change the S-x curve (sediment transport along the shoreline), such that gradients become zero. A zero gradient means zero erosion. When considering the sediment balance of 2018 in Figure 8.1, a net out flux of ca. 30,000 $m^3/year$ is detected. Ideally, a solution would reduce this to loss to 0, implying no sediment losses in the whole beach system.
Thereby, the gradients along the coastal stretch are large: there is an eroding and an accreting part (the boundary is located at x = 1.6 km longshore (ray 2260) in 2018). The left part then experiences an annual loss of ca. -100.000 $m^3/year$ (implying a net import of +100.000 $m^3/year$ for the right part). The right part thus experiences a net import of +100,000 - 30,000 = +70,000 $m^3/year$.

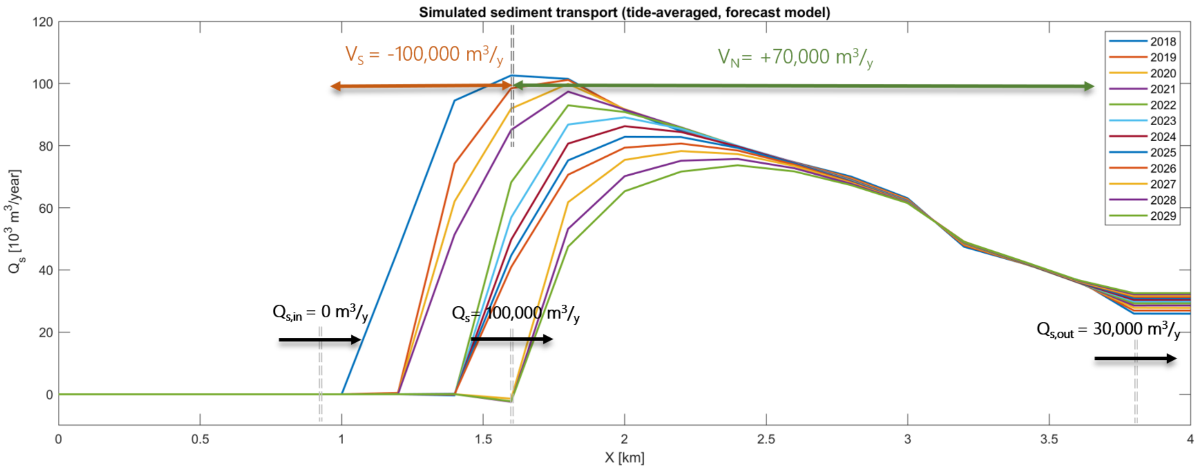


Figure 8.1: Simulated yearly sediment transport rates averaged over the tidal cycle, forecast model (2018-2030). Black arrows indicate sediment transport rates at boundaries. The southern (eroding) and northern (accreting) part of the beach in 2018 are indicated by the orange and green double-sided arrows, respectively. V indicates the yearly volume change of the considered stretch.

Along the coastal stretch, the equilibrium coastline orientation slightly varies, but is 270 ° N on average. The rate at which the current coastline orientation deviates from its equilibrium configuration can be assessed when considering the $S - \phi$-curves along the beach (depicted in Figure 8.2). In this figure, you can see that mainly in the southern edge of the beach, the coastline orientation deviates a lot from its equilibrium (note that the defined ray is not exactly perpendicular to the shoreline, and thus a small overestimation of coastline orientation is depicted for ray 2300). The equilibrium coastline orientations can be used in the design of a solution, as the beach would experience no shift if the coastline orientations are at their equilibrium orientation.

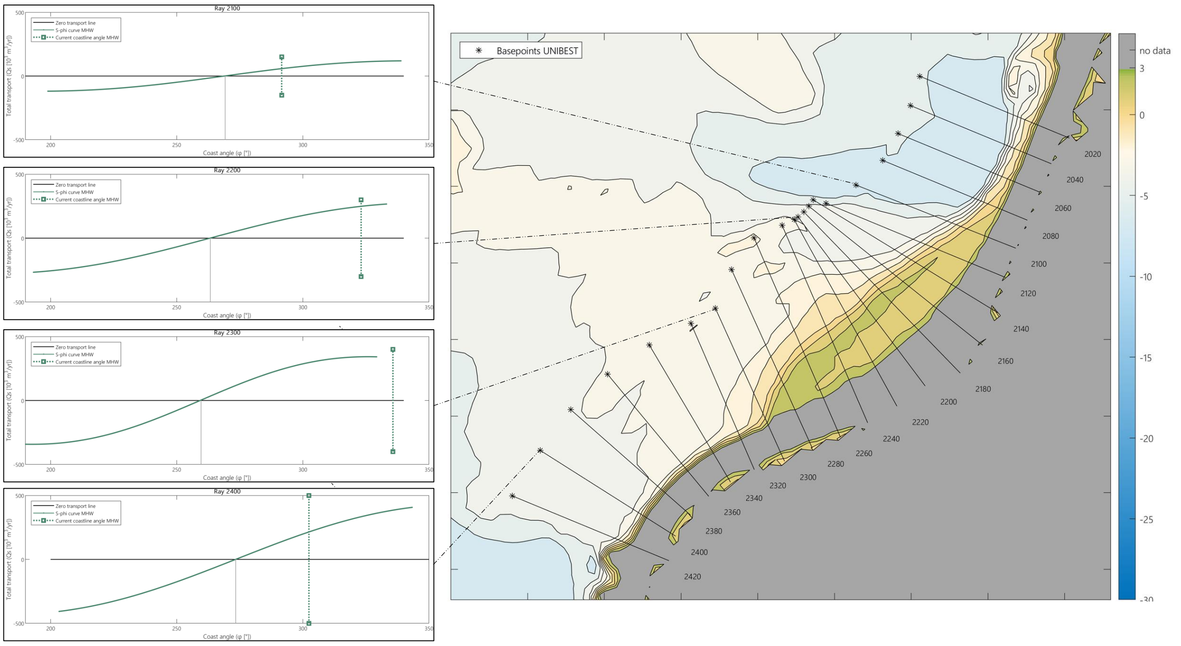


Figure 8.2: $S - \phi$ curves of rays 2100, 2200, 2300 and 2400 along the beach during high water conditions, for 2018 (retrieved from UNIBEST forecast model).

8.1.2. Mitigation of effects

Mitigation of the erosion was examined, based on the causes explained in the previous section. This resulted in the following list of possible features a solution can contain :

1. Mitigate the wave attack at the intertidal area of the southern part of the beach, predominantly the attack of wind-generated waves directed from the southwest-west to northwest-west with a significant nearshore wave height of $0.8 < H_s < 1.2$ m.
2. Reduce the wave angle of incidence (mainly the waves referred to in 1.) approaching the beach's southern part.
3. Mitigate the tidal flow velocity in the intertidal area, especially flood conditions when the velocity is maximum, and the flow is directed to the northeast.
4. Interrupt the longshore sediment transport towards the northeast in the intertidal area of the southern part of the beach. This is most effective at the southern stretch of the convex part of the beach (near ray 2260), as the transport rates are particularly large in this stretch.
5. Trap the sediment of the southern part of the beach.
6. Compensate the reduction of sediment volume of the southern part of the beach.

The causes and possible mitigation features are depicted in Figure 8.3. Based on these possible features, alternatives are identified.

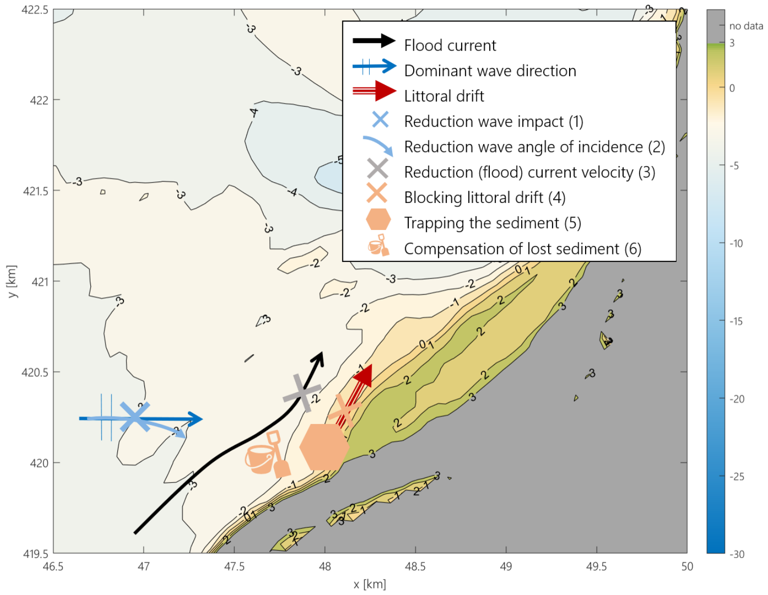


Figure 8.3: Main erosion causing mechanisms (indicated with straight arrows), and the 6 possible features a solution can contain to mitigate the erosion

8.2. Identification of alternatives

In this section possible solutions are examined. The investigation of using groynes leads to designs A, B and C (Section 8.2.1) and examining detached breakwaters leads to designs D and E (Section 8.2.2). In Section 8.2.3 the solution of frequent nourishing is discussed.

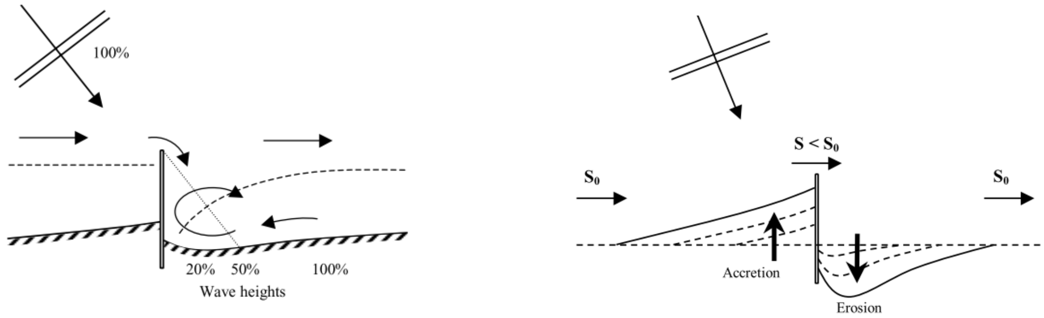
8.2.1. Groynes

A groyne is a small jetty reaching into the surf zone which can be used to preserve an eroding coast, to increase the width of a beach or to increase the lifetime of a beach fill. When designed properly, a groyne can reduce the existing wave- and tide-induced longshore transport rate efficiently. The reduction of littoral drift depends on the groyne length, height, orientation and permeability (Bosboom & Stive, 2015).

Two main types of groynes can be distinguished. The first type is an impermeable, high-crested groyne with the function of keeping the sediment in between two groynes. These groynes usually have crest levels above +1 m NAP. A disadvantage of this type is that structure-induced eddies are generated in the lee-side of the groyne, leading to high, local flow velocities. The other main type is the permeable, low-crested type. Because these groynes slightly reduce the longshore transport, these groynes are used on beaches with a small sediment deficit. The Brouwersdam beach has large gradients in littoral drift. Hence, the impermeable groyne (first type) is more applicable for the beach.

Morphological response to groynes

When groynes are designed perpendicular to the coastline, the updrift side of the groyne accretes as the groyne blocks the sediment transport. This results in lee-side erosion, as the downdrift side of the groyne has a lack of sediment supply. Also, the lee-side of the groyne has a reduced wave impact and longshore current velocity. Thereby, waves refract around the tip of the groyne: wave energy spreads over the wave crest and therefore smaller waves with a different angle of incidence progress beyond the tip of the groyne. The wave set-up in the lee side is thus reduced, which leads to a gradient in water level. Hence, structure-induced currents occur (Figure8.4a), leading to possible scour at the tip and accretion at the lee-side corner between the coastline and the groyne (Figure 8.4b).
The rate of transport reduction depends among other on the length of the groynes. A first estimate of the reduction of littoral transport can be made by assuming that the groyne totally blocks the transport, whereas seaward of the groyne the longshore transport is not affected (Figure 8.5). The consideration of the cross-shore distribution of the longshore transport is crucial in this estimate. For the construction of multiple groynes, the length of the groynes should be smaller than the width of the breaker zone if the sediment transport is not aimed to be reduced to zero.



(a) Structure-induced currents due to differences in wave set-up

(b) Shoreline development around groynes

Figure 8.4: Hydrodynamic and morphological response to groynes (Perdok, 2002)

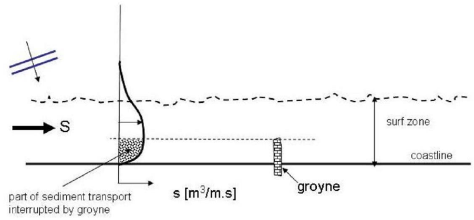


Figure 8.5: Sketch of rate of longshore transport that is interrupted by a groyne (Bosboom & Stive, 2015)

Next to amount of littoral sand movement, the height of the groyne determines the amount wave energy attenuation and current velocity reduction near the beach. Besides, the crest height determines the rate of wave reflection and the amount of construction material. Thereby, high groynes are likely to create rip currents and flows at the head of the structure. These flow patterns can lead to local scour and erosion channels, accompanied by a net offshore transport of sediment. This counteracts the function of the groynes, and can threaten the structural stability.

Groyne material

The material of the groyne must have a small permeability for reasons explained above. Moreover, it must be possible to construct the groyne at a sandy beach. A (nearly) impermeable groyne can be constructed with different materials, such as timber, rubble mound, gabions, or soft materials like sand. Timber groynes can be advantageous over other materials due to their lower costs, small environmental impact and relative ease with which the groyne dimensions (level and profile) can be adapted (Perdok, 2002). However, a straight wooden groynes form a hard, vertical barrier. This induces wave reflections and large flow velocities near the structure, causing local scour. Thereby, hardly any sheltered areas are created in which flora and fauna can grow.

Materials such as rubble mound and gabions are durable and have a large wave absorption due to their porous structure. They can be cost effective when using locally available materials. The hard substratum could provide habitat for different species, but the environmental impact of rocky groynes is larger than timber groynes (CIRIA et al., 2007). As the construction has to create benefits for nature as much as possible, the possibility of more ecological friendly materials was investigated. After the idea of Marian Lazar (M. Lazar, personal communication, November 3, 2021), the applicability of brushwooden structures filled with oyster shells near the Brouwersdam was investigated.

The use of brushwood in hydraulic structures is a traditional way of coastal protection in the Netherlands (Schiereck, 2012). A brushwood groyne can be constructed in several ways.

A possible design is a double row of wooden sheet piles, between which the space is filled with (willow or coniferous) wooden branches (Figure 8.7a). This type has the advantages of having a small width and therefore low costs. However, there are many downsides to this type: the permeability is large (ca. 50 % in case of a 1 m heart-to-heart distance of the sheet pile rows), the required sheet piles are relatively long (2/3 of the pile length is in the soil), bed protection is needed around this vertical wall structure, and lastly, this type is sensitive to maintenance as the replacement of the sheet piles is not easily done.

Another type of brushwood groyne is a construction of layered willow mattresses, also known as fascine matresses (*zinkstukken*). A fascine mattress is constructed of bundles of young willow branches (called faggots, *wiepen*), which are bound together to form a grid of 1 m × 1 m modules (CIRIA et al., 2007). The the thickness and spacing of the faggots can be chosen based on the purpose and dimensions of the structure. The faggots serve as the skeleton of the structure, whereas the bottom, cross-wise arranged twigs carry the stones or different material. A geotextile can be attached at the bottom to ensure a sufficient filter function of the structure. The downside of this type is that it is more costly and that it takes up more space.

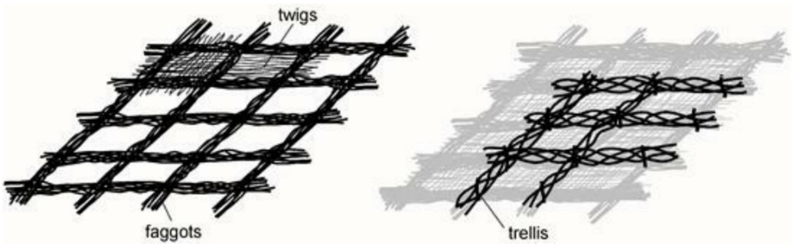


Figure 8.6: Sketch of classical fascine matresses, obtained from Schiereck (2012)

An advantage is that these structures can be filled with many types of material such as sand or shells, which decreases the permeability up to ca. 10 %, and provides shelter zones for flora and fauna. Sheet piles can be used for extra stability, but as the bottom layer (made of piles bound together perpendicularly) settles in the soil the stability of the structure is preserved without piles. Thereby, extra bed protection is not needed, as the bottom mattress can be constructed to extent sufficiently wide in lateral direction.

(a) Sheet pile groyne filled with coniferous branches at a salt marsh in the Wadden Sea (collection Van Aalsburg BV)

(b) Brushwood groyne of layered fascine matresses (collection Van Aalsburg BV)

Figure 8.7: Groyne materials

As part of the Innovative Coastline Program (IKZ), Tauw & Van Aalsburg (2019) conducted an investigation on the applicability of the second type of brushwood groynes to mitigate erosion of the foreshore of a coastal environment. This type of groyne can reduce costs and has a positive effect on the ecology. Thereby, brushwood groyne types have the advantage of being adaptable over time. The lifetime of submerged brushwood groynes is ca. 70 to 100 years (Tauw & Van Aalsburg, 2019). A groyne in a tidal environment which is flooded two times per day, has an approximate lifetime of 15 to 25 years (D. Van Aalsburg, personal communication, May 8, 2021). The wood that weathers ends up in the seabed, causing no harm to the ecosystem. The technical feasibility of the groynes is further elaborated in Section 8.3.

Brushwood constructions provide substratum for many types of seaweed such as kelp (*blaaswier*), knotted wrack (*knotswier*) and ulva (*zeesla*) and for benthos such as mussels, oysters and periwinkle (*alikruik*). The framework of the faggots (*wiepen*) provides a sheltered, warm and lee zone. These zones could serve as nurseries for fish and benthos. Thereby, the hard substratum provides habitat for certain waders (*steltlopers*) to forage (Section 4). Moreover, Tauw & Van Aalsburg (2019) show that the CO_2-footprint of brushwood groynes is minimally CO_2-neutral and most likely CO_2-negative. The latter means that during the total lifetime of the groynes (including the growth of the trees), they remove more CO_2 from the air than is emitted during construction. Due to the above mentioned advantages, this groyne type is used in the designs of alternatives A, B, C and E.

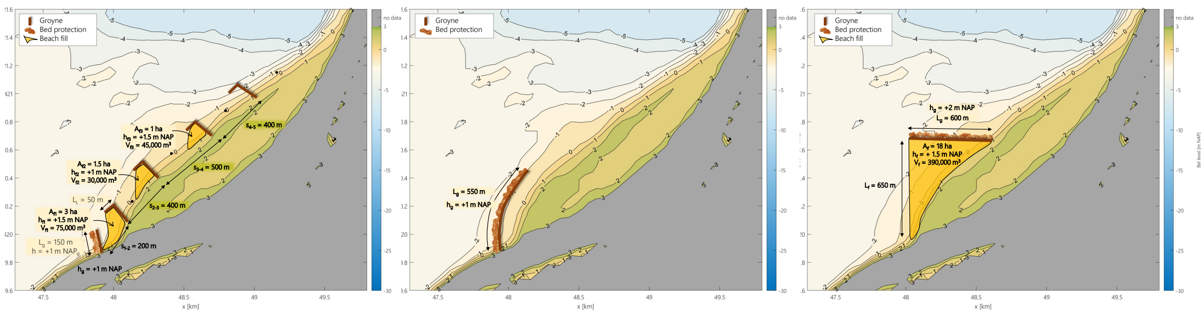
Groyne designs

To mitigate the erosion of the beach with a groyne or multiple groynes, three groyne configurations are designed.

A common design is the creation pocket beaches along the coastal stretch by constructing multiple groynes (**A - Pocket beaches**). In each pocket beach, a certain part of the sediment transport is reduced. Between two groynes, the shoreline will be oriented perpendicular to the dominant wave direction (Figure 8.4b). Hence, this groyne configuration leads to a saw-tooth appearance of the shoreline. When designed properly, the beach can reach an equilibrium. An initial beach fill of the pocket beaches speeds up the reach of an equilibrium coastline.

The second groyne concept that is elaborated is the construction of a large, curved groyne (in the order of magnitude of the cross-shore beach width) at the southern egde of the beach. This alternative is named a C-shaped groyne in this research due to its form (**B - C-shaped groyne**). The idea behind this construction is that the transport rates in the south are minimized due to reduced flood current velocities and wave impact from the west. This would lead to a shift of erosion and the beach shape towards the north. Thus, at the downdrift side of the groyne erosion occurs, but due to the fact that waves are partly diffracted and the current velocities are reduced by the groyne, the erosion rate is smaller than in the current situation.

The third concept that is being analyzed is the construction of a large, straight groyne in combination with a beach fill (**C - Straight groyne with beach fill**). The reasoning behind this concept is to create a shoreline at the equilibrium coastline angle. The equilibrium orientation is ca 270 $°N$ at the southern stretch of beach (Figure 8.2). A nourishment fills up the southern stretch of the beach with sediment and a large, straight groyne (orientated 270 $°N$) maintains the position of this part. Downdrift erosion is again not prevented with this option, but due to the sheltering effect of the extension of the southern edge of the beach, the northern part will experience less erosion.



(a) Sketch of design A - Pocket beaches

(b) Sketch of design B - C-shaped groyne

(c) Sketch of design C - Straight groyne with beach fill

Figure 8.8: Groyne designs A, B and C

8.2.2. Detached emerged breakwater

Detached breakwaters are parallel to the coast orientated breakwaters without a connection to the coast (Bosboom & Stive, 2015). They may be segmented. A breakwater can be submerged or emerged. Emerged breakwaters have a crest level above mean sea level and can effectively reduce longshore transport in the shadow zone due to the effect of wave energy dissipation and diffraction. The construction of submerged breakwaters is not further discussed, as the effects of this measure are uncertain; in some

cases it enhances coastline erosion instead of mitigating it.
A disadvantage of breakwaters is that the construction and maintenance costs are usually relatively high. Another disadvantage is the possible inconvenience or danger to swimmers and water sporters (Bosboom & Stive, 2015). However, because a breakwater has the advantage of shoreline erosion mitigation without creating a structure on the beach, this measure is a promising alternative.

Morphological response to detached emerged breakwaters

The shape of the shoreline that forms behind the breakwater depends mainly on the dimensions and the geometry of the breakwater (breakwater length L, offshore distance to the initial shoreline D and length between the segments L_{gap}, as depicted in Figure 8.9. In the shadow zone (lee-zone) of the breakwater, a salient can occur (allowing sediment to be transported in this shadow zone) or a tombolo (preventing sediment transport).

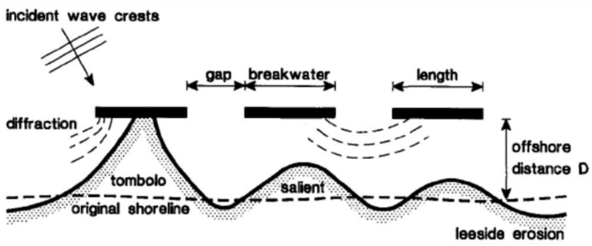


Figure 8.9: Detached breakwater parallel to the shore (retrieved from Bosboom & Stive (2015))

Near the Brouwersdam beach, a breakwater would be located at the southern side of the beach, perpendicular to the west (the dominant wave direction). The main transport is directed northward. There is, however, no sediment supply from the south. The coastline can thus only be maintained by a detached breakwater; the coastline will not take the shape of a tombolo or salient. An offshore breakwater should thus be designed and constructed with a tombolo to ensure a sufficiently stable shoreline.

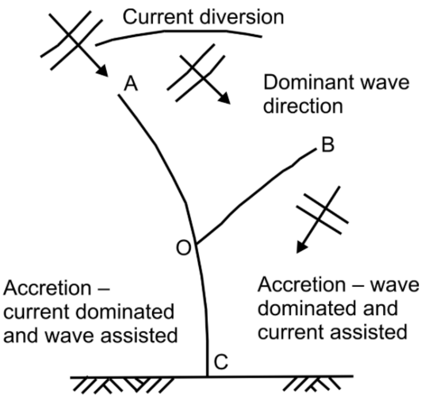
Breakwater material

A breakwater can be constructed of many types of materials. A rubble mound breakwater is one of the traditional designs. As the environmental impact of the solution is aimed to have a minor impact on the environment, the construction of an innovative breakwater is preferred over a more traditional, rubble mound breakwater.
The construction of an artificial island could serve as an offshore breakwater as well, while serving as a new habitat at the same time. In the case of the Brouwersdam beach, northern and western banks of the island should be protected with a revetment, as these sides are prone to the largest wave attacks. Bed protections and revetments can be made of granular material, asphalt, geotextiles with concrete elements, etc. Another type of bed or bank protection is the use of fascine matresses (zinkstukken) for bed protection or slope matresses (kraagstukken) for bank protection in combination with geotextile. These matresses are frameworks made of faggots (bundles of willow branches). Usually, stones are placed on the matresses after construction to give them more weight (Schiereck, 2012). This could be a possible, relatively natural friendly way of protecting the banks of the island. A suitable bank protection should be investigated in a further stage of the design process. For this design, a bank protection of rubble mound is assumed for the computation of the construction costs and for the impact on ecology and recreation.

Alternatively, a breakwater can be constructed of brushwood fascine matresses covered by a single layer of stone. The construction of a breakwater with a natural core is more nature-friendly than constructing it with only stone and rubble mound, as the core of the breakwater is naturally degradable. Section 9.1.3 provides further elaboration on a breakwater with a brushwooden core.

Breakwater designs

The first alternative breakwater design is an artificial island with a constructed tombolo (**D - Artificial island with tombolo**). The island serves as a breakwater and as a habitat for birds and benthos at the same time.

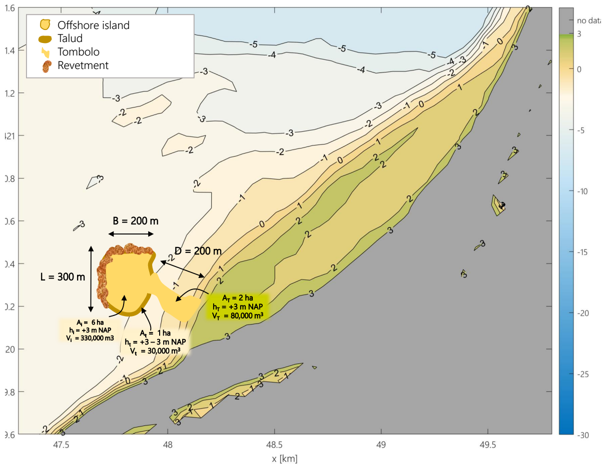


Orientation of arms in fishtail groyne (CIRIA et al., 2007)

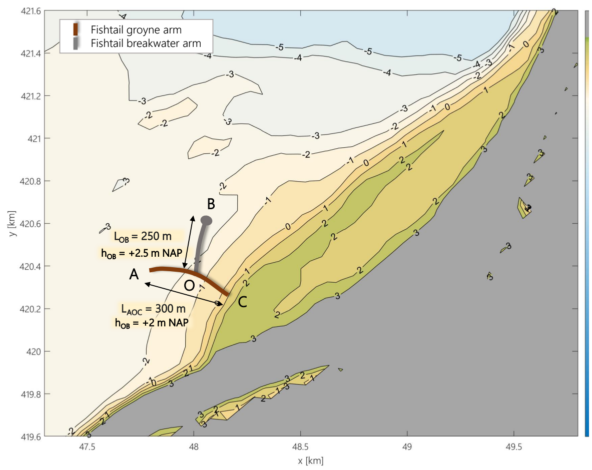
(a) Fishtail groyne, Llanelli, UK (CIRIA et al., 2007)

Figure 8.10: Design of a Fishtail groyne

Another option is to combine the beneficial features of an offshore breakwater, a groyne and a tombolo in a so-called fishtail groyne (depicted in Figure 8.10) (**E - Fisthtail groyne**). The geometry is such that currents and sediment transport is reduced by the groyne arm (the updrift arm) and waves are dissipated by the breakwater arm (downdrift arm). The latter thus aids in the preservation of the beach in the lee-side of the structure.



(a) Sketch of design D - Artificial island with tombolo



(b) Sketch of design E - Fishtail groyne

8.2.3. Beach nourishment

Another way of dealing with the problem of structural erosion is by nourishing with sand, instead of building structures (called 'soft' solutions) (Bosboom & Stive, 2015). The basic concept is the artificial supplementation of sediment. The advantage is that the coast is left in a more natural state than in the case of a construction. When a nourishment compensates for losses due to structural erosion, which is an ongoing process, the nourishment has to be repeated. This has the advantage of being a flexible solution and providing the possibility to spread the costs over a longer period of time. Another advantage is that it does not result in lee-side erosion. The disadvantages are that a nourishment at the Brouwersdam is very expensive, due to the shallow area. Sediment has to be dredged offshore (outside the -20 m depth contour (Rijkswaterstaat, 2014b)), and transported to the beach. Large hopper vessels cannot reach the beach as their draught is too large. Smaller vessels are used to get near the dam, an then the sediment is transported via tubes from the Brouwerssluis to the beach (M. Lazar, personal communication, October 9, 2020).

The Brouwersdam beach is nourished in 2016 with 500,000 m^3 of sand. The costs for this nourishment were 4,000,000 €. The mobilization costs of this execution are estimated on 1,500,000 €, implying costs per cubic meter of dredging of 5 €/m^3. As was concluded from Section 3.4, this nourishment has an expected lifetime of 6 years with a mean sediment loss from the south of 80,000 $m^3/year$.

8.3. Technical feasibility

This section elaborates on the technical feasibility of the preliminary design of the groyne structure. The feasibility of the breakwater arm of the fishtail groyne (depicted in Figure 9.9) is discussed in Appendix G.5. In this section, the design parameters are discussed. Thereafter, the two main failure mechanisms are elaborated.

A considerable amount of literature has been published on the flow resistance and wave damping of wooden structures. Studies by H. T. Dao et al. (2020) and Schmitt & Albers (2014) examine the the wave and current reduction of wooden fences and bamboo breakwaters on mangrove coasts. T. Dao et al. (2018) elaborate that wave damping increases with increasing fence thickness and increasing density of the (woody) material in the fences. However, these studies elaborate on a configuration of two rows of vertical poles with brushwood inserted in between (similar to the sheet pile groyne depicted in Figure 8.7a). This design deviates significantly from a design of layered fascine mattresses filled with shells (having larger dimensions, a sloping front, a more compact filling of shells instead of only twigs, etc.). Hence, the wave transmission and flow over these structures is assumed to be similar to conventional designs such as rubble mound groynes. This is further elaborated in Appendix G.7.1. However, the failure mechanisms of the designs deviate from these conventional structures and are therefore examined further in this section.
In principle, a structure will not fail when the strength is larger than the load. There are three primary types of loads that can be considered in the description of failure mechanisms for generic flood defence structures, namely: the water level difference across a structure, wave loading and lateral flow velocity (Allsop et al., 2007). As there is no significant water level difference across the structure (which is the case in water retaining structures), the wave loading and flow velocity remain as being the primary loads.

As this thesis aims to provide insight in preliminary designs, the focus is on the overall (macro-)stability of the structure. The structure is not composed of loosely layered grains, but is constructed as one large, rigid structure. The failure mechanisms are thus based on the notion that the construction fails as a whole. Whether the construction is sufficiently rigid, will be tested in the wave flume of Deltares, commissioned by Van Aalsburg B.V.. In other words, these tests will determine the ultimate strength of the different elements of the structure. For example, the connections between faggots are in this thesis assumed to be able to withstand certain tensile forces, as this aspect cannot be deduced from the present investigation. The results of the physical model tests should determine whether the construction elements are indeed sufficiently strong.

The groyne structure is supported by a soil stratum near the ground surface and therefore the foundation is denominated as shallow. Failure mechanisms of structures on shallow foundations are therefore examined. However, it is important to note that the groyne structures can be supported by vertical, wooden sheet piles to support the (horizontal) stability. This can be applied if in a later design stage more horizontal support is required.

The main failure mechanisms that apply to the shallow founded groyne structure are the exceedance of the critical pressure gradient near the bottom and a collapse of the horizontal stability.

8.3.1. Design parameters

To check whether the constructions can withstand the largest wave forces, failure of the structure during a 1/10, 1/20, 1/50 and 1/100 year storm are checked. The design lifetime of the structure is T = 15 years. Hence, if the structure can withstand a 1/100 year storm (return period R = 100 years), the probability of failure is lower than $p_f = 1 - (1 - \frac{1}{R})^T = 14\%$.

The waves that enter the basin mainly lose their energy before the shoreline of the beach is reached, due to depth-limited breaking and bottom friction (as elaborated in Section 6.3). In other words, the waves are depth-limited. When assuming that the ratio of wave height and still water depth is constant throughout the surf zone, the relation between breaking waves and water depth can be expressed by means of the breaker index:

$$\gamma = \frac{H_b}{h_b} \tag{8.1}$$

with γ the breaker index, H_b the breaking wave height and h_b the water depth at the breaking point. For shallow water, a breaking index of $\gamma \sim 0.88$ can be taken for a first estimate (Bosboom & Stive, 2015). This relation can provide a maximum breaking wave height when the water depth during storms is known, but the significant wave height is the needed design parameter. When assuming a maximum wave height of $H_{max} = 2H_s$ (based on the notion that the waves are Rayleigh distributed, reference is made to Bosboom & Stive (2015)), rewriting the expression and rounding up the outcome gives:

$$\frac{H_s}{h} \sim 0.5 \tag{8.2}$$

Hence, the design wave height is half of the design water depth. In Table 8.1, the maximum water depths with a certain return period are listed. The computations are performed for the most seaward tip of the structure, which is exposed to the largest waves. The bed level at this point is -1 m NAP on average. Hence, for the computations of the water depth, one meter is added to the water level values to obtain the design water depth. The table includes the design wave height $H_{s,d}$ and design peak period $T_{p,d}$ per return period as well. The latter is based on the relation between wave height and wave period, which is formulated in Equation 6.1 and depicted in Figure 6.3.

Storm return period $R[year]$	**1**	**5**	**10**	**20**	**50**	**100**
Water level* $h[m]$	2.8	3.2	3.4	3.55	3.8	4
Water depth $h_d[m]$	3.8	4.2	4.4	4.55	4.8	5
Significant wave height $H_{s,d}[m]$	1.9	2.1	2.2	2.275	2.4	2.5
Peak wave period $T_{p,d}[s]$	6.5	6.9	7.1	7.2	7.4	7.6

Table 8.1: Design parameters for 1/1, 1/5, 1/10, 1/20, 1/50 and 1/100 year conditions at -1 m depth at the tip of the (submerged) groynes. * *Water levels based on the characteristic values at the Brouwershavense Gat 08 station, listed in Appendix A, obtained from (Rijkswaterstaat, 2013)*

8.3.2. Failure mechanism 1: Critical pressure gradient

A structure that is built on loose sediment such as sand needs a filter in order to prevent erosion or drain to prevent pressure build-up. Willow twigs are too open to serve as a filter (their critical gradient parallel to the bottom is about 3-4 %) (Schiereck, 2012), and therefore the filter function under the fascine mattress is performed by a maize geotextile (or a similar bio-degradable geotextile type). A wave that propagates over the structure leads to pressures in the transition between the geotextile (functioning as a fine filter layer) and the coarse top layer (the fascine matresses and the layer of shells). A large pressure gradient at the bottom due to (non-broken) waves (which is depicted in Figure 8.12a) can lead to failure of the geotextile when the critical gradient of the geotextile material is exceeded. The pressure gradient at the bottom, expressed in piezometric gradient in percent, is calculated by means of the following equation:

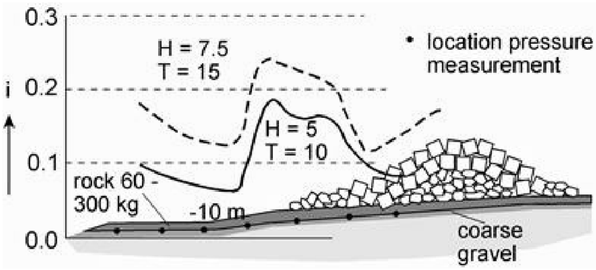
$$i_{max} = \frac{kH}{2cosh(kh)} \tag{8.3}$$

with H = wave height, h = water depth and k = $\frac{2\pi}{L}$ = wave number. This relationship was used to determine the pressures under the *Hoek van Holland* breakwater (near the Port of Rotterdam) and were compared to laboratory model measurements (Schiereck, 2012). This method is based on linear wave theory and is proved to give a reasonable value for preliminary designs (Schiereck, 2012). The maximum pressure gradient is computed for different wave conditions with a certain return period. Table 8.2 gives the outcomes.

Storm return period R [year]	1	5	10	20	50	100
Significant wave height H_{sd} $[m]$	1.9	2.1	2.2	2.275	2.4	2.5
Offshore wave length L_0 $[m]$	66.58	74.31	78.25	81.24	86.27	90.34
Check shallow $\frac{h}{L_0} < 0.05$	0.057	0.057	0.056	0.056	0.056	0.055
Wave length L $[m] = T * \sqrt{(}gh)$	39.9	44.3	46.5	48.2	51.0	53.3
Wave number k [rad/m]	0.16	0.14	0.14	0.13	0.12	0.12
imax [-]	0.13	0.13	0.13	0.13	0.13	0.13
imax [%]	13	13	13	13	13	13

Table 8.2: Calculation of pressure gradient near bottom for wave conditions with a certain return period

These computed gradients are compared to the critical gradient of different filter layers. All wave conditions induce a critical gradient of 13%. What stands out is that the pressure gradients of the wave conditions is equal. This is due to the fact that the significant wave heights with different return periods are quite close to each other. Moreover, as the wave height and wave length increase with increasing water depth, the terms kH and $cosh(kh)$ are more or less equal (as k decreases whereas h and H increase for larger return period). Hence, the difference in pressure that is induced by the different waves is not that large. What can be concluded from this calculation, is that for a preliminary design a geotextile should be applied with a critical gradient larger than 13 %. Maize geotextile, which is recommended by Van Aalsburg BV, has a critical gradient between 30-50 % and therefore suffices (D. Van Aalsburg, personal communication, June 3, 2021). Table 8.12b shows the critical gradients of different types of geotextiles.



