Towards engineering the ecosystem services of a mega-nourishment

A forecast of the ecosystem service dynamics of the Sand Motor

S. C. van Zanten

Technische Universiteit Delft

Delft University of Technology

Challenge the future

Cover photo: Aerial view of the Sand Motor in January 2016 faced northwards. Photo made by Rijkswaterstaat/Jurriaan Brobbel.

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Author:
S. C. VAN ZANTEN

University Professor:
Prof. dr. ir. M. J. F. STIVE[1]

Supervisors:
Ir. A. P. LUIJENDIJK[1,2]
Dr. J. H. SLINGER[1]
Dr. B. K. VAN WESENBEECK[1,3]
Dr. ir. S. DE VRIES[1]
Dr. A. P. E. VAN OUDENHOVEN[4]

TU Delft   Deltares Enabling Delta Life

[1]Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology
[2]Deltares, Hydraulic Engineering
[3]Deltares, Sea and Coastal Systems
[4]Institute of Environmental Sciences CML, Leiden University

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SUMMARY

The Sand Motor is a unique and dynamic solution for coastal erosion, aimed at distributing the nourished sand along the Delfland coast. Besides enhancing coastal protection, the Sand Motor has been designed to also provide opportunities for recreation and nature development. The contributions of ecosystems to human well-being, that arise from interaction between biotic and abiotic processes, are called ecosystem services (Haines-Young and Potschin, 2010). The Sand Motor provides several ecosystem services, such as recreation, coastal protection, a fresh water supply by dune filtration and it provides different types of habitats for species.

The effectiveness of the Sand Motor's design can be evaluated using the ecosystem services approach. Typically, such an evaluation is made for one snapshot in time, usually at the initial state of the design. However, due to the dynamics of the Sand Motor, the ecosystem services are likely to change over time and across space. To research the ecosystem service dynamics of the Sand Motor in the future, there is a need for an objective and concrete framework that is able to assess the services on a temporal and spatial scale. Predicting the response of a nourishment on the ecosystem services by means of a process-based model could improve the decision-making regarding integrated coastal zone management.

The aim of this study is to assess the decadal development of the ecosystem services of the Sand Motor. This research focused on some of the services the mega-nourishment provides, namely coastal protection, recreation and habitat provision. Future morphological behavior of this intervention is being studied by process-based numerical models, which has resulted in morphological predictions, made with Delft3D, up to forty years ahead.

There are many factors that are important to the actual occurrence of ecosystem services that are difficult to incorporate into a long-term prediction. Therefore, instead of evaluating the actual use of the ecosystem service, this research focused on the long-term potential of the ecosystem to contribute to human well-being, based on the physical capacity of the ecosystem to provide the service. In the study, the abiotic factors that describe the preconditions of the biotic system are specified and related to the potential ecosystem service provision of the sandy shore. The ecosystem service potential of the Sand Motor is evaluated on a yearly basis, forty years ahead and on a large spatial scale from Hoek van Holland to Scheveningen.

In this study, assessment methods are set up that quantify the ecosystem service potential in the future, based on the changing morphology of the considered coastal stretch. The impact on the habitats is predicted using ecotopes: spatially defined ecological units, of which the abiotic characteristics are more or less homogeneous. In the habitat analysis the ecotopes are distinguished using the computed bed shear stresses (due to currents and waves) and evolving depth. The evolution of the ecotopes is analyzed inter annually and on an annual basis and visualized as ecotope maps. The impact of the Sand Motor on coastal protection is evaluated by calculating the coastline position of the Delfland coast with the Momentary Coastline method (MKL) over time. The contribution of the Sand Motor to the recreation potential is evaluated for kitesurfing, strolling and sunbathing. The indicators used for these services are the area sheltered from waves, the length of the strolling route and the dry beach area respectively.

The state-of-the-art Delft3D model was set up to make a long-term forecast of the morphology and, according to literature, has not been used previously in (dynamic) ecosystem service assessments. To verify the model performance regarding the prediction of ecosystem service dynamics, the computed ecosystem service potential was validated using the first four years of observations.

The validated methods to quantify ecosystem service potential were used to assess the ecosystem service dynamics of the Sand Motor. The results indicate a robust enhancement regarding coastline maintenance that holds beyond the envisaged lifetime of twenty years. North of the Sand Motor, the coastline orientation is predicted to change, thereby decreasing the sediment transport gradients. Beach width available for recreation is expected to increase drastically along the entire Delfland coast. This may threaten the recreational potential at the beach of Scheveningen South, Kijkduin and Hoek van Holland. Regarding nature development, the diversity of habitats has increased on a spatial scale and will be preserved over time. Furthermore, an extensive supratidal area develops increasing the potential for dune formation.

To generalize the quantification methods and compare the effects of changing design parameters on the potential, the ecosystem service dynamics are evaluated for two alternative mega-nourishment designs: an offshore Island and an upscaled traditional foreshore nourishment that is implemented every four years. The Delft3D simulations of the alternatives predict that changing design parameters will result in a different ecosystem service potential. For example, the predicted morphological development of the Island results in a larger surface area of the lagoon, affecting the potential for kitesurfing and habitat provision. The higher nourishment frequency of the upscaled traditional foreshore nourishment has a distinct impact on the evolution of the habitat areas, disturbing the benthos communities with every nourishment.

This study was the first to use a morphological Delft3D model for the prediction of ecosystem service dynamics. The research turned out to be a useful exploration of the opportunities of using a morphological model forecast for ecosystem service prediction. Furthermore, a dynamic assessment in which the long-term situation is evaluated annually, on a large spatial scale, has proven to be valuable to Building with Nature solutions. Ecosystem services are not yet explicitly incorporated in the design of Building with Nature projects and this research takes a step towards integrating ecosystem services into the design of future nourishments.

Further research should try to overcome the current model limitations, such as incorporating aeolian transport into the model. Furthermore, this research focused on the physical potential of the ecosystem to provide ecosystem services, and not on the actual use of the services, for which many other factors are important as well (i.e. a clean, safe beach and accessibility to the site). The next step in predicting ecosystem service dynamics would be to incorporate those factors into an ecosystem service prediction.

CONTENTS

1 INTRODUCTION

Coasts provide a wide range of resources and services to society, and society depends on these goods and services for its survival and well-being. The contributions of ecosystems to human well-being are also called ecosystem services (De Groot et al., 2010). A sandy shore ecosystem provides multiple ecosystem services to society, such as flood safety, recreation and a fresh water wedge by dune filtration (Van Der Moolen, 2015).

Currently, the pressure on coastal zones is increasing due to human development (Nordstrom, 2004) and climate change (Hanley et al., 2014). The expanding human population and the population shift towards the coast, has led to a focus of the anthropogenic pressure on the coastlines. Population growth, sea level rise, land use change, pollution and many other drivers are responsible for change, degradation or loss of coastal ecosystems and its ecosystem services (Unep, 2006). This phenomenon of increasing pressure is referred to as the 'coastal sqeeze' (Defeo et al., 2008, McLachlan et al., 2013).

This increased pressure on the coastal zone is also applicable to the sandy shores of the Netherlands (Janssen et al., 2008). Structural coastline retreat at the Dutch coast requires human intervention. In the Netherlands, sand nourishment is preferred as an engineering solution to combat erosion. Since 1990, the Dutch government applies regular shoreface nourishment to counteract structural coastline retreat. This has dynamically preserved the coastline at a required minimum position (Rijkswaterstaat, 2013). A new strategy is needed to cope with climate change and keep the Netherlands safe from flooding the coming decades (Stive et al., 2013). In this light, a mega-nourishment called the 'Sand Motor' was constructed in 2011 in the Province of South Holland. The Sand Motor is an innovative project, possibly providing a sustainable solution for maintenance of the Dutch coastline.

Nourishment often results in a change or degradation of coastal and marine ecosystems (Holzhauer, 2014, Speybroeck et al., 2006) and the accompanying ecosystem services (Bennett et al., 2009, Unep, 2006). Sandy shores are dynamic systems with a complex interaction between the physical environment and the biota. Despite regular monitoring, there are due to the complexity of the ecosystem many uncertainties about the ecological impact of nourishments (Peterson and Bishop, 2005, Speybroeck et al., 2006), especially the impact of a mega-nourishment (Van den Hoek et al., 2012). There is a need for identification and characterization of relevant factors that contribute to the provision of ecosystem services (Defeo et al., 2008, Holzhauer, 2014) and research that provides aid to integrate them in the design of soft hydraulic projects (Bennett et al., 2009, Carpenter et al., 2009, Speybroeck et al., 2006, Unep, 2006).

Understanding the relationships between multiple ecosystem services calls for a developed theoretical understanding of the beach ecosystem. Research that aims to understand these relationships and the driving processes and factors behind the ecosystem services could improve the ability to maintain ecosystems and provide ecosystem services in a sustainable way (Baptist et al., 2008, Bennett et al., 2009, Carpenter et al., 2009, Speybroeck et al., 2006). Insight into the status and development of critical abiotic (e.g. sediment size and current velocity) and biotic (e.g. predation and food availability) factors at the beach after a perturbation is essential for proper system management (Holzhauer, 2014, Speybroeck et al., 2006). If the sandy system is managed properly, it could provide sustainable means to cope with climate change and add to the value of the Dutch coast.

In the study of Van Der Moolen (2015), a framework is proposed that links the natural processes with critical abiotic and biotic factors to the ecosystem services of sandy shores. These factors, processes and services evolve over time, however so far only static assessments of ecosystem services have been made. The relevant factors (Holzhauer et al., 2009) and ecosystem services need to be dynamically assessed, over time and space, and alternative designs of nourishment need to be evaluated, to be able to manage the ecosystem services effectively (Bennett et al., 2009).

Predicting the response of a nourishment on the ecosystem services by means of a process-based morphological model forecast could improve the decision-making regarding integrated coastal zone management. This study will focus on the prediction of ecosystem services provided by the Sand Motor, to help develop effective and sustainable nourishment practices. The coastline is analyzed over time and space, to study the impact of the nourishment on the ecosystem services. This leads to a dynamic assessment of the ecosystem services of the Sand Motor, in which the services are evaluated on a yearly basis. To help integrate ecosystem service objectives in the design of future nourishments, the effects of changing nourishment design parameters are explored with morphological models of mega-nourishment alternatives. This will take a step towards engineering the ecosystem services of a mega-nourishment.

1.1. PHYSICAL ENVIRONMENT OF THE CENTRAL DUTCH COAST

This study focuses on the evolution of the ecosystem services of the Delfland coast after construction of the Sand Motor, located along the Dutch central west coast (see Figure 1.1). The Dutch coast is generally erosive and the coastline will retreat if it is not maintained. The coast can be characterized as a sand barrier system with a beach, dunes and a surf zone with generally two breaker bars, one intertidal and one surf zone bar (Bosboom and Stive, 2013). The beaches of the central Dutch coast can be described as mesotidal and dissipative, with a low relative tidal range. The Dutch beach is more influenced by wind and wave action than by tide (Janssen and Mulder, 2005). The tidal current during flood runs in the northward direction and during ebb in the southward direction (Bosboom and Stive, 2013). Near Scheveningen, typical maximum flood velocities are in the order of 0.7 m/s and maximum ebb velocities in the order of 0.5 m/s.

Figure 1.1: Location of the peninsula shaped Sand Motor (Zandmotor) on the Dutch coast. (Provincie Zuid Holland, 2015).