(a) Gradient in filter under breakwater. Example for waves with H = 7.5 m and H = 5 m. Obtained from Schiereck (2012)

Nr.	Type of fabric	Critical gradient (%)
1	None (classical fascine mattress)	7
2	Synthetic geotextile (not penetrable for roots)	59
3	Synthetic geotextile (penetrable for roots)	16
4	Reed (classical filter cloth in fascine mattresses)	18
5	Coconut fibre cloth	12
6	Coconut fibre cloth filled with 4 cm of woodpulp	14
7	Jute cloth	26
8	Jute cloth filled with 4 cm of woodpulp	56

(b) Critical gradients for various types of filters (Schiereck, 2012)

Figure 8.12: Pressure gradient due to waves (a) and critical pressure gradient for various types of filters (b)

8.3.3. Failure mechanism 2: Horizontal stability

The groyne structure can fail as a whole when the wave forces are large enough to lift up (a part of) the structure, inducing a downdrift displacement. To test the structure on this failure mechanism, a comparison with a rubble mound structure is made. For breakwaters, there are many relationships relating a certain grain size diameter to a wave condition, in which the grains have sufficient weight to stay in place. For structures with a crest below water level, the following relationship (which is deduced from the equation established by Van der Meer (1991)) can be applied (Schiereck, 2012):

$$\frac{H_s}{\Delta d_{n50}} = -7ln(\frac{1}{2.1 + 0.1S}\frac{h_c}{h})s_{0p}^{1/3} \tag{8.4}$$

with s_{0p} the (deep water) wave steepness, computed with $s_{op} = \frac{2\pi H_s}{gT_p^2}$, h the water depth, h_c the crest height of the structure, and S the accepted damage level. For the latter, a value of 0 means that no damage is accepted, whereas 10 means that the armour layer is locally completely removed (Schiereck, 2012). For wave conditions with a return period up to 20 years, the level of damage is set on 0, as zero damage is accepted for storms with such a high frequency of occurrence. For conditions that occur less than 1/20 years, the damage level is set on 2, which represents the threshold of damage. Table 8.3 gives the calculated nominal stone diameter per wave condition.

Storm return period R [year]	1	5	10	20	50	100
Damage level S $[-]$	0	0	0	2	2	2
Wave steepness $S_{op} = \frac{2\pi H_s}{gT_p^2}[m/m]$	0.025	0.025	0.025	0.024	0.024	0.024
Crest height h_c $[m]$	2	2	2	2	2	2
Relatative density Δ $[-]$	1.65	1.65	1.65	1.65	1.65	1.65
Nominal stone diameter d_{n50} $[m]$	0.41	0.42	0.43	0.41	0.42	0.43

Table 8.3: Calculation of nominal stone diameter for wave conditions with a certain return period

With the necessary stone diameter known, the weight of the structure is calculated and compared to the weight of the rubble mound layer. From Table 8.3, it can be concluded that a nominal stone diameter of d_{n50} = 0.43 m suffices. When a layer of 1.5 times the d_{n50} is applied, the weight per square meter is ca. 1000 kg/m^2 (interpolated from Table G.3, which includes standard stone gradings). The groyne structure is composed of brushwood and shells. The shells provide the largest part of the weight of the structure. Mo et al. (2018) discuss the physical properties of seashells and report a loose bulk density of ca. 1100 kg/m^3 for oyster shells. Consequently, as the construction is filled with a layer of ca. 2 m oyster shells, the weight per square meter is 2200 kg/m^2. Hence, weight of the groyne structure (2200 kg/m^2) exceeds the minimal weight per square meter that is needed (1000 kg/m^2) to prevent horizontal displacement.

8.4. Analysis and selection of integral solutions

In this section, the identified alternatives of the previous section are evaluated by means of a brief MCA. The criteria are functionality, certainty, costs (construction and maintenance), recreational value and ecological value. The criteria result from the Program of Requirements (Chapter 7). The choice for an MCA as decision-making tool and the applied method is discussed in Section 9.7.

In Appendix G, all five designs are discussed, including the design choices, the coastline simulation, expected coastal development and the cost calculation. The future coastline development for each of these alternatives is simulated with the forecast model.
The scores for these criteria are determined based on the model simulations and on literature review on coastal development with certain structures. The construction costs are based on literature as well, but moreover, the costs for the brushwooden structures are based on indicative prices discussed with Van Aalsburg BV. Costs for maintenance nourishments are deduced from the costs of the nourishment that was executed in 2016.
Furthermore, the recreational value per alternative was discussed with the stakeholders during a gathering with the PGB (Projectgroep Brouwersdam) at 4-5-2021. The stakeholders were asked to value each of the solution based on shoreline development and impact on the recreational value. Lastly, the ecological value was assessed based on the ecological system analysis performed in Chapter 4.

Figure 8.13 provides an overview of the MCA. Each alternative is scored per criterion. The score is indicated by a color (green for positive, yellow for neutral and red for negative) to get quicker insight in the score of a criterion. In the most right columns, an explanation is given for the score. The three designs with the highest scores, which are A, C and E, are worked out in more detail in the next chapter. Designs B and D are not considered to be feasible. Note that the periodic nourishing (alternative F) is not taken into account in this MCA, as this soft solution will be compared to the hard solutions in a later stadium of the design process.

8.4.1. Analysis

The solutions are assessed based on their functionality, certainty, construction and maintenance costs, recreational value and ecological value.

Functionality

With respect to functionality, A scores best as this groyne configuration leads to a significant reduction of erosion and the beach reaches a desired equilibrium shape. Alternative B experiences large lee-side erosion and the equilibrium beach shape is not desired, as the beach will be divided into two parts. The erosion reduction with alternatives C, D and E is significant, and the beach shape of alternative C, D and E are similar: The beach is wide (C) or long (D and E). However, the functionality is not ideal as periodic nourishing will be frequently needed.

Certainty

The beach development of behind the groynes of A and C can be predicted with sufficient certainty, because the main goal of the groynes is to interrupt the sediment transport and their lee-side effects (which are hard to simulate and predict) are side effects. The creation of a shadow zone with subsequent lee-side effects is the main goal of alternatives B, D and E, which shoreline development is thus harder to predict. In the case of alternative D, the morphological development of the island itself poses extra uncertainty.

Construction costs

The construction costs of alternative B are below €1,000,000 and are thus the least. Alterntive C and D have costs over €4,000,000 and are therefore the highest. The costs of solution E are in between those values.

Maintenance costs

The maintenance costs of alternative A are the least (< €5,000,000 /30 y), whereas B and D have the highest maintenance costs (> €15,000,000 /30 y). Maintenance costs of solutions C and E are in between with a value around €10,000,000 /30 y.

Recreational value

The recreational value of each of the solutions was discussed with the stakeholders during a gathering with the PGB (Projectgroep Brouwersdam) at 4-5-2021. In that session, scores were given to each of the alternatives. The main thing that became clear was that any structure near the beach causes hinder and possible danger for kite surfers and other extreme water sports. Alternative A is thus considered to be dangerous for kiters, which leaves the beach with only two of the three recreational purposes.
Alternative B was considered to decrease the value of the beach for kiters as well, and in addition: the southern edge of the beach gets closed off and the recreational value of the beach decreases as a whole.
Alternative C creates a large coastline in which swimmers and kiters can enter the beach, but there are two downsides for kite surfers. First of all, the kite surfers cannot enter the beach at the location of the groyne, which minimizes the places to enter the beach (note that kite surfers enter the water in the south and enter the beach in the north, due to the predominant wind direction from the west-southwest). Secondly, the orientation of the coastline is perpendicular to the dominant wind direction (west-southwest), which complicates entering the water for kite surfers. Despite those disadvantages, kite surfing can be done with option C.
Option D and E both pose a structure in the southern part of the beach, which causes little hinder to the recreational activities. However, in the case of option D, the safety near the island cannot be preserved due to the unpredictable development of the island. Therefore D is scored lower than E.

Ecological value

The ecological value of the area is expected to increase with alternatives A and B, as the groynes create a shellfish habitat. This is also the case for option C, D and E, but because these structures are emerged, extra (supralittoral, hard substrate) habitat is created for birds like waders (*steenlopers*).

8.4.2. Selection

The alternatives that are considered to be feasible are alternative A (Pocket beaches), C (Straight groyne) and E (Fishtail groyne). These alternatives score best in the MCA (15, 13 and 14 points respectively), whereas alternative B (C-shaped groyne) and D (Artificial island) score less good (both 10 points). Alternative B has the downsides of a relative small functionality (which induces high maintenance costs) combined with a low recreational value, as it creates a barrier between the southern part of the beach and the sea. Alternative D is not considered to be feasible, mainly because of a large uncertainty in the prediction of the morphological development, combined with high construction and maintenance costs.

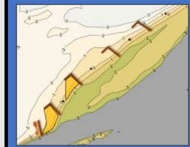
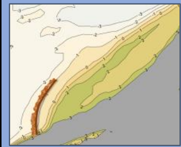
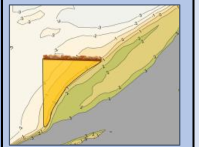
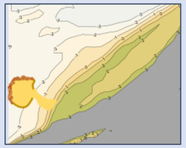
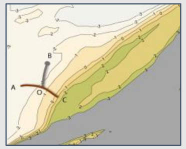
	Criterion score 1	Criterion score 3	A	B	C	D	E	A Pocket 	B C-shaped 	C Straight 	D Island 	E Fishtail 
Functionality	Beach surface area reduces at nearly same pace but in an undesired shape	Beach surface area reduces at a lower pace and reaches a desired equilibrium shape	3	1	2	2	2	Long and wide beach that reaches a desired equilibrium	Beach will be divided into two parts	Wide beach	Long beach	Long beach
Certainty	The uncertainty in the prediction of the morphological development of the beach is high	The uncertainty in the prediction of the morphological development of the beach is low	3	2	3	1	2		Shelter effect in lee-side		Shelter effect in lee-side and morphological evolution of island uncertain	Shelter effect in lee-side
Construction costs	C > € 4,000,000	C < € 1,000,000	3	3	1	1	2	Groyne construction	Groyne construction	Groyne construction and initial nourishment	Large initial nourishment and construction of bank protection	Construction of fishtail groyne (breakwater)
Maintenance costs	C > € 400,000 / year	C < € 100,000 / year	3	1	2	1	2	One nourishment in 30 years, one time replacement of groynes in 30 years	4 nourishments in 30 years, one time replacement of groyne in 30 years	2 nourishments in 30 years, one time replacement of groyne in 30 years	2 nourishments in 30 years, frequent filling of island, maintenance for bank protection and intensive monitoring	2 nourishments in 30 years, one time replacement of groyne in 30 years, maintenance for breakwater
Recreational value	One of the recreational purposes of the beach is lost	All three recreational purposes are preserved (beach sports, water sports and sunbathing)	1	1	2	2	3	Watersports cannot be done	Watersports can hardly be done, value of beach sports and sunbathing decreases severely	Value of watersports slightly decreases	All recreational purposes preserved, buy safety not ensured due to uncertain island development	All recreational purposes preserved
Ecological value	Ecological value of the area is maintained	Ecological value of the area increases significantly (creation of multiple habitats)	2	2	3	3	3	Shellfish habitat	Shellfish habitat	Shellfish habitat and supralittoral hard substrate habitat	Shellfish habitat and supralittoral hard substrate habitat	Shellfish habitat and supralittoral hard substrate habitat
		Sum	15	10	13	10	14					

Figure 8.13: Concise Multi-Criteria Analysis on alternatives A to E

9
Design II: Refinement and evaluation

Resulting from the previous chapter, the best solutions for the preservation of the beach turned out to be pocket beaches (A), a straight groyne with a beach fill (C) and a fishtail groyne (E). In this chapter, these solutions are worked out in more detail (relating to BwN design step 4) and evaluated based on the Program of Requirements (relating to BwN design step 3). This chapter covers Design phase II.

Section 9.1 is divided into three parts (9.1.1 up to 9.1.3), in which solution A, C and E are discussed respectively. These section elaborate on the (summarized) design considerations such as dimensions, orientation and material (of which the full elaboration can be found in Appendix G) and the the expected shoreline development based on model results (the model set-up and more information on the expected shoreline development per solution is given in Appendix G).

Thereafter, the functionality (Section 9.2), costs (Section 9.3), recreational value (Section 9.4), ecological value (Section 9.5) and aesthetic value (Section 9.6) of each of the solutions are discussed. Finally, in Section 9.7, an MCA is performed in which the designs are weighted against each other, based on the requirements of the PoR that are listed in Table 7.1.

9.1. Designs and shoreline development

This section elaborates on the designs of solution A (pocket beaches), C (straight groyne with beach fill) and E (fishtail groyne) and the expected shoreline development for each solution. Note that the reference situation is the situation in which no measures are taken. The shoreline will then most likely develop according to Figure 6.20.

It is important to highlight that the designs discussed in this Section are indicative designs. The dimensions indicate an order of magnitude of the elements of the structures. The dimensions are based on rules of thumb. In other words, this research gives a direction, but further analysis on the feasibility of the structures should be done to determine the optimal dimensions, materials and other design choices.

Another important note is that the shoreline simulations have been carried out up to the year 2030 (12 years of simulation). The simulation is not done for a longer period of time, as the simulation results are not considered as reliable after a certain period of time: one of the underlying assumptions of UNIBEST-CL+ is that the shape of the cross-shore profile is stable and that the relation between the sediment transport rate and coastline orientation is not changing in time. However, when coastal structures intervene in the system, these assumptions are getting less and less valid as shelter effects (and other secondary effects) change the coastal profile more and more. Therefore, the simulation is executed up to 2030 to get insight in the initial shoreline response. This insight is then used to predict the further developments.

9.1.1. Solution A - Pocket beaches

Design

Design A consists of 5 groynes, with a lateral spacing of 200-400 m. The shape of the groynes is an L, of which the long side is 150 m and the shorter side 50 m (see plan view in Figure 9.3). The most southern groyne forms an exception as this groyne has the goal of reducing the current velocities from the south instead of trapping sediment. The crest level of the groynes is at +1 m NAP. This implies that the groyne height ranges from 0.7 (minimum) to 2.5 m (see cross-section B-B in Figure 9.3). For the reasoning behind these design choices, reference is made to Appendix G.1.1. The three southern pocket beaches are initially nourished to reach the equilibrium coastline orientation rapidly.

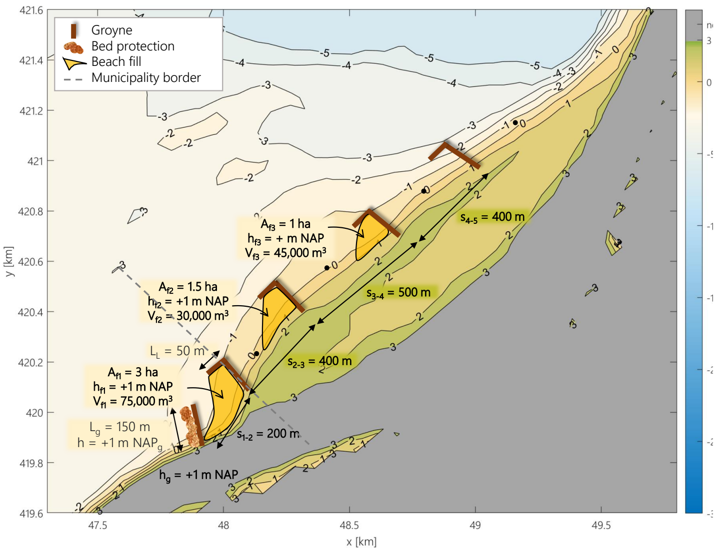


Figure 9.1: Design of solution A: pocket beaches with L-shaped groynes

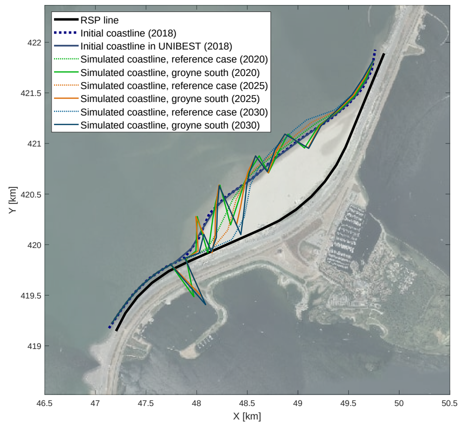
The groynes are made of brushwood (reference is made to Section 8.2.1 for the features of this type of material). To provide benefits to the coastal system (a characteristic of a Nature-based Solution), the construction is filled with oysters. The ecosystem services that an oyster can provide are enhanced coastal protection (by increasing the density of the structure and therefore the dissipation of currents and waves) and an improvement of the water quality (by trapping sediment and filtering nutrients). Appendix D.6 elaborates on the benefits and disadvantages of oysters in a system and discusses the habitat requirements in which oysters can grow and survive. The largest part of these requirements is met near the Brouwersdam, whereas some of the conditions should be made suitable for oyster survival in the groynes. The groyne design with respect to these requirements is as follows (See cross-section A-A in Figure 9.3).

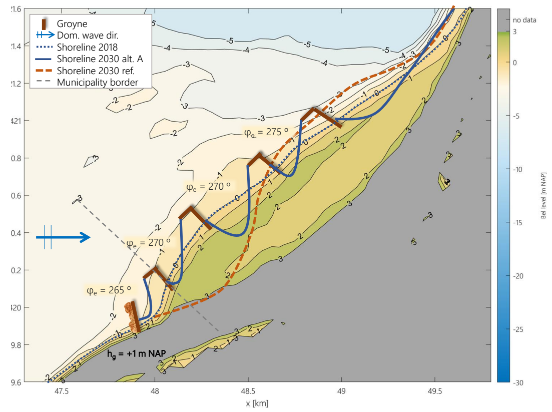
The inundation time of the oysters has to be larger than 50 %, therefore the oysters are placed around and below the mean water line (0 m NAP). The exposure to waves and currents should be low to moderate. Biodegradable, maize geotextile is placed vertically at both sides of the groyne to reduce the horizontal current velocity inside the groyne. Maize geotextile weathers within 5-10 years. After this period, the necessity of replacing it should be investigated. Possibly, the oyster habitat is self-sustaining and geotextile is not needed anymore. The wave exposure (which impacts the oysters vertically during high tide) is reduced by placing cross-wise arranged willow branches on top of the oysters. This is also beneficial for the temperature regulation of the oysters, as this layer overcomes direct sunlight exposure.
With respect to turbidity, SSC (suspended sediment concentration) and sedimentation, the bottom layer of the construction has cross-wise arranged willow branches. Jute or a permeable textile could be supplemented to make the bottom layer more sand-tight.
The substrate on which the oysters grow should be hard, so shells provide a good substrate. The brushwood is hard substrate as well, so oysters could also attach to the structure itself.

Shoreline development

The expected shoreline development up to 2030 with several pocket beaches is depicted in Figure 9.2b. This figure is created partly based on the simulation in UNIBEST. It is not possible to simulate the sheltering effect behind the multiple groyne system with the UNIBEST-CL module. This is due to a different transport pattern - and thus equilibrium coastline orientation - in the cross-shore transect behind the groyne. Appendix G.1.2 elaborates further on this shortcoming. Hence, the simulation of the shoreline development with multiple groynes requires some adaptations to predict the coastline development, which are also explained in Appendix G.1.2.

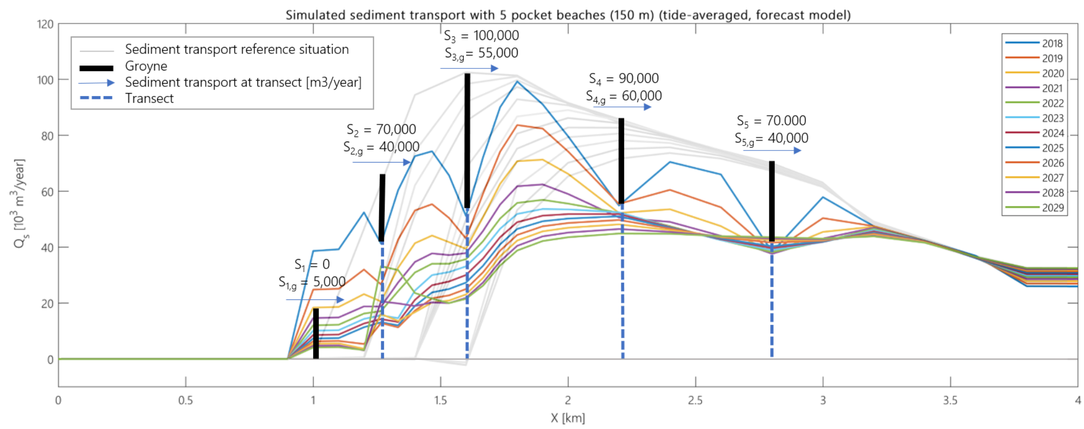
After a period of shoreline development, the coastline changes its orientation towards the equilibrium orientation between the groynes. The sediment transport will thus reduce in time. The sediment balance from 2018 up to 2030 is depicted in Figure 9.2c. Note that after a few years of coastal development, the shoreline reaches the landward tip of the second groyne and erosion proceeds landward of it. In other words, the second groyne loses its function because the most left pocket is 'empty'. The initial beach fill in the south prevents this, as the equilibrium coastline orientation is reached before this can happen. This is elaborated in Section G.1.2.
What further can be seen is that at the northern part of the northern groyne, the transport gradient is nearly 0 after ca. 3 years of development, implying a stable coastline. Hence, periodic nourishments are not needed with this groyne configuration.





a: Simulated shoreline development with 5 pocket beaches (L = 150 m , h = +1 m NAP, shelter effect not taken into account in simulation. Simulated with UNIBEST-CL+ forecast model (2018-2030).

b: Simulated shoreline development up to 2030 with solution A (Simulated with forecast model (2018-2030), blocking = 100 %, groyne length = 150 m). ϕ_e indicates the equilibrium shoreline orientation.



c: Sediment balance of the coastal stretch between 2018-2030 with 5 groynes of 150 m, spaced 200 to 500 m, simulated with UNIBEST-CL+ forecast model without effect of sheltering

Figure 9.2: Shoreline development of solution A - Pocket beaches

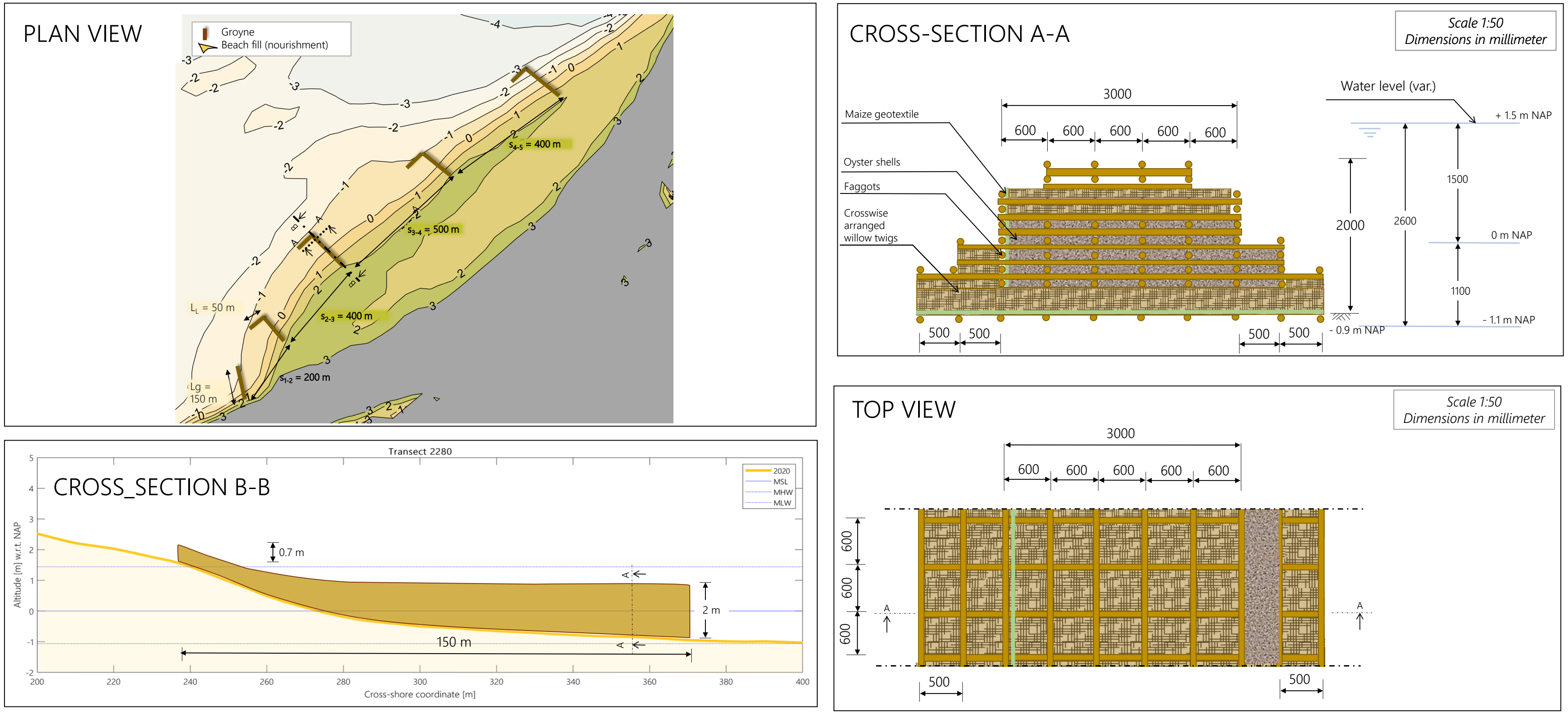


Figure 9.3: Design of solution A - pocket beaches

9.1.2. Solution C - Straight groyne with beach fill

Design

This design contains a groyne structure and a beach fill. The beach fill is a nourishment to increase the bed level up to +1.5 m NAP, so that this part of the beach is above the high water level (+1.44 m NAP). The nourishment configuration should include a design talud of the placed sediment (but for the computation of the nourished volume a horizontal plane is assumed). The groyne of 600 m long has the function of retaining this beach fill. The groyne has a crest height of + 2 m NAP, implying that the groyne reaches a heights of ca. 4 m (which is depicted in cross-section B-B in Figure 9.6).

The construction material and layered configuration with brushwood and oysters is similar to the design of the groynes in design A. However, as the groyne is placed more offshore and thus at larger depths, the width of the groyne is larger for stability reasons (see cross-section A-A in Figure 9.6). Thereby, the geotextile reaches the top of the groyne at the landward side, to prevent sedimentation with sand from the beach into the groyne. The geotextile at the seaward side reaches up to +1 m NAP, to make sure that the oysters are inundated each tidal cycle.

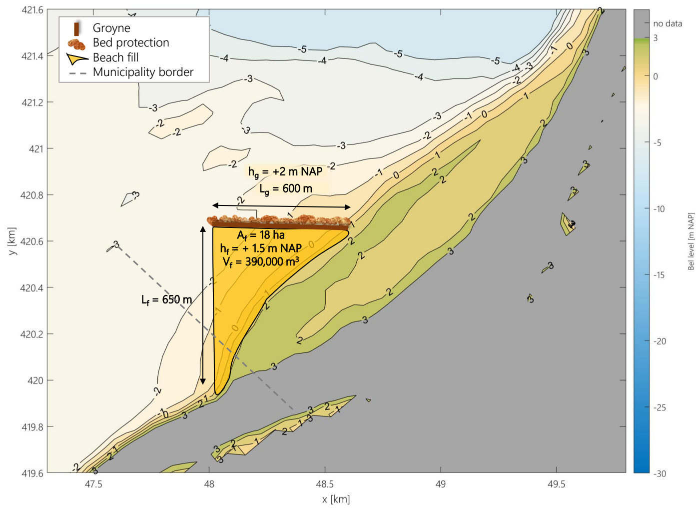
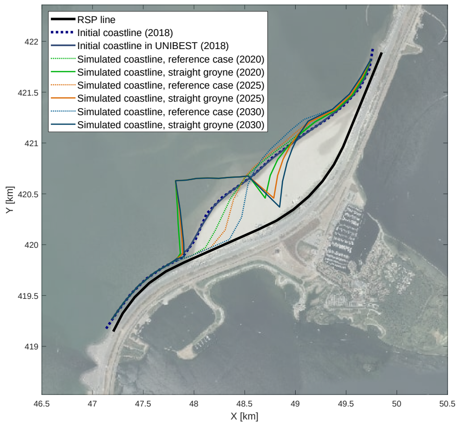


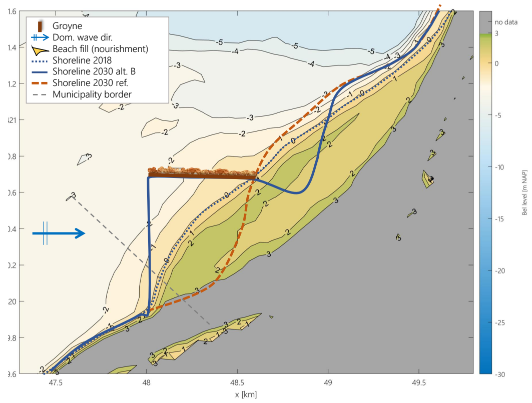
Figure 9.4: Design of solution C: straight groyne with beach fill

Shoreline development

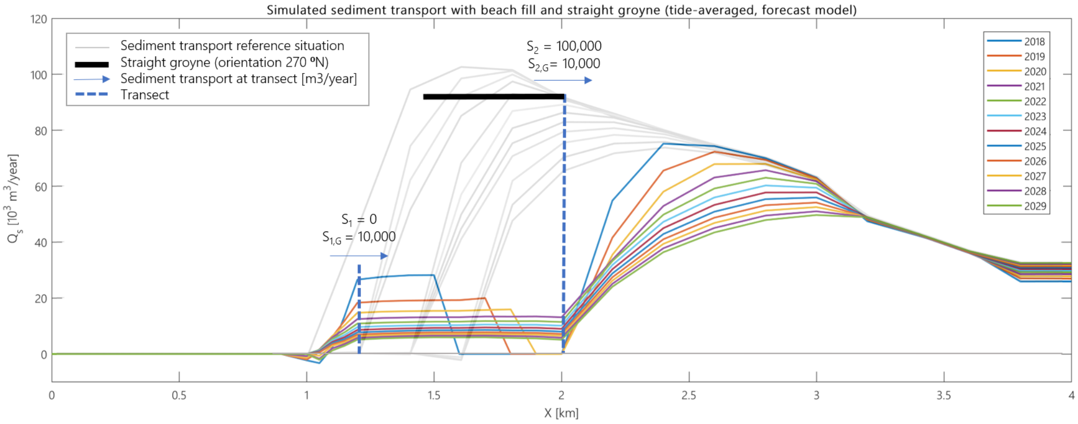
The expected shoreline development up to 2030 is depicted in Figure 11.3b. It can be seen that the straight shoreline between the tip of the groyne and the original coastline is in equilibrium: the shoreline maintains it position. At the downdrift side of the groyne, lee-side erosion occurs. When considering the sediment balance (Figure 9.5c), a positive transport gradient between x = 2 and x = 3 km in the sediment balance is detected (implying erosion). This transport gradient along the beach reduces over time. The mean erosion value at this stretch is ca. 50 $m^3/m/y$ (-50,000 $m^3/year$ over a stretch of 1 km). As shelter effects are not taken into account in UNIBEST, the real value is estimated to be somewhat lower: -35,000 $m^3/year$ is assumed. Thus, less sediment losses have to be compensated compared to the reference situation. Two nourishments of 500,000 m^3 are needed compensate the loss of about 30 years (total loss of $35,000 * 30 = 1,050,000m^3/30years$, which is compensated by $2 * 500,000m^3 * 1,000,000m^3$).



a: Simulated shoreline development with straight groyne (L = 600 m, orientation 270 °N). Simulated with forecast model (2018-2030)



b: Simulated shoreline development up to 2030 with solution C (straight groyne with beach fill) (Simulated with forecast model (2018-2030)), blocking = 100 %, groyne length = 600 m.



c: Sediment balance of the coastal stretch between 2018-2030 with solution C (straight groyne with beach fill), simulated with UNIBEST-CL+ forecast model without effect of sheltering

Figure 9.5: Solution C - Straight groyne with beach fill

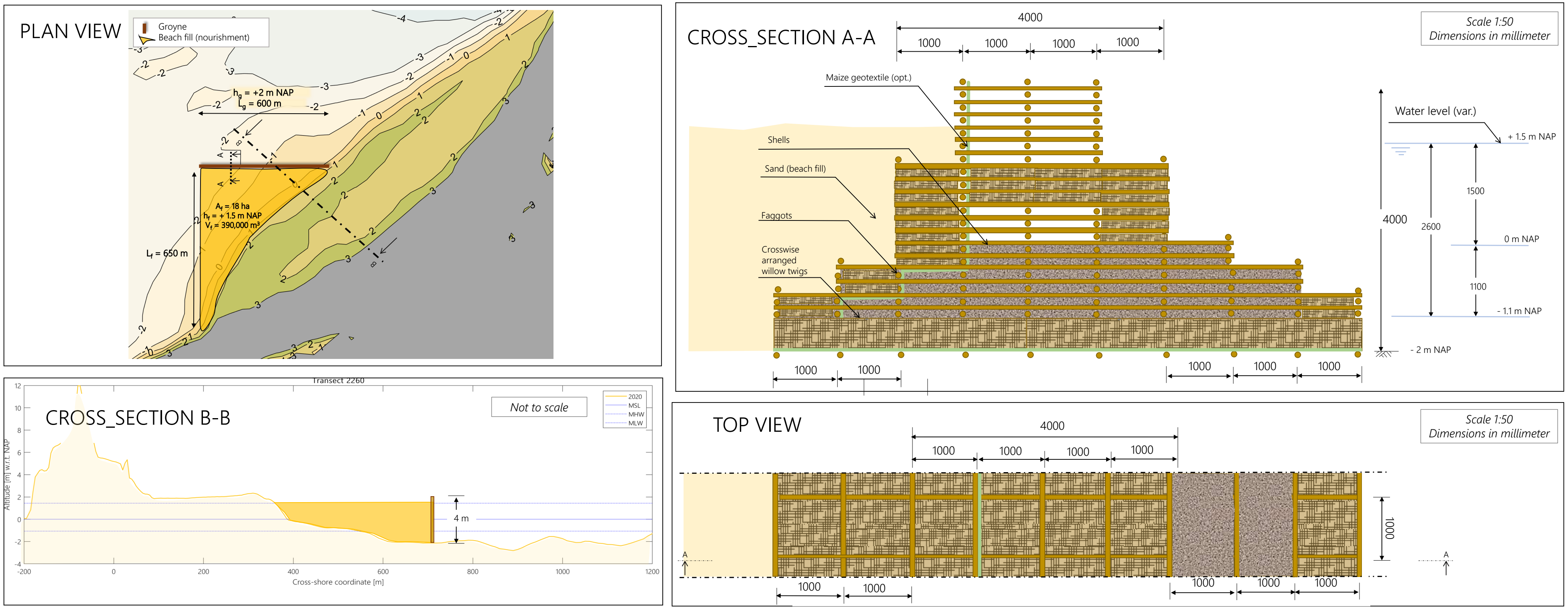


Figure 9.6: Design of solution C

9.1.3. Solution E - Fishtail groyne

Design

The geometry of this construction is such that currents and sediment transport are reduced by the groyne arm (the updrift arm) and waves are dissipated by the breakwater arm (downdrift arm). The latter thus aids in the preservation of the beach in the lee-side of the structure. Appendix G.5 elaborates on the design choices. The arm AC has the function of a groyne, is gently curved and is 300 m long. It extends from +1 m NAP to -2.5 m NAP. The material and construction of the arm are similar to the construction of the groynes in design A (pocket beaches). The crest height is thus +1 m NAP, the width is 3 m (cross-section C-C in Figure 9.9).

Arm OB has the function of a breakwater and has a length of 250 m, perpendicular to the dominant wave direction. The crest level of the breakwater is at +3 m NAP, and the slope is 1:2. The total width of the structure is 22.5 m, of which 2.5 m is a horizontal crest (as depicted in cross-section A-A in Figure 9.9). The breakwater is located on the -2 m NAP depth contour, implying a height of 5 m. The core of the breakwater is made of fascine matresses filled with oyster shells (see Section 9.1.1 for the elaboration on these shells and their position in the structure). Above the mean water line, the structure is porous. The top layer consists of rubble mound for the required stability of the structure.

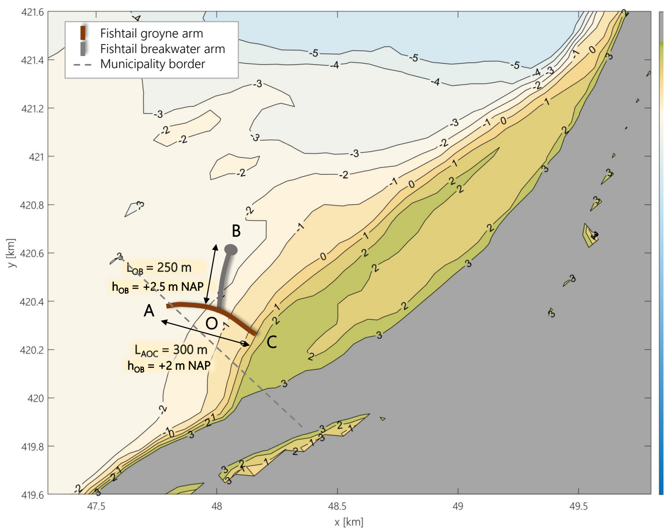
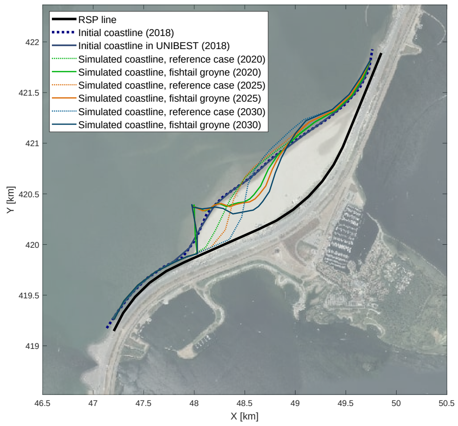


Figure 9.7: Design of solution E: Fishtail groyne

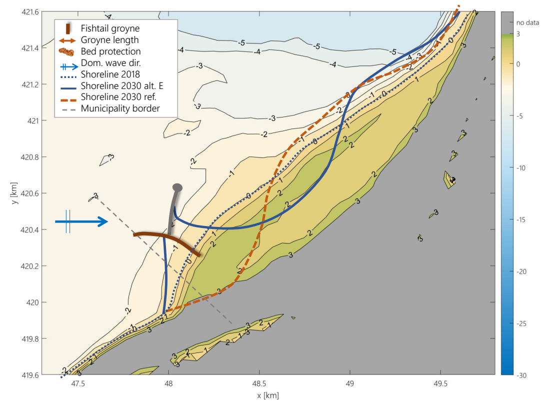
Shoreline development

The expected shoreline development up to 2030 is depicted in Figure 11.3b. It can be seen that the shoreline at the updrift side of the structure is in equilibrium: the shoreline maintains it position. At the downdrift side of the groyne, lee-side erosion occurs. When considering the sediment balance (Figure 9.8c), a positive transport gradient between x = 1.5 and x = 3 km in the sediment balance is detected (implying erosion). This gradient in transport along the beach reduces over time. The mean erosion value at this stretch is similar to the values discussed for solution C. Hence, two nourishments of 500,000 m^3 are needed compensate the loss of about 30 years.