THE SAND MOTOR PROJECT

The Sand Motor is a mega-nourishment project between Ter Heijde and Kijkduin, where 21,5 Mm^3 of sand was nourished as a hook-shaped peninsula. The nourishment was completed in August 2011 and is expected to have a lifetime of approximately twenty years, while redistributing sand along the adjacent coastline. The Sand Motor pilot project was initially a 2 km long nourishment that protruded approximately 1 km into the sea (www.dezandmotor.nl, 2015b). Natural processes are expected to spread the nourished sand along the coast, thereby restoring and protecting the coastline and creating valuable nature and recreation areas. To be able to make an accurate model forecast of the ecosystem service dynamics, large data sets on the natural dynamics of the physical conditions and the biota communities are necessary. The extensive research and sampling at the Sand Motor provides such a data set.

The Sand Motor was constructed with the philosophy of Building With Nature. This concept focuses on building hydraulic infrastructure *with* nature, and not *in* nature. Projects with the Building with Nature philosophy make use of natural processes to create integrated solutions that boost ecology, are cost effective and sustainable (de Vriend and Van Koningsveld, 2012).

The main policy objectives of the Sand Motor are (Fiselier, 2010):

1. To stimulate natural dune growth in the coastal area from Hoek van Holland to Scheveningen. This dune growth will serve several functions, namely safety, nature and recreation.

2. To generate knowledge and innovation to answer the question whether this method of coastal maintenance can create surplus value for recreation and nature.

3. To add attractive recreation and nature areas to the Delfland beach.

1.2. PROBLEM DEFINITION AND RESEARCH OBJECTIVE

The Sand Motor is a large perturbation along the Delfland coast and under the influence of waves, tides and wind the morphology of the Sand Motor changes fast. It is expected that these changes of the physical environment may affect the ecosystem services in the future, however the long-term influence of the Sand Motor on the ecosystem services was not assessed yet. Furthermore, the long-term effects on the ecosystem services when changing the design parameters of mega-nourishments are unknown. To investigate this, there is a need for an objective and concrete framework that is able to evaluate the ecosystem service dynamics. Developing a framework that is able to assess and predict ecosystem service dynamics enables the possibility of engineering the ecosystem services of a mega-nourishment.

The main objective of this study is therefore:

"To assess the long-term development of the ecosystem service dynamics of the Sand Motor using a morphological model forecast, to specify the relation between abiotic factors and ecosystem services, so as to help in comparing the ecosystem services of the Sand Motor to different (mega-)nourishment alternatives."

A particular interest is expressed in the spatial and temporal development of the coastal protection, the recreation and the habitat provision ecosystem service. The evolution of these ecosystem services will also be evaluated for two alternative nourishment designs, to research the possibility of engineering the ecosystem services.

The objective will be addressed by answering the following sub questions:

1. What are the ecosystem services of the Sand Motor?

2. Which abiotic factors describe the preconditions of the biotic system and the potential of the ecosystem services at a sandy shore?

3. According to the morphological model forecast, how does the ecosystem services potential evolve at the Sand Motor?

4. Is a morphological model forecast qualified to make a prediction of the ecosystem services potential and what are its limitations?

5. Is it possible to enhance the ecosystem services potential of a mega-nourishment by adjusting the shape?

1.3. APPROACH

The effectiveness and the benefits of the Sand Motor are evaluated using an ecosystem service approach. An ecosystem service approach is increasingly used to study the relationship between humans and nature and to support decision-making that utilizes ecosystems in a sustainable way (Schröter et al., 2014). This concept recognizes that human activities both affect and are dependent on the ecosystem. It considers anthropogenic activities, habitats, species and physical processes, integrates them and thereby provides a broad view on the consequences of decisions.

The ecosystem services are assessed dynamically, over time and space, because the environment of the Sand Motor is dynamic. A long-term prediction of the ecosystem services is made, evaluating them on a yearly basis. The ecosystem services will be analyzed at the large spatial scale of the Delfland coast, because the Sand Motor is a project of which the nourished sand is intended to spread out along the coast.

To be able to evaluate the evolution of the ecosystem services in the future, a process-based, numerical, morphological Delft3D model will be used to calculate bed level changes. The morphological model can predict the bathymetry decades ahead. The state-of-the-art Delft3D model of the Sand Motor is set up and calibrated by Arjen Luijendijk[1], based on previous work of Tonnon et al. (2009). More information on how this model is set up can be found in Appendix C.

The morphological model prediction has limitations with respect to the variables it can predict. For instance, it cannot make a forecast of the number of visitors participating in a recreation activity at the Sand Motor. There are many factors that are important to the actual use of ecosystem services and those factors are difficult to incorporate into a morphological model prediction. Therefore, this thesis focuses on the potential of the ecosystem to contribute to human well-being, based on the physical environment. In other words, in this study the capacity of the ecosystem to provide an ecosystem service is analyzed, instead of the actual use of the service.

In order to make a forecast of the ecosystem service potential, several steps have to be taken prior to the assessment. The steps of the methodology used for the evaluation of the ecosystem service dynamics at the Sand Motor are displayed in Figure 1.2. First of all, a study on the sandy shore ecosystem will be performed. A list of critical abiotic factors is made, to specify the factors that play an important role in the functioning of an ecosystem and that may set out the preconditions of the ecosystem service potential. After this, the relationship between the critical abiotic factors and the ecosystem services is studied qualitatively using literature. Their relative importance to the potential of the ecosystem service is hypothesized, in order to identify the critical abiotic factors that define the preconditions of the ecosystem service potential. Next, assessment methods are set up that use the abiotic factors as indicators to quantitatively evaluate the ecosystem service potential.

The morphological model can predict long-term morphology, however it is not made with the intention to evaluate ecosystem services. While setting up the Delf3D models, assumption were made and the model has limited capabilities. To verify the model performance, the computed ecosystem service potential was validated using the first four years of observations.

The validated assessment method is applied to the site of the Sand Motor. Coastal protection, recreation and habitat provision are evaluated spatially and temporally with the morphological model forecast up to 2050 and compared to the reference situation in 2010, prior to the Sand Motor.

Furthermore, two alternative nourishment designs will be used to study the effect of varying design parameters, namely an offshore island and a traditional shoreface nourishment. Traditionally, the volume of a shoreface nourishment is much smaller (around 1 -2 Mm^3) and the lifetime is shorter (3 -5 years) compared to the Sand Motor. To study the effect of a higher nourishment frequency on the ecosystem service potential, the volume of the Sand Motor is split up into five partial, upscaled shoreface nourishments that in total amount to the same volume and are implemented every four years.

1.4. READER'S MANUAL

This report is divided into chapters. Chapter 2 elaborates on the background of the subject and provides a system description of the sandy shore ecosystem. Chapter 3 describes the ecosystem service methodology that is used in this research. In this chapter, the qualitative relationship between abiotic factors are described and a quantitative assessment method is explained. Evaluating ecosystems service dynamics, using a morphological model forecast is a new approach and therefore the model performance regarding the ecosystems service prediction is validated using the first years of observations in Chapter 4. The validated assessment methodology is applied to the Delfland coast. In Chapter 5 the prediction of the ecosystem service dynamics of the Sand Motor is presented. In Chapter 6, a generalization of the assessment method is made by comparing the Sand Motor to two alternative designs of a mega-nourishment, namely an upscaled traditional foreshore nourishment and an offshore island. The findings of this study are discussed in Chapter 7. The conclusions and several recommendations are summarized in Chapter 8.

[1] Researcher at Delft University of Technology and Senior Coastal Engineer at Deltares

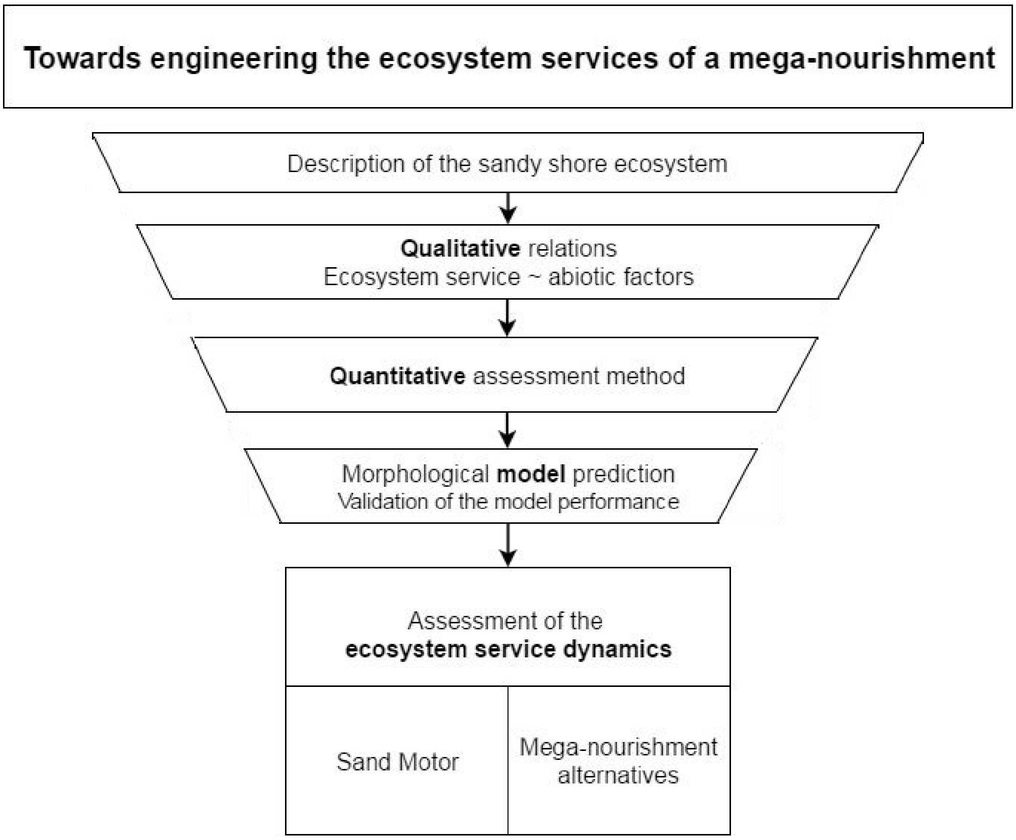


Figure 1.2: Flow chart of the ecosystem service assessment process.

2

THE SANDY SHORE ECOSYSTEM

2.1. CROSS-SHORE ZONATION OF THE ECOSYSTEM

Sandy beaches are dynamic ecosystems[1] under the influence of natural forces, such as waves, tides and wind. Beach ecosystems hold a variety of species that are adapted to the energetic conditions. The zonation of the biota is affected by several abiotic factors, such as substrate sediment characteristics, bathymetry and currents (Holzhauer et al., 2009). Variability on a daily or seasonal basis in tidal levels, wind, waves and temperature influence the organisms with respect to predation, migration, food supply, etc (Janssen and Mulder, 2004). This leads to a dynamic ecosystem that shows a strong variability in diversity, abundance and biomass on a spatial and temporal scale, suggesting a complex interaction between the biota and the abiotic factors (Rodil et al., 2008).

Several ecosystem components can be found at the sandy shore ecosystem and the species communities are strongly dependent on the beach state of the sandy shore (McLachlan et al., 1996). In this study the focus will be on the Dutch mesotidal, dissipative, moderately exposed beach. This beach type holds the following major ecosystem components (Speybroeck et al., 2006):

Fauna

- Terrestrial arthropods, comprises insects and arthropods inhabiting the wrack line and dry beach;
- Zoobenthos, consists of micro-, meio- and macrobenthos and includes aquatic arthropods;
- Fishes;
- Avifauna;

Flora

- Microphytobenthos;
- Vascular plants;

Note that macrophytes are not on this list, as they are not a relevant component of the Dutch coastal waters (Deltares, 2010).