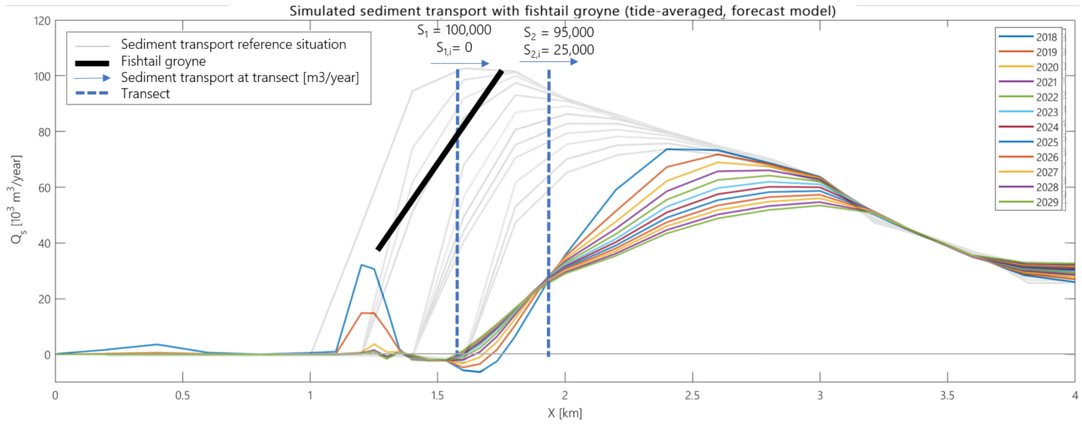
What is interesting about this shoreline development, is that the construction of a shore-parallel breakwater at the northern edge of the beach would result in a parabolic bay, which is a coastline shape that is in equilibrium. Thus, in the case that the tidal inlet is constructed at the northern part of the beach (and a shore-normal breakwater is likely to be built), the coastline will probably reach this parabolic shape. Further elaboration on this coastline form is given in Appendix G.4 and in Lausman et al. (2006).



a: Simulated shoreline development with fishtail groyne (h = +2 m NAP). Simulated with forecast model (2018-2030)



b: Simulated shoreline development up to 2030 with solution E (Simulated with forecast model (2018-2030)).



c: Sediment balance of the coastal stretch between 2018-2030 with a fishtail groyne, simulated with UNIBEST-CL+ forecast model

Figure 9.8: Solution E - Fishtail groyne

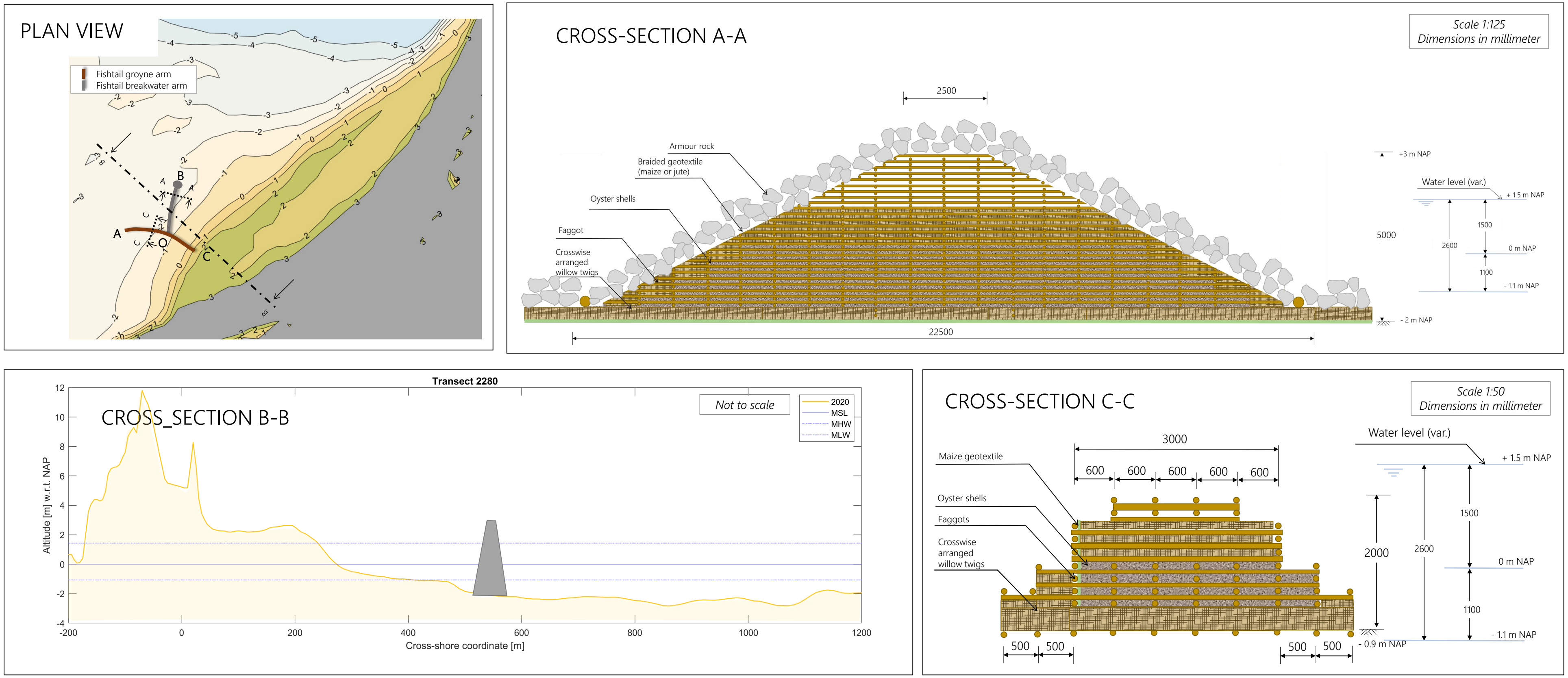
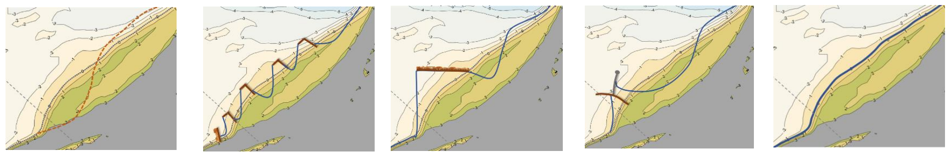


Figure 9.9: Design of solution E

9.2. Functionality

9.2.1. Beach surface area and width

The beach surface area is assessed using the forecast model. The simulated coastline areas in the year 2030 are compared. For solution A, the coastline remains more or less stable up to 2050 without period nourishments, whereas in solutions C and E the beach is being nourished after ca. 10 years of development (so twice in a period of 30 years). Hence, the surface area of the beach in 2030 is expected to stay more or less equal up to 2050, assuming that these periodic nourishments are executed. The surface areas of the entire beach and of the area within the borders of Schouwen-Duiveland are listed in Table 9.1. Note that this table includes the reference situation in the left column, which also depicts the coastline of 2030. This coastline can be seen as a snapshot in time: the coastline will not be maintained at this position in the reference situation, as the erosion is not mitigated or compensated. For the calculation of the surface area of solution F (periodic nourishing), it is assumed that the coastline is maintained at the position of 2018.



	Ref	A	C	E	F
A_{tot} [ha]	57*	74	87	72	74
A_{S-D} [ha]	0	5	4	4	4

Table 9.1: Expected surface area of the beach (0 to +3 m NAP) after 10 years of development, which will be more or less maintained with the periodic nourishment scheme. Note that A_{tot} indicates the surface area of the entire beach, whereas A_{SD} stands for the surface area within Schouwen-Duiveland.
* *The coastline in the reference situation will not be maintained at this position, as the erosion will proceed. Figure 6.20 depicts the coastline up to 2050.*

9.2.2. Adaptivity

The adaptivity with respect to the possible future construction of a tidal inlet in the Brouwersdam is based on the notion that with the inlet, a shore-normal breakwater is built between the inlet and the beach. The possibility of combining the solution with an inlet in the North is assumed to be more important as the chances of that location are higher. Solution C is very suitable in combination with an inlet in the North, as a spiral beach shape will probably occur (with a desired equilibrium, see Appendix G.15). A tidal inlet in the south, at location 3 in Figure C.1 (more than 2 kilometers south of the beach), is not expected to affect the functionality of the solutions.

9.3. Costs

This section elaborates on the costs of each of the solutions. A convenient way of comparing multiple solutions into a common frame of reference is, according to Wetekamp (2011), using a parameter called Net Present Value (NPV). This is a parameter that reflects the actualized value of a future amount of money over a time period t, which can be used in the decision-making process. The concept of NPV covers the idea of the temporal value of money and considers that money that is spent (or earned) at a moment in future has a different value than money spent (or earned) in the present (Wetekamp, 2011). This is due to interest rates and inflation developments. By calculating the NPV, the total amount of money that is spent during the lifetime is counted back to the amount of money that is needed at the start of the project. The equation for calculating the NPV is as follows:

$$NPV = \sum_{N}^{t=0} \frac{CF_t}{(1+r)^t} \tag{9.1}$$

with NPV the Net Present Value in €, CF_t the expected net cash flow at period t in €, t the time period in years, r the discount rate and N the total lifetime of the project in years. Per solution, the NPV is calculated for the total lifetime of N = 30 years. A discount rate of 2 % used in this thesis. This value is based on the by Werkgroep discontovoet (2020) suggested standard discount rate for social cost-benefit analyses.

An example is given to clarify the concept of NPV. If a nourishment of €1,000,000 is executed at t = 0, this means that the present value of the project is - €1,000,000.
However, when the nourishment is executed at t = 10 years, many factors influence the costs. The main factors are interest rate and inflation. When money is not spent, an annual payout is earned (due to interest rates). Hence, spending money at a later moment in time is more beneficial when considering the interest. However, inflation causes the same amount of money to decrease in value over time. For example, when the annual inflation is 4 %, €1000 at t = 0 can buy the same as €1040 at t = 1 year. These aspects, interest rate and inflation, are included in the discount rate.
The discount rates thus incorporate that the moment at which the money is spent has a large impact on the total costs of the project. In other words, maintenance can be relatively more cost-efficient than constructing at t = 0 for a long lifetime if r > 0. Hence, simply calculating the cumulative costs within the lifetime of the project does not give a right implication of the costs (as depicted in Figure H.2). Therefore, the costs are counted back to the money that has to be spent at t = 0: the Net Present Value. The comparison of the NPV's of the solutions enables a more reliable decision-making process.

When taking into account the costs and benefits during the lifetime and recounting these back to the NPV, the most beneficial solution can be easily distinguished (which is the one with the largest NPV). However, in this thesis, only the costs of the project are taken into account in the calculation of the NPV, because the benefits of a solution are very uncertain. As elaborated in Section 5, the recreational activities at the beach are credited to support the local economy by 9 M€/ year and the decrease of the beach surface area negatively affects the financial benefits of the Municipality of Schouwen-Duiveland with 0.8 to 5.4 M€per year. There are two main reasons why these numbers are not used in the calculation of the NPV. First of all, the ranges of these estimates are very large, even larger than the yearly costs of the solutions. Hence, the uncertainty in the NPV would become very large. Secondly, there is no information about the contribution of different sources of income. For example, the contribution of the kite surfing activities to the total benefits is unknown, and therefore the benefits of a solution that decreases kite surfing possibilities are unknown as well. Consequently, the benefits of a solution could not be deduced from the present research. It is thus more convenient to compare the negative NPV's of the solutions. The solution with the least negative NPV is the best option in terms of costs.

The cost estimates are based on the past expenses on nourishments at the beach, indicative cost estimates done by Van Aalsburg B.V. and unity prices that are defined in literature (Appendix G.6 elaborates further on the sources of the cost estimates). These estimates have uncertainties. These uncertainties can relate to the feasibility and durability of the solution (e.g. when the design turns out to be over- or under-dimensioned, which induces less or extra maintenance costs) or the expected costs (e.g. when the costs for the same construction turn out to be higher due to external factors such as fluctuating prices for materials). These uncertainties are taken into account in the calculation of the NPV. In other words, the maximum and minimum NPV is calculated per solution, to incorporate the uncertainties. A distinction is made between three types of uncertainty, namely:

- **Uncertainty in construction costs**. This is mainly due to the expected feasibility and durability of the structure; calculations in further design steps could alter the estimated construction costs. The uncertainty in the cost estimate of the designed structures is considered to be low, because the indicative prices were made by a contractor. A range of 30 % is assumed for the uncertainty in construction costs.
- **Uncertainty in nourishment costs**. This uncertainty is considered to only cover the cost estimation, as the feasibility and durability is deduced from observed data. Therefore, a range of 10 % is assumed for the uncertainty in the nourishment costs.
- **Uncertainty in maintenance costs of the structure**. This type encompasses both uncertainty in the cost estimation (due to uncertainty in unity prices for construction material) and in the feasibility and durability of the structure. Mainly the latter induces large uncertainty, as the structures have not yet been applied in a coastal environment. Hence, a range of 50 % is assumed for the uncertainty in the structure maintenance costs.

Per action (construction, nourishing and performing maintenance activities), the uncertainty of the NPV increases with the associated uncertainty range. This results in a different uncertainty range of the NPV of the solutions. A summary of the main parameters for the computation and the outcome of the NPV is provided in Table 9.10.

Solution	Cumulative costs [M€]	**Net Present Value (NPV) [M€]**	Max Net Present Value (NPV) [M€]	Min Net Present Value (NPV) [M€]	**Absolute uncertainty range [M€]**	Uncertainty range as fraction of NPV
A	-4.7	**-4.3**	-5.8	-2.9	**1.5**	34%
C	-14.5	**-12.0**	-14.4	-9.5	**2.4**	20%
E	-13.8	**-11.2**	-13.4	-8.9	**2.2**	20%
F	-22.0	**-16.9**	-18.6	-15.2	**1.7**	10%

Table 9.2: Net Present Value of solutions A, C, E and F during the total lifetime of the structure (30 years), with inclusion of uncertainty per action. The Net Present Value and the absolute uncertainty are marked bold to highlight the importance of these values. Reference is made to Table G.1, in which the cost calculations are depicted.

The temporal development of the NPV is depicted in Figure 9.10. This figure includes the uncertainty ranges of the total NPV by means of vertical line plots. Note that, in fact, the uncertainty increases with increasing t, which is not depicted in this graph: only the uncertainty of the total NPV is depicted (Figure H.1 shows the temporal decrease of the NPV).

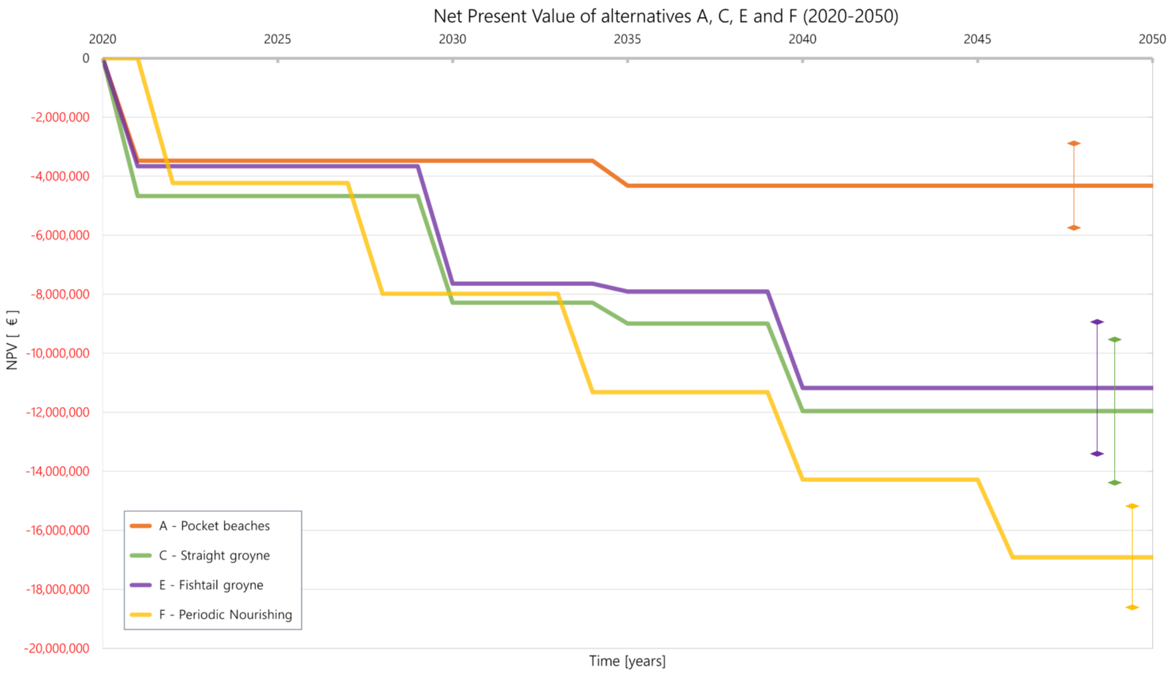


Figure 9.10: Net Present Value of solutions A, C, E and F during the total lifetime of the structure (30 years), with inclusion of uncertainty per action. The vertical line plots mark the uncertainty range of the calculated NPV of the associated solution.

The analysis of the NPV of solutions A, C, E and F results in the following remarks.

- The NPV of solution F (-16,9 M€) is 4 times smaller than solution A (-4.3 M€). The NPV of solutions C and D are in between these. Solution F is thus the most expensive solution, whereas solution A is the cheapest.
- When evaluating the temporal changes in the NPV, the following things stand out. Up to 2027, the NPV of the solutions is more or less equal. Up to 2033, solutions C, E, and F run fairly even

(ca. 8 M€). When looking up to 2050, options C and E become more important, as mainly the NPV of solution F decreases significantly, whereas C and E show a smaller decrease (ca. 11.5 M€).

- The absolute uncertainty ranges of solution A (±1.5 M€) and F (±1.7 M€) are the smallest, and thus the maximum deviation of the estimated NPV is in absolute value smaller than for solutions C and E (±2.4 and ±2.2 M€respectively). However, the ratio between the uncertainty and the total NPV is smallest for solution F (10 %). This is due to the fact that this solution only includes nourishing, which has the smallest uncertainties in the cost estimate. Moreover, a more expensive solution has a smaller uncertainty ratio with a nearly equal absolute uncertainty range.
- The uncertainty ranges in the costs of solutions A and F are quite similar, but have different causes. The uncertainty in the costs of solution A, are mainly due to construction costs, whereas the uncertainty for solution A is caused by the number of nourishments. Hence, this should be taken into account in the decision-making. For example, if in a further design stage the construction costs of solution A are calculated with more certainty, then the uncertainty range of solution A decreases. For periodic nourishing, this uncertainty range is not likely to decrease, as nourishments are paid in the future and the uncertainty due to external factors will not decrease in further design stages. The same reasoning can be applied to solutions C and E, which both contain uncertainty in construction, maintenance and nourishing costs.

A few conclusions are drawn on the best solution with respect to costs. When there is in the decision-making process aimed for a short time solution (ca. 7 years), periodic nourishing is advised, because the short-term costs are nearly equal to solutions A, C and E and the uncertainty range is much smaller. When the benefits of the beach are credited such that the aim is to preserve the beach for a longer term (ca. 30 years), constructing is a better option than nourishing. Solution A is the cheapest. Solutions C and E have more or less equal costs. As constructing on the beach affects the recreational value (and thus the benefits) of the beach, an investigation on the relative benefits of several types of recreation is advised. When these insights are obtained, a full cost-benefit analysis can determine the most cost-effective solution.

9.4. Recreational value

Whether the recreational value of the area increases or decreases with a certain measure is assessed in this section.

9.4.1. Water recreation

Water depth

Even though scour protection is applied near the groynes, the structures will induce gradients in the bed level. The updrift side of the groynes will accrete, whereas the downdrift side erodes. Solution A (Pocket beaches) will induce local water depth differences near the tip and over the length of the groyne. The groynes are submerged and therefore pose obstructions below the water level for the surfers, over the whole stretch of the beach. In case of the straight groyne (C), the water depth gradient at the tip of the structure will be significant, just as at the seaward side of the groyne. The fishtail groyne (E) will induce gradients in the water depth, but only at the southern side of the beach (hence, the influence is locally).

Accessibility

The accessibility of the structures is discussed with the stakeholders during a gathering with the PGB (Projectgroep Brouwersdam) at 4-5-2021. In that session, scores were given to each of the solutions. The accessibility was one of the main points of attention, next to safety. With solution A, the accessibility for surfers decreases a lot, as the groynes minimize the locations in which the water can be entered by surfers, especially with their (widespread) gear.
Solution C (straight groyne) creates a longer shoreline, but 600 m of this shoreline is not accessible. For sunbathing tourists, the new shoreline (orientated west), suffices. However, surfers cannot easily enter the water at this orientation, as the beach is orientated to the dominant wind direction. Hence, the recreational value for surfers with respect to accessibility of solution C is also deteriorated.
Soltuion E (fishtail groyne) hinders accessing the water in the southern part for surfers, but the rest

of the beach provides sufficient space for extreme water sports to be carried out. So, the sunbathing and extreme sports area as depicted in Figure 5.4 could be exchanged in the case of solution E (i.e. the southern part could become the sunbathing area instead of the northern part).

Safety
The presence of the structures could result in dangerous situations, mainly for extreme water sports. The groynes of solution A (pocket beaches) pose many obstructions which the surfers can hit when loosing control. Unsafe situations are likely to occur when extreme water sports are executed in case of solution A: this solution thus means that these sports can no longer be carried out safely near the beach. For sunbathing, the groynes possibly cause unsafe situations to occur as well, as the groynes are easy to access when strolling and swimming.
Solution C (straight groyne) poses the chance of unsafe situations for extreme water sports and sunbathing tourists as well, as the straight groyne blocks a large part of the shoreline with a hard structure. Solution E (fishtail groyne) poses a structure that is located at the southern edge of the beach and is therefore considered to pose less safety issues.

9.4.2. Beach recreation

Substratum type
Solution A (pocket beaches) creates a lot of hard substratum at the beach. Hence, this will impact the recreation negatively. Solutions C (straight groyne) and E (fishtail groyne) also create hard substratum, but to a lesser extent and not as centered on the beach as is the case with solution A.

Sediment size at the beach
A nourishment is considered to have a median grain size diameter that somewhat larger than the current grain size, which is beneficial for the recreational purpose of the beach.

Turbidity
For the assessment of the turbidity, reference is made to Section 9.5.

Safety
With respect to safety, the maximum current velocity and the presence of structures at certain locations are assessed. Note that for all solutions safety measures are required, such as flags that indicate the locations of (temporarily submerged) groynes, buoys in the water that indicate swimming zones or the presence of a lifeguard. Designing these safety measures is part of further design steps and is not further elaborated.

It is known that structures can increase local current velocities (CIRIA et al., 2007). This depends, among others, on the height (compared to the water level), slope and permeability of the structure. A quantitative analysis of the flow velocities near the structures is outside the scope of this research, and hence only the amount of possible locations where the flow velocity could be enhanced are assessed. In case of solution A and C (pocket beaches and straight groyne, respectively), the flow velocity near the groynes are pretty close to the beach and are, even more important, widespread over the beach. In case of solution E (fishtail groyne), local flow velocities can be enhanced as well, but the higher velocities are only occurring in the southern part of the beach (near the structure).

9.5. Ecological value

Substratum type
The creation of hard substratum is evaluated based on the habitat that the substratum may create. If the hard substratum is submerged during a part of the tidal cycle, it is considered to create mainly habitat for benthos. However, if also hard substratum is created above the mean high water level, then this also creates habitat for birds.

Turbidity
The sea water turbidity depends on the combinations of hydrodynamic processes. Engineering structures intervene and alter the hydrodynamics and are therefore a large determinant of turbidity. However, turbidity is hard to model in coastal systems. Therefore, the approach of Heath et al. (2017) approaches the induced the relation between turbidity and the seabed depth, mud content, time-dependent

bed shear stress and sediment erodibility.
As can be seen in Figure D.3, the silt content near the beach is very small ($D_{10} > 125\mu m$). Heath et al. (2017) assume that the water column turbidity is mainly to to suspended fine-grained material (mud and silt, $D < 63\mu m$). The amount of fine-grained material is not increased by the solutions. Hence, the turbidity of the water is not expected to increase due to the measures, even though local wave impact and flow velocities are enhanced. Thereby, if the oyster habitats within the structures survive, sediment is being trapped and the water is being filtered.

Bed shear stress
The presence of hard structures induces local high flow velocities due to its flow retaining feature and higher orbital velocities due to centered wave energy near the structure. High bed shear stresses are assumed to occur near the structures of all solutions. Hence, the total length of the structure near which local high flow velocities are expected is considered to be normative. For solution A (pocket beaches), that is 900 m groyne length, for solution C (straight groyne) that is 600 m and for solution E, that is 500 m. Hence, all structures negatively impact the ecology with respect to bed shear stress.

Rest
The amount of rest in the area is assessed based on the frequency of construction activities in the area as the presence of vessels and construction works disturbs the ecosystem. Hence, the ratings of the solutions are based on the amount of construction activities in a period of 30 years. Therefore, periodic nourishing (solution F), has the least score.

9.6. Aesthetics

View over the North Sea
Solution A contains structures that obstruct the view when standing at the sublittoral part of the beach during low tide (at high tide, the structures are submerged). Therefore, A is scored medium. The breakwater arm of the fishtail of solution E blocks the view (from the southern part of the beach towards the North Sea) during the full tidal cycle, and is therefore scored lowest. Solutions C and F do not obstruct the view.

Structures on the beach
The amount of structures on the beach is assessed partly quantitatively: solution A has the most structures. Solution C and E contain structures at a smaller area of the beach.

Shape of the shoreline
Solution A and C induce the shape of the shoreline to contain (artificial appearing) sharp angles and straight coastline instead of a (desired, natural appearing) gradual curvature. Solution E creates some artificial appearance in the southern part of the shoreline, but the middle and northern stretch show a gradual shape. Periodic nourishing (F) creates a gradually curved shoreline.

Innovation
The level of innovation is assessed by looking at the construction material and configuration of the structure or structures. The brushwood groynes filled with shells to provide habitat for several species is considered to be innovative. However, the configuration of solutions A and C is quite conventional. The application of a fishtail shaped groyne (solution E) is not completely conventional, but the construction of a rubble mound groyne is. Therefore, solutions A, C and E are scored with a medium value.

9.7. Multi Criteria Analysis
As the decision-making process of the beach consists of multiple conflicting economic, environmental, societal, technical, and aesthetic criteria, the consideration of different solutions is a multiple criteria decision-making (MCDM) problem (Belton & Steward, 2002). A common multi-criteria decision-making method to help decision makers is the Multi-Criteria Analysis (MCA) (Belton & Steward, 2002). This method aims at determining the general preference among different solutions. Each solution that is examined is assessed based on its performance in relation to a number of decision criteria. Belton & Steward (2002) highlight that an MCA is an aid to decision-making, which does not give the 'right'

answer, nor does it provide an objective analysis. In fact, it manages and makes explicit subjectivity. The MCA process helps to structure the problem. Moreover, Belton & Steward (2002) state that the principal benefit of an MCA is to facilitate the decision makers' learning and understanding of the problem.

As the decision-making process on the preservation of the beach deals with many stakeholders with partly conflicting interests, a Multi-Criteria Analysis (MCA) on solutions A, C, E and F is performed in this chapter.

Choice of MCA method

There are many methods to perform an MCA. Velasquez & Hester (2013) analyze several common methods. In this review, it is stated that a convenient method applied in environmental and construction problems is the SMART (Simple Multi-Attribute Rating Theory) method, which has the main advantage of being simple and easy to execute. This method is particularly useful in a situation in which much information is available and access to decision-makers is easy to obtain. Hence, as this both applies to the problem of the preservation of the beach, this method is used in this thesis for the performance of the MCA. For further elaboration on this and other MCA methods, reference is made to the extensive amount of studies on MCAs in decision-making (e.g. the research of Gamper & Turcanu (2007), which elaborates on the governmental use of Multi-Criteria Analyses).

Steps

In the SMART method, an overall value of a given solution is calculated as the sum of the performance score of each criterion multiplied with the weight of that criterion. The steps that are taken in the application of this method are explained while referring to Table 9.4, which includes the outcome of the MCA. The first steps of the MCA include the identification of the purpose of the decision (Chapter 1), the decision-makers (Chapter 5) and the different solutions (Chapter 8 and 9). Then, the criteria are identified, which are summarized in the Program of Requirements, listed in Chapter 7. The criteria are grouped into different categories (functionality, costs, recreational value for water and beach sports, ecological value and aesthetics). Next, the weight of each of the criteria is determined (on a scale of 1 to 100) that reflects its relative importance. Within a category, the summed weight of the criteria represents the weight of the category (e.g. the category functionality has a weight of 30/100). Then, scores are assigned for each criterion. In Table 9.4, the scores are visualized by a color scale (green and red implying the highest and lowest score, respectively). A score can be a 1, 2 or 3. A score of 1 indicates that the solution does not (sufficiently) comply with the requirement, whereas a 3 indicates that the solution complies with the requirement more than well (note that the score for costs deviate from these rounded values: the cheapest solution is given a 3, the most expensive solution is given a 1, and the other solutions have a weighted score based on these extremes.). The sixth and seventh column of the table include per criterion what the scores imply, and the reasoning behind a given score is mentioned in the column of the associated solution (A - D, the four columns on the right). Lastly, before the MCA results can be used in the decision-making, the weighted average of the values assigned to each solution is calculated. This is done for each solution per category (indicated in the light gray-shaded rows) and for the total score (indicated in the darker gray-shaded bottom row).

Interpretation of the results

The weighted average of each solution is shown in the bottom row of the table. Based on these numbers, one could conclude that the solutions are similarly feasible (because the scores are 2.2, 1.9, 2.0 and 2.0 for solutions A, C, E and F respectively). However, that conclusion is drawn, based on the currently assigned weighting factors. These weighting factors can be altered, based on priority. Hence, a conclusion based on the total score of the solutions can only be drawn in cases with a general consensus among the stakeholders about the relative importance of the criteria and the assigned weights to each category. The assessment of the priorities of each of the stakeholders and the translation of these into weighing factors is not within the scope of this thesis. Therefore, a general consensus could not be deduced from the present research. The assigned weight factors as listed in Table 9.4 are thus arguable, as they are influenced by a select group of stakeholders and a certain level of subjectivity of the writer (this is further elaborated in Chapter 10).

Hence, in negotiations as part of the decision-making process, the results of the MCA illustrate that the conclusion on the solution depends on the priority of the stakeholders. The results of the MCA should thus be interpreted based on the scores of each solution per category. In this way, the MCA can be used by decision-makers as a tool with which the trade-off between the advantages and disadvantages of different solutions is clarified. The decision-makers can alter the weighing factors of the criteria (and hence, the categories), preferably based on a balanced average of the stakeholders' priorities.

Table 9.3 provides an overview of the scores of the solutions per category. This table provides insight in the above mentioned trade-off: if, for example, a low cost solution is the priority, then solution A scores much higher than solution F. But if a high ecological value is considered to be most important, this is vice-versa.

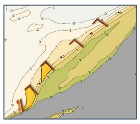
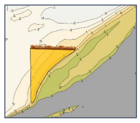
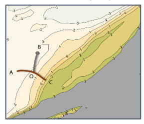
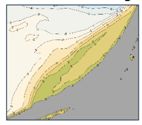
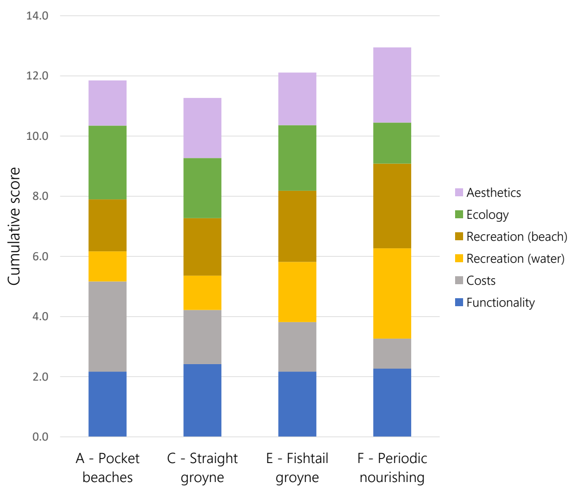
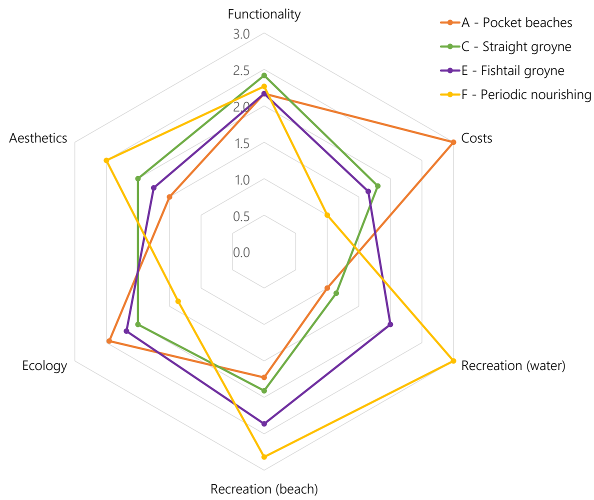
	A - Pocket beaches 	C - Straight groyne 	E - Fishtail groyne 	F - Periodic nourishing 
Functionality	2.2	2.4	2.2	2.3
Costs	3.0	1.8	1.7	1.0
Recreation (water)	1.0	1.1	2.0	3.0
Recreation (beach)	1.7	1.9	2.4	2.8
Ecology	2.5	2.0	2.2	1.4
Aesthetics	1.5	1.8	1.8	2.5

Table 9.3: Results of the MCA summarized per category. Scores range from 1 to 3, of which a 3 indicates that the solution complies more than well with the requirements and is thus preferred, whereas a 1 indicates that the solution does not (sufficiently) complies with the requirements.

The bar chart of Figure 9.11a clarifies the above reasoning: the MCA results in a similar total score for the four different solutions, but the relative scores per category vary from one solution to another. Another way of depicting these differences is by representing the solutions in a spider diagram (which is depicted in Figure 9.11b. From the shapes that represent the solutions, it can be deduced that solution E scores medium on all categories (its shape is nearly a regular hexagon). By contrast, the shape representing solution F nearly takes the form of a rectangle: the scores on costs and ecology are low, whereas the scores for other categories are significantly higher.



(a) Bar chart representing solutions A, C, E and F and the total value of the summed scores



(b) Spider diagram representing solutions A, C, E and F and their scores on the different categories.

Figure 9.11: Representation of the results of the MCA in a bar chart (a.) and a spider diagram (b.)

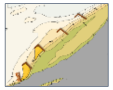
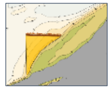
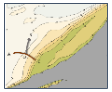
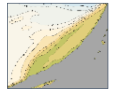
	Nr.	Requirement	Criterion	Weight [/100]	Score = 1	Score = 3	A	C	E	F	A - Pocket beaches 	C - Straight groyne 	E - Fishtail groyne 	F - Periodic nourishing 
Functionality	1	Total beach surface area	> 70 ha	7.5	Area is less than 70 ha	Area is is more than 80 ha	2	3	2	2	74 ha	87 ha	72 ha	74 ha
	2	Beach surface area in S-D	> 4 ha	7.5	Area is less than 4 ha	Area is more than 8 ha	2	2	2	2	5 ha	4 ha	4 ha	4 ha
	3	Minimum beach width	> 200 m	3	Min. width is smaller than 200 m	Min. widht is larger than 400 m	2	2	2	3	Min width is ca. 300 m	Min width is ca. 200 m	Min width is ca. 200 m	Min width is ca. 500 m
	4	Combi inlet North	Possible	5	Solution is not feasible in combination with an inlet in the North	Feasibility increases in combination with an inlet in the North	2	2	3	2	No impact on efficiency of solution	No impact on efficiency of solution	Inlet in the North (with a shore-normal breakwater) would make the beach a spiral beach; the beach would reach a desired equiliubrium	No impact on efficiency of solution
	5	Combi inlet South	Possible	1	Solution is not feasible in combination with an inlet in the South	Feasibility increases in combination with an inlet in the South	2	2	2	2	No impact on efficiency of solution	No impact on efficiency of solution	No impact on efficiency of solution	No impact on efficiency of solution
	6	Combi nourishment	Possible	1	Nourishing is not possible in combination with solution	Nourishing is possible in combination with solution	2	2	2	2				
	7	Certainty		5	Efficiency of solution is uncertain; shoreline development is hard to predict	Efficiency of solution is almost certain	3	3	2	3	Efficiency based on blocking sediment transport	Efficiency based on blocking sediment transport	Efficiency based on (1) blocking sediment transport and on (2) shelter effect in lee-side, which is harder to predict	Efficiency is proven at this site
			Sum	30			2.2	2.4	2.2	2.3				
Costs	8 9	Construction costs Maintenance costs		30	NPV (2050) > - € 5,000,000	NPV (2050) < - € 10,000,000	3	1.8	1.65	1	€ -4,300,000	€ -12,000,000	€ -11,200,000	€ -16,900,000
			Sum	30			3.0	1.8	1.7	1.0				
Recreational value (water)	10	Water depth	No large gradients	2	Solution induces large gradients in the water depht	Solution has no impact on water depth near the beach	1	2	2	3	Differences in water depth near groynes is large, groynes submerged during high water	Large gradient in water depth at tip of groyne and on seaward side of groyne	Gradients in water depth near the structure, but most part of the area will not be affected w.r.t. the water depth	N/a
	11	Accessibility	Sea accessible from beach	6	Shoreline is blocked by a structure	Shoreline is not blocked	1	1	2	3	Multiple groynes prevent the water to be accessible at several places (especially with surfing gear)	Groyne prevents water from being accessible for 600 m)	Fishtail prevents entering the water in a part of the southern stretch, but northern stretch is fully accessible	No structure on beach
	12	Safety (structures)	Investigation per location	6	Presence of sructure(s) can lead to unsafe situations for surfing and sunbathing	Presence of structure(s) causes no unsafe situation for any recreational activity	1	1	2	3	Surfers can hit the groyne when loosing control (high chance of unsafe situation), groynes are easily accessible for sunbathing tourists and are widespread over the beach	Surfers can hit the groyne when loosing control (high chance of unsafe situation), groynes are easily accessible for sunbathing tourists	Surfers can hit the groyne when loosing control	N/a
			Sum	14			1.0	1.1	2.0	3.0				
Recreational value (beach)	13	Substratum type	As soft as possible	2	Hard substratum on the beach	No hard substratum on the beach	1	2	2	3	Groynes on beach	Groyne near beach	Groyne and breakwater near beach	No structure on beach
	14	Sediment size at beach	>= 210 μm	2	Very small sediment size (e.g. < 200 μm)	Sediment size gets coarser (e.g. > 210 μm)	3	3	3	3	Nourished sediment is coarse	Nourished sediment is coarse	Nourished sediment is coarse	Nourished sediment is coarse
	15	Turbidity	Minimal disturbance	2	Turbidity increases (locally)	Turbidity decreases (locally)	3	3	3	2	No increase in fine grained material, oysters filter the water	No increase in fine grained material, oysters filter the water	No increase in fine grained material, oysters filter the water	No changes
	16	Safety (current velocity)	< 0.7 m/s	5	Possible occurence of max. current velocities of > 0.7 m/s	No enhancement of the current velocity anywhere	1	1	2	3	Possibly high velocities near the groynes	Possibly high velocities near the groynes	Possibly high velocities near the groyne, but only in southern part	N/a
			Sum	11			1.7	1.9	2.4	2.8				
Ecological value	17	Substratum type	Hard substratum is desired	2	Solution creates hard substratum for both birds and benthos	Solution creates no hard substratum	2	2	3	1	Hard substratum created, mainly for benthos (submerged)	Hard substratum created, mainly for benthos (submerged)	Hard substratum created for benthos (submerged) and for birds (emerged)	No hard substratum created
	18	Turbidity	Minimal distrurbance	2	Turbidity increases (locally)	Turbidity decreases (locally)	3	3	3	2	No increase in fine grained material, oysters filter the water	No increase in fine grained material, oysters filter the water	No increase in fine grained material, oysters filter the water	No changes
	19	Bed shear stress	Minimal changes	2	Bed shear stress increases (locally)	Bed shear stress decreases (locally)	1	1	1	2	Local high shear stresses near groynes	Local high shear stresses near groyne	Local high shear stresses near fishtail groyne	No changes
	20	Rest	Minimal disturbance	5	Construction activities more frequent than once in 7 years	Construction activities les frequent than once in 15 years	3	2	2	1	After construction, only maintenance on groynes is done (1/15 years)	After construction, 2 nourishments in 30 years and maintenance on groyne (1/15 years)	After construction, 2 nourishments in 30 years and maintenance on groyne (1/15 years)	Every 6 years a beach nourishment has to be executed
			Sum	11			2.5	2.0	2.2	1.4				
Aesthetics	21	View over North Sea	Minimal obstruction	1	Obstruction of the view over the North Sea	No possible obstruction of the view over the North Sea	2	3	1	3	View is obstructed at low tide	View not obstructed	View is obstructed during high and low tide	View not obstructed
	22	Structures on the beach	Minimal obstruction	1	Many constructions on the beach	No constructions on the beach	1	2	2	3	Five structures along the coastal stretch	One large structure along the shoreline	One structure located at the southern part of the beach	No structures on the beach
	23	Shoreline shape	Smooth, natural appearance	1	Shoreline has an artificial appearance	Shoreline has a natural appearance	1	1	2	3	Sawtooth pattern of shoreline	Straight shoreline	Artificial shoreline around the fishtail, but a gradual curvature in the middle and northern part of the shoreline	Gradual curvature of the shoreline
	24	Innovation	Innovative design and appearance	1	Solution is not conventional	Solution is very innovative	2	2	2	1	Partly innovative (groyne structure) and partly conventional (multiple L-shaped groynes, nearly perpendicular to the shoreline)	Partly innovative (groyne structure) and partly conventional (straight groyne configuration with beach fill)	Partly innovative (groyne structure and fishtail shape) and partly conventional (rubble mound at breakwater arm)	Conventional solution
			Sum	4			1.5	2.0	1.8	2.5				
Total				100			2.2	1.9	2.0	2.0				

Table 9.4: Multi-Criteria Analysis (MCA) on solutions A, C, E and F. Criteria are divided into categories, listed in the most left column.

10
Discussion

This chapter contains a discussion on the methods and results of the research and the associated implications for the main conclusions.

10.1. Data analysis and modelling study

First of all, the assumption of a constant beach profile shape in the 1D UNIBEST-CL+ shoreline model poses an implication for the conclusions based on the simulations. This assumption induces an overestimation of the net yearly longshore sediment transport rates at eroding parts. This is caused by the fact that cross-shore transports are not taken into account: the yearly shoreline retreat that is simulated is assumed only to be caused by gradients in the longshore transport, whereas in real life sediment is also transported towards higher parts of beach and the dunes (i.e. gradients in the cross-shore transports). Hence, in real life, this cross-shore redistributed sediment is not lost from the system, whereas the model simulates as if it is. Consequently, the sediment balance of the model shows overestimated values of the longshore transport rates. These graphs should thus be interpreted with caution when concluding on (future) sediment transport rates. However, the model provides thorough insight in the longshore transport gradients, wave-induced longshore sediment transports and shoreline developments. These results are sufficiently accurate and the model thus serves as a tool that can be used for further research on the beach.

Secondly, for the prediction of the shoreline development with the UNIBEST-CL+ forecast model, assumed is that the nearshore hydrodynamic conditions (tidal signal an wave climate) stay more or less equal in the next 30 years. However, the Grevelingen outer delta undergoes large-scale morphodynamic developments as a result of damming of the estuary. As the sediment transport is mainly wave-driven along the beach, predominantly a change in the wave climate can induce significant changes in the shoreline development. Hence, the assumption of a stationary wave climate may decrease the quality of the forecast the model results. To what extent the wave climate will change in the future depends mainly on the development of the shore-parallel bar the Bollen van de Ooster. The wave analysis of Section 6.3 has shown that this shoal is responsible for the dissipation of 30 to 60 % of wave energy of north-westerly waves (during high and low water respectively). The influence of this shoal on the wave climate near the beach is thus significant and something to consider.
In Section 6.8, two scenarios are distinguished to analyse the implications of the above described assumption for the beach development forecast. That is, the scenario in which this bar breaches or does not breach within in the period up to 2050. This analysis concludes that in the case of no breach, the changes in the wave climate will not be significantly large to affect the quality of the model prediction. In other words, the morphological changes of the bar in case of no breach are part of the intrinsic uncertainty in numerical modelling due to spatial and temporal changes of the environment. However, in the case of a breach, it is hard to predict how large the changes will be. On the one hand, the wave angle of incidence will be reduced, which reduces gradients in longshore transport and erosion of the southern part of the beach. On the other hand, the larger impact of (storm) waves on the beach results in a larger offshore transport in cross-shore direction, which is likely to enhance the erosion. Therefore,

in this scenario, the UNIBEST-CL+ forecast model may overestimate or underestimate the erosion and displacement of the beach, based on the relative contribution of the two above described mechanisms. Section 6.8 elaborates on the chance of breaching in the period up to 2050. The findings of van der Spek & Elias (2021) state that breaching of the bar is preceded by a trend of decreasing height, which is not the case for the Bollen van de Ooster. Hence, a breach in the coming few years (e.g. a decade) is not expected. An examination with a larger temporal horizon is not within the scope of this thesis. Therefore, to be able to simulate the future developments of the beach, it is assumed that the bar is not breaching in the period up to 2050. To be able to underpin these speculations with larger certainty, an investigation should be carried out to determine the exact effect of a bar breach on the nearshore wave climate.

10.2. Ecosystem analysis

The research on possible ecosystem enhancement takes mainly primary effects of habitat creation into account. For example, the secondary effects of oyster growth are not examined. According to Smaal et al. (2008), the forming of oyster reefs can induce structural changes in the ecosystem, e.g. the make up of the reef by an invasive species or a shift in the benthic population. However, in the design process of this thesis, the designs are dimensioned for optimal coastal protection rather than for optimal oyster growth in the ecosystem of the outer delta. The ratings on ecological value in the MCA are based on primary effects. Possibly, when secondary effects would have been taken into account, the ratings for ecological value would differ. This implies that the outcome of the MCA may differ from the current outcome. For the conclusion of this research this implies that the score for the ecological value should be considered as reasonable estimate, but that the secondary effects for the ecosystem should be assessed before a final decision is made.

10.3. Social system analysis

The focus of this thesis is on the stakeholders that are already engaged with the topic. In other words, the stakeholders were analysed in a descriptive rather than a normative way. The resulting designs are thus mainly influenced by the analyzed stakeholders, because their values are taken into account in the PoR and the design process. Most likely, there are other institutions, collaborations or groups of individuals with a stake in the beach which are not considered in this research. Consequently, certain information, knowledge and values of these stakeholders is lacking. For example, if people living in the nearby area, who may have a stake in the project, were analyzed, probably aspects like construction nuisance would be given a larger weight. For the conclusion of this research this implies that, on the one hand, the acceptance among non-analyzed stakeholders might be smaller, which may induce a smaller feasibility of certain solutions. On the other hand, because stakeholders with many different viewpoints were analyzed, the feasibility of the solutions is not expected to change significantly.

Furthermore, the stakeholders are not equally (or relative to their power) involved in the design process. The members of the PGB have had a particularly large influence on the resulting designs, as their opinion is taken into account in the set up of the PoR and in the final assessment of the solutions. If, for example, environmental NGOs would have been present during meetings with the PGB, the final designs would probably have had a larger focus on ecology. Moreover, within the PGB, the representation of stakeholders is not along with their power. For example, the PPB (*Platform Pioniers Brouwersdam*), which represents interests the entrepreneurs of the beach, covered a larger part of the attending participants than other stakeholders with more power (such as the Province of Zeeland). It should be kept in mind when reading the conclusion of this thesis, that this select group of stakeholders (with recreation as main interest) have had a large influence on the resulting designs and the attributed scores. For the conclusion this implies that, even though many stakeholders with partly conflicting interests were analyzed, the choices made in the design process contained a bias towards recreation. Moreover, this can be overcome by alternating the relative weights of each category; the MCA tool can be used conveniently for this.

10.4. Identification, evaluation and selection of solutions

First of all, this research is not conclusive on all possible nature-based solutions for the beach. Possibly different solutions could have been identified if more data would be available. The Jarkus profiles used in the data analysis and modelling study of this research are measured yearly and resemble mostly the winter profile rather than the summer profile (as they are measured in spring). The impact of storms could not be investigated based on these data. Possibly, when data could give insight into the impact of storms, a seasonal solution (such as a temporal floating breakwater) could have been designed to mitigate the most severe erosion during winter.
In addition, the conclusion of the small feasibility of an artificial island as an erosion mitigating measure for the beach is partly based on the uncertainty in predicting morphological development. This is a result of the choice for a coastline model, which is only useful in the simulation of the shoreline development. In combination with high construction and maintenance costs, the feasibility of this structure could not be concluded based on this research. This implies for the conclusion that, if a different modelling strategy would have been chosen, this solution (or other solutions requiring complex morphological modelling) could have been assessed and could potentially be regarded as a feasible solution. The implication for the research is that the list of resulting designs is not conclusive.

Secondly, the emission of greenhouse gasses was not taken into account in the assessment of the solutions. However, the permitted amount of emission of nitrogen during construction projects is limited by national regulations. This could thus pose obstruction in the decision-making process, as solutions which are regarded as feasible in this thesis may be rejected by the Ministry of LNV (which is responsible for compliance with environmental legislation) on the nitrogen emission rate.

Thirdly, the role of aesthetics may be significant in the acceptance of the designs. As elaborated in Section 7.4, aesthetics have to do with overall human perceptions of quality, and are governed by subjective criteria. In the MCA, the scores for the aesthetic criteria are assigned by the writer of this thesis. Hence, the conclusion and final score of the aesthetic value of the solutions has a limited value in the decision-making process as the perception of only one person is reflected in these scores. This implies that the conclusion that is drawn has a degree of subjectivity. This is not necessarily wrong, but decision-makers (e.g. the Municipality of Schouwen-Duiveland) will have to look whether the scores assigned to aesthetics are representative for the (weighted) opinion of the stakeholders. This could be checked if the stakeholders would assign a value to each of the aesthetic criteria of the solutions, or if a survey among many recreationists would be held. Then, based on the weighted outcome of this survey, the scores may be altered. This may lead to a different conclusion on the most feasible alternative with respect to aesthetics.

Lastly, to determine the most cost-effective solution, in general, the costs have to be offset against the financial benefits (i.e. a monetary cost-benefit analysis). In this research, the assessment of the alternative solutions has shown to (positively or negatively) affect the different recreational functions of the beach (water sports, beach sports and other recreational activities), and thereby the financial benefits for the local economy. However, there is currently no insight in the financial benefits of different recreational functions, implying that a quantification of the financial benefits of each solution is not possible.
Even if there would be insight in the current financial benefits per recreational function, there is a lot of uncertainty in the future decrease or increase of recreational value. This depends not only on the decision for a nature-based solution, but also on external factors such as socio-economic developments and recreational trends. Consequently, based on the present research, it is not possible to weigh the solutions' costs against the financial benefits. Note that the ecological benefits of the solutions are partly virtual, like most ecosystem services (Verhagen, 2019), and these benefits cannot be used as direct financial benefits. This complicates the comparison of alternatives. However, on the one hand, environmental value can have indirect financial benefits, which can be included in the cost-benefit analysis. On the other hand, nature has implicit value (Stålhammar & Pedersen, 2017); it is thus arguable whether the quantification of nature value should be included in the financial cost-benefit analysis, as the implicit value of nature is not completely quantifiable (Randrup et al., 2020).

Hence, this research expressed only the costs of the solutions, in terms of negative NPV (Net Present

Value). For example, the assessment of the solutions shows that the solution with the least negative NPV, i.e. the construction of pocket beaches (solution A), has a negative effect on the water recreational value of the area. Vice versa, periodic nourishing (solution F) maintains all recreational functions at its current level but is the most expensive solution (i.e., has most negative NPV). For the conclusion, this implies that the solution scoring best on costs in the MCA is not necessarily the most cost-effective one. This should be kept in mind in the decision-making process. When, after a thorough investigation, the insight on the financial benefits due to different types of recreation is obtained, a financial cost-benefit analysis can determine the most cost-effective solution in a further design stage.

11 Conclusion

This thesis aims to identify effective solutions for the preservation of the Brouwersdam beach with the inclusion of the ecological and recreational value of the beach. This chapter elaborates on the answers to the research sub-questions in Section 11.1 and the main research question in Section 11.2.

11.1. Research sub-questions

This section contains the answers to the formulated sub-questions in the introduction.

1. What are the morphodynamic characteristics of the Grevelingen outer delta and the main morphological developments of the Brouwersdam beach?

The Grevelingen outer delta is not in dynamic equilibrium. Its morphology undergoes large-scale morphodynamic changes, which include the shift of the Brouwersdam beach. From the analysis of Jarkus data between 1990 and 2015, a spatial shift of the shoreline at the southern edge towards the northeast with approximately 40 m/y in alongshore direction was concluded. The beach surface area (from 0 to +3 m NAP) decreases with 1.6 ha/y. The total volume (-3 to +3 m NAP) of the beach stays equal, but the southern part loses approximately 60,000 m^3/y to the northern part. In cross-shore direction, the sediment is distributed from the foreshore (-1 to +1.5 m NAP) mainly to the supralittoral part of the beach (+1.5 to + 3 m NAP) and the dunes (+ 3 m NAP). In 2016-2017, the beach was nourished. This nourished volume eroded faster (2017-2020), namely 80,000 m^3/y is lost from the southern part, of which only half was transported to the northern part. The other half was transported elsewhere, i.e. out of the system. Hence, the design of the nourishment induced larger erosion rates.

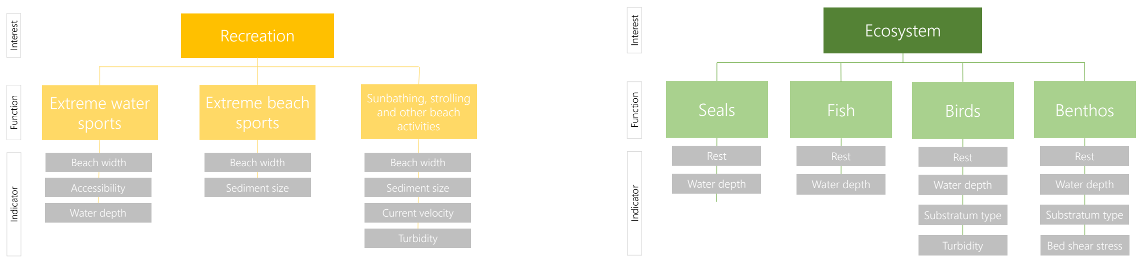
2. Which features characterize the ecosystem of the Grevelingen outer delta and how can the solution potentially enhance the ecosystem?

The outer delta can be characterized as a saline, mainly sublittoral area with two offshore littoral zones. It mainly consists of soft substratum, except for the natural oyster reef near the Blokkendam, which contains hard substratum. The area is highly dynamic concerning the wave impact but lowly dynamic concerning the tidal current velocity. The solution can potentially enhance the ecosystem by the creation of a shoal or a shellfish reef, mainly through increasing biodiversity. Moreover, the investigation on these characteristics proved to be useful in a later design stage to determine how a groyne structure can comply with the necessary habitat requirements for Pacific oysters. Furthermore, from the literature study, it can be concluded that the habitats of seals, birds, fish and benthos are particularly important.

3. Which stakeholders are engaged in taking a measure at the beach, and which indicators reflect their goals and interests?

The involved stakeholders consist of government agencies, environmental NGOs and entrepreneurial collaborations. Five governmental agencies and one entrepreneurial collaboration are represented in the Project Group Brouwersdam (PGB), a cooperation between directly involved stakeholders aiming to preserve the beach. The main interests in the beach are recreation and ecology. The visualisation of the relative power and interest of the stakeholder by means of a power-interest matrix clarifies one of the main problems in the decision-making process: there are no stakeholders with both high power and high interest. The stakeholder with the largest power, the Ministry of Infrastructure and Environment (IenW), has only little interest in the beach. The stakeholder with the most interest is the Platform Pioniers Brouwersdam, followed by the Municipality of Schouwen-Duiveland. Recent developments near the beach such as the recreative nourishment of 2016 and the development of the concept of a recreational BKL (Basiskustlijn) show that stakeholders are willing to take action and to contribute (financially) to the preservation of the beach.

Furthermore, the main interests of the area (recreation and ecology) are translated into indicators by means of an interest framework (as depicted in Figure 11.1). The interest recreation is subdivided into the functions of water sports, beach sports and sunbathing, strolling and other beach activities. The indicators that facilitate these functions concern the beach width, the sediment size, the accessibility of the shoreline, the water depth, the maximum current velocities and the turbidity of the water. These outcomes were discussed during two meetings with the PGB.
The interest ecology is subdivided into the habitats of the main species, which are seals, birds, fish and benthos. Their habitat requirements were translated into indicators. Rest (relating to the disturbance of the bed and other types of nuisance) is the most important indicator for the ecological value of the area, as the main species require a habitat with minimal disturbance. Furthermore, the abiotic conditions that indicate the ecological value of the area are the water depth, substratum type, turbidity and bed shear stress.



(a) Interest framework for recreation

(b) Interest framework for ecology

Figure 11.1: Interest frameworks to translate the stakeholders' interests and the main functions of the ecosystem into requirements for the solution

4. How are the longshore sediment transport rates temporally and spatially distributed along the shoreline, and which wave conditions have the largest contribution to the observed morphological evolution of the beach?

Analysis of the net sediment transport rates along the beach, based on the results of a calibrated hindcast coastline model in UNIBEST-CL+ of the period 2010-2015, shows that the net sediment transport rates during high water are up to eight times larger than during low water. In total, approximately 80 % of the total sediment transport over a tidal cycle takes place during high water conditions. This can be explained by the following three mechanisms. Firstly, the larger wave attack. As waves are depth-limited in the shallow outer delta, their wave energy is much higher during high water. The mean significant wave height ranges from H_s = 0.3 m during low water to H_s = 0.55 m during high water. Another reason for a higher wave attack during high tide is that the offshore shoals (mainly the Bollen van de Ooster) function as a natural breakwater. During low tide, 60 % of the wave energy of waves approaching from the northwest is dissipated at this shoal, whereas during high tide this is only 30 %. Secondly, during high water, the beach has a large inundated, active zone, in which a lot of sediment transport can take place. Thirdly, the flood tidal current velocity, which maximum value is ca. 0.6 m/s in northeastern direction during high tide against 0.3 m/s in southwestern direction during low tide, enhances a tide-induced current in the same direction as the predominant wave-induced current.

Hence, larger sediment transport rates towards the northeast occur during high water.

Furthermore, the sediment transport rates in the southern part are up to three times larger than in the northern part, which is mainly caused by a large difference in wave angle of incidence in the southern part of the beach, combined with larger tidal flow velocities (directed northward) and water depth in front of this part (which induces waves to break near the beach instead of further offshore). These high sediment transport rates are located between - 0.5 and + 1 m NAP. Moreover, the sediment balance of the hindcast model is in line with the morphological observations of the beach, which underscores the validity of the hindcast coastline model.

Analysis of the nearshore wave climate, simulated by translating the offshore conditions to the nearshore using a Delft3D-WAVE model, shows that the significant wave height near the beachhas a tidal averaged value of $H_s = 0.45m$. The southern part of the beach experiences mostly westerly waves, whereas westerly and northerly waves dominate the wave climate in the northern stretch. These differences are due to the location of shoals and former tidal channels in the Grevelingen outer delta. Thereby, the Bollen van de Ooster functions as a natural breakwater for westerly and northerly waves.
The investigation of the contribution of wave conditions to the main sediment transport rates shows that wind-generated (sea) waves that approach the beach from the west cause more than 65 % of the total net, northern directed sediment transport in the southern stretch. These wave conditions occur ca. 20 days/year. The nearshore characteristics of these waves are a significant wave height of $H_s = 0.8 - 1.2$ m, a peak wave period of $T_p = 5.5 - 7.5$ s and a wave angle of incidence at the closure depth of $\phi = 35 - 55°$ with respect to the coast normal (waves directed from the southwest-west to northwest-west). Hence, the dominant wave direction near the beach is West.

5. What is the expected future morphological evolution of the beach in the coming three decades?

Based on simulations with the UNIBEST-CL+ coastline (forecast) model up to 2050, as shown in Figure 11.2, it can be concluded that from 2020 to 2030, the simulated shoreline develops similarly to the observed shift of the decade before the beach was nourished. This means that up to 2030, the shoreline retreat goes on, and the surface area (0 to +3 m NAP) decreases towards approximately 57 ha (-16 ha in 12 years). Beyond 2030, the shoreline will develop with the same trend but at a slower pace. The southern part of the beach develops towards a coastline position perpendicular to the dominant wave direction (west). The sediment balance of this simulation suggests that the beach will not reach an equilibrium within the coming three decades. It must be highlighted that the simulated shoreline migration is based on the notion that the hydrodynamic boundary conditions in the Grevelingen outer delta stay more or less equal in the coming three decades. This is a reasonable assumption, provided that the Bollen van de Ooster does not breach before 2050.

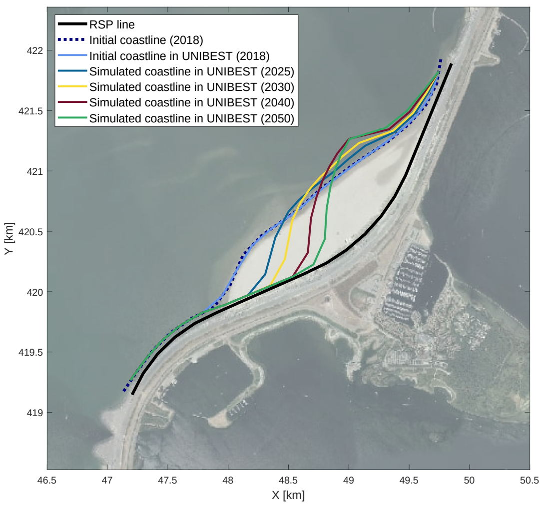


Figure 11.2: Top view of the simulated coastline development of 2025, 2030, 2040 and 2050 (forecast model UNIBEST)

6. Which requirements must a solution for the beach meet?

The Program of Requirements consists of requirements that are subdivided in the following categories: functionality, recreational value (water), recreational value (beach), ecological value and aesthetics. The functional requirements state that the beach must have a minimum surface area, the solution should be adaptive and that the construction and maintenance costs must be offset against the benefits. The requirements for both water and beach recreational value encompass the safety and convenience for the recreationists on the beach. The ecological requirements cover the preservation and enhancement the main habitat types. Lastly, the requirements for the aesthetics, which have to do with the overall human perception of quality, are covered by the view over the North Sea, the amount of structures on the beach, the (natural or artificial appearing) shape of the shoreline and to which extent the solution is innovative.

11.2. Main research question

What are alternative Nature-based Solutions to preserve the Brouwersdam beach?

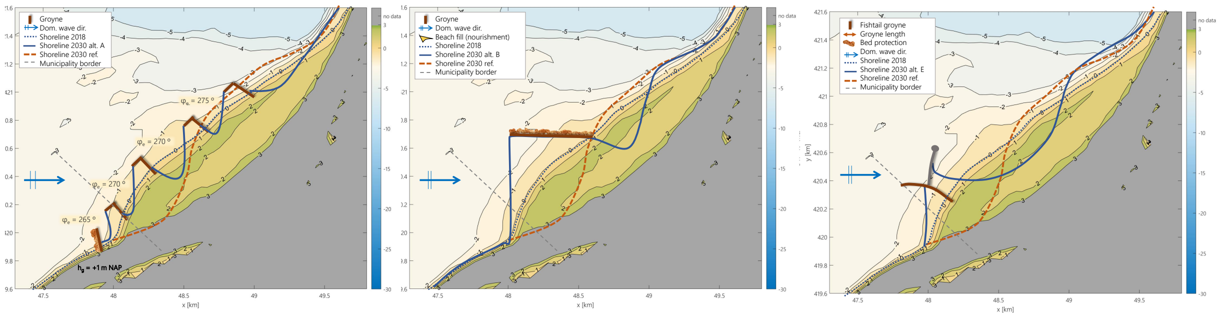
The investigation of erosion mitigation measures has shown that a groyne configuration or a shore-parallel breakwater can sufficiently mitigate the erosion. As the dominant wave direction is west, the equilibrium orientation of the shoreline is from north to south, i.e. the shore normal directed towards the west. A groyne configuration should thus be such that a western directed shoreline is maintained or reached within a few years of shoreline developments. Furthermore, a potential breakwater should be located in front of the southern edge of the beach, For optimal protection of the beach, a breakwater should be located in front of the southern edge, orientated to the west and connected to the shoreline by an artificial tombolo or a hard structure, because there is hardly any sediment supply from the updrift side (south).

The investigation of the construction material, focused on ecological enhancement, resulted in structures consisting of layered (brushwood) fascine matresses filled with hard substratum such as shells. The bottom layer of the structure contains biodegradable (maize) geotextile for the filter function. The updrift side of the structure contains a vertically placed geotextile as well, to avoid large deposits of sediment within the core of the groyne, preventing the oyster habitat from high sedimentation rates. The investigation on the habitat requirements for several types of oysters shows that, if the hard substratum is placed below the mean water level and the structure provides sufficient shelter (locally small flow and orbital velocities), Japanese oysters will attach and settle at the lee side of the groynes. The consultation with marine ecologist Karin Didderen confirms that the groyne will most likely create a shellfish reef with mainly Japanese oysters. With respect to the impact on the environment, it is concluded that the structures can be constructed CO_2 neutral. Moreover, the ecosystem services of the oyster reef are the enhancement of biodiversity, water quality improvement through filtering nutrients and contaminants and the provision of shelter for other species. Lastly, the temporal behaviour of the structure is enhancing its functioning: over time, the young oysters will create a fixating crust, which decreases its permeability and strength.

A study on the technical feasibility shows that the structure is able to withstand the maximum pressure gradient near the bottom of a 1/100 year occurring wave condition. Moreover, the weight of the structure is sufficiently large to prevent horizontal displacement of the structure during a 1/100 year occurring wave attack.
The lifetime of brushwood structures, located in the intertidal zone, is 15 to 25 years. This limited lifetime is a disadvantage due to higher maintenance costs. However, it is an advantage when regarding that it creates the possibility to reconsider the location, dimensions and other design aspects after 2 decades of shoreline migration in this highly morphodynamic environment.
Furthermore, the construction of brushwood groynes filled with Japanese oysters is innovative; the Brouwersdam beach is suitable as a pilot location because of its shallow foreshore (resulting in a small groyne height and hence, costs) and the presence of a natural oyster reef close by (which proves the presence of oyster larvae and other requirements for the biosphere, and thus enlarges the possibility of a successful pilot project).

The assessment of different groyne and breakwater configurations (some with a beach fill) was done by modelling the shoreline development and calculating the indicative costs of each alternative. This first assessment of feasibility showed that feasible solutions (depicted in Figure11.3) are:

- A groyne configuration, creating multiple pocket beaches, of 1 straight groyne and 4 L-shaped groynes, with an orientation slightly tilted towards the dominant wave direction (Solution A)
- A straight groyne with a west-east orientation, combined with a beach fill between the current coastline and the groyne (Solution C)
- A fishtail groyne, which is a structure with a slightly curved, shore-normal groyne arm and a shore-parallel breakwater arm (Solution E)



(a) A - Pocket beaches) (b) C - Straight groyne with beach fill (c) E - Fishtail groyne

Figure 11.3: Sketches of designs A, C and E. The expected shape of the shoreline after several years of development is depicted as a blue line. The dotted, orange line represents the shoreline in the reference situation (taking no action).

These alternative solutions were worked out into indicative detailed designs and evaluated based on the requirements of the PoR. Within this analysis, they were compared with periodic nourishing (solution F).

Based on the weighted average score of each solution, the conclusion can be drawn that the solutions are similarly feasible. However, the solutions score differently on the categories. The results of the MCA thus illustrate that the conclusion on the most feasible solution depends on priority. The bar chart of Figure 9.11a clarifies the above reasoning: the MCA results in a similar total score for the four different solutions, but the relative scores per category vary from one solution to another (e.g., solution A is the cheapest but decreases water recreational value, whereas solution E maintains this value but is more expensive). The main conclusions that can be drawn based on the MCA are:

Alternative A (Pocket beaches) is the best solution when low costs are the main requirement. However, this solution deteriorates the function of the beach as a suitable area for water sports. This is due to the number of (nearly) shore normal structures that may impose dangerous situations for surfers. The beach recreation is not enhanced either, as the groynes impose structures on the beach. The recreational value of the beach will thus decrease significantly. Moreover, the aesthetic quality of this solution is the least of all solutions. However, the ecological enhancement is large.

Alternative C (Straight groyne with beach fill) scores averagely on nearly all requirements, except for the negative impact on water recreation. This is due to the fact that the northern part of the shoreline is not accessible for a length of 600 m; the water recreationists have to enter the water in the west. Because the western coastline orientation is perpendicular to the predominant wind direction, this is a significant disadvantage as it complicates entering the water for surfers. The beach will lose a large part of its applicability as a (kite) surfing area.

Alternative E (Fishtail groyne) has the advantage of maintaining the value of the beach for water recreation. The costs are equal to those of solution C, i.e. significantly higher than for solution A. However, its ecological enhancement is significant.

Alternative F (Periodic nourishing) is the best solution for recreational purposes, as it poses no obstructions on or near the beach. However, the costs are the highest of all solutions. Moreover, the frequent presence of dredging vessels and other construction equipment negatively impacts the ecosystem. Lastly, having no structures on or near the beach results in the highest score on aesthetic value.

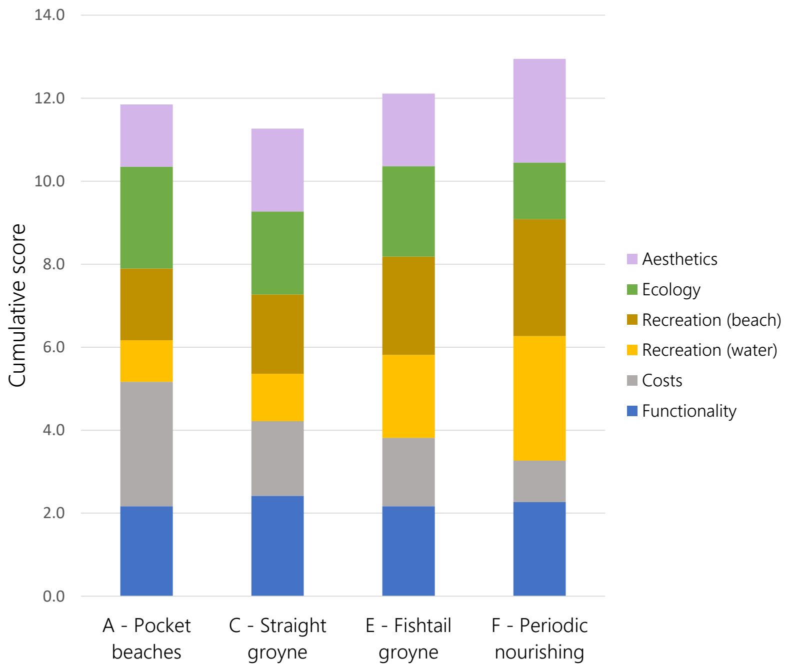


Table 11.1: Bar chart representing solutions A, C, E and F and the total value of the summed scores

The main objective of this study is to design nature-based solutions for the ongoing erosion and shift of the shoreline to which the Brouwersdam beach is subjected. The conclusion is drawn that this goal is achieved, as three feasible, ecosystem-enhancing designs were created with the involvement of the main stakeholders. The research provides, per alternative, insight into the efficiency, costs, enhancement of the ecological and recreational value and the aesthetics of the solutions. The MCA tool can potentially support future decision-making processes (following this study) by clarifying the trade-offs between different designed solutions. Further exploring the economical benefits of recreational functions will contribute to validating the weight factors in these categories. The next chapter provides several recommendations for further design steps and research on the beach.

12 Recommendations

This chapter contains the recommendations for further research, which either follow from the discussion or the conclusions of the conducted research. First, in Section 12.1, suggestions are given to give a follow-up on the designs that were created. Subsequently, in Section 12.2, recommendations are given on how to proceed in the decision-making process. Lastly, suggestions on possible research on the Brouwersdam beach are discussed in Section 12.3.

12.1. Recommended improvements of the designs

For the potential design steps following this research, several recommendations on the improvement are listed in this Section.

- First of all, if a nature-based design is selected for further refinement and preparation for implementation, the alternative solution of a fishtail groyne (solution E) is recommended. The reasoning behind this recommendation is that the solution scores sufficiently well on all requirements. This recommendation is underlined by the fact that there is a reasonable chance of the construction of a shore-normal breakwater in the northern edge of the beach. This breakwater will most likely be constructed if the location of the future tidal inlet is northward of the beach. As explained in Chapter 9, the beach will, when combined with a fishtail groyne, reach the equilibrium coastline profile of a spiral beach. This is a desired shoreline shape, which preserves all recreational activities.
- Secondly, in further design steps, it is recommended to perform a research to determine the permeability (which changes over time) and the wave-attenuating capacity in the brushwood groynes filled with oyster shells. The groyne sufficiently provides the habitat requirements for Japanese oysters. Still, a pilot project and further research is advised to determine for example the optimal spacing between the faggots and the optimal hard substratum type (filling of the groyne) to improve the self-sustaining capacity of the oyster habitat.
- Thirdly, to improve the design of the fishtail groyne, research on possible materials that could replace the layer of rubble mound on the breakwater arm is recommended because this could enhance the ecological function of the design. For example, eco-friendly concrete elements or the creation of water-retaining pools in the revetment are interesting improvements, aiming to increase the biodiversity in the intertidal zone.
- Fourthly, the groyne structure, consisting of layered fascine mattresses, will be tested on strength and stability in the wave flume of Deltares in the coming year, commissioned by Van Aalsburg Griendhouthandel BV (D. Van Aalsburg, personal communication, May 10, 2021). The results of these scaled physical modelling tests will probably provide sufficient information for a definitive answer whether these structures are applicable at the Brouwersdam beach. It is recommended to use these results in further design steps.

- Furthermore, concerning the creation of a self-sustaining oyster reef within the brushwood structures, it is highly recommended to commission an ecological consultancy company to draw up a plan of action and extensive ecological assessment. Thereby, Rijkswaterstaat was working on the concept of brushwood groynes near the coast as part of the Innovative Coastline Care programme (IKZ). Therefore it is advised to consult and involve Rijkswaterstaat as well.
- Lastly, in assessing the designs, the emission of the greenhouse gasses such as nitrogen is not taken into account. This could pose obstruction in further design phases, as explained in the discussion of Section 10.4. Hence, in further design steps, these emissions should be taken into account.

12.2. Recommended steps in the decision-making process

The decision-making process is complicated, predominantly because there are currently no stakeholders with high power and high interest. To increase the likelihood of the implementation of a nature-based solution for the beach, the following actions are recommended. Several interventions in the social system are recommended.