The spatial scale on which an ecosystem is analyzed is of importance when determining the impact of a disturbance or the relevant factors that influence the species communities. The size of the ecosystem may vary from a tidal flat at the Sand Motor to the entire Dutch North Sea coast. The spatial scale of this study concerns the nearshore and reaches from the subtidal zone to the supratidal zone. The ecosystem properties of the cross-shore zones can be described as follows:

[1] Ecosystem definition of the United Nations Environment Programme: *"An ecosystem is a dynamic complex of plant, animal and microorganism communities and the non-living environment, interacting as a functional unit."* (Unep, 2006)

SUBTIDAL ZONE

The subtidal zone in this study reaches from a maximum depth of -20 m NAP[2] to Mean Low Water (MLW), which is at -1 m NAP in the morphological model. The subtidal zone is continuously submerged and landward of the closure depth the bed level is very dynamic. The closure depth at the Holland coast is around -6 m to -12 m NAP (Bosboom and Stive, 2013). Seaward of the closure depth there is minimal variability in the bed level changes and limited cross-shore exchange on a morphological time scale of years. In the subtidal zone birds, microphytobenthos, fishes and marine zoobenthos can be found (Speybroeck et al., 2006). There is relatively little ecological knowledge regarding this zone, because it is a very dynamic environment and difficult to reach by people with measuring equipment. The robustness of the habitats present in the subtidal zone and the influence of a nourishment on them remains uncertain (Holzhauer et al., 2009). Characteristic for this zone are the breaker bars. The height, length and number of sand bars changes over time and vary alongshore. The troughs are considered to have a distinct ecological value, as the hydrodynamics are less energetic, the silt content possibly higher and the benthos abundance larger. A nourishment in the subtidal zone (foreshore nourishment) changes the hydrodynamics, the morphology, the sediment transport and therefore also the transport of organic material and nutrients (Holzhauer et al., 2009).

INTERTIDAL ZONE

The intertidal zone is defined as the area between Mean Low Water (MLW) and Mean High Water (MHW). The species communities in the intertidal zone are significantly influenced by abiotic factors such as substrate sediment characteristics, morphology and beach type. Avifauna, microphytobenthos, marine zoobenthos and some fish species can be found in this zone (Speybroeck et al., 2006). Nourishment influences this habitat, particularly by adjusting grain size and sediment sorting, silt fraction and organic content (Holzhauer et al., 2009).

SUPRATIDAL ZONE

The supratidal zone reaches from MHW upto the top of the dunes. The wrack line (also called strand or drift line) is the boundary between the wet (intertidal zone) and the dry beach (supratidal zone) and is located between Mean High Water Spring (MHWS) and Mean High Water Neap (MHWN). Seaward of the wrack line, morphological changes are governed by marine processes. Landward of the wrack line, in the supratidal zone, marine processes are absent during average climate conditions. The wrack line is an important component of the beach ecosystem with wrack material deposits as a source of organic material. In the supratidal zone avifauna, vascular plants, terrestrial arthropods can be found, with additionally zoobenthos and microphytobenthos at the wrack line (Speybroeck et al., 2006). Sediment characteristics are of great influence on the development of the dry beach and dunes (Holzhauer et al., 2009). Recreation and grooming can be considered as the biggest threats to supratidal biota and embryonic dunes (Speybroeck et al., 2008).

The five different groups of biota have their preferred habitat locations and some are strongly tied to a specific cross-shore zone. The cross-shore zonation of the groups of biota is depicted in Figure 2.1.

2.2. ABIOTIC FACTORS INFLUENCING THE ECOSYSTEM

There is a wide range of factors and issues that affect the use and functioning of sandy shores and thereby influence the ecosystem services of sandy shores. The factors can be grouped into (McLachlan et al., 2013):

- Factors relating to the physical environment, e.g. waves, sediment size and tide;
- Ecological factors, e.g. macrobenthic diversity and abundance;
- Socio-economic factors, e.g. available infrastructure to support the recreation activity, the safety and health status of the beach and the socio-economic environment.

Ecosystems are complex, dynamic systems. The system cannot be conceived as a linear relation from factor to direct benefits for society with no feedback, thresholds or other complexities (Bennett et al., 2009). The relationships between ecosystem services and the characterization of the critical factors should recognize that and work with it (Bennett et al., 2009, Costanza, 2008). There are optimum ranges and limiting requirements for each critical factor that can differ per ecosystem service. Only outside a certain range it can be said with certainty that an ecosystem does not provide potential for a specific ecosystem service. Several abiotic factors influence multiple ecosystem services. This overlap adds to the complexity of the system.

[2]Normaal Amsterdams Peil (NAP), reference height used in the Netherlands. NAP is approximately equal to mean sea level.

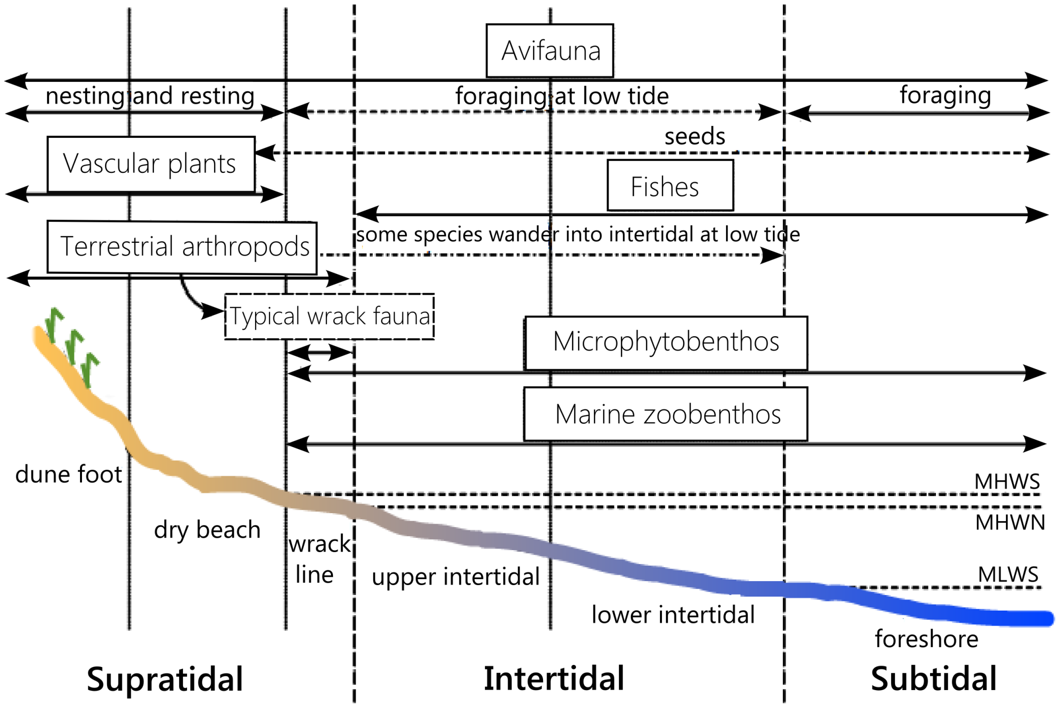


Figure 2.1: Scheme of the zonation of biota on the sandy shore ecosystem. Adapted from Speybroeck et al. (2006).

Recent studies, such as by Van Der Moolen (2015), generate insight into which natural processes, with their driving measurable parameters, contribute to the delivery of specific services and functions. In the overwhelming load of information on the functioning of the ecosystem and the interaction between biotic and abiotic factors, key factors and linkages need to be identified. Some studies suggest that the zonation of benthic communities at a sandy shore is determined by an interaction between biotic (e.g. predation and abundance) and abiotic (e.g. beach width) factors (McLachlan et al., 2013, Schoeman and Richardson, 2002). Those factors do not share the same importance in this potential, but do interact and build on each other. In other studies, it is hypothesized that the benthic communities are primarily controlled by abiotic factors and physical processes (such as beach slope, salinity and grain size), rather than by biotic factors and interactions (such as food availability, competition and predation) (McArdle and McLachlan, 1992, McLachlan et al., 1996). However, when considering beaches with a rather dissipative state, biological interactions do become more significant (Defeo and McLachlan, 2005).

By analyzing the evolution of critical abiotic factors, the prerequisite of the potential for ecosystem services is researched. The underlying physical factors that have led to the current state of the ecosystem services are the indicators of the service potential. Without the presence of certain physical characteristics, a particular ecosystem service cannot exist.

It is assumed that by developing a set of abiotic indicators that create potential for a specific ecosystem, a design approach can be determined that optimizes the potential for the desired ecosystem services of a (mega-)nourishment. In other words, if an accurate forecast can me made on how abiotic factors will evolve, then it might be possible to give an indication on how the sandy beach ecosystem and the potential of ecosystem services will develop in the future. It is essential that the relationships of abiotic factor to ecosystem service is concretized, in order to assess the evolution of the ecosystem services and the policies and practices that are supposed to enhance them (Carpenter et al., 2009).

SELECTED SET OF ABIOTIC FACTORS

Describing an entire ecosystem with its numerous species and biotic and abiotic processes is impractical due to the many linkages between ecosystems, measurable parameters and processes (Laane and Peters, 1993). Therefore, this study will focus on quantitative, measurable, abiotic factors that indicate the potential for ecosystem services as a result of the Sand Motor. The abiotic factors considered to have a significant influence on the sandy shore ecosystem and the studied ecosystem services of the Sand Motor are summarized below in a arbitrary sequence, followed by the literature that has mentioned the factor as well. Unfortunately, for some parameters no data is available. Therefore, only a limited set of abiotic factors will be analyzed in this study. The factors that are used in this study to assess the potential of ecosystem services are marked bold on the following list of the abiotic factors.

1. Sediment size (Baptist et al., 2008, Brazeiro et al., 2001, Fanini et al., 2009, Janssen and Mulder, 2005, Kaji, 2013, Lastra et al., 2005, McLachlan et al., 2013, 1996, Peterson and Bishop, 2005, Rogers, 1992, Speybroeck et al., 2008, Van der Zwaag, 2014)
2. Sediment sorting (Brazeiro et al., 2001, Fanini et al., 2009, Fenu et al., 2012, Janssen and Mulder, 2005, McLachlan et al., 2013, Peterson and Bishop, 2005, Rodil and Lastra, 2004, Rogers, 1992, Speybroeck et al., 2008, Van der Zwaag, 2014)
3. Substrate compaction (Defeo et al., 2008, Fanini et al., 2009, Janssen and Mulder, 2005, Leung and Meyer, Peterson and Bishop, 2005, Rodil et al., 2008, Speybroeck et al., 2008)
4. Silt contents (Bouma et al., 2005, Janssen and Mulder, 2005)
5. **Cross-shore slope** (Baptist et al., 2008, Brazeiro et al., 2001, de Zeeuw et al., 2012, Defeo et al., 2008, Fanini et al., 2009, Hanley et al., 2014, Janssen and Mulder, 2005, Lastra et al., 2005, McLachlan et al., 2013, 1996, Rodil et al., 2006, Schoeman and Richardson, 2002, van Ettinger and de Zeeuw, 2010)
6. **Water depth** (Bouma et al., 2005, Rogers, 1992)
7. **Beach width** (Broer et al., 2011, Defeo et al., 2008, Fanini et al., 2009, Hanley et al., 2014, Hillen et al., 1991, Lastra et al., 2005, McLachlan et al., 2013)
8. **Inundation duration of the intertidal zone** (Janssen and Mulder, 2005, Speybroeck et al., 2008)
9. Inundation frequency of the supratidal zone (Janssen and Mulder, 2005, Ministerie van Verkeer en Waterstaat, 2007, Speybroeck et al., 2006, 2008)
10. Currents (longshore and cross-shore) (de Zeeuw et al., 2012, Kaji, 2013, McLachlan et al., 2013, Rogers, 1992, van Ettinger and de Zeeuw, 2010)
11. Vertical erosion/accretion rate (Brazeiro et al., 2001)
12. **Curvature of the coast** (de Zeeuw et al., 2012, Kaji, 2013, Van den Hoek et al., 2012, van Ettinger and de Zeeuw, 2010)
13. Wrack material deposition (Defeo et al., 2008, Speybroeck et al., 2008)
14. Availability of organic matter in sediment (Brazeiro et al., 2001, Fenu et al., 2012, Peterson and Bishop, 2005, Rodil et al., 2008, Speybroeck et al., 2008)
15. **Wave exposure** (McLachlan and Brown, 2010)
16. **Bed shear stress** (Bosboom and Stive, 2013, Bouma et al., 2005, Vlaams Nederlandse Schelde Commissie, 2014, Wesenbeeck van et al., 2008)
17. **Beach and dune volume** (Arens et al., 2012, Bosboom and Stive, 2013, Hanley et al., 2014, Hillen et al., 1991)

The parameters on the list are not independent from each other. For example, a change in wave action may result in a change in grain size and erosion/accretion dynamics. However, studies suggest that these factors could have an independent influence on different species and biological, hydrodynamic and morphodynamic processes (Brazeiro et al., 2001, McLachlan et al., 1996). The listed parameters are characterized temporally and spatially in Appendix B.

The factors that are analyzed for the ecosystem service potential with the model output are the cross-shore slope, the water depth, the beach width, the inundation duration of the intertidal zone, the curvature of the coast, the wave exposure, the bed shear stresses and the beach and dune volume. These factors will be investigated spatially and temporally for the Sand Motor, in order to give insight in the potential of the ecosystem services. In Section 3.3, the relative importance of the abiotic factors to the potential of the ecosystem services is hypothesized, to check whether crucial information regarding the ecosystem service potential is missing.

2.3. ECOLOGICAL IMPACT OF A NOURISHMENT

When implementing a nourishment, many of the, in Section 2.2 selected abiotic factors, are affected. New habitats are created and original habitats are altered (Speybroeck et al., 2008). A shoreface nourishment causes burial of the local benthic communities on the sandy beach. The thickness of the applied sand layer determines the severity of the burial. The lethal thickness of a sand layer for some species is up to 90 cm. In most nourishment projects, the thickness of the applied layer exceeds this value and stays there for a long time and therefore the nourishment results in a total mortality of the benthic community (Speybroeck et al., 2006). Besides a local impact, the ecosystems of adjacent beaches are influenced through accretion due to longshore and aeolian transport (Speybroeck et al., 2006).

According to Baptist et al. (2008) and van Dalfsen and Essink (2001), the negative ecological effects of shoreface nourishments in the Netherlands are usually short-term. This means that the reduction of abundance and biomass of species in general recovers quite fast. For most species, the community will largely have recovered one year after completion of the nourishment. It is estimated that a large part of the ecosystem will have recovered after one year and that a full recovery of the benthic species communities will take 2 - 5 years (Baptist et al., 2008). The general pattern of the benthic community after a nourishment is that the 'opportunistic' species develop rapidly, followed by a recovery of the community composition and structure (van Dalfsen and Essink, 2001).

Recolonization of the habitat after nourishment depends on two factors. The first is the species specific dispersal and migration capacities. The second is species specific habitat requirements and their optimum ranges, which includes both physical and biological factors (Speybroeck et al., 2006). Recovery of the ecosystem by recolonization of the organism communities may take place by immigration from surrounding habitats, via the water column or by recruitment (Baptist et al., 2008, Speybroeck et al., 2006, van Dalfsen and Essink, 2001). This means that the scale of the nourishment and the length of the impacted beach are of influence on the immigration speed of the infauna. A relatively short distance between nourished and unnourished beaches allows for quicker immigration (Speybroeck et al., 2006). Adaptation of the beach habitat while nourishing will affect the recovery process of the beach ecosystem. This adaptation of the habitat may occur when a grain size is imported that deviates from the initial sediment size. The speed and degree of recovery is mainly dependent on the sediment quality and quantity, the applied nourishment strategy, the place and size of the nourishment and the original physical environment (Speybroeck et al., 2006).

On a aggregated level, two factors predominantly determine the impact of the nourishment on the ecosystem: the degree to which the ecosystem is disturbed and the frequency of disturbance. A mega-nourishment, like the Sand Motor, is implemented once and feeds the adjacent coasts for a longer period of time. This gives species that live longer or need relatively more time to grow the opportunity to settle. However, the scale and the degree of the disturbance in the case of a mega-nourishment is relatively large. The severity of the disturbance of a traditional Dutch nourishment is ought to be smaller. However it needs to be implemented with a higher frequency and the ecosystem needs to recover more often, leading to an advantage for opportunistic species.

It must be noted that sandy shore habitats are dynamic systems. While evaluating the impacts of a nourishment on a temporal scale, it is implicitly assumed that the ecosystem characteristics would have remained constant in the case of no nourishment. This is however not the case, as biota populations have a strong seasonal and inter-annual variation on sandy shores (Fanini et al., 2009). Conclusions on the impacts of nourishments must be unbiased towards natural spatial and temporal variation (Peterson and Bishop, 2005). However, it is difficult to distinguish the impacts due to anthropogenic interventions and natural dynamics. There are two methods to determine whether the biota have recovered after a disturbance by nourishing: 1) By comparison of the situation prior to the nourishment to the situation post nourishment. This method assumes little temporal dynamics and can be useful to study the direct impact of a nourishment. 2) Comparison of the situation post nourishment to a reference community which is undisturbed by nourishments. This method is valid in highly dynamic systems because it takes the natural development into account and is therefore suitable to study the recovery process after a nourishment (van Dalfsen and Essink, 2001).

2.4. ECOTOPE CLASSIFICATION

Ecotopes are spatially defined ecological units, of which the abiotic characteristics are more or less homogeneous. In the ecotope scheme of Bouma et al. (2005) for benthos, several ecotope classes are identified. The ecotope classification scheme provides a tool to analyze the spatial variation of species communities that are predominantly determined by the physical environment. The ecotope maps give relevant ecological information on the potential of the occurrence of benthos communities, making it possible to predict the impact of interventions on the functioning of the ecosystem. It must be mentioned that an ecotope suggests a potential niche and does not precisely describe the species communities that are present in an ecosystem (Bouma et al., 2005). An ecotope map describes a static state of the ecosystem, it is a snapshot, while ecosystems vary dynamically in time and space. Therefore, for the purpose of an ecological analysis, ecotope maps or ecotope area calculations should be made frequently. An ecotope map can be used to visualize how the ecosystem evolves over a long period of time. A drawback of this tool is that anthropogenic influences, such as pollution, are not taken into account (Bouma et al., 2005). The benthos ecotope classification is hierarchical and is based on the dominance of the physical factors and the logical construction of a map. In Table 2.1 the six hierarchy layers of the ecotope classification, as is defined in Bouma et al. (2005), are presented together with the sub classes per layer.

Table 2.1: Layers of the benthos ecotope classification hierarchy (Bouma et al., 2005)

Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**
Salinity	*Substrate 1*	*Depth 1*	*Hydrodynamics*	*Depth 2*	*Substrate 2*
Saline	Hard	Subtidal	Highly dynamic	Water depth	Silt
Brackish	Soft	Intertidal	Low dynamic	Inundation duration	Fine sand
Variable		Supratidal	Stagnant	Inundation frequency	Course sand

Salinity The salinity of the water predominantly determines the type of ecosystem, therefore this is the first layer of the ecotope hierarchy. There are no benthos species that can survive in both fresh and saline water. There is a strong relationship between the salinity of the water and the biodiversity of an ecosystem. In general this relationship attributes a high biodiversity to fresh water, an even higher biodiversity to saline water and a low biodiversity to brackish water (Bouma et al., 2005).

Substrate 1 The second layer of the hierarchy differentiates between soft and hard substrate. The biggest difference between hard and soft substrate is that a sandy soft substrate is mobile. A hard substrate offers a 2D environment while the sediment of a soft substrate allows for a 3D environment (Bouma et al., 2005).

Depth 1 The third layer differentiates between the subtidal, intertidal and supratidal zone. Species communities are strongly connected to one of these zones (Bouma et al., 2005).

Hydrodynamics The fourth layer describes the level of hydrodynamics of an environment influenced by waves and tides. The open North Sea coast is regarded as a highly dynamic environment due to wave action. Areas sheltered from waves with relatively low currents are ecotopes with low dynamics. The hydrodynamics of an ecosystem relates to the wave impact in the supratidal zone during a storm and the currents and wave action in the subtidal and intertidal zone, leading to reworking of the soil. In a highly dynamic environment benthos species need to bury themselves in the bed or find another way to stay in a fixed position. Larval settlement is determined by currents and turbulence. The hydrodynamic conditions influence the food supply for organisms indirectly by determining the amount of water (and thus phytoplankton) that passes (Bouma et al., 2005).

Depth 2 The fifth layer distinguishes depth/altitude within the cross-shore zones. In the subtidal zone this is done by the water depth, in the intertidal zone by the inundation duration and in the supratidal zone by the inundation frequency. Factors like light penetration in and stratification of the water column, forage duration, predation and salt spray can be related to the depth/altitude within a cross-shore zone and influence the species communities (Bouma et al., 2005).

Substrate 2 The final and sixth layer of the ecotope hierarchy describes the sediment composition. The median grain size and the silt contents are, for example, of influence on the burrowing ability and nutrient uptake. It is probable that many species can survive in a broad range of grain diameters and silt contents (Bouma et al., 2005).

When defining the ecotope classes it is important to bear in mind the scale of the studied ecosystem. On larger scales, salinity and depth predominantly determine the species community characteristics, while on a smaller scale, such as a tidal flat, salinity is of less importance and sediment composition can be decisive for the zonation (van Wesenbeeck et al., 2010).

ECOTOPE CLASSIFICATION OF THE SAND MOTOR

In Figure 2.2, the ecotope classes that are likely to be present at the study site have been displayed. The ecotope classes of all hierarchy layers are listed and they are marked to indicate their presence, absence or whether the information regarding the class cannot be extracted from the morphological Delft3D model. As can be seen from the figure, the Delft3D model forecast does not provide information on grain size of the 'substrate 2' layer. However, there are sediment samples which can be used to analyze the substrate characteristics during the first years after construction of the Sand Motor. For this reason the ecotope classes will be defined by means of analyzing the top five layers of the ecotope hierarchy. Furthermore, the morphological Delft3D model only predicts the stresses and bathymetry changes of the wetted shore. For this reason it only is possible to distinguish ecotopes, based on bed shear stresses, in the subtidal and intertidal zone. Therefore the zone above the mean high water level will be defined as one ecotope altogether.

Taking into account the limitations of the morphological model, the ecotopes that are (permanently or temporarily) present in the environment of the Sand Motor are listed in Table 2.2. The ecological characteristics of the individual ecotopes are described in Appendix A.