- First of all, the stakeholders with a medium power and medium to high interest (the provinces, municipalities and the PPB), can form a coalition, i.e., as if they are one stakeholder with high power. This 'new' stakeholder has large interest and much power, and may convince the ministry of IenW (the stakeholder with the most power) to support a nature-based solution for the Brouwersdam. Consensus among these stakeholders on the best approach to preserving the beach is required, to be able to form a collaboration with a clear vision. Hence, these stakeholders should assign certain weight factors to different requirements (low costs, high efficiency, high ecological value, high recreational value, etc.), to make their common interest clear. However, to decide on these weight factors, the relative financial benefits of the types of recreation is necessary.
- Secondly, the interest of the Ministry of LNV could be increased by pointing out the nature enhancing benefits of a nature-based solution. If the interest of this stakeholder is larger, it may collaborate in convincing other stakeholders with high power to take action.
- Thirdly, this thesis contains a descriptive analysis of the social system rather than a normative analysis. It is however recommended to perform a normative analysis and engage the stakeholders resulting from this analysis in the decision-making process.
  Moreover, it is advised to increase the acceptance among all stakeholders (mainly the stakeholders with low power but medium to high interest). This could be done by setting up an open collaboration in which every stakeholder that is willing to can cooperate. This creates awareness for the problem among all stakeholders, including for example people living near by and recreationists at the beach. Other advantages of such an open collaboration are that it may lead to creative and innovative input from different perspectives and increase acceptance of designs among different stakeholders.
- Lastly, it is recommended to increase the engagement of certain stakeholders in the design process. For example, environmental NGOs should be incorporated in the discussions of the PGB, to obtain a more balanced representation of the partially conflicting interests. If environmental NGOs are engaged closely in the design process, the interest of powerful stakeholders such as the Ministry of LNV, which is concerned about environmental legislation, may be increased, which increases the likelihood of the realisation of a solution.

12.3. Recommended research on the Brouwersdam beach

- Firstly, concerning the available hydraulic data in the Grevelingen outer delta, in-situ measurements of the wave climate and current velocities are lacking. As was also stated by Jansen et al. (2012), it is advised to measure the wave and tidal characteristics, to check the hydrodynamic simulations that were done in many studies (such as Schrijvershof (2015), Huibregtse (2013), de Boom (2016) and Jansen et al. (2012)). For the tidal current velocities, a time series of two spring-neap tidal cycles suffices, preferably during calm (summer) conditions to avoid noise caused by (winter) storm surges. For wave data, a time series of minimal a year would be convenient to capture the seasonal variations in the wave climate. If this is too time-consuming or too expensive, it is advised to measure during winter and make sure that one or more storms are included in the time series. This enables the possibility to investigate the impact of storms on the beach.

- Secondly, a modelling study or in-situ measurements could determine the impact of a storm on the beach profile. Then, possibly, a seasonal solution (such as a temporal floating breakwater) could be designed to mitigate the most severe erosion during winter. A 2D model such as Xbeach is advised to predict the development of the beach in cross-shore direction.
- Thirdly, the construction of an offshore, artificial island with the function of a breakwater could be a feasible solution if the morphological evolution of this island can be predicted sufficiently well. This could be done using a 2DH or 3D morphological model of the total area (for example, with a morphological model in Delft3D).
- Lastly, for a better understanding of the ecosystem of the Grevelingen outer delta, it is recommended to create an ecotope map of the area. Ecotopes are classified according to certain abiotic variables (as discussed in Appendix D). By creating an ecotope map, the gradual transitions in these variables are converted to discrete, manageable units. Changes in the ecological system due to changing conditions relevant to ecology (such as flow velocity and water depth) are then quantifiable. This is very useful for further investigation of the impact of human interventions in the Grevelingen outer delta.

References

Aarninkhof, S., & van Kessel, T. (1999). *Data analyse Voordelta: Grootschalige morfologische veranderingen 1960 – 1996* (Tech. Rep. No. Z2694). Deltares.

Ackermann, F., & Eden, C. (2011). Strategic Management of Stakeholders: Theory and Practice. *Long Range Planning*, *44*(3), 179–196. doi: 10.1016/j.lrp.2010.08.001

Allsop, W., Kortenhaus, A., Morris, M., Buijs, F., Hassan, R., Young, M., ... ter Horst, W. (2007). *Failure Mecahnisms for Flood Defence Structures* (Tech. Rep. No. T04-06-01). FLOODsite Consortium.

Arcadis. (2012). *Gebiedsvisie Brouwersdam* (Tech. Rep. No. 075629703:0.24). Gemeente Schouwen-Duiveland, Gemeente Goedereede.

ARK Natuurontwikkeling. (n.d.). Retrieved from `https://www.ark.eu/`

Baks, J. (2020). *Natuurfotografie Goeree-Overflakkee.* Retrieved from `https://www.janbaks.nl/`

Baptist, M., van der Wal, J., Folmer, E., Gräwe, U., & Elschot, K. (2019). An ecotope map of the trilateral Wadden Sea. *Journal of Sea Research*, *152*, 101791. doi: 10.1016/j.seares.2019.05.003

Belton, V., & Steward, T. (2002). *Multiple Criteria Decision Analysis, An Integrated Approach* (1st ed.). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Boelskifte, P. (2014). Aesthetics and the Art of Engineering. *Artifact*, *3*(3), 1–2. doi: 10.14434/artifact.v3i3.3121

Bosboom, J., & Stive, M. (2015). *Coastal Dynamics I lecture notes CIE4305.* Delft: VSSD.

Bouma, H., de Jong, D., Twisk, F., & Wolfstein, K. (2005). *Zoute wateren EcotopenStelsel (ZES . 1) Voor het in kaart brengen van het potentiële voorkomen van levensgemeenschappen in zoute en brakke rijkswateren.* Middelburg: Rijkswaterstaat.

Broer, J., de Pater, M., & Blikman, D. (2011). *Ruimte voor recreatie op het strand; onderzoek naar een recreatiebasiskustlijn.* Decisio.

CIRIA, CUR, & CETMEF. (2007). *The Rock Manual. The use of rock in hydraulic engineering (2nd edition).* London: CIRIA.

Cleveringa, J. (2008). *Morphodynamics of the Delta Coast (South-west Netherlands): Quantative analysis and phenomenology of the morphological evolution 1964-2004* (Tech. Rep. No. A1881). Alkyon.

Cohen-Shacham, E., Marie Walters, G., Walters, G., & Maginnis, S. (2016). *Nature-based solutions to address global societal challenges* (No. 244). Gland, Switzerland: IUCN. doi: 10.2305/IUCN.CH.2016.13.en

Costanza, R., D'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., ... van den Belt, M. (1998). The value of the world's ecosystem services and natural capital. *Ecological Economics*, *25*(1), 3–15. doi: 10.1016/S0921-8009(98)00020-2

Dankers, N., Duin, W., Leopold, M., Martakis, G., Smit, C., van der Werf, D., & Wolfert, H. (2001). *Ontwerp-ecotopenstelsel Kustwateren; Voorstel voor classificatie en advies voor validatie* (Tech. Rep. No. 177). Wageningen: Alterra.

Dankers, N., van Duin, W., Baptist, M., Dijkman, E., & Cremer, J. (2012). The Wadden Sea in the Netherlands: Ecotopes in a World Heritage Barrier Island System. In *Seafloor geomorphology as benthic habitat* (pp. 213–226). Elsevier Inc. doi: 10.1016/B978-0-12-385140-6.00011-6

Dao, H. T., Hofland, B., Stive, M. J., & Mai, T. (2020). Experimental assessment of the flow resistance of coastal wooden fences. *Water (Switzerland)*, *12*(7). doi: 10.3390/w12071910

Dao, T., Stive, M., Hofland, B., & Mai, T. (2018). Wave Damping due to Wooden Fences along Mangrove Coasts. *Journal of Coastal Research*, *34*(6), 1317–1327. doi: 10.2112/JCOASTRES-D-18-00015.1

de Blois, M., & De Coninck, P. (2008). The dynamics of actors' and stakeholders' participation: An approach of management by design. *Architectural Engineering and Design Management*, *4*(3-4), 176–188. doi: 10.3763/aedm.2008.0097

de Boom, A. (2016). *Modelling hydrodynamics and sediment transport in the Grevelingen outerdelta in response to human interventions.* MSc Thesis, Universiteit Utrecht.

de Jongste, A., Dusseljee, D., Smit, M., & Jansen, M. (2013). Morphological impact on ebb-tidal deltas of reintroducing tide in a former estuary. *Coastal Dynamics*, *6*(1), 465–476.

Deltares. (2011). UNIBEST-CL+ User Manual.

Deltares. (2014). *Delft3D-WAVE User Manual.*

Didderen, K., van der Have, T., Bergsma, J., van der Jagt, H., Lengkeek, W., Kamermans, P., ... Sas, H. (2019). *Shellfish bed restoration pilots Voordelta, the Netherlands. Annual report 2018.* Bureau Waardenburg, Wageningen Marine Research, Sas Consultancy.

Ecoshape. (n.d.-a). *Building shellfish reefs.* Retrieved from `https://www.ecoshape.org/en/concepts/building-shellfish-reefs/`

Ecoshape. (n.d.-b). *Guidance in stakeholder analysis.* Retrieved from `https://www.ecoshape.org/en/enablers/stakeholder-model/enabler-guidance/`

Ecoshape. (2020). *De Building with Nature filosofie.* Retrieved from `https://www.ecoshape.org/nl/de-building-with-nature-filosofie/`

Elias, E., van der Spek, A., & Lazar, M. (2016). The 'Voordelta', the contiguous ebb-tidal deltas in the SW Netherlands: Large-scale morphological changes and sediment budget 1965-2013; Impacts of large-scale engineering. *Netherlands Journal of Geosciences*, 1–27. doi: 10.1017/njg.2016.37

European Commission. (n.d.). *Nature and biodiversity law - Environment - European Commission.* Retrieved from `https://ec.europa.eu/environment/nature/legislation/`

Faste, R. A. (1995). The Role of Aesthetics in Engineering. *Japan Society of Mechanical Engineers (JSME) Journal.* doi: 10.1299

Gamper, C. D., & Turcanu, C. (2007). On the governmental use of multi-criteria analysis. *Ecological Economics*, *62*(2), 298–307.

Grabowski, J., & Peterson, C. (2007). Restoring oyster reefs to recover ecosystem services. *Theoretical Ecology Series*, *4*(C), 281–298. doi: 10.1016/S1875-306X(07)80017-7

Haasnoot, M., Bouwer, L., Diermanse, F., Kwadijk, J., Spek, A. v. d., Essink, G. O., ... Mosselman, E. (2018). *Mogelijke gevolgen van versnelde zeespiegelstijging voor het Deltaprogramma; Een verkenning* (Tech. Rep. No. 11202230-005-0002). Deltares.

Harrington, R., Anton, C., Dawson, T., de Bello, F., Feld, C., Haslett, J., ... Harrison, P. (2010). Ecosystem services and biodiversity conservation: Concepts and a glossary. *Biodiversity and Conservation*, *19*(10), 2773–2790. doi: 10.1007/s10531-010-9834-9

Harris, F. (1993). *Onderzoek naar de toepasbaarheid van offshore golfbrekers langs de Nederlandse kust; eindrapport* (Tech. Rep.). Harris.

Heath, M., Sabatino, A., Serpetti, N., McCaig, C., & O'Hara Murray, R. (2017). Modelling the sensitivity of suspended sediment profiles to tidal current and wave conditions. *Ocean and Coastal Management*, *147*, 49–66. doi: 10.1016/j.ocecoaman.2016.10.018

Hermans, L., & Cunningham, S. (2018). *Actor and Strategy Models: Practical Applications and Stepwise Approaches*. Hoboken, New Jersey: John Wiley & Sons, Inc.

Hughes, S. (1991). Wave-Induced Scour Prediction at Vertical Walls. In *Coastal sediments*. American Society of Civil Engineers.

Huibregtse, W. (2013). *Morphological analysis of the beach at the Brouwersdam*. MSc Thesis, Delft University of Technology.

Jansen, M., de Jongste, A., & Dusseljee, D. (2012). *Morfologische analyse Voordelta* (Tech. Rep. No. SDM113-4). Witteveen + Bos.

Janssen, S., Vreugdenhil, H., Hermans, L., & Slinger, J. (2020). On the nature based flood defence dilemma and its Resolution: A game theory based analysis. *Science of the Total Environment*, *705*, 135359. doi: 10.1016/j.scitotenv.2019.135359

Kamermans, P., Blanco, A., & van Dalen, P. (2020). *Sources of European flat oysters (Ostrea edulis L .) for restoration projects in the Dutch North Sea* (Tech. Rep. No. C085/20). Wageningen Marine Research. doi: 10.18174/532003

Kerngroep Handhaving Voordelta. (2014). Handhavingsplan bij Natura2000 Beheerplan Voordelta 2015-2021..

Lausman, R., Klein, A., & Stive, M. (2006). Uncertainty in the application of the Parabolic Bay Shape Equation: A case study. *Coastal Engineering*, *57*(2), 132–141.

Lazar, M., & Elias, E. (2019). *Enhancing Brouwersdam After the Complete Damming of the Grevelingen Estuary in 1971, in the SW Netherlands* (Tech. Rep.).

Massie, W. (1976). *Coastal Engineering. Volume III - Breakwater Design*. Delft: Department of Civil Engineering, TU Delft.

Milleninium Ecosystem Assessment. (2005). *Ecosystem and Human well-being: Synthesis*. Washington, DC.: Island Press.

Ministerie van Landbouw Natuur en Voedselkwaliteit. (2008). *Aanwijzingsbesluit Voordelta* (Tech. Rep. No. DRZO/2008-113). Directie Regionale Zaken.

Mo, K. H., Alengaram, U. J., Jumaat, M. Z., Lee, S. C., Goh, W. I., & Yuen, C. W. (2018). Recycling of seashell waste in concrete: A review. *Construction and Building Materials*, *162*(January), 751–764. Retrieved from `https://doi.org/10.1016/j..2017.12.009` doi: 10.1016/j.conbuildmat .2017.12.009

Mooyaart, L. (2010). *Getijcentrale in de Brouwersdam: Variantenstudie* (Tech. Rep. No. 9V9366.A0). Royal Haskoning.

Nipius, K. (1998). *Dwarstransportmodellering m.b.v. Bailard, toegepast op de Voordelta Grevelingen monding*. MSc Thesis, Delft University of Technology.

Olsen, O. (1883). *The piscatorial atlas of the North Sea, English and St. George's Channels, illustrating the fishing ports, boats, gear, species of fish (how, where, and when caught), and other information concerning fish and fisheries*. London: Taylor and Francis.

Perdok, U. (2002). *Application of timber groynes* (No. December). MSc Thesis, Delft University of Technology.

Persson, U., & Olander, S. (2004). Methods to estimate stakeholder views of sustainability for construction projects. In *Proceedings of the 21th conference on passive and low energy architecture (plea2004), 19-22 september*.

PMI Standards Committee. (2000). *A Guide to the Project Management Body of Knowledge (PMBOK Guide)* (Vol. 69) (No. 5). Newton Square, Pennsylvania, USA: Project Management Institute (PMI). doi: 10.1093/ajcp/69.5.475

Prins, T., van der Meer, J., & Herman, P. (2020). *Eindrapportage monitoring - en onderzoeksprogramma Natuurcompensatie Voordelta (PMR-NCV).* Ijmuiden, Delft: Wageningen Marine Research. doi: https://doi.org/10.18174/524298

Randrup, T. B., Buijs, A., Konijnendijk, C. C., & Wild, T. (2020). Moving beyond the nature-based solutions discourse: introducing nature-based thinking. *Urban Ecosystems*, *23*(4), 919–926. doi: 10.1007/s11252-020-00964-w

Reise, K. (1985). *Tidal flat ecology : An Experimental Approach to Species Interactions* (Vol. 54). Berlin: Springer-Verlag Berlin and Heidelberg GmbH & Co. KG. doi: 10.1007/978-3-642-70495-6

Rijkswaterstaat. (n.d.-a). *Morfologie.* Retrieved from `https://waterinfo-extra.rws.nl/monitoring/morfologie/`

Rijkswaterstaat. (n.d.-b). *Rijkswaterstaat Waterinfo - Expert.* Retrieved from `https://waterinfo.rws.nl/#!/nav/expert/`

Rijkswaterstaat. (n.d.-c). *Voordelta - Natura 2000.* Retrieved from `https://rwsnatura2000.nl/gebieden/voordelta`

Rijkswaterstaat. (2013). *Kenmerkende waarden Getijgebied 2011.0* (Tech. Rep.). RWS Centrale Informatievoorziening.

Rijkswaterstaat. (2014a). *Nota Indicatief ontwerp strandsuppletie Brouwersdam 2015-2016.* Rijkswaterstaat.

Rijkswaterstaat. (2014b). Suppletielocaties 2012-2015.

Rijkswaterstaat. (2019). Onderbouwing suppletieprogramma 2020-2023.

Rijkswaterstaat. (2020). *Mariene Strategie (deel 2). Actualisatie van het KRM-monitoringprogramma 2020-2026.* (Tech. Rep.).

Rijkswaterstaat, & Royal HaskoningDHV. (2016). *Beheerplan Natura 2000 Voordelta 2015-2021.* Ministerie van Infrastructuur en Milieu.

Sas, H., Didderen, K., van der Have, T., Kamermans, P., van den Wijngaard, K., & Reuchlin, E. (2019). *Recommendations for flat oyster restoration in the North Sea* (No. April).

Sas, H., Kamermans, P., van der Have, T., Christianen, M., Coolen, J., Lengkeek, W., ... Weide, B. v. d. (2018). *Shellfish bed restoration pilots Voordelta, the Netherlands. Annual report 2017.*

Sas, H., Kamermans, P., van der Have, T., Lengkeek, W., & Smaal, A. (2016). *Shellfish reef restoration pilots Voordelta, the Netherlands. Annual report 2016.*

Schellekens, T., Wijsman, J., & van den Brink, A. (2012). *A habitat suitability model for Pacific oysters (Crassostrea gigas) in the Oosterschelde.* (Tech. Rep. No. C057/11). IMARES Wageningen UR.

Schiereck, G. (2012). *Introduction to Bed, bank and shore protection. Updated by Henk Jan Verhagen. 2nd edition.* VSSD.

Schmitt, K., & Albers, T. (2014). *Area Coastal Protection and the Use of Bamboo Breakwaters in the Mekong Delta.* Elsevier Inc. doi: 10.1016/B978-0-12-800007-6.00005-8

Schrieken, N., & Engelbos, V. (2017). *Wasroos nieuw aan de Noordzeekust.*

Schrijvershof, R. (2015). *Morphological modelling of a nourishment at the Brouwersdam beach.* BSc Thesis, Universiteit Utrecht.

Sha, L. P., & van den Berg, J. H. (1993). Variation in ebb-tidal delta geometry along the coast of the Netherlands and the German Bight. *Journal of Coastal Research*, *9*(3).

Slinger, J., Stive, M., & Luijendijk, A. (2021). Nature-based solutions for coastal engineering and management. *Water*, *13*(7), 3–7. doi: 10.3390/w13070976

Slinger, J., & Vreugdenhil, H. (2020). Coastal engineers embrace nature: Characterizing the metamorphosis in hydraulic engineering in terms of four continua. *Water*, *12*(9), 1–12. doi: 10.3390/w12092504

Smaal, A., Kamermans, P., van der Have, T., Engelsma, M., & Sas, H. (2015). *Feasibility of Flat Oyster (Ostrea edulis L.) restoration in the Dutch part of the North Sea* (Tech. Rep. No. C028/15). IMARES Wageningen UR.

Smaal, A., Kater, B., & Wijsman, J. (2008). Introduction, establishment and expansion of the Pacific oyster Crassostrea gigas in the Oosterschelde (SW Netherlands). *Helgoland Marine Research*, *63*(1), 75–83. doi: 10.1007/s10152-008-0138-3

Smit, N. (2020). *The impact of coastal development on the societal and ecological system.* MSc Thesis, Delft University of Technology.

Staatscourant. (2021). *Regeling van de Minister van Landbouw, Natuur en Voedselkwaliteit van 28 mei 2021, nr. WJZ/ 21081523, houdende wijziging van de Uitvoeringsregeling visserij in verband met een visserijverbod in de Oesterbank Voordelta* (No. 26898).

Stålhammar, S., & Pedersen, E. (2017). Recreational cultural ecosystem services: How do people describe the value? *Ecosystem Services*, *26*, 1–9. doi: 10.1016/j.ecoser.2017.05.010

Stigter, C., Verhagen, H. J., de Vriend, H. J., van der Weijde, R., van Raalten, C., & Loxham, M. (1990). The Influence on the Environment of Coastal Structures recently built in the Netherlands. *Pergamon - PIANC*.

Tauw, & Van Aalsburg. (2019). *'Constructing with Nature'. Vasthouden en aangroeien van zand met rijshouten constructies.*

Tonnon, P., Huisman, B., Stam, G., & van Rijn, L. (2018). Numerical modelling of erosion rates, life span and maintenance volumes of mega nourishments. *Coastal Engineering*, *131*, 51–69. doi: 10.1016/j.coastaleng.2017.10.001

Troost, K. (2010). Causes and effects of a highly successful marine invasion: Case-study of the introduced Pacific oyster Crassostrea gigas in continental NW European estuaries. *Journal of Sea Research*, *64*(3), 145–165. doi: 10.1016/j.seares.2010.02.004

Turlings, L., Smale, A., Boon, M., & Nieuwkamer, R. (2008). *Notitie optimale locatie(s) doorlaatmiddelen.* Witteveen + Bos.

van den Boomgaard, M., & Eikema, B. (2006). *Rapportage veldmetingen Westerschelde januari 2003 t/m mei 2006* (No. december).

van den Heuvel, M., & Rabelink, G. (2014). *Regionaal bod zandsuppletie Brouwersdam.*

Van der Meer, J. (1991). *Stability and transmission at low-crested structures* (Tech. Rep. No. 453). Delft Hydraulics.

Van der Moolen, L. (2015). *An interdisciplinary process based framework for sandy coastal developments.* MSc Thesis, Delft University of Technology.

van der Spek, A., & Elias, E. (2021). Half a century of morphological change in the Haringvliet and Grevelingen ebb-tidal deltas (SW Netherlands) - Impacts of large-scale engineering 1964 – 2015. *Marine Geology*, *432*, 106404. doi: 10.1016/j.margeo.2020.106404

van der Wegen, M., van der Werf, J., de Vet, P., & Röbke, B. (2017). *Hindcasting Westerschelde mouth morphodynamics (1963-2011)* (Tech. Rep. No. 1210301-001). Deltares.

van Eekelen, E., & Bouw, M. (2020). *Building with Nature: Creating, Implementing and Upscaling Nature-Based Solutions*. Rotterdam: Nai010 Publishers.

van Moorsel, G., van Horssen, P., Poot, M., & Soldaat, L. (2020). *Ruimtelijke analyse en trends benthos Voordelta*. doi: 10.13140/RG.2.2.35520.76800

Van Rijn, L. (1994). *General view on sand transport by currents and waves* (Tech. Rep. No. Z2899.20/Z2099.30/Z2824.30). Delft Hydraulics.

Van Zanten, S. (2015). *Towards engineering the ecosystem services of a mega-nourishment*. MSc Thesis, Delft University of Technology.

Velasquez, M., & Hester, P. (2013). An Analysis of Multi-Criteria Decision Making Methods. *International Journal of Operations Research*, *10*(2), 56–66. doi: 10.1007/s13748-016-0093-1

Verbeek, W. (n.d.). *Muien - zachte kust*. Retrieved from `https://www.muien.nl/nl/muien-zachte-kust/index.html`

Verhagen, H. (2019). Financial benefits of mangroves for surge prone high-value areas. *Water (Switzerland)*, *11*(11). doi: 10.3390/w11112374

Wang, Z. (2010). *Morfologische effecten van een getijdecentrale in de Brouwersdam* (Tech. Rep. No. 1201650-000). Deltares.

Werkgroep discontovoet. (2020). *Rapport Werkgroep discontovoet 2020*. Rijksoverheid.

Wetekamp, W. (2011). Net present value (NPV) as a tool supporting effective project management. In *Proceedings of the 6th ieee international conference on intelligent data acquisition and advanced computing systems: Technology and applications, idaacs'2011* (Vol. 2, pp. 898–900). Prague, Chech Republic: IEEE. doi: 10.1109/IDAACS.2011.6072902

Williams, A., & Micallef, A. (2009). *Beach Management: Principles and Practice*.

Wolfert, H. (1996). *Rijkswateren-Ecotopen-Stelsels: Uitgangspunten en plan van aanpak*.

Wolff, W. (1973). The Estuary as a habitat. An analysis of data on the soft-bottom macrofauna of the estuarine area of the rivers Rhine, Meuse, and Scheldt. *Zoologische Verhandelingen*.

WWF-NL. (n.d.). *Stichting Het Wereld Natuur Fonds - Nederland*. Retrieved from `https://www.wwf.nl/`

Ysebaert, T., & Herman, P. (2002). Spatial and temporal variation in benthic macrofauna and relationships with environmental variables in an estuarine, intertidal soft-sediment environment. *Marine Ecology Progress Series*(244), 105–124. doi: 10.3354/meps244105

A

Hydrodynamic boundary conditions

Noordzeekust
Brouwershavense Gat

Standen in cm t.o.v. NAP

	Slotgemiddelden			Waarden maansverloop	
Getijtype cq grootheid	**HW-stand**	**LW-stand**	**tijverschil**	**HW**	**LW**
Gem. springtij	172	-118	290	0:51	6:52
Gem. tij	144	-106	250	0:55	7:06
Gem. doodtij	106	-93	199	1:01	7:28
Gem. duur rijzing				6:14	
Gem. duur daling				6:11	
Gem. waterstand		0			

Gemiddelde over- en onderschrijdingsfrequenties		
Frequentie	**Overschrijding hoogwaterstanden**	**Onderschrijding laagwaterstanden**
1x per 10.000 jaar	530	
1x per 5.000 jaar	510	
1x per 4.000 jaar	500	
1x per 2.000 jaar	480	
1x per 1.000 jaar	460	
1x per 500 jaar	440	
1x per 200 jaar	420	
1x per 100 jaar	400	
1x per 50 jaar	380	
1x per 20 jaar	355	-245
1x per 10 jaar	340	-245
1x per 5 jaar	320	-245
1x per 2 jaar	295	-245
1x per jaar	280	-240
2x per jaar	265	-240
5x per jaar	240	-230
LAT		-155

Hoogst bekende waarde   351 cm   9 nov 2007   Periode 1981-2010
Laagst bekende waarde   -244 cm   14 feb 1994   Periode 1981-2010

Bijzonderheden:
- 1979 Aanvang waarnemingen

Figure A.1: Characteristic values water level [cm NAP] (Rijkswaterstaat, 2013)

B

Nourishment 2016

The total volume of the nourishment was approximately 500,000 m^3 and was planned to be dumped in between transects 2360 and 2260. In Table B, the indicative volumes per ray field are given (Rijkswaterstaat, 2014a).

Ray field	**Width [m]**	**Volume (indicative) [m^3/m]**
2240	200	0
2260	200	200
2280	200	400
2300	200	500
2320	200	700
2340	200	700
2360	200	0
2380	200	0
Total	**1000 m**	**500,000 m3**

Table B.1: Indicative volumes of beach nourishment at Brouwersdam beach 2015-2016 (Rijkswaterstaat, 2014a)

Depending on the bed level at the time, the contractor could adapt the design with a few m^3/m to nourish an in-situ volume that fitted within the specifications. According to the Jarkus data, the nourishment increases the beach volume with ca. 450,000 m^3. It is important to notice that the actual nourished volume was 500,000 m^3. There are multiple explanations for the fact that this data analysis led to a smaller amount of total volume. Reasons can be: (i) the sediment is nourished outside the +3 m and -3 m NAP zone (ii) the executed nourishment did not use as much as sediment as planned, (iii) the Jarkus data does not provide enough information. The first explanation is truthful but does not explain the huge difference. In Figure B.2 can be seen that nearly no sediment is deposited below -3 m. The second explanation is theoretically possible but is not considered to be likely: the total nourished volume will have been more or less 500,000 m^3. The third explanation is thought to have the largest contribution. The fact that Jarkus data is obtained yearly makes it plausible that the measurement in 2017 was executed a while after the nourishing activities were finished. Therefore, part of the nourished volume was lost already before the measurements were taken and therefore a smaller amount is measured.
In Figure B.1 the volumes per transect section (between -1 and +3 m NAP) are depicted. The observed volume increase is more northward and more widespread than stated in the indicated volumes. The increase is located between rays 2320-2240 instead of between 2340-2260. The largest increases are seen at rays 2300 and 2280.
Figure B.2) shows the southern transects in which the nourishment was executed.

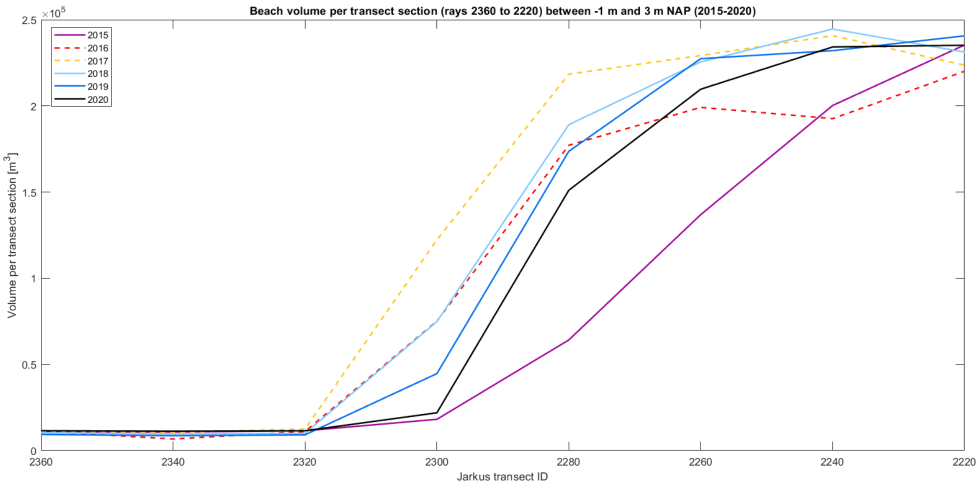


Figure B.1: Volume per transect section between 2015 and 2020, in the southern part of the beach

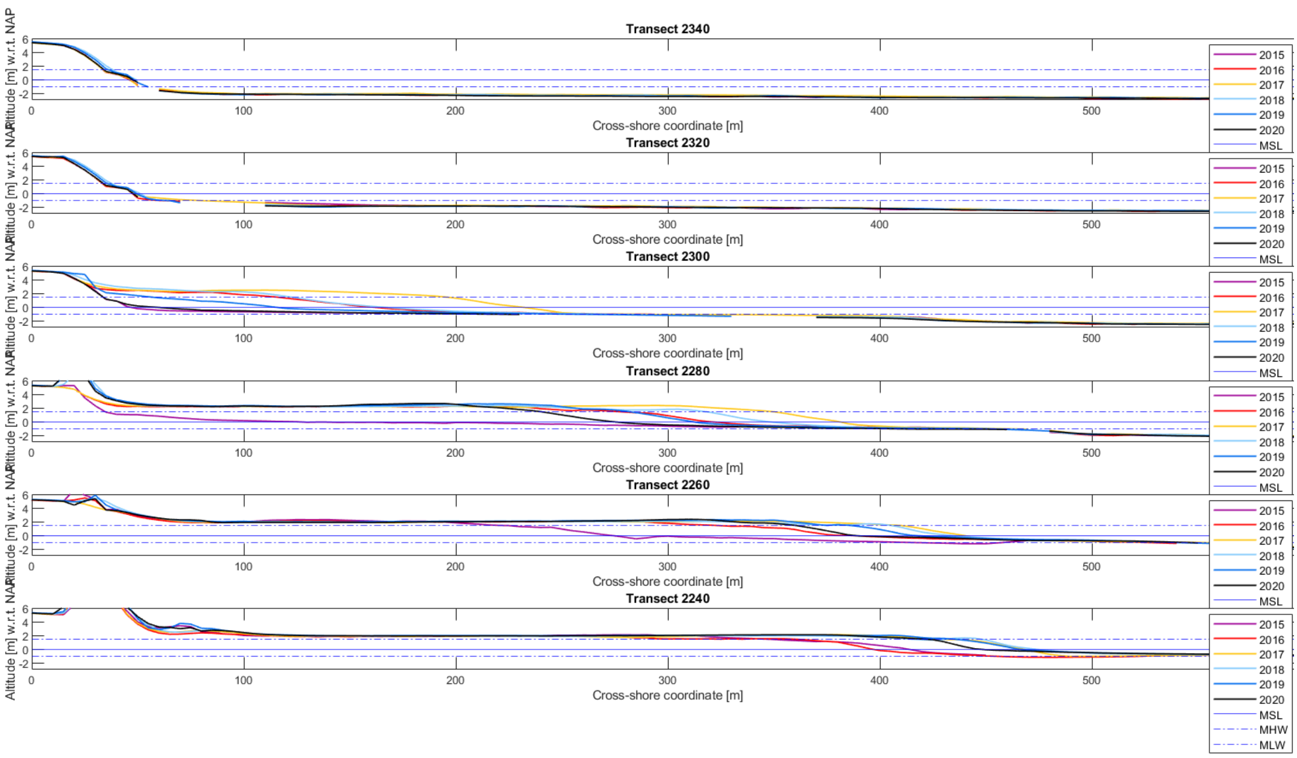


Figure B.2: Cross-shore profiles of Jarkus transects 2340 (south) to 2240 (north) (derived from the Jarkus dataset)

C
Tidal inlet in the Brouwersdam

Observations and research in the past two decades have shown that the closure of the Grevelingen by the Brouwersdam has undesirable effects on the natural value of this salt water lake (which used to be an estuary). (Mooyaart, 2010) It is also expected that the situation will deteriorate further if corrective action is not taken. As a result, it has been proposed to increase the discharge capacity of the Brouwersdam and to allow tidal action again in the lake Grevelingen. Several studies on the best location and the impact on the morphology of the earea have been carried out, for example by Wang (2010), Jansen et al. (2012), Mooyaart (2010) and Turlings et al. (2008).

Still, no conclusion has been drawn on the optimal location in the dam. During the research period of this thesis, an investigation is executed on the optimal location. Based on this research, executed by Deltares, the decision on the location will be made.

The possible locations of the inlet that were assessed by Turlings et al. (2008) are depicted in Figure C.1.

Figure C.1: Possible locations of the tidal inlet (obtained from Turlings et al. (2008))

D

Ecological background

D.1. Assessment of abiotic conditions according to the ZES-1 Ecotope System

For purposes such as research and conservation of an area, it can be very useful to classify the ecosystem based on geographical and ecological criteria into spatially distinct units (Dankers et al., 2012). Multiple classification systems were proposed in the past (Baptist et al., 2019). For all Dutch waters managed by the national government, an ecotope classification system was developed in 1996 (Wolfert, 1996). Subsequently, a classification system for estuarine and coastal waters was proposed by Dankers et al. (2001) and further elaborated by Bouma et al. (2005). This resulted in an ecotope system for coastal waters: the Salt Water Ecotope System ('Zoute wateren EcotopenStelsel'), abbreviated as ZES.1. The basis of this system is the notion that the main determinants of local communities are physical factors and processes of the environment. The system was set up for tidal zones and therefore the focus is on benthic fauna and salt marshes. The main environmental factors and processes in this system are mean and variability of salinity, substratum type, mean water depth and hydrodynamics. In order to define distinct ecotopes, class boundaries are used for the classification of the continuous variables. The ZES.1 ecotope system arranges the variables hierarchically. This hierarchy is based on the dominance of the physical environmental factors and processes for the determination of the biotic community (Bouma et al., 2005). This thesis follows the classification structure of ZES.1, proposed by Bouma et al. (2005), which thus serves as basis for this section. The different variables, classes and class boundaries are listed in Table D.1. A few class boundaries are adapted in order to use the most suitable ranges for the Grevelingen outer delta. The ecological importance and different classes of each variable are discussed separately from Section D.1.1 to D.1.6.

D.1.1. Mean salinity and salinity variability

The first level of the ZES.1 hierarchic system distinguishes between mean salinity and salinity variability. The mean salinity is categorized into fresh, brackish and marine. The variability class is either stable or variable.

Ecological importance

Water salinity has a large influence on the existence of species. There are no benthic species that can survive in fresh and salt water. All species are limited to a certain range in salinity, which makes it possible to distinguish between fresh, brackish and marine species (Bouma et al., 2005). The salinity variation has a significant effect on the distribution of benthic fauna as well (Wolff, 1973).

Classification

The mean salinity at the Brouwershavense Gat 08 measuring station (Figure 3.1) in 2015 - 2019 is computed and visualised in a graph in figure D.1. The mean salinity value is 31.4 ppt, with a standard deviation of 1.80 ppt. The salinity variation is computed as $\frac{Standarddeviation}{Mean}$, which is 0.06 at Brouwershavense Gat. As the mean salinity is larger than 18 ppt and the salinity variation is smaller than

Variable	Class	Class boundaries
Mean salinity	Fresh	Yearly mean <0.5 ppt
	Brackish	0.5 ppt ≤ yearly mean <18 ppt
	Marine	Yearly mean ≥ 18 ppt
Salinity variablity	**Stable**	Std/mean ≤ 0.25
	Variable	Std/mean >0.25
Substratum	**Sediment**	Soft sediment (sand, silt)
	Hard	Stone, wood, peat etc.
Depth	**Deep sublittoral**	Depth <-5 m LAT
	Shallow sublittoral	-5 m LAT <depth <MLW
	Low littoral	MLW <depth <MHW, 4 % ≤ mean exposure <25 %
	Middle littoral	MLW <depth <MHW, 25 % ≤ mean exposure <75 %
	High littoral	MLW <depth <MHW, 75 % ≤ mean exposure <85 %
	Supralittoral	Depth >MHW
Hydrodynamics	**Low dynamic sublittoral**	Max. current vel. <0.8 m/s
	High dynamic sublittoral	Max. current vel. ≥ 0.8 m/s
	Low dynamic littoral	Max. current vel. <0.8 and Max. orb. vel. <0.2 m/s
	High dynamic littoral	Max. orb. vel. <0.2 m/s or Max. orb. vel. ≥ 0.2 m/s
	Low dynamic supralittoral	Max. orb. vel. <0.2 m/s
	High dynamic supralittoral	Max. orb. vel. ≥ 0.2 m/s
Sediment composition	Silt	Silt content ≥ 25 %
	Fine sand	D_{50} <250 μm
	Coarse sand	250 μm < D_{50} <2000 μm

Table D.1: Variables, classes and class boundaries to describe the ecotopes of the Grevelingen outer delta. A bold term indicate that the ecotope class is present.