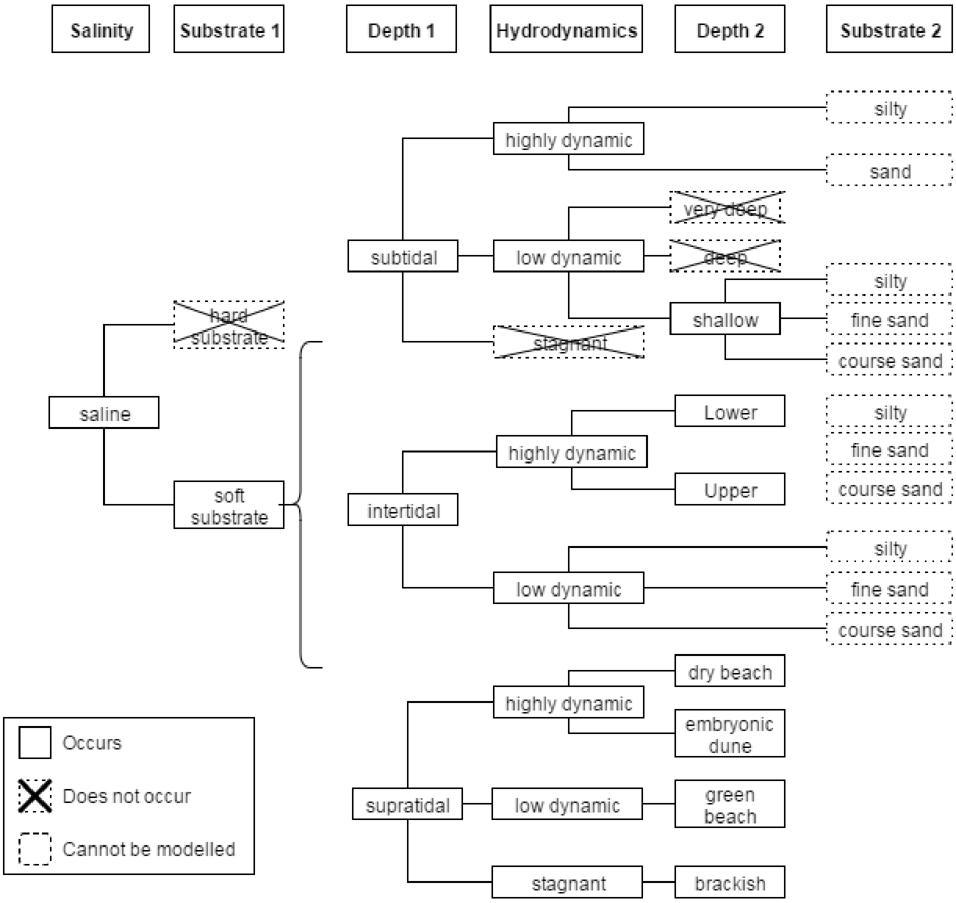


Figure 2.2: Ecotope classification layers applied to the site of the mega-nourishment. The boxes indicate an ecotope occurrence or non occurrence (crossed box) at the studied site or an ecotope layer of which the information cannot be extracted from the morphological Delft3D model (dashed line).

Table 2.2: List of the habitats present at the Sand Motor and the factors that will be used to distinguish the ecotopes.

	Ecotope	height/depth	hydrodynamics
1	Surf zone	< MLW	very high
2	Seaward side of the surf zone	< MLW	high
3	Nearshore	< MLW	moderate
4	Offshore	< MLW	low
5	Sheltered subtidal	< MLW	very low
6	Exposed lower intertidal	between MLW and MSL	-
7	Exposed upper intertidal	between MSL and MHW	-
8	Sheltered intertidal	between MLW and MHW	very low
9	Supratidal zone	between MHW and dune foot	-

2.5. CHARACTERIZATION OF THE PHYSICAL ENVIRONMENT

On the long term, the impact of the Sand Motor will have a much wider reach as the sediment spreads out. On longer time scales (e.g. years), it is interesting to monitor the development of the coast further away from the Sand Motor. The impact area of the Sand Motor is mainly restricted between the harbour jetty of Scheveningen and the Noorderdam at Hoek van Holland. As the nourishment spreads out over time, the beach and the ecosystem services along the entire Delfland coast will be affected.

To analyze the morphological changes, in this study the coastline between Hoek van Holland and Scheveningen has been divided into sections. The spatial and temporal variation further away will not be as strong as near to the Sand Motor, therefore the resolution of the analysis will be lower at these sections. Furthermore, not all ecosystem services are analyzed at the beaches adjacent to the nourishment. Only the coastal protection and the bathing potential will we assessed at those beaches, because the Sand Motor will not have a measurable, additional effect there regarding kitesurfing, strolling and habitat provision.

2.5.1. SPATIAL CHARACTERIZATION OF THE DELFLAND COAST

To specify the impact of the Sand Motor on locations along the Delfland coast, the coastline will be divided into four sections: the nourishment, Scheveningen, 's Gravenzande and the Hoek van Holland section. In Figure 2.3 the locations of the section boundaries[3] are shown together with the bathymetry right after construction of the Sand Motor. The alongshore distance of the section boundary to the origin is depicted as well, where Hoek van Holland is defined as the origin.

[3] The coordinates are presented in the Dutch Rijksdriehoeks (RD) coordinate system.

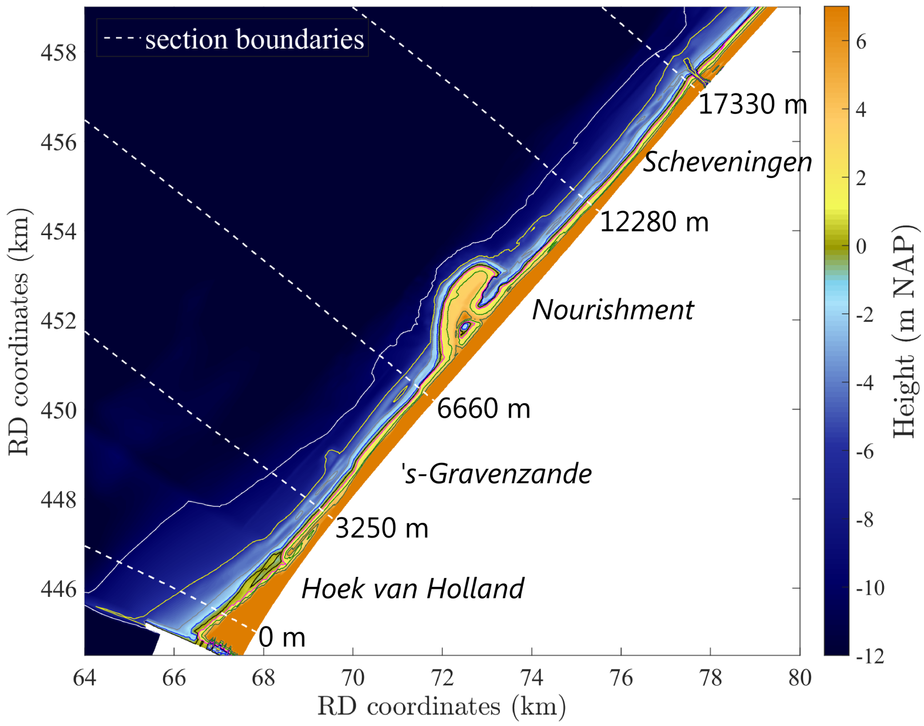


Figure 2.3: The four sections along the Delfland coast. Hoek van Holland is defined as the origin and the distance of the section boundary to the origin is indicated in the figure as well.

2.5.2. SPATIAL CHARACTERIZATION OF THE SAND MOTOR

When describing the Sand Motor, specific terms are used to indicate certain locations. These locations are illustrated in Figure 2.4.

Furthermore, the analysis will be performed using a cross-shore zonation:

1. The supratidal zone: from the MHW line up to the dunes. Specifically for the Sand Motor, this zone includes the dune lake, the dry beach and the (embryonic) dunes.

2. The intertidal zone: from MLW to MHW. At the Sand Motor this includes the tidal flats (wet beach) and parts of the lagoon.

3. The subtidal zone: from -20 m NAP until MLW. Specifically for the Sand Motor, this includes the sea, parts of the lagoon and the submerged sand banks.

The cross-shore profile Sand Motor diverts strongly from a standard beach profile. To illustrate this deviation, the profiles of two cross-shore transects are shown in Figure 2.5. The upper figure presents a cross-shore profile at the lagoon and the lower figure at the dune lake. The locations of the cross-shore profiles are visualized in Figure 2.6.

Figure 2.4: Aerial photograph taken in October 2013 by Rijkswaterstaat/Jan van Houdt. Terms to specify certain locations at the Sand Motor are indicated in the picture.

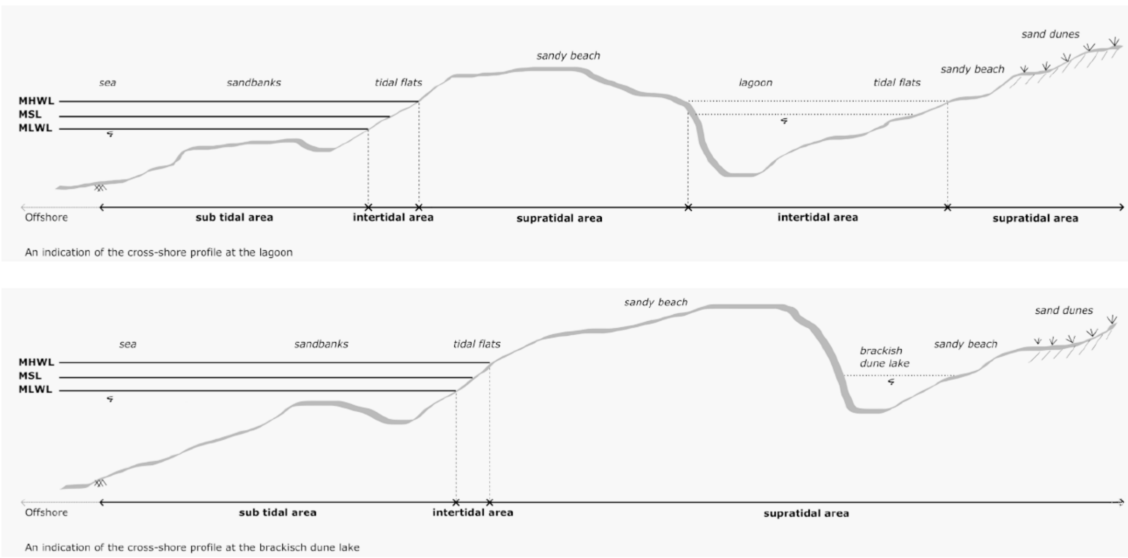


Figure 2.5: Cross-sections of the Sand Motor at the lagoon and the dune lake. The dotted lines represent an indication of the water levels in the lagoon and the brackish lake (Van Der Moolen, 2015)

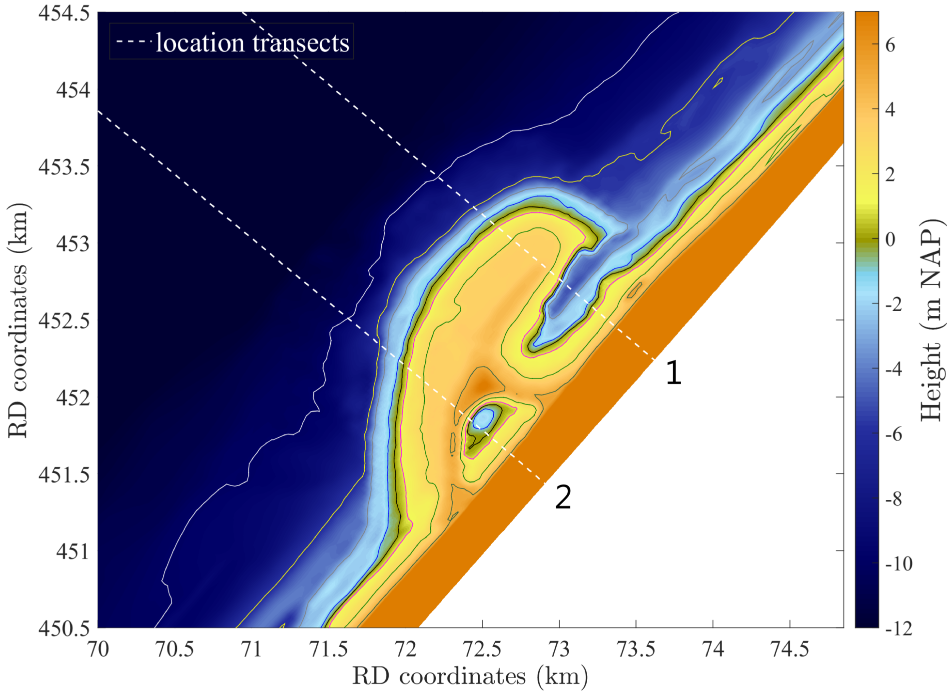


Figure 2.6: Locations of the cross-shore profiles of Figure 2.5 at the lagoon (cross-section 1) and the dune lake (cross-section 2).

3
ECOSYSTEM SERVICES

An ecosystem service approach, incorporating the benefits that nature provides to humans, is increasingly used throughout the world. The White House, for example, recently issued a memorandum that promotes integration of ecosystem services into planning and decision-making (Dickinson et al., 2015).

According to (Haines-Young and Potschin, 2010), ecosystem services are defined as "the direct and indirect contributions of ecosystems to human well-being, arising from the interaction between biotic and abiotic processes". The contributions are underpinned by properties of an ecosystem and are appreciated by humans, socio-culturally or economically. Ecosystem services directly or indirectly influence the benefits (e.g. health, security) for society in multiple ways (De Groot et al., 2010). Ecosystem services can be divided into four main categories: provisioning, regulating, cultural and supporting or habitat services. Provisioning services involve products or goods obtained from ecosystems, such as food, water and raw materials. Regulating services entail the contributions of ecosystems in regulating processes, such as climate regulation, erosion prevention and protection during extreme (storm) events. Cultural services concern non-material contributions of ecosystems to human well-being, such as opportunities for recreation and spiritual experience. The habitat service is a category that highlights the importance of ecosystems in providing habitats for species which are necessary for the production of the other ecosystems services. Because of their contested nature (Carpenter et al. (2009) and others) and the risk of 'double counting' ecosystem services, supporting services have in recent classifications been replaced by habitat services.

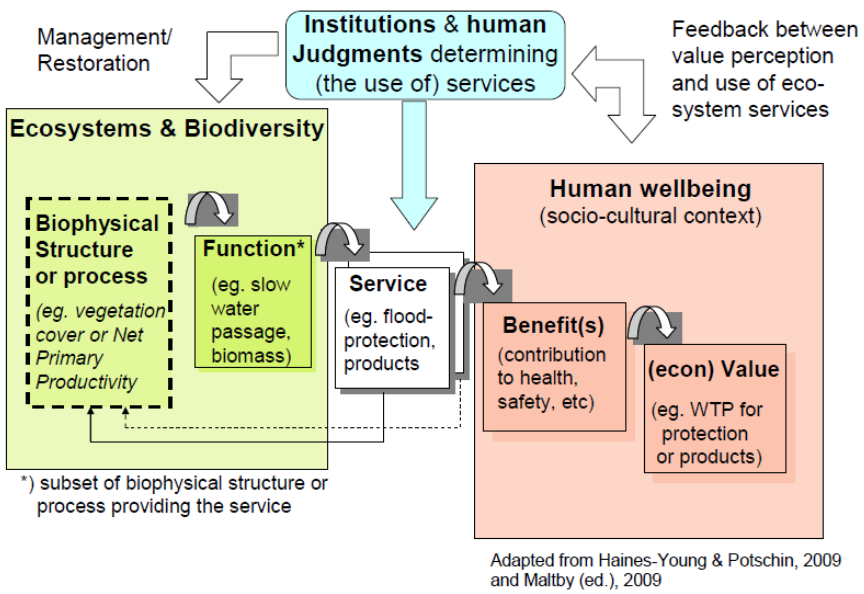


Figure 3.1: Framework describing the pathway from ecosystem process to human well-being (De Groot et al., 2010).

In the framework of De Groot et al. (2010), a distinction is made between the capacity ('function') of an ecosystem to deliver an ecosystem service and the actual use of the services. Interactions between physical, chemical and/or biological factors and processes are the building blocks of the ecosystem service potential. The framework is illustrated in Figure 3.1. Note that potential service provision has recently been referred to as capacity or stock, rather than function, to avoid confusion with the ecological term ecosystem function. Actual use of the service is commonly referred to as 'flow'. The use of services can affect the underlying ecosystem properties in various ways and thereby influence the potential to provide other ecosystem services (De Groot et al., 2010).

Evaluation of the potential to provide a service entails an analysis of factors, for instance, a beach area suitable for recreation (= potential) activities, such as walking or sunbathing (= service). Many other factors together determine whether the service potential materializes into an actual service. For example, increased dune volume (= potential) only contributes to actual flood protection (= service) if valuable properties exist or people live in the hinterland that would be at risk during flooding. Similarly, a beach area must be accessible, clean and safe before people actually will actually consider using it for recreational activities. Generally speaking, the assessment of actual ecosystem services provision involves accounting for factors that are both physical, ecological and social in nature. Due to the complexities involved in such an assessment and the data available for this study, this thesis will focus on potential ecosystem services only. However, consequences for actual service provision will be discussed and speculated on where possible.

The ecosystem services of an ecosystem are interrelated: a change in one service may affect availability or provision of others (Bennett et al., 2009). Some services strengthen each other (synergy), others counteract (trade-off) (Bosonderzoek, 2014). For example, the presence of breeding spots for certain birds limits the amount of beach and dune area that can be accessed by recreationists. An example of synergy is the extension of sandy dunes, which contributes both to the level of coastal protection and the presence of a fresh water reservoir by dune filtration.

3.1. ECOSYSTEM SERVICES OF THE SAND MOTOR

The Sand Motor provides several ecosystem services. To give an impression of the environment at the Sand Motor, two images are presented in Figure 3.2.

(a) Recreationists at the Sand Motor (b) Tidal flats at the southern side of the Sand Motor

Figure 3.2: Impression of the environment at the Sand Motor. On the left, kitesurfers and people going for a stroll at the lagoon. On the right, tidal flats at the southern end of the lagoon. Pictures taken by Rijkswaterstaat/Joop van Houdt.

It is important to clearly define the ecosystem services and identify separate processes that are important for the potential of those services. According to Van Der Moolen (2015) and Alexander van Oudenhoven[1] (personal communication), at least four ecosystem services can be identified as a direct result of the Sand Motor's implementation. The ecosystem services can be divided into several sub-services, according to the framework of Van Der Moolen (2015).

[1] Postdoctoral Researcher Coastal Ecosystem Services, Leiden University

1. **Coastal protection**
    - Flood protection.
    - Maintenance of the coastline position.
2. **Recreation**
    - Kitesurfing
    - Sunbathing
    - Strolling
3. **Fresh water provision**
4. **Habitat provision**
    - Nursery area
    - Refuge and forage area

ECOSYSTEM SERVICE 1: COASTAL PROTECTION

Coastal protection consists out of two components: protection of the hinterland against flooding by storms and preservation of the current position of the coastline, also referred to in the Netherlands as BKL (Basis Kustlijn). This ecosystem service 'Coastal Protection' can be subdivided into two sub services:

FLOOD PROTECTION

The first sub-service involves enhancing the safety of the hinterland against flooding. The beach and dune area protect the hinterland against storm erosion. This ecosystem service potential entails the current state and volume of the sand dunes and the potential for new dune development.

The aspect of nature development (habitat provision) has an important contribution to this service. Presence of vegetation is crucial for dune formation, because it stabilizes and stimulates the accumulation of sediment (Hanley et al., 2014). The abiotic factors necessary to create a dune ecosystem must be present in order to enhance the potential for this service.

MAINTENANCE OF THE COASTLINE POSITION

The second sub-service is the maintenance of the position of the coastline, to compensate for losses due to sea level rise and structural erosion and thus preventing coastline retreat. The protection of the sandy beach and maintaining coastal quality is important to guarantee space for the utilization of the coast and to protect the accommodations and infrastructure present on the beach and near to the dunes. The indicator for the potential of this ecosystem service is the location of the coastline position.

ECOSYSTEM SERVICE 2: RECREATION

The coastal zone accommodates more than a million inhabitants and entrepreneurs and is visited by tourists and recreationists. The attractiveness of the coastal zone requires beach quality and space for development (Stuurgroep Deltaprogramma Kust, 2013). This ecosystem service is divided into three sub services: kitesurfing, swimming and strolling. For the assessment of this ecosystem service social and economic factors also play a role, such as accessibility, a clean beach and awareness of the location. It is important to realize that the actual occurrence of this ecosystem service is a result of potential, accessibility and factors related to human perception. The parameters in this study linked to the recreation service are related to the physical potential for an activity.

KITESURFING

The lagoon in the Sand Motor has grown out to be a kiter's paradise. With its sheltered water, large area and stable sea wind, the lagoon is ideal for kitesurfing.

SUNBATHING

The Sand Motor attracts many visitors that utilize the beach for relaxation and sunbathing. This recreation activity is related to people that visit the Sand Motor to just be there, enjoy the surroundings and who stay there for some time. Some people visit the Sand Motor for swimming as well. However swimmer safety cannot be guaranteed at all areas of the Sand Motor, especially at the head of the Sand Motor. For this reason, in some areas swimming is prohibited, such as round the head of the peninsula. The main activity associated with this recreational service is sunbathing and enjoying the surroundings, which is located at the dry beach. Therefore, the physical indicator associated with the potential of this service is related to the dry beach area. For the actual occurrence of the ecosystem service, other factors such as a clean beach, sunny weather, accessibility, facilities and attractive nature areas (habitat provision) are important as well.

STROLLING

During the year, many visitors at the Sand Motor go for a stroll or walk their dogs. The peninsula is a dynamic environment, where large parts are under water during flood twice a day. On the peninsula, a walking route is specified which prevents people from being isolated and surprised by the upcoming tide (www.dezandmotor.nl, 2015a).

ECOSYSTEM SERVICE 3: FRESH WATER SUPPLY

The protrusion of the Sand Motor into the sea creates an extension of the fresh water reservoir of the dunes. The dune sand filtrates the rain water, which creates a fresh water volume. The area for rain water catchment has increased due to the cross-shore extension of the Sand Motor (Van Der Moolen, 2015). The Sand Motor spreads out alongshore and may enlarge the fresh water volume by broadening the dunes of the adjacent beach.

ECOSYSTEM SERVICE 4: HABITAT PROVISION

Ecosystems provide a habitat for plants and animals and are therefore a prerequisite for biological diversity. Habitat provision entails the adding of new habitats and maintenance of existing habitats that are crucial for the successful life cycle of species, such as nurseries and migratory routes (Liquete et al., 2013). Creating an environment that has a high potential for new species and maintaining the life cycles of all species will lead to new biodiversity niches and an increased overall biodiversity. Many migrating or nursing species as well as high biodiversity in general can be valued by fishermen, birders and policy makers, respectively. The policy makers of the Sand Motor project also value the provision of habitats: the policy objectives of the Sand Motor entail the stimulation and adding of nature areas (see Section 1.1).