0.25, the salinity at Brouwershavense Gat 08 can be classified as 'Marine, stable'. This salinity regime is assigned to the whole Grevelingen outer delta.

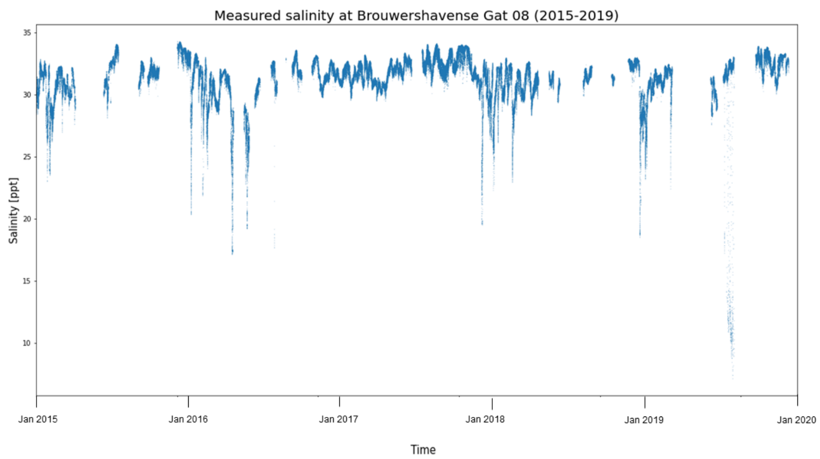


Figure D.1: Measured salinity in ppt at Brouwershavense Gat from 2015 up to 2019 (missing values are due to lacking measurement data), obtained from www.waterinfo.rws.nl (Rijkswaterstaat, n.d.-b)

D.1.2. Substrate

The seconds level discerns between two substrate classes, i.e. hard substratum (stone, wood, peat, etc) and soft substratum (bed of sediments like sand or silt). The grain size distribution influences the presence of flora and fauna in the seabed and therefore the soft substrate is subdivided into several categories at a lower level in the hierarchy. Almost all hard substrate that is present in Dutch brackish and marine is artificial. Examples are dike slopes, breakwaters and wrecks. This hard substrate is made of rubble or concrete elements, possibly covered by asphalt and wood. Natural hard substrate are peat and clay shoals, shellfish reefs and gravel banks (Bouma et al., 2005).

Ecological importance

For organisms, the most important difference between hard and soft substrate is that mainly a two-dimensional habitat is created by hard substrate, where the habitat in soft substrate is three-dimensional. In soft substrate, plants can take root and benthic animals like worms can burrow. Consequently, there is a clear difference between the flora and fauna on hard and on/in soft substrate. There are few species that can live both on hard and soft substrate. Examples are mussels (Mytilus edulis) and the Japanese Oyster (Crassostrea gigas).

Classification

Sediment beds cover the largest part of the natural parts of the Grevelingen outer delta. There is one exception. A little port is located at the northern part of the Brouwersdam, near Goeree. A breakwater called 'Blokkendam' provides shelter for the port. At both sides of this breakwater, natural oyster reefs emerged (van Moorsel et al., 2020). As this oyster reef is the only area with natural hard substrate in the Grevelingen outer delta, the features of this distinct area are discussed separately in Section 4.3.2 and the remainder of the outer delta is classified as soft substrate.

D.1.3. Depth

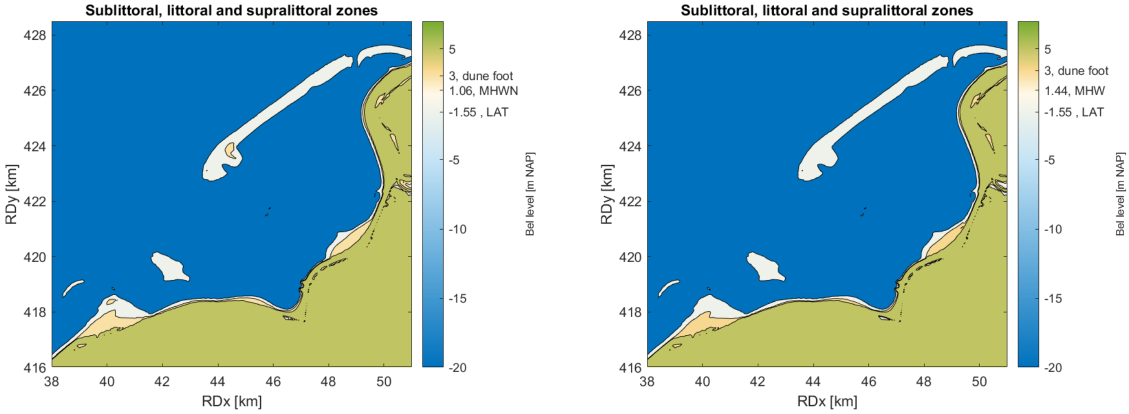
On the third level of the hierarchic system, a distinction is made based on mean tidal levels, namely the sublittoral zone (permanently under water), the littoral zone (flooded each tide, also called 'intertidal zone') and the supralittoral zone (not flooded each tide). The classes are bounded by depths with respect to certain tidal levels. Characteristic values of the tide at the Brouwershavense Gat 8 station are obtained from Rijkswaterstaat (2013). The tidal data characteristics are listed in Appendix A.

Ecological importance

There is a large difference between the occurrence of species in the sublittoral, the littoral and the supralittoral zone. For example, these differences relate to the way in which organisms feed themselves. The sublittoral soft substrate consists of gullies and deep or shallow flat areas. The littoral soft substrate consists sandy and silty tidal flats ('slikken'), possibly covered with pioneer vegetation. Lastly, the supralittoral soft substrate consists of beaches and salt marshes ('schorren').

Classification

The level that distinguishes the sublittoral from the littoral zone is in Bouma et al. (2005) set on MLWS (Mean Low Water at Spring tide), however according to Natura2000 regulations the value of the LAT (Lowest Astronomical Tide) is applied (Rijkswaterstaat & Royal HaskoningDHV, 2016). In the next section, the ecosystems and habitat types are described by means of the latter, and therefore the lower boundary is set on LAT . The same reasoning is applied for the class boundary between littoral and supralittoral, which is set on MHW (Mean High Water) instead of MHWN (Mean High Water at Neap tide) for this research. The classes are thus discerned as follows: Sublittoral zones have depths smaller than LAT ($d < -1.55$ m NAP), littoral zones is the zone with depths between LAT and MHW ($-1.55 < d < 1.44$ m NAP) and the supralittoral zone is the acreage above MHW ($d > 1.44$ m NAP). Figure D.2b shows the sublittoral, littoral and supralittoral zones in the Grevelingen outer delta with these class boundaries. From this figure, it can be concluded that there are only 2 offshore zones that are not sublittoral. These areas are the Bollen van de Ooster and the Middelplaat. Both areas are littoral. It is however interesting to point out that the Bollen van de Ooster has got a small supralittoral part when the boundary between littoral and supralittoral is set on MHWN (1.06 m NAP), which is smaller than the chosen boundary MHW (1.44 m NAP). Nearshore littoral and supra-littoral zones are found along the whole coastline in the Grevelingen outer delta, including the beach.



(a) Class boundary between littoral and supralittoral = 1.06 m NAP, MHWN

(b) Class boundary between littoral and supralittoral = 1.44 m NAP, MHW

Figure D.2: Sub-littoral (blue), littoral (white) and supra-littoral (beige) zones in the Grevelingen outer delta Bathymetry 2018-2019, derived from the Vaklodingen data set

D.1.4. Hydrodynamics

The hydrodynamic conditions are used as a characteristic at the fourth level of the hierarchic system. A distinction is made between high dynamic and low dynamic zones. The class boundaries differ for the sublittoral, littoral and supralittoral zone. For the sublittoral zone, the distinguishing class boundary is the maximum current velocity during an average spring tide. For the supralittoral zone, the distinction is made based on a wave attack during a storm, therefore the boundary is the maximum orbital velocity at spring tide with average storm conditions (storm occurrence of once per year). In the littoral zone, both currents and waves play an important role and therefore both boundaries apply.

Ecological importance

The influence of hydrodynamics on flora and fauna is diverse. When the current velocity or the wave action is able to move the sediment or bring it in suspension on a regular basis, benthic animals can hardly stay in place (Reise, 1985). Thereby, the depth to which sunlight reaches the bed depends on the the sea water turbidity due to suspended particulate matter (SPM) (Heath et al., 2017), which is a key factor in the determination of of the productivity of the ecosystem and the composition of the species (Heath et al., 2017). At locations where the top layer of the seabed is moving almost continuously, only some specific species can survive. For example, mussels are likely to be flushed away when the current velocity exceeds 0.6 m/s (Bouma et al., 2005). Another example is the wave action during storms in high dynamic supralittoral zones, which hinders the growth of vegetation on salt marshes.

Classification

The Grevelingen outer delta is a sheltered area, in with different hydrodynamic conditions can be distinguished. The hydrodynamics are discussed in detail in chapter 3.

D.1.5. Depth and submergence

On the fifth level of the system, sublittoral and littoral zones are subdivided based on elevation and flood duration, respectively. Deep and shallow sublittoral zones and low littoral, middle littoral and high littoral zones are distinguished.

Ecological importance

The ecological importance of depth of the sublittoral zone has mainly to do with the amount of sunlight that reaches the seabed. Some plant species are present in the sublittoral zone up to a depth of 5 m. Besides that, many juvenile and adult fish species find shelter and food in the shallow sub-littoral zone.

The littoral zone is subdivided into three zones on the basis of exposure time (%). The exposure time has a direct influence on the occurrence and growth of benthic animals in soft substrate. There is a distinct level above which benthic animals cannot survive, because the duration of submergence is too short (Reise, 1985).

Classification

As the Grevelingen outer delta contains several distinct sublittoral and littoral zones, it can be concluded that all types of ecotopes, from deep sublittoral to shallow littoral, are present.

D.1.6. Sediment composition

The sixth classification characteristic is the composition of the sediment (the grain size distribution). The variables are the median sediment diameter of the fraction of sand (D50 μm) and the content of silt (% < 63 μm).

Ecological importance

In addition to salinity, the most important factor in the spreading and existence of benthic animals in estuaries is the sediment composition (Ysebaert & Herman, 2002). The grain size distribution for instance influences the efficiency of the food intake. All benthic species have a range of sediment composition in which it can survive. Also foraging possibilities of certain waders ('steltlopers') depend on the sediment composition.

The sediment distribution is a reflection of the hydrodynamic conditions. In general it can be said that the more dynamic the hydrodynamics, the larger the average grain size. In areas with higher flow velocities, the sediment is mostly composed of coarse sand, whereas the sediment in places with milder hydrodynamic conditions contains fine sand and silt. The silt content of the sediment also depends on the amount of silt in the water column, the presence of benthic animals that are capable of trapping silt (such as mussel banks) and the cohesion of the sediments. The silt content often shows a seasonality, with higher levels in summer and fall.

However, most of the benthic fauna species in the Grevelingen outer delta is able to survive in seabeds with a wide range of the sediment composition. The bottom shear stress is in general more determinant for benthic fauna than the sediment composition (T. Prins, personal communication, November 18, 2020).

Classification

According to Prins et al. (2020) (Figure D.3), the median grain size (D_{50}) in the Grevelingen outer delta can be classified as fine sand (125-250 μm). Prins et al. (2020) also concludes that the silt content near the Bollen van de Ooster and the coast of Goeree increased in the past decade, whereas near the coast of Schouwen the sediment composition content got coarser. These changes are mainly induced by changes in morphology, current velocities and wave action.

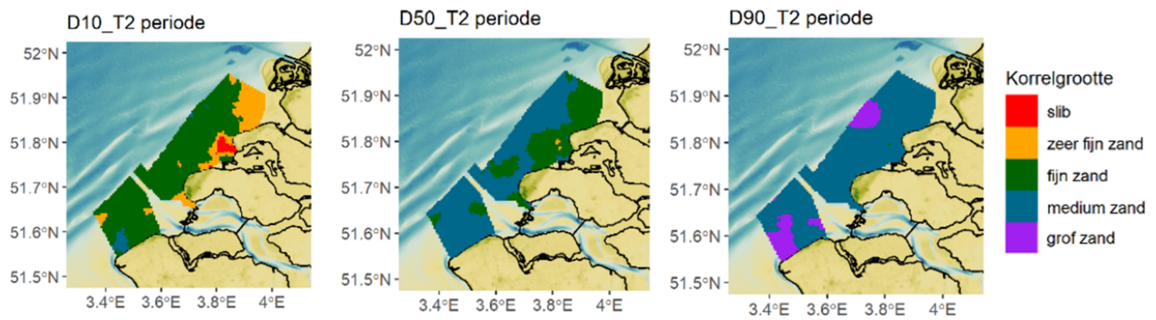
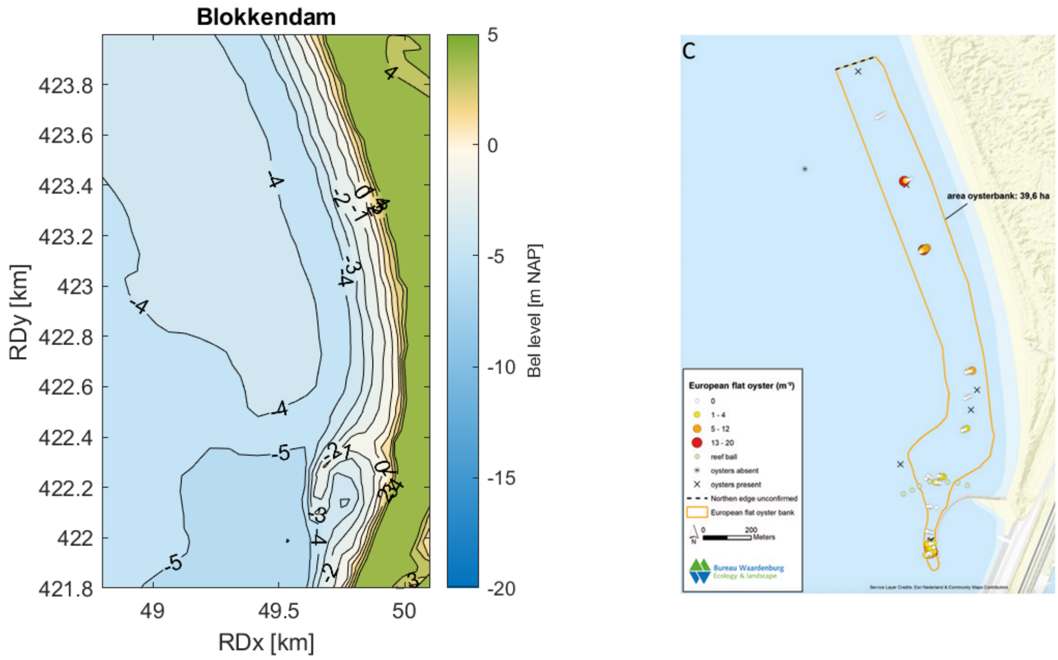


Figure D.3: Sediment composition distribution in Voordelta, expressed in median grain size diameter (middle panel), and the 10th and 90th percentiles (left and right panel, respectively), in period 2016-2018. Maps are based on an interpolation of sediment data from benthos sampling. Silt: D < 63 μm, very fine sand: D = 125-250 μm, medium fine sand: D= 250-500 μm, coarse sand: D > 500 μm. Obtained from Prins et al. (2020)

D.2. Shellfish reef Blokkendam

The Dutch part of the North Sea floor once contained a total surface area of 20.000 km^2 of shellfish reefs, which was about 20% of its total surface area, consisting of mainly flat oysters (Olsen, 1883).

The flat oyster was common in the estuaries of the Dutch South-West delta until the end of the 19th century (Kamermans et al., 2020). The reefs have almost entirely disappeared as a result of habitat destruction, overfishing and diseases (Smaal et al., 2015). Oyster reefs were a key element in the North Sea because of the hard substrate that was offered in a soft substrate environment. This is important for biodiversity, the regulation of water quality and an increase of fish production (Kamermans et al., 2020). Therefore, a shellfish bed restoration project was stared in the Voordelta. This project is part of the Haringvliet Dream Fund Project and ARK Nature and Worlds Wildlife Fund Netherlands (Sas et al., 2018). The project was designed for a minimum of 3 years and for at least 2 pilot locations. Certain criteria for the pilot locations, based on favourable conditions for flat oyster presence, led to the choice of the Hinderplaat in the Haringliet estuary and the Blokkendam. During one of the surveys at the Blokkendam, scuba divers discovered the bed with Pacific and flat oysters (Sas et al., 2016) (Sas et al., 2018). The contours of the reef were surveyed in August-October 2017 (Figure D.4a). The estimated surface area that is covered by the shellfish bed was estimated to be at least 39.6 hectares (Sas et al., 2018). The reef is situated in the shallow sublittoral zone, more specific between 2 and 5 m depth.



(a) Bathymetry at shellfish reef near Blokkendam, 2018-2019, derived from the Vaklodingen data set

(b) Acreage of oyster reef at Blokkendam (oyster reef area indicated by orange line) (Sas et al., 2018)

Figure D.4: Oyster reef near Blokkendam, Grevelingen outer delta

As part monitoring and evalution of the Nature Compensation Voordelta (NCV), van Moorsel et al. (2020) conducted a spatial analysis of benthic fauna in the Voordelta. This analysis showed that the reef near the Blokkendam provides habitat for many unique species. The Japanese and flat oyster provided substrate for other unique species like sponges (sponzen), ascidians (zakpijpen), brittle stars (brokkelsterren) and sea spiders.

The above mentioned data highlight the importance of the conservation of the shallow sublittoral acreage near the Blokkendam which is thereby labeled as a design condition.

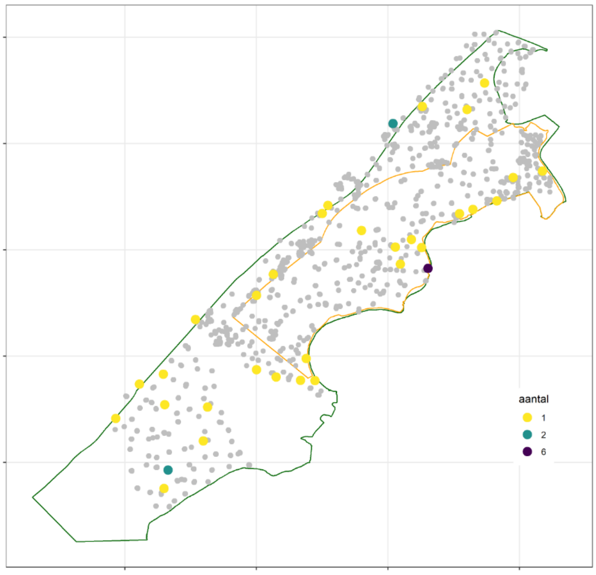


Figure D.5: Number of unique species per study location of the Monitorying and Evaluation Programme (MEP) of the NCV. A colored dot shows the amount of species that during the monitoring phase (2004-2019) was only found at that location. On grey locations no unique species were found. (van Moorsel et al., 2020)

D.3. Habitat requirements for oysters

Oysters provide many benefits to the coastal system. The main ecosystem services that they can provide for the Brouwersdam beach are coastal protection (by dissipation of waves) and improvement of the water quality (by trapping sediment and filtering nutrients). They also provide habitat for many other species and can therefore enhance biodiversity. (Smaal et al., 2015) The impact on the coastal system can be positive, in cases of wave reduction, erosion limitation, the trapping of fine sediment an organic matter and the creation of shelter. Disadvantages are that the presence of the shellfish can result in a shift of the benthic population, the present ecosystem can be degraded and that the species that the shellfish species can be an invasive species. (Ecoshape, n.d.-a)
Every shellfish species (or more specific: oyster species) has different habitat requirements. As a full analysis of all types of shellfish types is not within the scope of this thesis, a first assessment is made on the feasibility of the Japanese oyster (also called Pacific oyster or Zeeuwse oester). A temperate and intertidal habitat with soft sediments is ideal for this species. However, there are aspects that may form the bottleneck to guarantee the survival of this species. This section elaborates on the habitat requirements for the Japanese oyster and whether the necessary conditions are present (or can be created) near the beach of the Brouwersdam, so that oysters can be a part of the Nature-based design. Note that this is a first-order assessment. The guidelines that are followed originate from Ecoshape (n.d.-a).

The critical habitat requirements as described by Ecoshape (n.d.-a) is based on the four spheres approach, which states that the biosphere, hydrosphere, lithosphere and atmosphere interact with each other and therefore have to be considered together. The relevant parameters for oyster establishment and the critical values are depicted in Figure D.6, derived from Building with Nature studies and literature and summarized in Ecoshape (n.d.-a). If the requirements are (made) suitable, then the location may be suitable for oysters.

Biosphere

The conditions of the biosphere are similar near the beach and at the Blokkendam. The food availability, such as zooplankton, is sufficient. Oyster larvae are needed to create an artificial substrate reef. These larvae can be supplied. The aspect of biofouling is a problem that mostly occurs in the higher intertidal zone; the oysters shall therefore be placed near and below the mean water level. Predation by e.g. crabs or shrimps is assumed to be low as that is the case in the present shellfish reef near the Blokkendam. The same holds for diseases that can deplete the oyster population.

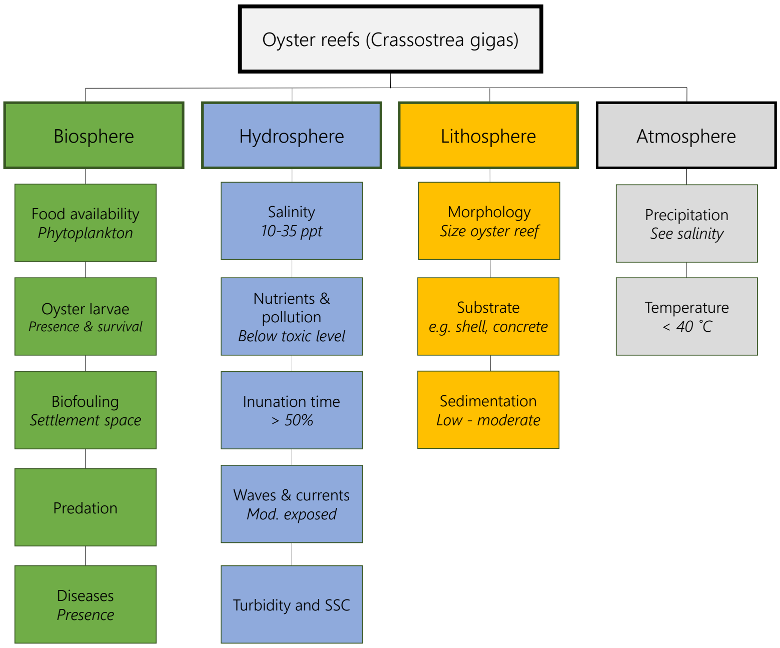


Figure D.6: Habitat requirements for oyster reefs (Japanese oyster) (adapted from Ecoshape (n.d.-a))

Hydrosphere
The salinity of the water should be between 10-35 ppt. This requirement is met (Section D.1.1). The level of nutrients and pollution is below the toxic level, as the water quality is (nearly) equal to the Blokkendam area.
Some requirements of the hydrosphere can be partly created to be suitable for oysters, namely the inundation time, wave and currents and the turbidity.
The oysters should be located at a location which is inundated roughly 40-50 % of the time. Less inundation times mean that the oysters have less time to feed and have a higher chance of being overheated and dehydrated. According to Walles (unpublished) (Ecoshape, n.d.-a), oyster larvae settle most and grow best in the intertidal area, at a level that is ca. 60 cm below MSL (based on experiments in the Netherlands).
Waves and strong currents can negatively affect oysters by dislodging them, resuspending sediment and inducing erosion. In wave-dominated areas (which is the Brouwersdam beach), the oysters should be kept in cages, to prevent the hard substratum from being spread.
The turbidity of the water and the SSC (suspended sediment concentration) can influence the oysters by clogging and negatively impacting their feeding and breathing capabilities. (Troost, 2010) However, when the turbidity is below a certain level, the oysters can reduce the turbidity and concentration of phytoplankton. (Grabowski & Peterson, 2007)

Lithosphere
The most suitable substrate for oysters is dependent on the rate of exposure of the location. The exposure time, bottom shear stress, wave action and flow velocities have a large impact on the occurrence of oyster reefs. (Schellekens et al., 2012) In sheltered areas almost all types of hard substrates, ropes and even plant material are applicable for oysters to settle on. Oyster shells are mostly the basis of artificial reefs. At the North Sea coast, fixed substrate is needed to prevent the shells from displacement, tossing and turning. Structures like gabions are stabilizing and are applicable. Mostly, the substrate must be fixed for a certain period of time, after which the larvae have created a fixating crust. (Ysebaert & Herman, 2002) Local testing is necessary to investigate this.
The rate of erosion or accretion is very important for oyster survival. Large sedimentation rates result in dying of the oysters, whereas erosion can damage a reef as well.

Atmosphere
Heat and freeze can damage oysters, but the Japanese oyster can withstand relatively large ranges of temperature. The boundary of lower than $40\ ^{\circ}C$ is met. Thereby, precipitation will not influence the salinity level of the North Sea. The atmospheric conditions are thus limiting factors.

E

Model input

E.1. Reduced wave climate

Table E.1 – Schematized offshore wave climate

Nr.	H_s [m]	T_p [s]	θ_{wave} [^oN]	U_{wind} [m/s]	θ_{wind} [^oN]	$Dur.$ [d/y]	$Type$
1	0.35	4.55	347.85	5.07	17.28	2.90	Sea
2	0.77	5.01	3.57	7.46	17.31	5.38	Sea
3	1.40	6.17	2.42	9.60	16.61	7.08	Sea
4	2.39	7.70	355.34	12.21	15.09	1.59	Sea
5	3.31	8.81	344.97	14.69	12.65	0.33	Sea
6	0.34	4.56	359.57	5.18	43.84	3.22	Sea
7	0.77	4.97	17.40	7.27	43.79	5.16	Sea
8	1.41	6.12	14.91	9.77	44.79	7.14	Sea
9	2.35	7.47	11.09	13.11	44.61	1.58	Sea
10	3.30	8.80	4.23	15.31	41.99	0.17	Sea
11	0.35	4.57	7.43	5.02	77.42	3.14	Sea
12	0.76	4.96	30.39	7.23	76.29	5.94	Sea
13	1.38	6.06	24.94	10.19	74.48	6.40	Sea
14	2.22	7.35	5.75	12.93	70.03	0.43	Sea
15	0.35	4.49	26.85	5.43	105.96	4.55	Sea
16	0.73	4.74	59.49	7.85	105.56	6.19	Sea
17	1.26	5.56	58.69	11.06	101.48	2.46	Sea
18	2.19	6.85	334.71	15.41	99.56	0.10	Sea
19	0.35	4.48	326.59	5.20	134.64	4.43	Sea
20	0.70	4.56	144.92	7.79	135.10	4.29	Sea
21	1.20	5.20	132.40	10.88	136.87	0.63	Sea
22	0.36	4.48	228.39	5.43	166.04	4.72	Sea
23	0.73	4.70	207.83	7.90	167.23	7.05	Sea
24	1.28	5.44	209.58	11.43	170.74	3.18	Sea
25	2.18	6.32	205.82	16.02	172.43	0.09	Sea
26	0.37	4.48	250.55	4.98	195.01	4.27	Sea
27	0.76	4.86	234.23	7.75	195.22	11.44	Sea
28	1.40	5.80	232.32	11.38	196.71	14.84	Sea
29	2.28	6.90	231.55	15.67	200.36	1.82	Sea
30	3.28	7.87	234.31	20.37	202.68	0.07	Sea
31	0.37	4.49	260.66	5.02	225.76	4.15	Sea
32	0.77	4.93	247.99	7.64	226.44	12.19	Sea
33	1.44	5.95	243.45	11.08	227.13	21.23	Sea
34	2.34	7.09	240.87	15.03	228.71	6.46	Sea

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Table E.1 – continued from previous page

Nr.	H_s **[m]**	T_p **[s]**	θ_{wave} **[^oN]**	U_{wind} **[m/s]**	θ_{wind} **[^oN]**	$Dur.$ **[d/y]**	$Type$
35	3.30	7.99	241.73	19.07	230.00	0.53	Sea
36	4.26	8.76	241.33	23.12	234.35	0.04	Sea
37	0.38	4.53	270.54	4.76	254.16	3.50	Sea
38	0.77	4.96	257.94	7.18	252.88	10.49	Sea
39	1.43	6.00	255.19	10.22	252.45	16.95	Sea
40	2.36	7.15	253.73	14.10	253.59	4.89	Sea
41	3.35	8.17	254.71	17.91	256.35	0.59	Sea
42	4.29	8.98	250.83	21.70	258.70	0.05	Sea
43	0.37	4.61	285.28	4.11	284.18	2.04	Sea
44	0.77	5.07	284.73	6.61	284.37	4.76	Sea
45	1.47	6.22	289.76	9.39	284.86	9.46	Sea
46	2.41	7.34	287.02	13.04	285.20	4.16	Sea
47	3.36	8.19	289.32	16.47	285.96	1.11	Sea
48	4.32	8.90	285.70	19.25	285.39	0.13	Sea
49	0.36	4.61	301.67	3.97	315.03	1.38	Sea
50	0.77	5.11	310.68	6.39	315.17	3.42	Sea
51	1.47	6.35	314.83	8.91	314.57	6.08	Sea
52	2.41	7.64	319.67	12.20	314.40	2.93	Sea
53	3.40	8.65	318.78	15.50	314.63	0.89	Sea
54	4.27	9.28	317.29	18.13	315.19	0.14	Sea
55	5.26	10.78	326.00	21.33	324.33	0.01	Sea
56	0.35	4.59	323.44	4.26	346.27	1.69	Sea
57	0.76	5.04	330.44	6.68	345.73	3.15	Sea
58	1.46	6.39	339.55	8.91	345.48	5.96	Sea
59	2.42	7.76	336.86	11.94	344.62	2.64	Sea
60	3.34	8.81	335.83	14.81	344.12	0.67	Sea
61	4.29	9.83	327.46	16.89	341.23	0.09	Sea
62	0.34	5.88	335.68	3.84	16.71	4.33	Swell
63	0.74	6.57	352.27	5.03	16.29	5.39	Swell
64	1.27	7.35	350.84	6.48	15.22	2.27	Swell
65	2.18	8.82	344.25	8.71	14.19	0.06	Swell
66	0.34	5.91	339.55	3.94	44.18	4.47	Swell
67	0.72	6.56	356.70	4.88	44.31	4.33	Swell
68	1.27	7.34	357.58	6.47	44.66	1.58	Swell
69	2.21	8.89	342.77	9.33	43.06	0.05	Swell
70	0.35	5.89	341.75	3.88	75.89	3.77	Swell
71	0.71	6.43	4.09	5.10	76.42	4.70	Swell
72	1.27	7.31	3.92	6.63	74.36	1.50	Swell
73	2.18	8.93	354.59	7.88	73.12	0.02	Swell
74	0.34	5.90	339.88	4.08	105.89	4.61	Swell
75	0.69	6.50	5.19	5.09	104.74	4.26	Swell
76	1.21	7.42	1.10	5.74	103.20	0.61	Swell
77	2.12	8.75	358.50	10.73	101.75	0.00	Swell
78	0.34	5.94	327.88	4.07	135.01	5.36	Swell
79	0.67	6.63	345.33	4.34	134.02	3.03	Swell
80	1.19	7.66	343.29	4.00	133.95	0.33	Swell
81	2.24	9.89	337.29	9.73	141.71	0.01	Swell
82	0.34	5.95	310.07	4.25	165.91	4.74	Swell
83	0.67	6.54	305.90	4.79	166.46	2.92	Swell
84	1.19	7.61	332.60	4.68	166.24	0.31	Swell
85	2.15	9.63	336.50	7.35	171.00	0.01	Swell
86	0.35	5.95	306.11	3.82	194.61	4.04	Swell
87	0.70	6.45	302.96	5.13	195.85	3.91	Swell

Continued on next page

Table E.1 – continued from previous page

Nr.	H_s [m]	T_p [s]	θ_{wave} [^oN]	U_{wind} [m/s]	θ_{wind} [^oN]	$Dur.$ [d/y]	$Type$
88	1.18	7.40	319.43	6.32	196.20	0.67	Swell
89	2.11	8.57	305.00	7.70	197.33	0.00	Swell
90	0.36	5.91	310.84	3.77	225.92	3.84	Swell
91	0.70	6.46	308.01	5.13	226.24	5.01	Swell
92	1.18	7.34	315.49	6.30	226.21	0.87	Swell
93	2.04	8.40	317.00	7.60	212.00	0.00	Swell
94	0.37	5.88	309.29	3.59	254.86	3.32	Swell
95	0.72	6.42	316.19	4.88	254.14	4.98	Swell
96	1.23	7.37	321.61	6.44	256.28	1.46	Swell
97	0.36	5.85	314.31	3.17	284.89	2.43	Swell
98	0.73	6.42	324.31	4.39	285.15	3.75	Swell
99	1.30	7.48	331.26	6.19	286.35	1.88	Swell
100	2.15	8.92	331.48	9.19	288.98	0.06	Swell
101	0.36	5.87	325.07	3.01	315.67	2.26	Swell
102	0.74	6.50	334.71	4.16	315.39	3.70	Swell
103	1.32	7.50	338.05	6.06	316.20	2.29	Swell
104	2.19	8.92	334.47	8.82	316.81	0.08	Swell
105	0.35	5.90	329.61	3.18	346.49	2.86	Swell
106	0.74	6.56	344.65	4.32	346.26	3.95	Swell
107	1.31	7.48	345.40	6.15	345.46	2.48	Swell
108	2.22	8.94	342.25	9.17	344.93	0.09	Swell

Table E.1: Schematized offshore wave climate

E.2. Delft3D-WAVE and UNIBEST-CL+ input parameters

	Parameter	Value	Unit	Description
Boundaries	BoundCond	Uniform	[-]	Conditions along boundary
	Spectrum	JONSWAP	[m]	Shape of the wave spectrum
	PeakFactor	3.3	[-]	Peak enhancement factor JONSWAP
	DirSpread	Cosine power	[-]	Directional spreading
Processes	Wave forces	Dissipation 3D	[-]	Method of wave force computation
	Set-up	False	[-]	Wave related setup
	GenModePhys	3rd	[-]	Generation mode for physics
	Breaking	True	[-]	Depth-induced breaking (B&J model)
	α	1.0	[-]	Alpha coefficient for wave breaking
	γ	0.73	[-]	Gamma coefficient for wave breaking
	NonLinTriad	True	[-]	Non-linear triad interactions (LTA)
	α_{tr}	0.1	[-]	Alpha coefficient for triads
	β_{tr}	2.2	[-]	Beta coefficient for triads
	BotFric	JONSWAP	[-]	Bottom friction type
	f_w	0.067	[m2s^-3]	Bottom friction coefficient
	Diffraction	False	[-]	Diffraction
	WindGrowth	True	[-]	Wind growth
	Quadruplets	True	[-]	Quadruplets
	WhiteCap	Komen et al.	[-]	Process of whitecapping
	Refraction	True	[-]	Refraction in spectral space
	FreqShift	True	[-]	Frequency shift in spectral space

Table E.2: Input parameters for the Delft3D-WAVE model

Parameters	Parameter	Value	Unit	Description
Waves	Formula	Fredsøe (1984)		Wave-current interaction formula
	α	1.0	[-]	Alpha coefficient for wave breaking
	γ	0.8	[m]	Gamma coefficient for wave breaking
	f_w	0.01	[-]	Coefficient for bottom friction
	k_b	0.1	[m]	Value of the bottom roughness

Wind	Formula	Smith & Banke (1975)		Formula for wind-driven currents
	C_{drag}	0.005	[-]	Wind-drag coefficient
	ρ_a	1.225	$[kg/m^3]$	Density of air
Transport	Formula	Van Rijn (2004)		Sediment transport formula
	D_{10}	130	[μm]	10% grain diameter
	D_{50}	210	[μm]	Median (50%) grain diameter
	D_{90}	300	[μm]	90% grain diameter
	D_{ss}	160	[μm]	50% grain diameter of suspended sediment
	ρ_s	2650	$[/m^3]$	Sediment density
	ρ_s	1025	$[/m^3]$	Seawater density
	n	0.4	[-]	Porosity
	T	15	$[^oC]$	Water temperature
	s	30	[ppm]	Salinity
	f_{cs}	1.0	[-]	Current related suspended transport factor
	f_{cb}	1.0	[-]	Current related bedload transport factor
	f_{ws}	1.0	[-]	Wave related suspended transport factor
	f_{wb}	1.0	[-]	Wave related bedload transport factor

Table E.3: Input parameters for the UNIBEST-CL+ model. For the

F

Model output

F.1. UNIBEST-CL+ sediment balance

Forecast model

This section includes the sediment balances of the forecast model for high water, mean sea level and low water conditions.

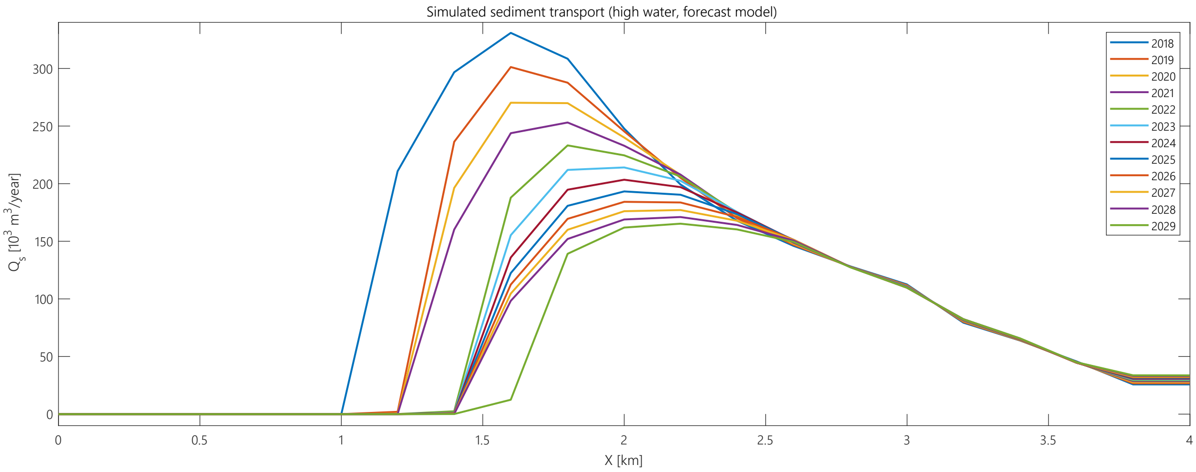


Figure F.1: Simulated yearly sediment transport rates during high water, forecast model (2018-2030)

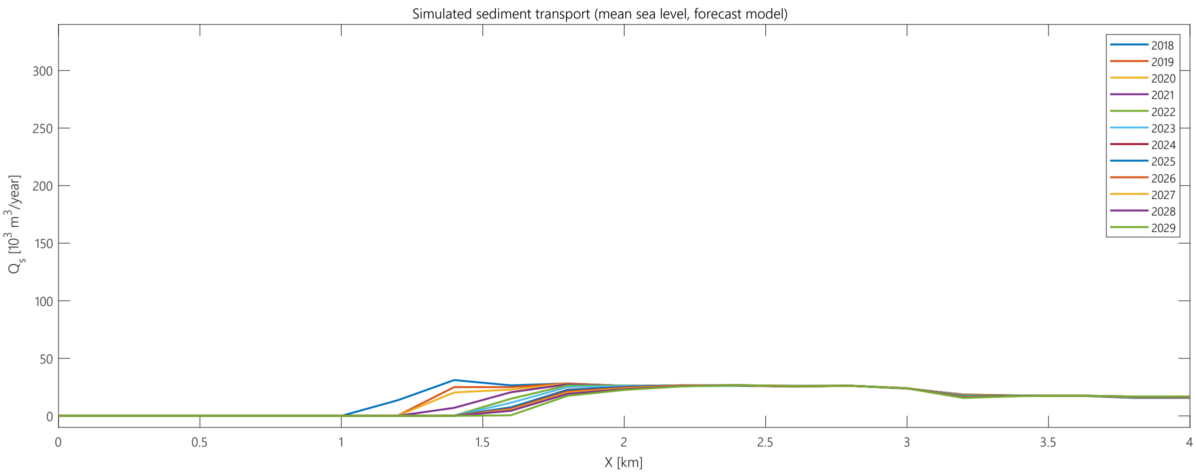


Figure F.2: Simulated yearly sediment transport rates during mean water level, forecast model (2018-2030)

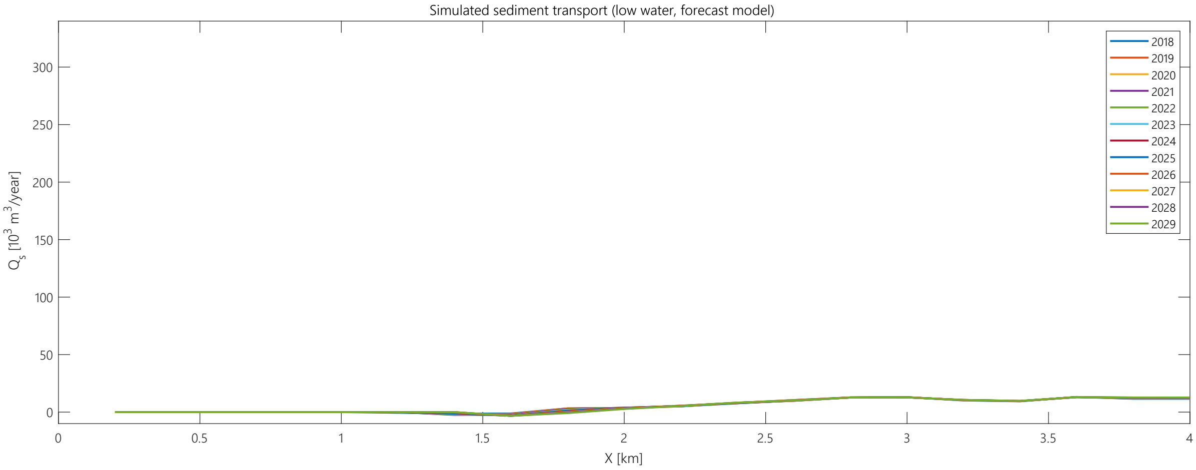


Figure F.3: Simulated yearly sediment transport rates during low water, forecast model (2018-2030)

F.2. Cross-shore distribution of longshore transport (2018)

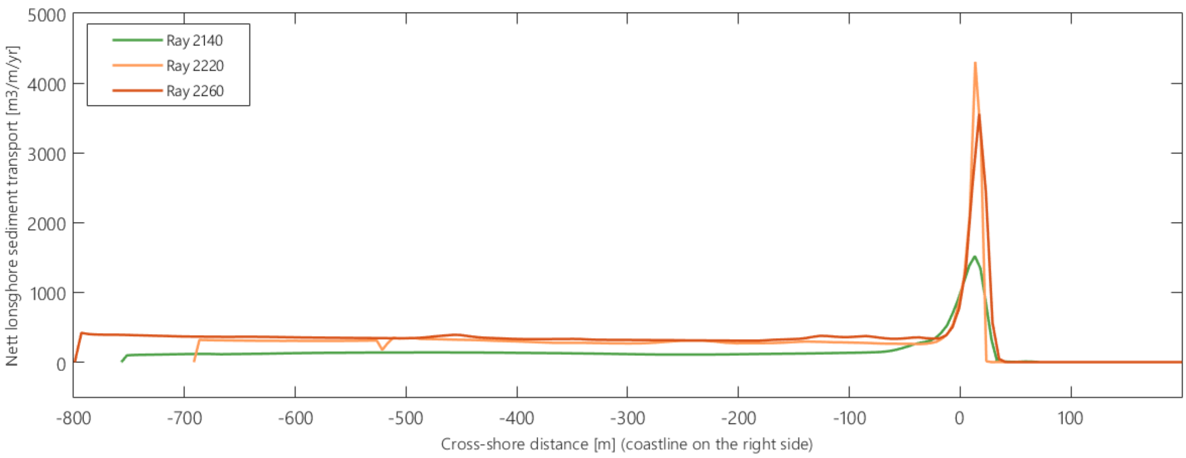


Figure F.4: Cross-shore distribution of longshore transport during high water conditions at ray 2260 (forecast model, 2018)

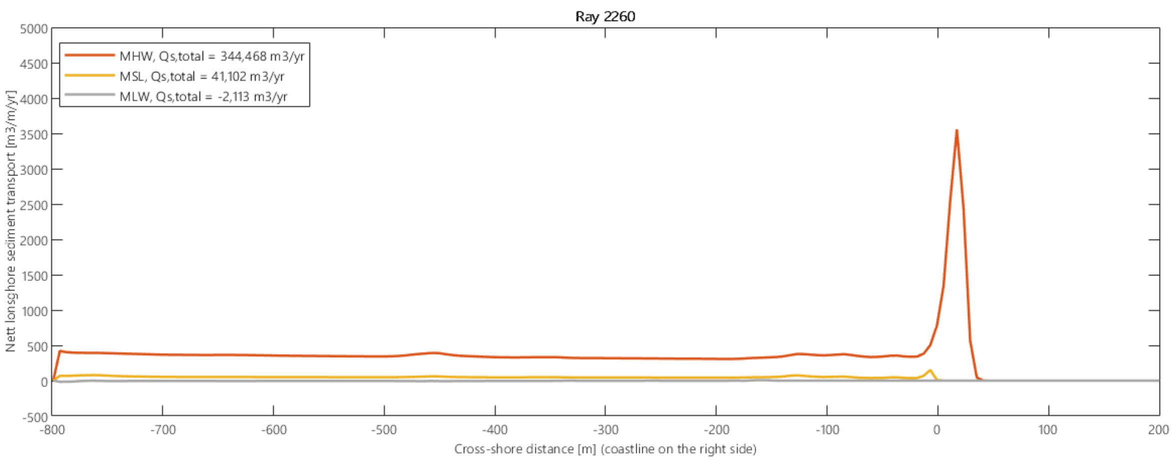


Figure F.5: Cross-shore distribution of longshore transport at ray 2260 during high. mean and low water conditions (forecast model, 2018)

G
Designs

This chapter provides the necessary background of the different alternatives (A up to E). Each section below discusses the background of the design choices, the model simulation of the shoreline and the resulting expected shoreline development. Section G.6 discusses the calculation of the costs and the expected lifetime. This chapter is concluded with a section that discusses the wave transmission at low-crested structures.

G.1. Design A - pocket beaches

G.1.1. Design A

Groyne length, shape and orientation

To determine the optimal groyne length, the cross-shore distribution of the longshore transport is examined (Figure F.4). Between cross-shore distances x = -100 and x = 50 m (i.e. 100 m seaward and 50 m in landward of the shoreline), 30 to 40 % of the transport takes place. Per 100 m extra groyne length, ca. 10% of the sediment transport is trapped. Create a stable beach but to minimize lee-side erosion, a groyne length of 150 m suffices. These groynes are positioned along the coast with an intermediate distance of 200 to 400 m. The most southern groyne is located at ray 2320. The updrift side of this groyne therefore experiences no accretion, as the sediment supply is zero at this point. This groyne has the function of sheltering the southern edge of the beach from wave attack and flood current velocities, in order to maintain the southern edge.
The groyne orientation is nearly perpendicular to shoreline, and has the shape of an 'L', tilted towards the equilibrium coastline angle (west). This creates a sheltered area in which, if the equilibrium coastline angle is reached, less lee-side erosion will occur (See Section G.1.2 for further elaboration). The total length of the L-shaped groynes is thus 200 m.

With respect to bed protection, a rough estimation of the expected scour depth is made. Scour is induced locally by, among others, increased orbital velocities due to reflected waves, high wave energy density in front of the structure due to wave breaking and accelerated flow velocities due to structure alignments redirecting the current (Hughes, 1991). A rule of thumb to predict the for scour under wave action alone is given by the Coastal engineering manual (CEM) (USACE, 2003), which suggests that $y_{max} = H_{max}$, in which y_{max} is the maximum depth of scour below the natural bed, and H_{max} is the maximum height of the unbroken wave that can be supported by the original water depth at the toe of the structure (CIRIA et al., 2007). As the waves are depth- limited, the unbroken H_{max} can be determined based on the water depth. According to Bosboom & Stive (2015), this maximum wave height is equal to twice the significant wave height in a Rayleigh distribution: $H_{max} = 2H_s$. As $H_s \simeq 0.5m$, this means that $H_{max} = 1m$. Hence, the wave breaking induced scour is approximately $y_{max} = H_{max} = 1m$. However, this formula applies to vertical structures. Moreover, the scour depth is directly proportional to the reflection coefficient of the structure (CIRIA et al., 2007). As this structure is submerged during high water (hence, reflection coefficient < 1 during the largest wave attacks), semi-permeable and has a sloping face, the scour depth due to waves is considered to be minimal.
However, along-structure currents can increase the scour depth (Hughes, 1991). During high water,

flow velocities are minimized but not reduced to zero. This reduced structure-parallel flows significantly. The rate at which the flow velocities near the groyne are enhanced by the structure configuration should be assessed in further study. For the design of this groyne, moderate scour potential (as elaborated by CIRIA et al. (2007)) is assumed. Here an armour stone toe with a width of ca. $3D_{n50}$ is suggested. As the material of this groyne is more natural, the fascine matresses of the bottom layer are extending a meter to create a toe structure.

Groyne height

A crest height of the groyne of ca. +1 m NAP results in groyne heights of 0.7 m at the landward side up to ca. 2 m at the seaward side. An exception is the most northern groyne, which seaward tip is located at ca. -2.5 m deep deep. This average groyne height reduces the littoral drift sufficiently, reduces wave impact and current velocities. To reduce the possibility of rip currents near the groynes, the crest level of the groyne is be below the high water level (which is +1.44 m NAP).

During mean and low water conditions, the wave attack and tidal currents at the lee side of the groyne are assumed to be zero (which is approximately 70% of the time). However, the littoral drift is small during these conditions: high water conditions are more important. During high water, the groynes are submerged (MHW is ca. 1.4 m NAP). The wave over-topping during high water conditions is assessed using the simplified formula for wave transmission of Van der Meer (1991) for low-crested structures. Appendix G.7.1 elaborates on the basis and assumptions this equation. As waves from the west with characteristics $H_s = 0.9m$ and $T_p = 5.5s$ are dominating the transport, these waves are used in the determination of the wave transmission. A value of $K_t = 0.61$ leads to a lee-side wave heights of $H_{s,lee} = 0.54m$. Thereby, waves diffract around the tip of the groyne and contribute to sediment transport in southern direction and thus reduce the northern directed littoral drift.

G.1.2. Shoreline development of alternative A

Model set-up

The groynes are simulated in UNIBEST as impermeable groynes with a length of 150 m. The orientation is parallel to the defined rays, which is a different orientation than the design. Thereby, the shelter effect of groynes is not taken into account, for reasons explained below in Paragraph G.1.2. The simulated shoreline development thus deviates quite substantially from the expected shoreline development.

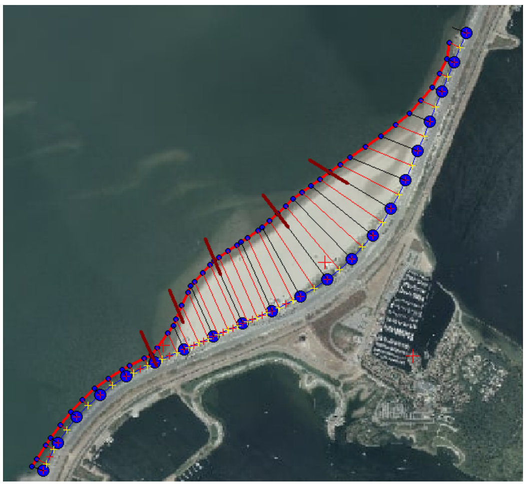


Figure G.1: Model set-up for alternative A - Pocket beaches

Accretion at tip of groyne

The shelter effect behind the multiple groyne system is difficult to simulate with the UNIBEST-CL module. In the real situation, the wave impact and longshore current at the lee-side of the groyne are reduced. This induces the equilibrium coastline angle behind a groyne to be different from the angle at the updrift side of the groyne. When in the model a local sheltered area is implemented (in UNIBEST this is done by so called 'local transport rays'), the shoreline behind the groyne will orientate to this new equilibrium angle. The model simulates a reasonable coastline position until the shoreline reaches the tip of the groyne. In reality, the accretion at the lee-side of the groyne stops at the tip, because the wave impact and current velocities are at their 'normal level' (so equal to or even larger then the situation without groynes), and thus the sediment transport at the tip of the groyne is directed towards the lee-side. Thus, the equilibrium coastline angle at the lee-side of a groyne differs in cross-shore direction. It is in UNIBEST not possible to account for these differences due to the underlying assumptions of the model. When the lee-side transport ray of a groyne is adapted to the conditions behind the groyne, the total cross-shore profile is adapted, leading to accretion at the tip of the groyne. Figure G.2 shows this accretion.

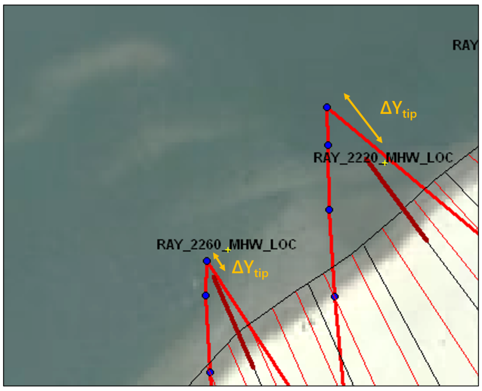


Figure G.2: Simulated accretion at the tip of two groynes when the sheltering effect for waves and currents behind groynes is accounted for in the model. ΔY_{tip} indicates the overestimated shoreline advance.

Influence of sheltering and shape of groyne on UNIBEST simulation

In the model UNIBEST-CL+, groynes can only be straight and orientated parallel to the user-defined rays. To simulate the effect of a groyne that crosses a ray is not possible. When the groynes are 150 m long and orientated at the defined rays, the equilibrium coastline angle is not reached within 12 years of shoreline development (according to the forecast model). Only when the equilibrium coastline orientation is reached, the sediment transport in the considered pocket beach is zero. This depicted in Figure 8.5. The equilibrium coastline orientation is in the middle of the beach 270 $^\circ N$ (ray 2260, MHW), see Figure 8.2, whereas the current coastline orientation is 320 $^\circ N$. The coastline between groynes 3 and 4 thus have to rotate ca. 50 $^\circ N$ in counterclockwise direction, to reach its equilibrium orientation. In UNIBEST, all updrift rays then erode until this coastline orientation is reached, whereas in real life sheltering would stop the erosion. This effect is even larger in the case of L-shaped groynes.

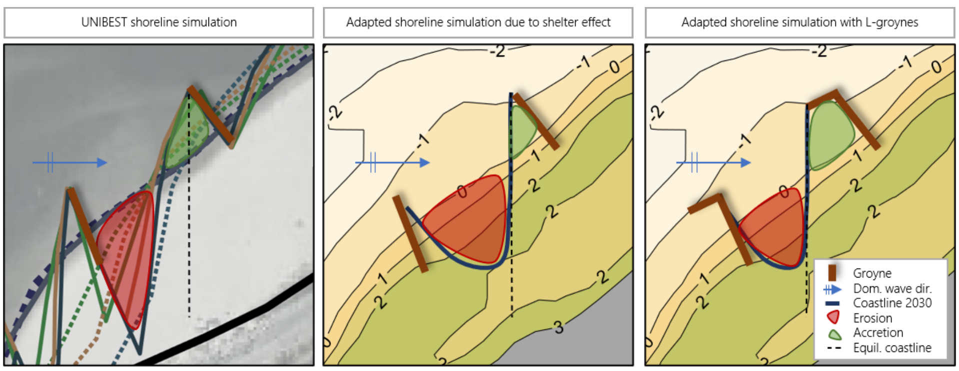


Figure G.3: Difference between simulated shoreline development in UNIBEST (left panel), expected shoreline development with shelter effect taken into account (middle panel) and expected shoreline development with shelter effect and L-groynes (right panel). Equilibrium coastline angle is ca. 270 $^\circ N$ (ray 2260).

G.2. Design B - C-shaped groyne

This section includes the design, the background of the expected shoreline development, the sediment balance and the criteria analysis of alternative B.

G.2.1. Design

This alternative can also be referred to as an artificial headland. This term is used for structures designed to mitigate downdrift erosion and ensure beach formation. Again, a the best design is made based on the sediment balance of 2018. The goal of the C-shaped groyne is to reduce the sediment transports in the south to nearly zero. The height of the groyne is equal to alternative A, which is approximately +1 m NAP. As the groyne is more or less constructed at the -1 m depth contour, the average height of the groyne is 2 m.
The construction material and dimensions of the groyne are similar to the design of solution A (brushwood groynes).

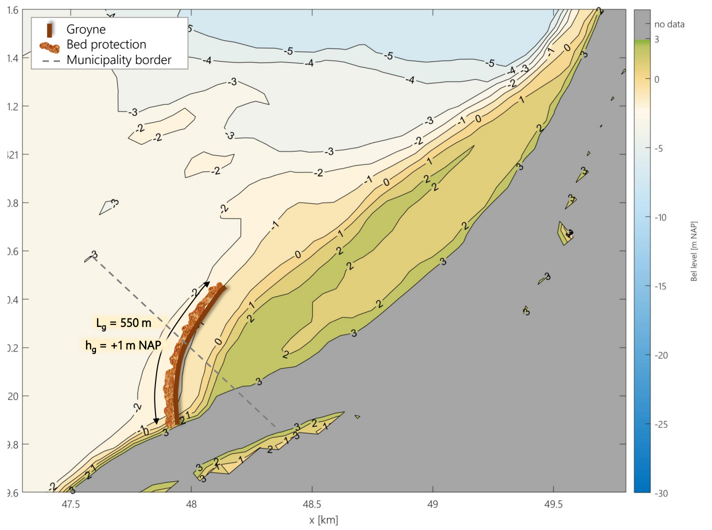


Figure G.4: Design of C-shaped groyne

G.2.2. Shoreline development of alternative B

Model set-up

The sheltering effect of the groyne during high water is simplified to be able to simulate the groynes with the coastline model. The sheltering effect of the groyne at an arbitrary point of -1 m NAP is considered (implying a groyne height of 1 + 1 = 2 m). The water depth is h = d + MHW = 2 + 1.45 = 3.45 m. When assuming a depth-averaged velocity profile over the water column and a linear relationship between groyne height and current decrease, the downdrift velocity is $\frac{3.45-2}{3.45} * 100\% = 40\%$ of the updrift velocity. Near the beach, the maximum current velocity during the tidal cycle is ca. 0.6 m/s (Section 3.2). This maximum would then reduce to 0.25 m/s. Hence, the tidal flood flow velocities are set to 40% of the reference value.
The effect of diffraction is not taken into account, which is a conservative assumption, because diffraction waves around the tip of the groyne would contribute to sediment transport in southern direction and thus minimize the northern directed littoral drift. However, an elaborate assessment of wave diffraction around the (submerged) tip of the groyne is outside the scope of this research. A conservative value for all waves approaching from the west and north-west (all waves with an angle of approach between 225-250 $^\circ N$), are assumed to have a transmitted wave height of $H_t = 0.6 * H_i$.

The dynamic profile of the beach is shorter in the sheltered area, because the longshore transport seaward of the groyne does not contribute to the shoreline advance or retreat. The dynamic profiles reach ca. 350 m from the shoreline in seaward direction instead of 800 m.

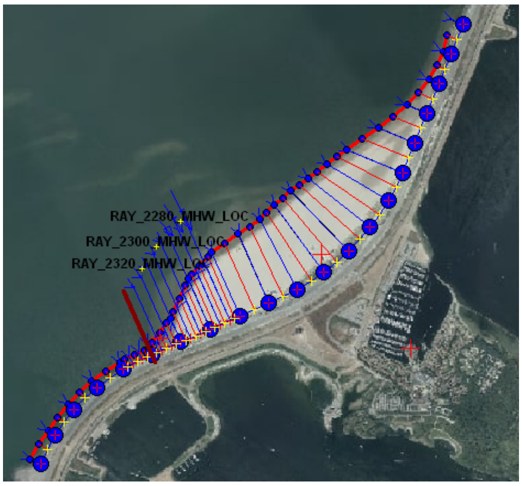
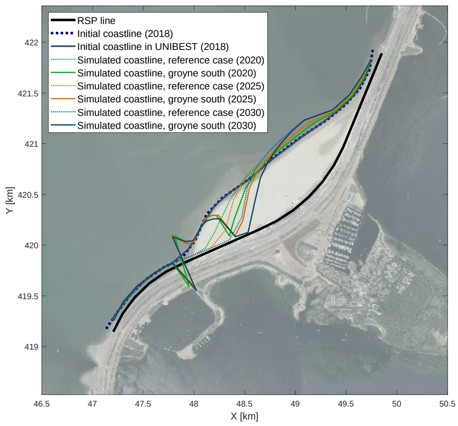


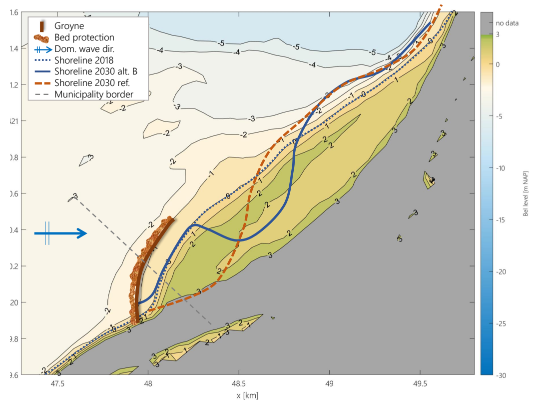
Figure G.5: Model set-up for alternative B - C-shaped groyne. Local transport rays replace the transport rays (and S-phi curves) of the reference situation. These local rays are depicted for high water conditions (blue arrows). A straight, shore normal groyne of 550 m represents the C-shaped groyne. The shelter effect of the groyne is taken into account by using the local transport rays.

Shoreline development

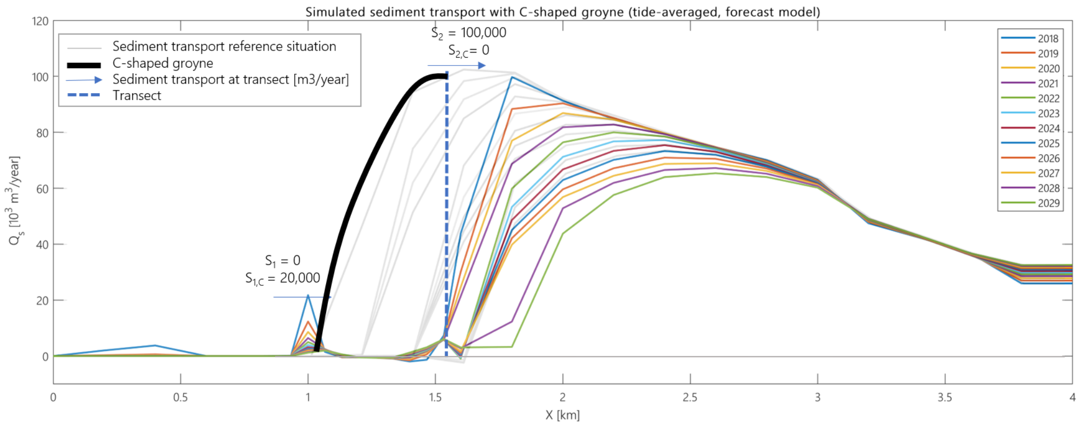
The expected shoreline development up to 2030 is depicted in Figure G.6b. It can be seen that the shoreline behind the groyne is in equilibrium: the shoreline maintains it position. At the downdrift side of the groyne, lee-side erosion occurs. When considering the sediment balance (Figure G.6c), a positive transport gradient between x = 1.5 and x = 2.5 km in the sediment balance is detected (implying erosion). This gradient in transport along the beach reduces over time. The mean erosion value of at this stretch is ca. 65 $m^3/m/y$ (-65,000 $m^3/year$ over a stretch of 1 km). Thus, less sediment losses have to be compensated compared to the reference situation, but the difference is small. Four nourishment of 500,000 m^3 are needed compensate the loss of about 30 years (total loss of $65,000*30 = 1,950,000m^3/30years$, which is compensated by $4*500,000m^3*2,000,000m^3$).



a: Simulated shoreline development with the southern groyne configuration (L = 550 m , h = +1 m NAP, shelter effect for dominant wave direction (225-350 °N) of 50%, zero current velocity at rays 2320 up to 2280. Simulated with forecast model (2018-2030). Note that the groyne is orientated nearly perpendicular to the shoreline, different from the design orientation



b: Simulated shoreline development up to 2030 with alternative B (C-shaped groyne) (Simulated with forecast model (2018-2030)), blocking = 100 %, groyne length = 550 m.



c: Sediment balance of the coastal stretch between 2018-2030 with alternative B (C-shaped groyne), simulated with UNIBEST forecast model with effect of sheltering

Figure G.6: Alternative B - C-shaped groyne

G.3. Design C - Straight groyne with beach fill

This section includes the background of the expected shoreline development of alternative C. This section is thus complementary to Section 9.1.2, which elaborates on the design of solution C.

G.3.1. Design

The beach fill is a nourishment to increase the bed level up to +1.5 m NAP, so that this part of the beach is above the high water level (+1.45 m NAP). The nourishment configuration should include a talud of the place sediment (but for the computation of the nourished volume a horizontal plane is assumed). The groyne of 600 m long has the function of retaining this beach fill. The groyne has a crest height of + 2 m NAP, implying that the groyne reaches a heights of ca. 4 m. The crest height of +2 m NAP is chosen as it is above the mean spring tidal level (+1.72 m NAP), i.e. the groyne is visible during the whole tidal cycle.

The construction material and layered configuration with brushwood and oysters is similar to the design of the groynes in design A. However, as the groyne is placed more offshore and thus at larger depths the width of the groyne is larger (see cross-section A-A in Figure 9.6). Thereby, the geotextile reaches the top of the groyne at the landward side, to prevent sedimentation with sand from the beach into the groyne. The geotextile at the seaward side reaches up to +1 m NAP, to make sure that the oysters are inundated each tidal cycle. Thereby, toe is constructed by fascine matrasses extending 2 m (landward side) and 3 m (seaward side). This should sufficiently mitigate scour depths.

G.3.2. Shoreline development of alternative C

Beach fill

The volume of the required beach fill is calculated by dividing the total nourished surface area into 4 different areas (Figure G.12). The boundaries between the areas are the depth contours. Each surface area and multiplied by the mean depth of the area. For example, area A_1 has a mean depth of - 2.3 m NAP, and a surface area of A_1 = 0.5 x 200 x 200 = 20,000 m^2 = 2 ha. Hence, V_{A_1} = A_1 x (-depth + 1 m) = 20,000 x 3.3 = 66,000 m^3.

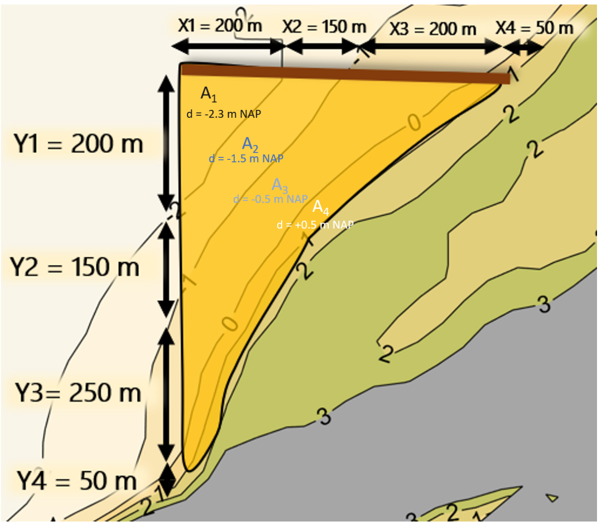


Figure G.7: Calculation of the required volume of a beach fill in case of solution C - straight groyne

Model set-up

For the simulation of this alternative, the groyne is simulated as if it is a revetment (as it is not possible to implement a shore-parallel groyne in UNIBEST). Furthermore, the simulation does not include the effect of sheltering (which will occur in reality at the northern part of the beach, as the wave impact and current velocity from the west are reduced in this area).

0.5

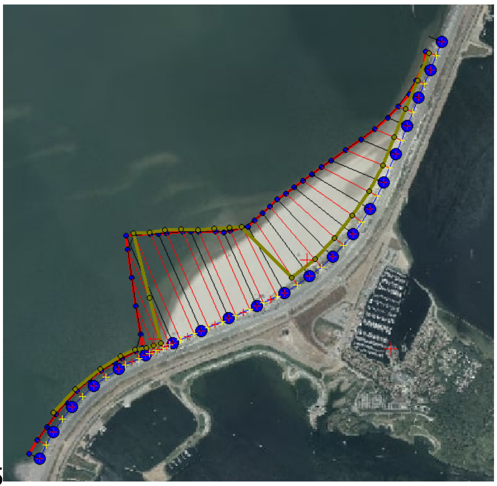


Figure G.8: Model set-up for alternative C - Straight groyne with beach fill. The groyne is simulated as if it is a revetment (light grey line).

G.4. Design D - Artificial island with tombolo

This section includes the design, the background of the expected shoreline development, the sediment balance and the criteria analysis of alternative D.

G.4.1. Design

To make a proper design of an offshore island, the design strategy of Harris (1993) for the lay-out of offshore, detached breakwaters is applied. The first step is to determine the with of the surf zone. This width is ca. X_s = 700 m due to water level differences in a shallow basin (Section 6.6). The second step is to determine the distance D from the coastline. If D < $\frac{1}{2}$ X_s, tombolo formation is likely. A tombolo is the desired shoreline shape, hence an offshore distance of D = 200 m is chosen. The third step is to determine the length of the breakwater (L). A tombolo is formed when L/D >1.3. (Bosboom & Stive, 2015) A breakwater length of 250 will suffice.
Furthermore, the height of the breakwater is designed such that the wave conditions causing the most erosion are dissipated and refracted. The crest height is governed by the acceptable overtopping rate (CIRIA et al., 2007), Usually, the crest height results in a freeboard of $R_c = (1.0 - 1.4) * H_s$, which is in this case $R_c = (1.0 - 1.4) * 0.9 = 0.9 - 1.26m \simeq 1.1m$. Taking high water conditions (h = + 1.45 m NAP), this leads to a crest height of $h_c = h + R_c = 1.45 + 1.1 = +2.55mNAP$ According to the relationships for wave transmission at low-crested structures of Van der Meer (1991), this results in a wave transmission of less than 10% of waves with a nearshore wave height $H_s = 0.9m$, which is the wave height of the wave condition that causes the most erosion at the beach (Section 6.6). A crest height of $h_c = +2.5mNAP$ is thus considered to be sufficient for wave transmission over a breakwater. Besides that, the offshore island should be above the mean water level during spring tide, which is + 1.72 m NAP (Appendix A), to make sure the island is emerged during the whole tidal cycle (and is thus visible for water sporters and other recreants).

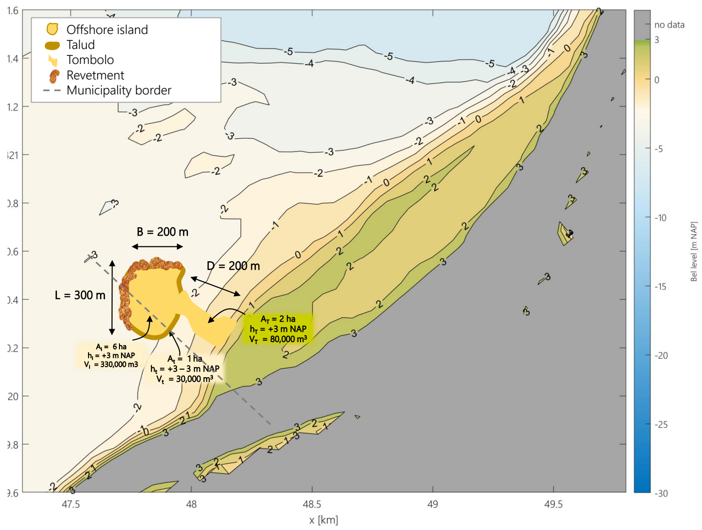
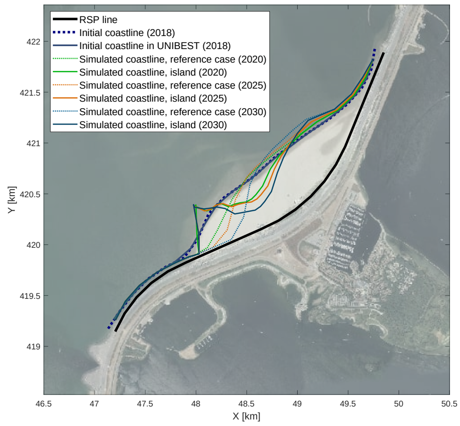


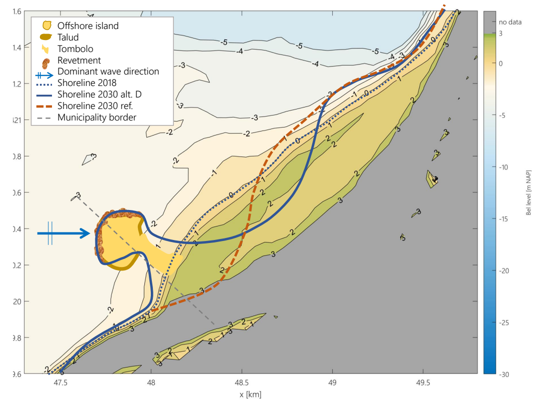
Figure G.9: Design of offshore island with tombolo

G.4.2. Shoreline development of alternative D

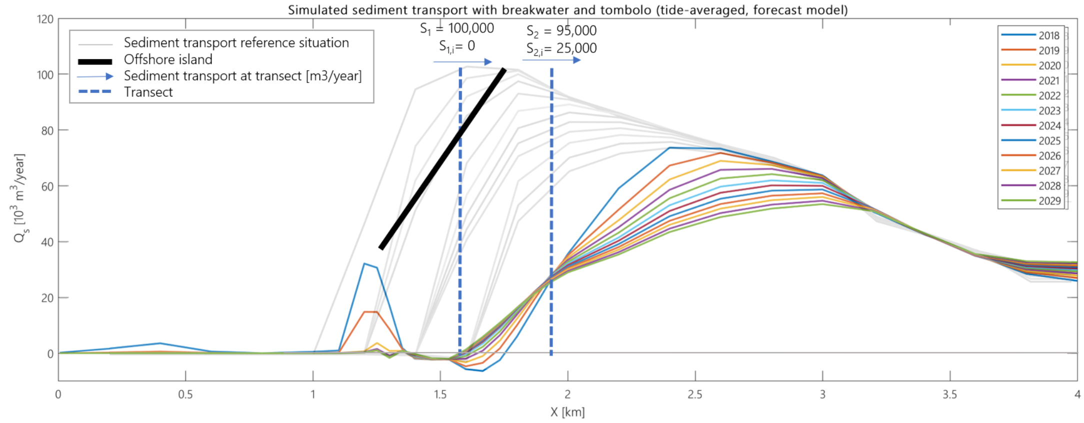
The development of the shoreline is considered to be similar to the situation with design E. Reference is thus made to Section G.5.2.



a: Simulated shoreline development with offshore island and tombolo (A = 300 m x 200 m, h = +3 m NAP, orientation 280 $^{\circ}N$) and tombolo (A = 200 m x 100 m, h = +3 m NAP). Simulated with forecast model (2018-2030)



b: Simulated shoreline development up to 2030 with alternative D (Simulated with forecast model (2018-2030))



c: Sediment balance of the coastal stretch between 2018-2030 with alternative D, simulated with UNIBEST forecast model without effect of sheltering

Figure G.10: Alternative D - Offshore island with tombolo

G.5. Design E - Fishtail groyne

This section includes the background of the expected shoreline development of alternative E. This section is thus complementary to Section 9.1.3, which elaborates on the design of solution E.