Using the framework of De Groot et al. (2010), the habitat provision service is identified as a separate category to highlight the importance of the provision of habitats for migratory species (e.g. as nurseries) and protection of the gene pool (maintaining vitality of the gene-pool by allowing natural selection processes). Habitat provision has an indirect effect on the contributions to human well-being and the availability of the ecosystem services is directly dependent on the state of the habitat that provides the services (De Groot et al., 2010). The maintenance of healthy habitats forms the basis for the provision of all ecosystem services, since the species living in these habitats play a role in the provision and conservation of ecosystem functions (De Groot et al., 2002). This service has direct value in the case of the nursery function, providing a habitat for species of which the adults are caught for commercial fishing. Also protection of the gene-pool by providing habitats for natural selection processes is increasingly recognized as important, as money is invested in maintaining the original gene-pool of commercial species and in conservation spots (De Groot et al., 2010).

The aim of this study concerns the development of the ecosystem in the future. The ecosystem service potential will be evaluated according to its capacity to inhabit different types of species. The ecosystem service potential is based on the physical surroundings, such as the height and level of hydrodynamic forcing. The prediction of potential niches gives information regarding the potential enhancement of the other ecosystem services. A habitat for dune vegetation enhances flood protection by the catchment of sand. A habitat that is known to have a high benthos abundance will attract species through the food web such as birds and seals and thereby potentially enhance the recreation service.

In the assessment of the habitat provision potential, biotic factors that can influence the actual abundance, biomass or diversity of the ecosystem are excluded. Factors such as food availability, predation pressure and disturbance by humans will affect the actual presence and abundance of species.

Habitat provision can be split into two sub functions:

REFUGE AND FORAGE
A suitable living habitat for plants and organisms, providing shelter and an area to collect food or provisions.

NURSERY AREA
A suitable reproduction habitat is necessary to protect juveniles and the maintenance of fish species (De Groot et al., 2002).

3.2. RESEARCHED ECOSYSTEM SERVICES
In Section 1.1, the three policy objectives of the Sand Motor are summarized. The ecosystem services that fit these objectives are the coastal protection, recreation and habitat provision services. The goal of this study is to aid the integration of ecosystem service objectives into the design of a nourishment. The ecosystem service of fresh water supply is an important contribution to human well-being, however it will not be elaborated in this research as it is not mentioned as a primary objective of the Sand Motor.

When predicting the occurrence of ecosystem services it is not possible to make a forecast, based on the physical environment, of the actual value of the ecosystem service. Instead, by defining indicators of the service, the potential for the ecosystem service can be assessed. For example, it is not possible to predict the number of people going for a stroll at the Sand Motor. Instead, the potential for the service will be estimated through physical indicators such as the length of the walking route. It is not possible to predict the number of species present at the Sand Motor. Instead, relevant abiotic factors will be combined to identify ecotopes that are known to have specific ecological characteristics. When further mentioning ecosystem services in this report, the potential for the occurrence of those services is implied.

3.3. QUALITATIVE RELATION BETWEEN ABIOTIC FACTOR AND ECOSYSTEM SERVICE
Previously in Section 2.2, several abiotic factors were listed that influence ecosystem services at the sandy shore. In this section, the relation between those abiotic factors and ecosystem services will be elaborated on qualitatively. Firstly, the linkages will be explained for the coastal protection ecosystem sub services. Secondly, the factors of the recreation ecosystem service are elaborated. To finalize, the factors related to habitat provision will be discussed.

INTRODUCTION TO THE RANKING METHOD
The factors listed in the previous chapter have been scientifically proven to be important to the ecosystem services. However, some factors have a bigger influence on the service than others. In order to make an accurate forecast, it is important to identify the physical factors that contribute the most to the ecosystem service potential. If data regarding these crucial factors is unavailable or the morphological model does not calculate them, it may not be possible to make an accurate forecast of the ecosystem service potential. For this reason, the relative importance of the abiotic factors to the ecosystem service is indicated in Table 3.1, 3.2 and 3.3.

The relative importance of the parameters per cross-shore zone will be hypothesized and indicated in the tables with a '-' or '+', where multiple pluses indicate a greater importance to the ecosystem service potential and a minus means the factor does not influence the ecosystem service potential. The relative importance of the factors related to the ecosystem service is partially based on expert opinions and scientific research and partially on subjective reasoning where there are gaps in the available literature. The factors that have been assigned a relative importance based on scientific research have been marked with a footnote, referring to the source of the research.

3.3.1. COASTAL PROTECTION
In Table 3.1 the abiotic factors are linked to the cross-shore zones of flood protection and protection of the coastline position.

FLOOD PROTECTION
The potential to grow dunes will be based on the theory of a supply limited coast proposed in De Vries (2013). Both supply and wind speed determine aeolian transport rates. In the case where supply is abundant, wind speed will determine the transport rate and wind driven equilibrium transport can be reached. In a supply

Table 3.1: Critical abiotic factors of coastal protection and their relative importance to the assessment of the sub services. More pluses indicate a greater importance and a minus a negligible relevance.

	Coastal Protection					
	Flood protection			Protection of the coastline position		
	subtidal	intertidal	supratidal	subtidal	intertidal	supratidal
Sediment size	++	++	++ [1]	++	++	+/-
Sediment sorting	-	+ [2]	+ [2]	-	-	-
Substrate compaction	-	-	-	-	-	-
Silt contents	-	-	-	-	-	-
Cross-shore slope	+/- [3]	+++ [2]	+	++	++	++
Water depth	-	-	-	-	-	-
Beach width	-	+++	++	++	++	++
Inundation duration		-			-	
Inundation frequency			+++			-
Currents	+	++	++	++	++	+/-
Vertical erosion/accretion rate	-	-	+	-	-	-
Curvature of the coast	+	+		+++	+++	
Wrack material deposition			+			-
Organic content	-	-	+	-	-	-
Wave exposure	+++	+++	+++	++	++	-
Bed shear stress	+	++	++	++	++	++
Volume	+/- [3]	++	++++ [3]	+++	+++	+++

[1] (De Vries, 2013, Van Der Wal, 1998); [2] (De Vries, 2013); [3] (Van Geer, P, 2012)

limited environment, the amount of sediment available limits the transport and the wind driven equilibrium transport rate is not reached. When assuming that the beach is a supply limited system, factors influencing the wind velocity field become less and supply-limiting factors more important (De Vries, 2013). This is contradictory to the theory in several other publications, such as Short and Hesp (1982), where the aerodynamic flow across a beach profile is claimed to have a dominant influence on the aeolian transport rates. In that theory, if the wind profile is disturbed the aeolian transport rates will decrease. A flat surface topography and a gentle **cross-shore slope** causes fewer fluctuations in the wind velocity field and will then lead to a higher equilibrium transport rate (Short and Hesp, 1982, Van Der Wal, 2000). However, in a supply limited system the wind driven transport capacity is not reached and therefore factors like surface topography and fetch length have a limited effect on aeolian transport. An observation in the field where aeolian transport rates increase up to a certain equilibrium, a phenomenon called the fetch effect, can also be ascribed to a temporal and spatial variability in the sediment supply (De Vries, 2013).

Two aspects determine the potential of flood protection: the resistance during storm impact and the process of dune recovery and growth. The assessment of flood protection will predominantly be based on the current **dune volume**, where a larger dune volume directly leads to a safer situation. During storms, the storm surge level can impact the dune face causing dune loss due to offshore directed transport. The **inundation frequency** of the supratidal zone is therefore a factor that determines the necessary dune volume to prevent a dune breach. After a storm, the dunes must be able to recover again. Marine and aeolian transport and the entrapment of sand by dune vegetation determine the potential for the growth of embryonic dunes. During milder conditions, the **waves** in the surf zone cause a net onshore directed sediment transport and deposits loosely packed sand to the intertidal zone (Bosboom and Stive, 2013). In this light, higher waves have a greater sand transporting ability and induce higher onshore directed wave-induced transport rates (Short and Hesp, 1982). For this reason sediment exchange processes by **currents** between the surf zone and the beach are interesting, however crucial knowledge of these processes and the effect of marine transport on dune growth is missing (De Vries, 2013). Furthermore, a sheltered beach is protected from **wave impact**. This prevents the storm surge level from reaching the dune face or it will lead to lower concentrations of suspended sediment near the dunes and a relatively weaker undertow **current** thus leading to relatively lower net offshore transport capacity and less sediment loss during storms (Bosboom and Stive, 2013).

In the study of De Vries at the Dutch coast no correlation was found between wind conditions and coastal dune volume change, however there was a significant correlation found between dune volume change and **beach slope**. De Vries did not measure significant morphological changes at the dry beach and found a correlation between the tidal level and aeolian sediment transport, suggesting that the intertidal zone is an important sediment source. The correlation found in the study of De Vries (2013) between **beach slope** and dune growth, between sediment transport and tidal level and the change in sediment transport with varying supply indicate that the aeolian transport rates are limited by supply and the magnitude of the sediment source predominantly determines dune growth at the Dutch central coast.

A possible explanation for the location of the sediment source at the intertidal zone is **sediment sorting**. During high water levels marine processes stir up the sediment and during low water levels this mixed and poorly **sorted** top layer becomes available for aeolian transport. In the supratidal zone the top layer of the bed is well **sorted** due to aeolian transport, leaving the coarser grains behind and armoring the bed (De Vries, 2013). A wider intertidal zone corresponds to a larger surface which is reworked by marine processes on a tidal scale and more sediment available for transport. An exception to this is the post-storm situation. Right after a storm, the water level has reached far up the dry beach and marine processes consequently has stirred up sediment in the supratidal zone, leaving a top layer that is susceptible for aeolian transport. After a storm, the water level drops again initiating the dune recovery phase. During dune recovery the dry beach also contributes to the supply of sediment. Once the process of armoring has made the dry beach non-susceptible for transport again, the supply is limited to the intertidal zone until the next storm occurs.

A relatively large intertidal **beach width** will increase the source for sediment transport and thereby increases the potential for aeolian transport. A beach nourishment usually leads to a significantly wider beach. Initially, the magnitude of aeolian sediment transports measured at a nourishment site is larger (Van Der Wal, 1998). This may be the result of an increased sediment supply. However, this effect is temporary because of sediment sorting and armoring of the surface layer at the dry beach (De Vries, 2013). In addition to being an indicator of the magnitude of the sediment source, an increased **beach width** also acts as a buffer against wave energy and impact on the dunes (Van Der Wal, 1998). A gentle subtidal **cross-shore slope** dissipates wave energy better than a steep slope. However this effect on dune safety is very limited, as was concluded in Van Geer, P (2012).

The **curvature of the coast** also plays a role in aeolian transport to some extent, by causing accreting or eroding zones leading to differences in the cross-shore beach slope. An accreting beach generally has a milder slope than the adjacent eroding beaches. A milder slope corresponds to a larger intertidal beach width and to a larger sediment supply.

In the study of Van Der Wal (2000) a significant effect on the aeolian transport rates was found by a varying **sediment size** of a nourishment at a beach at Ameland. Sediment size is an important transport factor not only in the marine environment, but also in the aeolian zone. A larger grain size increases the treshold velocity for motion and thereby leads to lower transport rates (Van Der Wal, 1998). With a median grain size that is too small hardly any dune growth will occur (Van Der Moolen, 2015) However, in the study of De Vries during an experiment at Vlugtenburg, the treshold wind velocity for transport varied only little while the average sediment concentration varied strongly, suggesting that the wind treshold velocity did not play a role in varying sediment transport rates during that experiment. The treshold velocity is dependent on **median grain size**, **cross-shore slope** and moisture content (Van Der Wal, 2000), indicating that for this part of the Dutch coast these factors could be less relevant to the rate of dune growth than the magnitude of the sediment source.