G.5.1. Design choices alternative E

The geometry of a fishtail groyne is discussed in CIRIA et al. (2007). Arm AC has the goal of intercepting and diverging the tidal current. Its axial alignment should therefore be perpendicular to the longshore current. The arm is mostly designed perpendicular to the shoreline at point C. The arm is thereby mostly curved, to reduce wave reflection (causing scour) in this concave side. The length of AC is typically 200-300 m. An arm of 300 m is chosen here.
Arm OA should have a gentle slope and should be porous to enhance diffraction of large waves and to induce sediment deposition in the corner between COA and the coastline.
Then, arm OB has similar requirements as an offshore breakwater. It should be parallel to the dominant wave crests. Its length depends on the desired diffraction effect. Equal to the detached breakwater design, a length of 250 m is chosen.

Design of groyne arm AC

The cross-sectional design of arm AC is equal to the groynes designed in alternative A.

Design of breakwater arm OB

For the design of the breakwater arm, certain rules of thumb are used.

Expected lifetime and ULS

The lifetime of the construction is designed for 15 years. The breakwater should be able to withstand storm conditions that occur once in 100 years, implying a probability of failure of $p_f = 1 - (1 - \frac{1}{100})^1 5$ = 14 %.

Design wave height

The design wave heights of a 1/100 year storm is calculated in Section 8.3 and is 2.5 m.

Talud

A regular breakwater slope is ca. 1:2 (Massie, 1976).

Rock diameter

The rock diameter on the breakwater is calculated with Van der Meer's formulae (Schiereck, 2012). These formulae are functions of the permeability (P), number of waves (N), the damage level (S), and the surf-similarity parameter (ψ_m). For the design of this breakwater, the following applies: P = 0.2 (nearly permeable core), N = 2000 (representing a storm of ca. 4 hours), S = 6 (intermediate damage), and ψ_m = 5.1 (surging waves, calculated with $[6.2 * P^{0.31} * \sqrt{tan\alpha}]^{(\frac{1}{P+0.5})})$. With an alpha of 1/2, the formula of Van der Meer reads:

$$\frac{H_s}{\delta d} = 1.0 * P^{-0.13} (\frac{S_d}{\sqrt{N}})^0.2\psi_m^P \sqrt{cot\alpha} = 3.01 \qquad \text{(G.1)}$$

Hence, the median diameter of the armor rock layer should be ca. 1/3 H_s. In this case, a diameter of ca. 0.8 m would be stable. The stone class that is sufficient is then $LM_A 300 - 1000$ (which creates a layer thickness of over 1.5 m when 2 layers are applied).

Layer extent and thickness

The number of layers of armor rocks is usually 2, but sometimes 1 or 3 (Massie, 1976). The value of 2 is chosen.

The armor units extend downward on the slope to an elevation of ca. 1.5 * H_s below the still water level. That is in this case down to ca. -3.5 m NAP (Massie, 1976). The armor layer extends upward along the slope minimal up to the crest elevation.

Crest width

The crest width should be ca. 3 stones wide when overtopping is expected and armor units cover the crest (Massie, 1976), implying that a crest with of ca. 2.5 m suffices.

Toe width For moderate scour potential (see Section G.1.1), the toe width of armour stone should be ca. dD_{n50}, potentially used with under layers or a geotextile filter. For simplicity, a toe structure of dD_{n50} is assumed.

G.5.2. Shoreline development of alternative E

The shoreline development with constructions D (artificial island with tombolo) and E (fishtail groyne) is simulated with the forecast model in the same way: the shoreline is expected to develop in a similar way, as the effects of the structures are similar.

Model set-up

When waves propagate past the tip of a breakwater, they diffract into the shadow zone. The wave heights in this sheltered region are thus significantly lower than in the undisturbed region. At the tip of the breakwater, the wave height is assumed to be reduced by half (H = 50%). (Bosboom & Stive, 2015) The deeper into the shadow zone (i.e. the further away from the breakwater tip), the wave height decreases even more. K(Θ) is the diffraction coefficient along a line at an angle Θ from the wave direction at the breakwater tip. It is determined by the fraction of the wave height at the tip. Approximations for this value near a breakwater are obtained by Goda and are shown in Figure G.11.

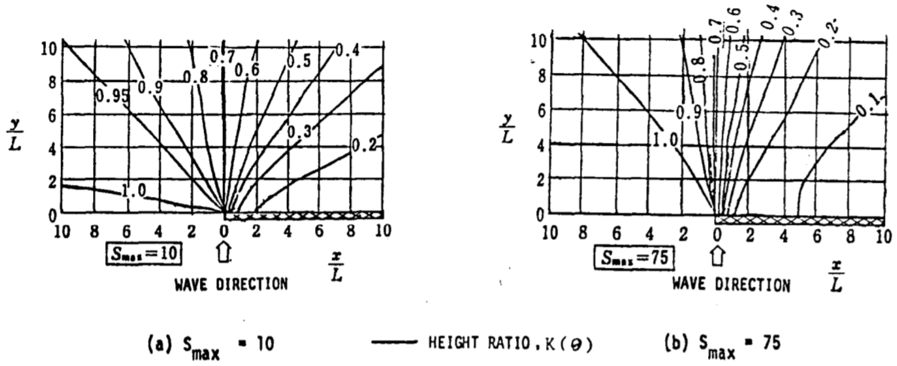


Figure G.11: Diffraction diagrams of a semi-infinite breakwater for directional random waves of normal incidence. (Goda, et al., 1978)

Using these diffraction schemes, the shadow zone behind the offshore breakwater in alternative D and E is determined to be able to simulate the effect of the breakwater. The lines at which H = 50 % and H = 20 % behind the breakwater are depicted in Figure G.12.

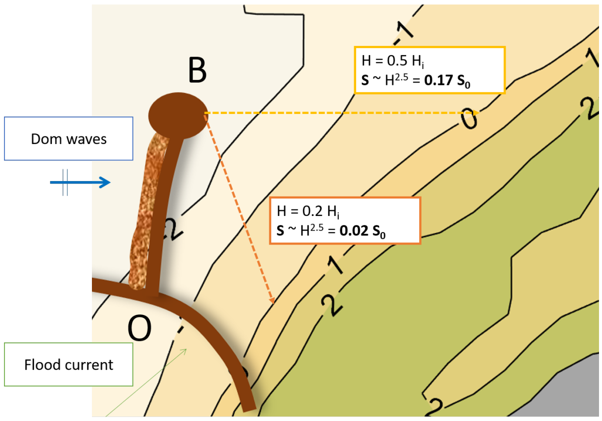


Figure G.12: Simplified diffraction scheme at diffraction point of arm OB

To translate the reduced wave energy behind the breakwater into a reduced sediment transport rate, the CERC formula is taken as a basis. This is done, as this formula gives the bulk longshore sediment transport (the total longshore transport over the breaker zone) due to the action of waves approaching the coastline with a nonzero angle of incidence. (Bosboom & Stive, 2015) In this formula, only the effect of wave-generated longshore currents is taken into account. In the case of alternative D and E, this approximation is assumed to be valid as the longshore currents due to wind and tide are minimized behind the tombolo and groyne for respectively alternative D and E. In the CERC formula, the sediment transport S is proportional to the wave height to the power 2.5, i.e. $S \sim H^{2.5}$ (for the full expression and assumptions of the CERC formula, reference is made to literature such as Van Rijn (1994)). Using this relationship enables a simple way of determining the shelter effect of the breakwater in the UNIBEST-CL module: the local transport rays in the lee-side of the breakwater are altered according to the expected wave energy and longshore transport reduction. This leads to the model set-up of Figure G.13. Note that not only the sediment transport rate at the local rays differs, but also the equilibrium coastline angle: due to refraction and diffraction, the waves approach the coastline at a different angle.

Simulated development

If a headland (or shore-normal breakwater) is constructed at the north-western side of the beach - which is not unlikely to happen due to the future construction of a tidal inlet in the dam - the planform of the bay is likely to have a parabolic shape. The equilibrium bay shape is assessed by the Parabolic Bay Shape Equation (PBSE), which is discussed in Lausman et al. (2006), among others.

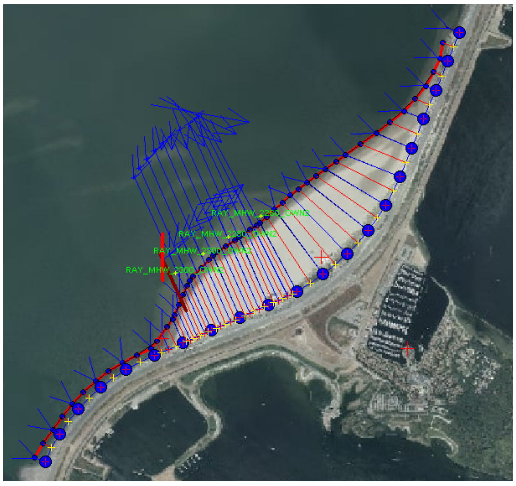
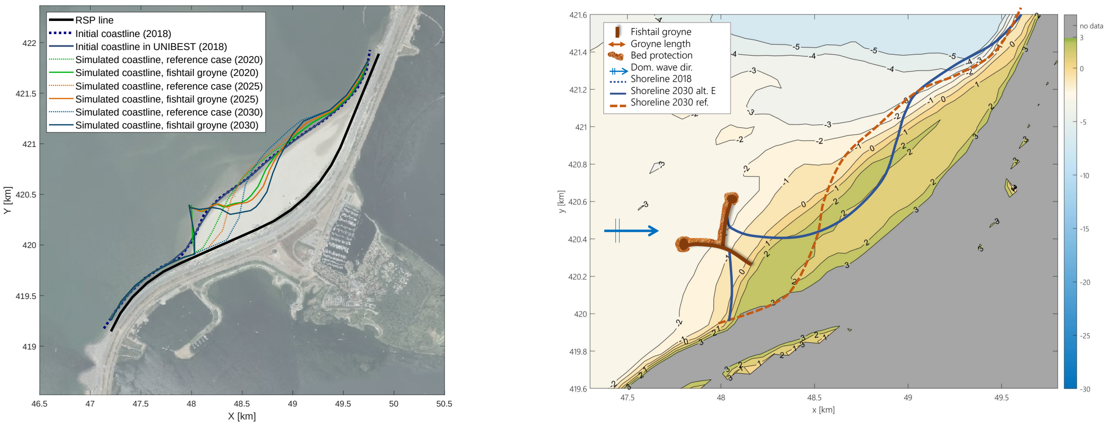


Figure G.13: Model set-up for alternative D and E. Local transport rays replace the transport rays (and S-phi curves) of the reference situation. These local rays are depicted for high water conditions (blue arrows). A groyne of 300 m represents respectively the tombolo and groyne arm of the fishtail. The island and breakwater arm of the fishtail groyne are depicted as a detached breakwater (solid red line).



a: Simulated shoreline development alternative C (L = 600 m , h = +1 m NAP, no shelter effect. Simulated with forecast model (2018-2030).

b: Sketch of developed shoreline in 2030 in case of alternative D and E

Figure G.14: Alternative D and E - Detached offshore breakwater in the form of an artificial island (D) and a fishtail groyne (E)

G.6. Costs for alternatives A to F

A few notes on the computation of the costs:

- The total costs are calculated for a period of 30 years (up to 2050)
- The costs and lifetime of a nourishment are regarded to be equal to the nourishment of 2016. However, as inflation plays a role, the costs for a nourishment in 2021 are higher than in 2016. With a inflation rate of 2 % per year, the costs of the nourishment are ten percent higher than in 2016 (inflation of 2 % per year, hence costs are multiplied by $(1+0.02)^5 = 1.1$). Hence, the costs of a nourishment of 500,000 m^3 are €4,400,000. The lifetime of this nourishment is 6 years (costs explained in Section 3.4). The mobilization costs are assumed to be euro 1,650,000, which implies a mean value of 5.5 €/m^3
- The estimated lifetime of a nourishment of 500,000 m^3 is based on the expected shoreline development. If the coastline is expected to reach an equilibrium, no periodic nourishing is needed. In the case of periodic nourishing without building any structure, 5 nourishments of 500,000 m^3 are needed to maintain the beach at its current position.

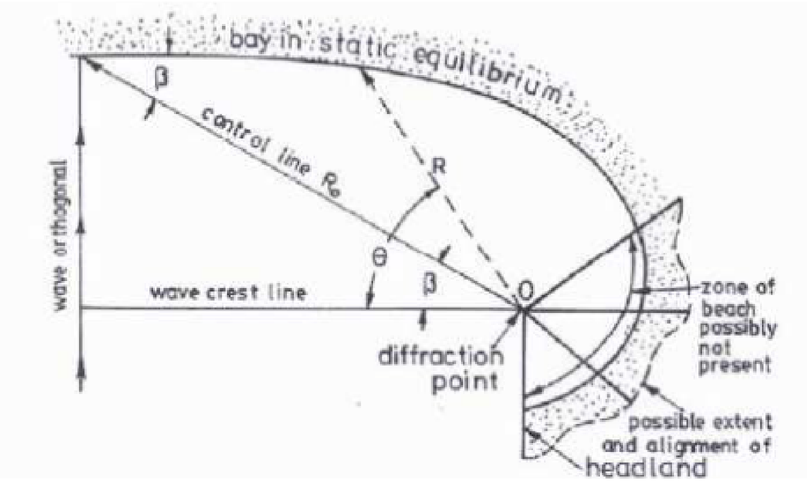


Figure G.15: Sketch of the equilibrium shape of a bay that is described by the parabolic bay shape equation, obtained from Lausman et al. (2006), modified from (Hsu and Evans, 1989)

- The brushwood groynes have a lifetime of 15-25 years. The assumption is therefore that the maintenance of the groynes holds that they have to be replaced once in a period of 30 years (D. Van Aalsburg, personal communication, May 11, 2021).
- The costs for bed protection near the groynes is included in the price per unit surface area. Extra costs are thus not included.
- This appendix elaborates on the cumulative costs that are made within 30 years. However, it is more convenient to look at the net present value (NPV) of each solution. While evaluating this parameter, it can be expressed more clearly what the cost implications of a particular solution are. This is elaborated in Section 9.

G.6.1. Lifetime and costs - A

Construction

The construction costs of alternative A consist of groyne construction and initial nourishment costs. The total groyne length is 950 m. The width of the groynes ranges from 2 to 3 m, of which the latter is taken for the computation. With a total surface area of $950x3 = 2850m^2$ The construction costs for the groynes are thus €1,140,000.
The initial beach fill between the groynes is ca. 140,000 m^3, i.e. €2,400,000.
The total construction costs are thus $C_{A,constr} = C_{A,gr} + C_{A,fill} = 1,140,000 + 2,400,000 = €3,550,000$.

Maintenance

The beach is considered to reach an equilibrium with this groyne configuration. Hence, no maintenance nourishing is needed. The maintenance of the groynes yields the replacement of the groynes, which costs the same as the construction of the groynes. Over a period of 30 years, this means that the maintenance costs are €1,140,000.

Total

Over a period of 30 years, the costs for alternative A are $€4,670,000$.

G.6.2. Lifetime and costs - B

Construction

The construction costs of alternative B consist of groyne construction. The total groyne length is 550 m. The width of the groyne is ca. 3 m. With a total surface area of $550x3 = 1150m^2$, the construction costs for the groynes are thus €495,000.
The total construction costs are thus $C_{B,constr} = C_{B,gr} = €660,000$.

Maintenance

The beach will not reach an equilibrium in 30 years with this groyne configuration. Hence, maintenance nourishing is needed. As discussed in Appendix G.2, erosion takes place at a lower speed as it otherwise would have done in the south (consider the sediment balance of Figure G.6c). Hence, a nourishment of 500,000 m^3 has a longer lifetime of as in the reference situation (which is 6 years), an estimation is made that it now lasts for 8 years. In a period of 30 years, ca. 4 nourishments of €4,400,000 have to be executed: $C_{B,maint,nour} = \frac{4*4,400,000}{30} = €17,600,000/30years$ The maintenance of the groynes yields the replacement of the groynes, which costs the same as the construction of the groynes. Over a period of 30 years, this means that the construction costs are €660,000.

Total

Over a period of 30 years, the costs for alternative B are $C_B = C_{B,constr} + C_{B,maint} = 660,000 + 17,000,000 = €17,660,000$.

G.6.3. Lifetime and costs - C

Construction

The construction costs of alternative C consist of groyne construction and initial nourishment costs. The total groyne length is 600 m. The width of the groynes is 4 m. With a total surface area of $600x4 = 2400m^2$ The construction costs for the groynes are thus €960,000.
The initial beach fill between the groynes is ca. 392,000 m^3 (Appendix G.3.2 includes the calculation of this amount), which costs €3,800,000.
The total construction costs are thus $C_{C,constr} = C_{C,gr} + C_{C,fill} = 960,000 + 3,800,000 = €4,770,000$.

Maintenance

The beach will not reach an equilibrium in 30 years with this groyne configuration. Hence, maintenance nourishing is needed. The erosion rate is much lower than in the reference situation, hence a nourishment of 500,000 m^3 has an estimated extended lifetime of 12 years instead of 6 years (as explained in Section 9.1.2). In a period of 30 years, ca. 2 nourishments of €4,400,000 have to be executed, implying maintenance costs of $C_{C,maint,nour} = 2 * 4,400,000 = €8,800,000$ in 30 years. The maintenance of the groynes yields the replacement of the groyne, which costs the same as the construction of the groynes. Over a period of 30 years, this means: $C_{C,maint} = C_{C,maint,gr} + C_{B,maint,nour} = 960,000 + 8,800,000 = €9,760,000/y$.

Total

Over a period of 30 years, the costs for alternative C are $C_C = C_{C,constr} + C_{C,maint} = 4,770,000 + 9,760,000 = €14,530,000$.

G.6.4. Lifetime and costs - D

Construction

An offshore island can be constructed in several ways. For example, the core can be made with fascine mattresses, which are filled and covered with sand. For the computation of this island, the island is considered to be constructed with dredged sediment only. Hence, the costs are equal to nourishment costs per cubic meter. The total volume of the island and tombolo together is ca. 470.000 m^3, which equals €4,235,000. The western and northern part of the talud of the island should be protected with bank protection. Assuming a rubble mound top layer of ca. 1 m thick at a talud of 1:2 from -3 to +3 m NAP, the costs equal ca. €770,000. Thus, $C_{D,constr} = C_{D,fill} + C_{D,bank} = 4,235,000 + 770,000 = €5,000,000$.

Maintenance

The lifetime of the island is hard to predict, as it is a soft solution that is prone to morphological developments. For instance, aeolian transports could lead to fast decrease of the volume, and thus its effectiveness. For the estimation of the lifetime, it is assumed that the island loses 30 % of its volume per 10 years, which is equal to ca. 155,000 m^3 per 10 years. Not only the island needs periodic nourishments, also the beach itself is not in equilibrium. In a period of 30 years, ca. 2 beach nourishments of 500,000 m^3 have to be executed (as explained in Section 9.1.3). When adding the beach and the

island nourishments, it is best to apply 3 times a nourishment of 500,000 m^3 in 30 years, which equals 3 times €4,400,000 in 30 years.
The bank protection is assumed to have a lifetime of more than 30 years, in which each decade extra stones have to be placed on the top layer (hence, two times in a period of 30 years). This induces maintenance costs of ca. 40 $€/m^2/10y$. The estimated surface area of bank protection is ca. 7,000 m^2.
Hence, $C_{D,maint} = C_{D,maint,nour} + C_{D,maint,island,bank} = 3 * 4,400,000 + 40 * 7,000 * 2 = 13,200,000 + 560,000 = 1€13,760,000/y$.

Total
Over a period of 30 years, the costs for alternative D are $C_D = C_{D,constr} + C_{D,maint} = 5,000,000 + 13,760,000 = €18,860,000$.

G.6.5. Lifetime and costs - E

Construction
The construction costs of alternative E consist of a groyne construction (arm AOC) and a breakwater construction (arm OB). The total groyne length is 300 m. The width of the groyne is ca. 3 m. With a total surface area of $300x3 = 900m^2$, the construction costs for the groyne are thus €360,000. The breakwater is more costly per square meter, mainly due to the use of rubble mound. The total breakwater length is 250 m and the width is ca. 22.5 m. With a price of $€600/m^2$, the costs for the breakwater arm are €3,375,000.
The total fishtail construction is thus $C_{E,constr} = C_{E,gr} + C_{E,bw} = 360,000 + 3,735,000 = €3,080,000$.

Maintenance
The maintenance costs of the fishtail groyne are divided into costs for the groyne and the breakwater arm. The groyne arm has to be replaced once in 30 years, which costs €360,000.
For the breakwater arm, the costs are estimated on €40 / m^2 per maintenance operation (the placement of rocks), which has to be executed ca. once in ten years (and thus twice in 30 years). The maintenance of the breakwater arm of 250 m long and 22.5 m wide is €225,000 per 10 years, i.e. €450,000 / 30 years.
This erosion rate is much lower than in the reference situation, hence a nourishment of 500,000 m^3 has an estimated extended lifetime of 12 years instead of 6 years (as explained in Section 9.1.3). In a period of 30 years, ca. 2 nourishments of €4,400,000 have to be executed: $C_{E,maint,nour} = 2 * 4,400,000 = €8,800,000/$ 30 years.
Thus, the maintenance costs of solution E are as follows: $C_{E,maint} = C_{E,maint,groyne} C_{E,maint,bw} + C_{E,maint,nour} = 360,000 + 450,000 + 8,800,000 \simeq €9,610,000/30years$.

Total
Over a period of 30 years, the costs for alternative E are $C_E = C_{E,constr} + C_{E,maint} = 3,735,000 + 9,610,000 = €13,0345,000$.

G.6.6. Lifetime and costs - F

The costs for periodic nourishing consist of nourishment costs. With a lifetime of 6 years, 5 nourishments have to be executed within 30 years. Over a period of 30 years, the costs for alternative F are thus $C_F = C_{E,maint} = 5 * 4,400,000 = €22,000,000$.

Summary

		Construction															Maintenance				Total costs		
		Beach fill					Groynes			Bank protection				Breakwater			Structure		Nourishing				
		C [€ /m3]			*€ 6*		*C [€ / m2]*		*€ 400*	*C [€ /m3]*			*€ 75*	*C [€ /m2]*		*€ 600*			*C [€/5E6 m3]*	*€ 4,400,000*			
		Cmob [€]			*€ 1,650,000*					*Cmob [€]*			*€ 250,000*										
		B [m]	L [m]	h [m]	V [m3]	C [€]	L [m]	B [m]	C [€]	d [m]	A [m]	V [m3]	C [€]	B [m]	L [m]		Constr. Maint	Cconstr [€/30y]	Nr / 30 y	Cnour [€/y]	Cconst [€]	Cmain [€/30y]	**Ctot [€/30y]**
A Pocket Beaches	Groyne 1	150	200	2.5	75000	412500	150	3	€ 180,000								Replacement 1/30y	€ 180,000					
	Groyne 2 - 5	100	150	2.5	37500	€ 206,250	800	3	€ 960,000								Replacement 1/30y	€ 960,000					
		100	100	2.5	25000	€ 137,500																	
						€ 1,650,000																	
	Sum				137500	€ 2,406,250			€ 1,140,000									**€ 1,140,000**	0	**€ 0**	€ 3,546,250	€ 1,140,000	**€ 4,686,250**
B Curved groyne							550	3	€ 660,000								Replacement 1/30y	€ 660,000					
	Sum								€ 660,000									**€ 660,000**	**4**	**€ 17,600,000**	€ 660,000	€ 18,260,000	**€ 18,920,000**
C Straight groyne	A1	200	200	3.3	81000	€ 445,500	600	4	€ 960,000								Replacement 1/30y	€ 960,000					
	A2	150	150	2.5	118125	€ 649,688																	
	A3	250	200	1.5	170625	€ 938,438																	
	A4	50	50	0.5	22500	€ 123,750																	
						€ 1,650,000																	
	Sum				392250	€ 3,807,375			€ 960,000									**€ 960,000**	2	**€ 8,800,000**	€ 4,767,375	€ 9,760,000	**€ 14,527,375**
D Offshore island	Island	200	300	6	360000	€ 1,980,000																	
	Talud of island	10	1000	6	30000	€ 165,000				1.00	6946.2	6946.222	€ 518,883				€ 40/m2/10y	€ 555,698					
	Tombolo	100	200	4	80000	€ 440,000																	
						€ 1,650,000							€ 250,000										
	Sum				470000	€ 4,235,000							€ 768,882.78					**€ 555,698**	3	**€ 13,200,000**	€ 5,003,883	€ 13,755,698	**€ 18,759,581**
E Fishtail	AOC						300	3	€ 360,000								Replacement 1/30y	€ 360,000					
	OB													22.5	250	€ 3,375,000	€ 40/m2/10y	€ 450,000					
	Sum								€ 360,000							€ 3,375,000		**€ 810,000**	2	**€ 8,800,000**	€ 3,735,000	€ 9,610,000	**€ 13,345,000**
F Periodic nourishing																							
	Sum																		5	€ 22,000,000	€ 0	€ 22,000,000	**€ 22,000,000**

Table G.1: Construction and maintenance costs per alternative

Solution	Lifetime nourishment [y]	Nr. of nourishments [/30 y]	Replacement (1/30 years) [M€]	Maintenance bank protection [M€/10 y]	Construction costs [M€]	Maintenance costs [M€/30 y]	Cumulative costs [M€/30 y]
A	30	0	1.1	-	3.5	1.1	4.7
B	8	4	0.7	-	0.7	18.3	18.9
C	12	2	1.0	-	4.8	9.8	14.5
D	10	3	-	0.6	5.0	13.8	19.3
E	12	2	0.4	0.5	3.7	9.6	13.8
F	6	5	-	-	0.0	22.0	22.0

Table G.2: Summary of the main outcomes of the cost computation of solutions A, B, C, D, E and F

G.7. Design rules

G.7.1. Wave transmission at low-crested structures

To determine the wave transmission at the groynes, the design formulas of Van der Meer (1991) are used. The governing variables are depicted in Figure G.16. The main variables are the crest freeboard, R_c (crest height expressed in meter above the water level), and the incoming wave height H_i. The transmission coefficient is defined as $K_t = \frac{H_t}{H_i}$, with H_t being the transmitted wave height.

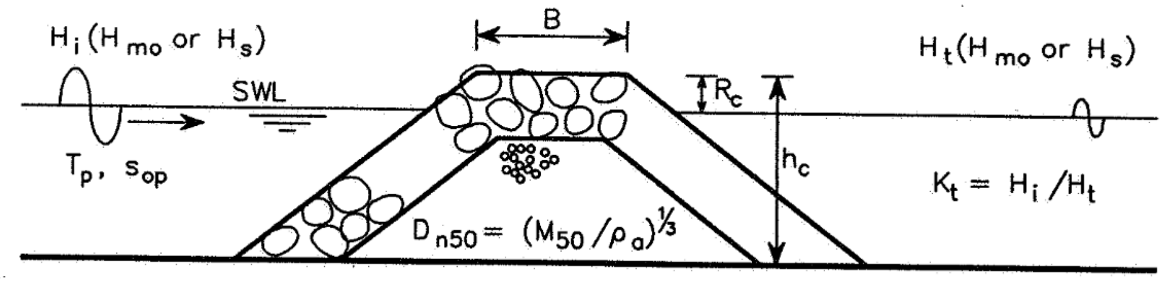


Figure G.16: Governing variables related to wave transmission (Van der Meer, 1991)

The equations of Van der Meer (1991) were the first proposed prediction formulas where the wave transmission linearly depends on the relative freeboard (dimensionless parameter of freeboard height divided by the incoming wave height $\frac{R_c}{H_i}$). The wave transmission is however, computed for a situation in which the structure has a sloping foreshore. The construction of straight groynes will not have this foreshore and thus the wave energy decay may be less (and thus the transmission may be higher). However, due to accretion at the updrift side of the groyne, a natural foreshore will develop. Thus, this formula is considered to give a reasonable prediction of the wave transmission of the dominant waves over the groyne, especially in this early stage of the design.

For the design of the groynes, wave condition 39 is taken as the main condition as this condition leads to the most sediment transport. Several other wind-generated conditions similar to condition 39 cause a lot of littoral drift as well. These conditions, having nearly equal wave characteristics, are discussed in Section 6.6. The dominant wave direction is ca. 270 degrees (West). The characteristic wave values are : H_i = 0.9 m, T_p = 5.5 s, H_0 = 1.6 m, L_0 = 20 m, during high water conditions (h = + 1.45 m NAP).

$$
\begin{aligned}
K_t &= 0.8 && for = -2.0 < \frac{R_c}{H_i} < -1.13, \\
K_t &= 0.46 + 0.3\frac{R_c}{H_i} && for = -1.13 < \frac{R_c}{H_i} < 1.2, \\
K_t &= 0.1 && for = 1.2 < \frac{R_c}{H_i} < 2.0
\end{aligned}
\tag{G.2}
$$

A crest level of h_c = + 1 m NAP results in a freeboard of $R_c = -0.45m$. The relative freeboard is $\frac{R_c}{H_i} = \frac{-0.45}{0.9} = -0.5$. Then, according to equation G.7.1, $K_t = 0.46 + 0.3\frac{R_c}{H_i} = 0.46 + 0.3\frac{0.45}{0.9} = 0.61$. This means that the transmitted wave height is approximately 60 % of the incoming wave height. (Van der Meer, 1991)

A crest level of h_c = + 2.5 m NAP results in a freeboard of $R_c = +1.1m$ and the relative freeboard is $\frac{R_c}{H_i} = \frac{1.1}{0.9} = 1.22$. This results in a transmission coefficient of $K_t = 0.1$, implying that less than 10 percent of the wave energy is transmitted over the structure.

Class name	described in EN13383		d_{50} (cm)	d_{85}/d_{15}	d_{n50} (cm)	(2)	(3)
	range	(1)					
CP45/125	45/125 mm	0.4-1.2	6.3-9.0	2.8	6.4	20	300
CP63/180	63/180 mm	1.2-3.1	9.0-12.5	2.8	9	20	300
CP90/250	90/250 mm	3.1-9.3	12.5-18	2.8	12.8	20	300
CP45/180	45/200 mm	0.4-1.2	6.3-9.0	4.0	6.4	20	300
CP90/180	90/180 mm	2.1-2.8	11-12	2.0	9.7	20	300
LM_A 5-40	5-40 kg	10-20	18-23	1.7	17	25	500
LM_A 10-60	10-60 kg	20-35	23-28	1.5	21	32	550
LM_A 40-200	40-200 kg	80-120	37-42	1.5	34	52	850
LM_A 60-300	60-300 kg	120-190	42-49	1.5	38	57	950
LM_A 15-300	15-300 kg	45-135	30-44	2.7	31	46	700
HM_A 300-1000	300-1000 kg	450-690	65-75	1.4	59	88	1325
HM_A 1000-3000	1-3 ton	1700-2100	103-110	1.4	90	135	2050
HM_A 3000-6000	3-6 ton	4200-4800	138-144	1.2	118	177	2700
HM_A 6000-10000	6-10 ton	7500-8500	167-174	1.2	144	216	3250

CP - Course gradings (1): range of W_{50} for category "A" (kg)
LM - Light gradings (2): Layer thickness 1.5 d_{n50} (cm)
HM - Heavy gradings (3): Minimal dumping quantity with layer of 1.5 d_{n50} (kg/m^2)

Table G.3: Standard gradings in EN13382 (Schiereck, 2012)

G.7.2. standard gradings

H
Uncertainty in costs

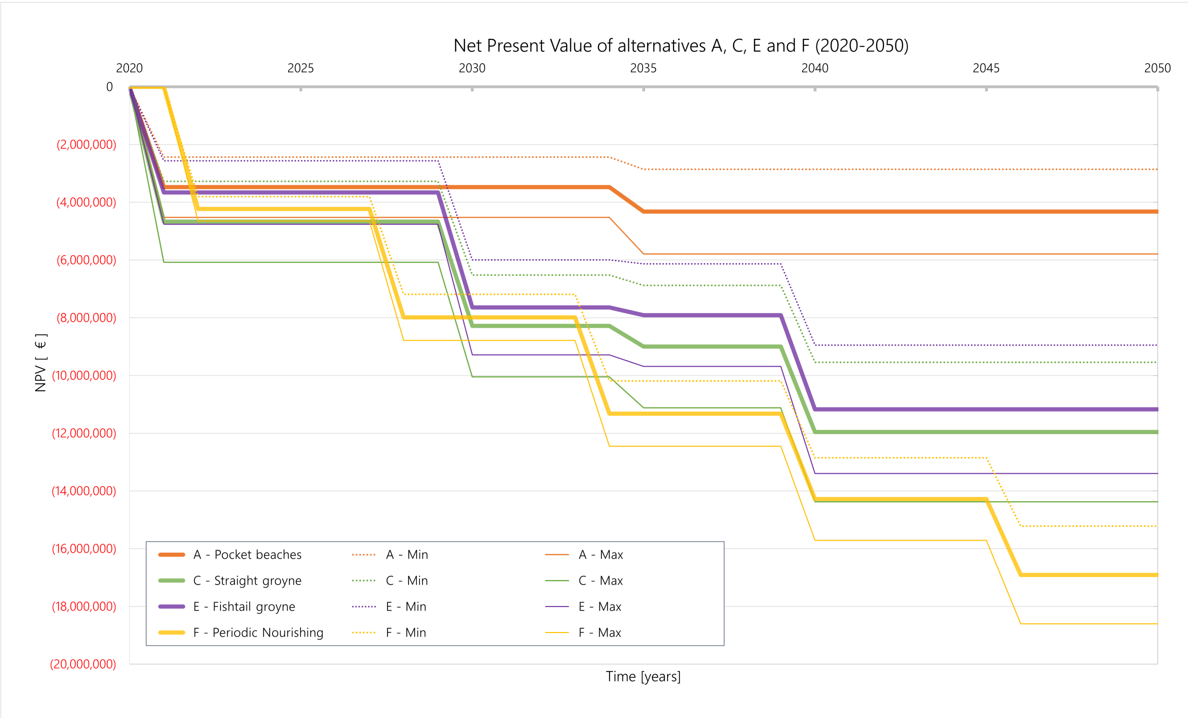


Figure H.1: Net Present value over the total lifetime of the solutions (30 years), with inclusion of a discount rate of 0.02 and different uncertainty ranges per action.

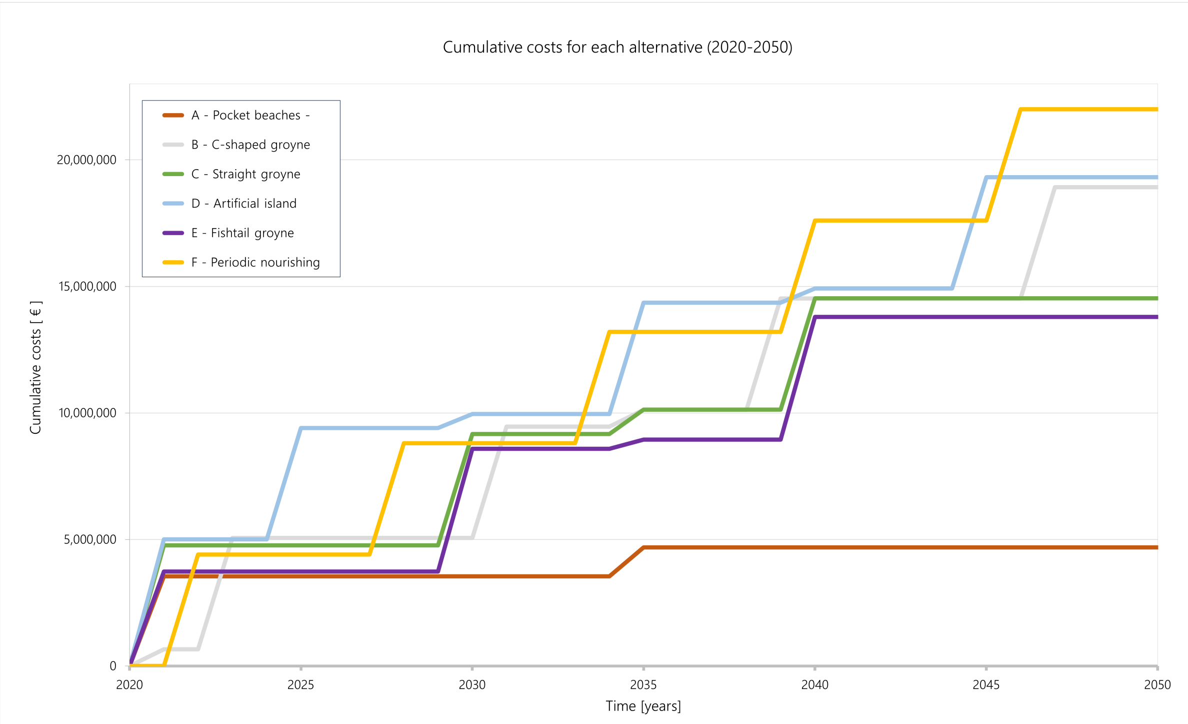


Figure H.2: Cumulative costs during the total lifetime of each of the solutions, without inclusion of a discount rate and uncertainties.

3D outlay of outer delta

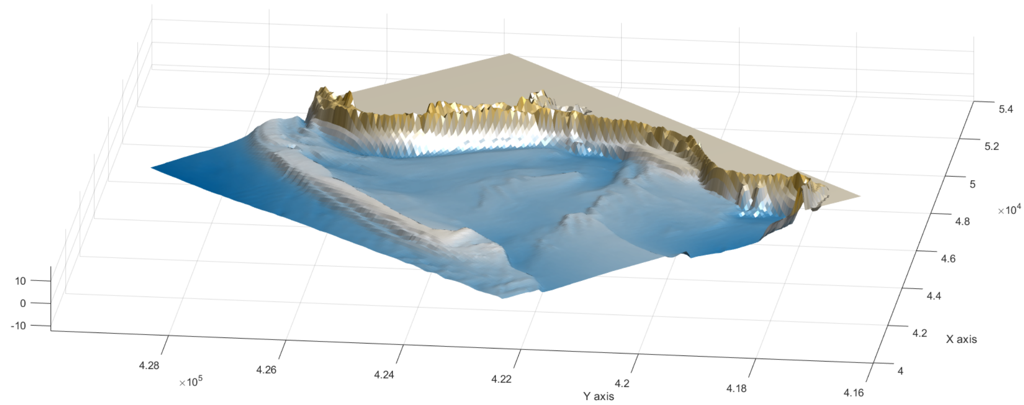


Figure I.1: 3D figure of the Grevelingen outer delta, 2018-2019, retrieved from Vaklodingen data set