Supply limiting factors such as **sediment sorting**, surface moisture content and shell fragments causing lag deposits (Van Der Wal, 1998) have an impact on the magnitude of the sediment supply (De Vries, 2013). Unfortunately, the relative importance of these factors is unknown. The intertidal zone is the area at the beach with the highest moisture content. Nonetheless, this zone appears to be the location of the sediment source due to the reworked, poorly sorted top layer. Perhaps the sediment at the intertidal zone dries very fast during low water, making it susceptible for transport after which it is immediately blown towards the dunes (Communication with Sierd de Vries).

The **wrack material** at the high water line contains, among other components, propagules of dune plants. Removal of this wrack will pose a threat to the formation of embryonic dunes and will therefore affect the potential for increasing the flood protection service (Defeo et al., 2008). Vegetation in the supratidal zone is necessary for the entrapment of the sand particles transported to the backshore by aeolian transport. Please note the link of flood protection to the service of habitat provision. Presence of perennial species enhance sediment stability and dune formation (Short and Hesp, 1982). To control and stimulate the vegetation community sand drift is an essential factor. However, too much **vertical accretion** will cause suffocation of the plant species. The factors that control the aeolian transport rate must lead to a transport capacity that ensures the transport of nutrients and **organic material** to the dunes, but does not suffocate the vegetation.

MAINTENANCE OF THE COASTLINE POSITION

The development of this sub service is determined by sediment dynamics in combination with the cross-shore slope. The **volume** of the active beach profile is directly related to the coastline position. The volume between a defined upper and lower boundary is related to the **cross-shore slope** of the beach profile and the beach width.

Longshore **currents** induce longshore transport and in the case of a gradient in this longshore transport, erosion or deposition takes place. The longshore current is mainly driven by breaking waves where the magnitude of the transport depends on the angle of incidence (Bosboom and Stive, 2013). The **exposure to waves** is therefore a factor to consider in combination with the **curvature of the coastline**. The curvature of the coastline affects the angle of wave incidence. Along the nourishment, this change in incident wave angle leads to a gradient in the alongshore sediment transport rates and therefore in erosion or accretion (Bosboom and Stive, 2013).

The **sediment size** has an important influence on the sediment transport rates. To initiate motion, a larger grain size needs a higher **shear stress** exerted by the current and waves, because it has a higher critical bed shear stress (Bosboom and Stive, 2013). A larger sediment size corresponds to a longer lifetime of the nourishment as the longshore transport rates are reduced. The sediment size also influences the aeolian transport rates. The dunes (> +3 m NAP) act as a sediment sink and a relatively large sediment size decreases the potential for aeolian transport.

Not only longshore transport, but also **cross-shore transport** is of relevance to this sub service. During storms, sediment in the dry zone is transported offshore. In the case of a positive gradient in the longshore current, this sediment is 'lost' from the profile and cannot be used to restore the beach during milder conditions. Aeolian cross-shore transport feeds the dunes while simultaneously decreasing the volume present in the beach zone. However, the magnitude of aeolian transport rates are significantly lower than the marine transport rates and storms that reach the dune face occur only occasionally.

INTERRELATION OF THE PARAMETERS

Some of the abiotic factors that are discussed in Subsection 3.3.1 are strongly related to each other. For example, the waves and currents affect the magnitude of the bed shear stress; the cross-shore slope determines the beach width, which are both related to the beach and dune volume; the wave action affects currents, the slope and the sediment sorting. It is important to realize that if one factors changes, other factors could change as well. The factors are interrelated, however some have a first order importance. For instance, the increased wave height and storm surge level during storms is the precondition of dune volume loss. Waves also affect currents and bed shear stresses, which set the sediment in motion, however the high waves during storms are the first order condition. The actual beach volume determines the coastline position, but a change in cross-shore slope changes the volume as well.

3.3.2. RECREATION

The abiotic factors that are relevant to the potential of the recreational experience of kitesurfing, (sun)bathing and strolling are listed in Table 3.2.

KITESURFING

The degree of **wave exposure** predominantly dictates the potential for kitesurfing. A sheltered area at the coast provides ideal circumstances for kitesurfing. A stable sea wind combined with a flat water surface, as in a lagoon is a unique surfing spot in the Netherlands. The sheltered area should be of substantial size to be able to allow a large number of kites. A mega-nourishment without this sheltered feature will not distinctively add to this ecosystem service, as it will be comparable to other parts of the Holland coast.

The **water depth** varies with the tide. The surface area of the subtidal zone is fixed and can be utilized at all times. A shallow water depth, in which it is possible for a person to stand, can be regarded as pleasant and can make the surfer feel more safe during calamities. This is especially the case for beginners. On the other hand, a water depth that is too shallow may lead to sand banks that can obstruct kitesurfing.

The dry beach in the supratidal zone is used for preparing the kites. Because of the long lines, quite some space is necessary. Therefore a minimum dry **beach width** is required to accommodate the kite surfers in preparing their gear.

Table 3.2: Critical abiotic factors of recreation and their relative importance to the assessment of the sub services. More pluses indicate a greater importance and a minus a negligible relevance to the potential.

	Recreation								
	Kitesurfing			Sunbathing			Strolling		
	sub-	inter-	supratidal	sub-	inter-	supratidal	sub-	inter-	supratidal
Sediment size	-	-	-	-	+	+	-	+	+
Sediment sorting	-	-	-	-	-	-	-	-	-
Soil compaction	-	-	-	-	-	-	-	+/-	-
Silt contents	-	-	-	++	++	++	-	+	-
Cross-shore slope	-	-	-	+	+	-	-	-	-
Water depth	+	+	-	-	-	-	-	-	-
Beach width	-	-	+	-	+	+++[1]	-	+	+
Inundation time	-	-	-	-	-	-	-	-	-
Inundation freq.	-	-	-	-	-	-	-	-	-
Currents	-	-	-	+++	+++	-	-	-	-
Vertical accretion	-	-	-	-	-	-	-	-	-
Coastline curvature	-	-	-	-	-	-	-	-	++
Wrack deposition	-	-	-	-	-	+	-	-	+
Organic content	-	-	-	-	-	-	-	-	-
Wave exposure	++	++	-	+	-	-	-	-	-
Bed shear stress	-	-	-	-	-	-	-	-	-
Volume	-	-	-	-	-	-	-	-	-

[1] (Broer et al., 2011);

SUNBATHING

The dry **beach width** determines the area available for visitors to enjoy the sun and surroundings and dictates whether it is possible to open a beach restaurant(Broer et al., 2011). However, a beach width that is too large can counteract the recreation potential, because the walking distance to the waterline is too large, decreasing the probability that visitors will take the effort. The dry and the wet beach width should be distinguished, because the dry beach is available to users at all times and the wet beach is not (McLachlan et al., 2013).

Excessive sand transport can be unpleasant for recreationists (Van Der Wal, 1998). A **sediment size** which is too fine will form a nuisance to recreationists by drifting sand, even at low wind speeds. On the other hand, a medium grain diameter which is too large is not comfortable while sunbathing.

Presence of **silt** or **wrack material** is unwanted at beaches used for recreation. Accumulation of silt at low energetic areas might cause a nuisance because of smell and dirt and wrack material at the high water line can be perceived as dirt (McLachlan et al., 2013).

When relating the potential for swimming to this recreation activity, other aspects should be taken into account as well. In terms of safety, a high **wave exposure** is not compelling for swimmers. A sheltered area provides a safer surrounding and adds a distinguishing feature to the bathing potential. Dangerous **currents**, such as rip currents or strong tidal currents, will potentially create a dangerous situation for swimmers (de Zeeuw et al., 2012). Therefore **currents** are an important factor in the assessment of the swimmer safety. A steep **cross-shore slope** causes the swimmer to enter deeper water relatively fast, which might be perceived as unpleasant or unsafe (Van Der Moolen, 2015).

STROLLING

The area available for strolling is predominantly determined by the dry **beach width** and beach length. The beach length along the waterline determines the length of the route that is attractive for strolling and is the result of the **coastline curvature** and magnitude of the nourishment.

A **sediment size** that is too small may form a nuisance to visitors by high rates of blowing and drifting sand.

A low **compaction** of the substrate increases the probability of drift sand. Drift sand is formed by sand blown on sheltered shallow water. Visitors might get stuck while walking on drift sand causing a panic reaction.

Accumulation of **silt** may lead to a sludge layer which is perceived as dirty by visitors. The same holds for the **wrack material** at the high water line.

3.3.3. HABITAT PROVISION

This ecosystem service consists of two sub services, the 'refuge and forage' and the 'nursery' function. In Table 3.3 the abiotic factors are listed that can be related to the sub services.

Table 3.3: Critical abiotic factors of habitat provision and their relative importance to the assessment of the sub services. More pluses indicate a greater importance and a minus a negligible relevance.

	Habitat Provision					
	Refuge and forage			Nursery		
	subtidal	intertidal	supratidal	subtidal	intertidal	supratidal
Sediment size	++	++	++	+++ [1]	++	
Sediment sorting	+/-	+/-	+/-	++ [1]	+/-	
Substrate compaction	+/-	+/-	+/-	-	-	
Silt contents	++	++		++	++	
Cross-shore slope	+/-	+/-	+/-	-	-	
Water depth	+[2]			++ [1]		
Beach width	-	+	+++	-	+	
Inundation duration		+++			-	
Inundation frequency			+++ [2]			
Currents	+++	+++		+++	+++	
Vertical erosion/accretion rate	-	+	++	-	-	
Curvature of the coast	-	-	-	-	-	
Wrack material deposition	-	-	+++	-	-	
Organic content	+	+	+	+ [1]	+	
Wave exposure	+++[3]	+++[4]	+++	+++	+++	
Bed shear stress	+++[5]	+++	+++	+++ [2]	+++	
Volume	-	-	-	-	-	

[1] (Rogers, 1992); [2] (Bouma et al., 2005); [3] (Speybroeck et al., 2006); [4] (Rodil et al., 2006);
[5] (Bouma et al., 2005, Speybroeck et al., 2006);

REFUGE AND FORAGE

The level of hydrodynamics is a dominant factor in the zonation of species communities. The **bed shear stresses**, as a result of **waves** and **currents** (induced by tide, waves and wind), cause a reworking of the sediment. This directly influences the habitat of benthos living in, on or near the bed. Benthos species need to bury themselves in the bed or find another way to stay in a fixed position. Furthermore, the currents determine the location of larval settlement and the amount of food available for filter feeders (Bouma et al., 2005).

Studies, like McLachlan et al. (1996) and Lastra et al. (2005), have shown a significant correlation at the beach between **sediment size** and species richness sediment size and abundance. The optimum range of the grain diameter may vary per species (McLachlan et al., 1996) and can change during the life phases, however multiple studies have shown a negative correlation between mean grain size and species richness (Lastra et al., 2005). Furthermore, the impact on the ecosystem will be least severe when the characteristics of the nourished sand corresponds to the original conditions (Hanley et al., 2014). The recovery duration of benthos species will be prolonged if unnaturally fine or course sediment is imported (Defeo et al., 2008). This is for example, due to the fact that particle size influences the burrowing rates of benthos, which is an essential factor for the suitability of a habitat (McLachlan and Brown, 2010, McLachlan et al., 1996). Fine-grained substrates are more likely to act as nursery areas, possibly because this substrate is easier to bury in (Rogers, 1992). According to Bouma et al. (2005), in the North Sea the sediment size is considered to be less important when comparing the impact on the benthos communities with the influence of the hydrodynamics. Sediment size influences the susceptibility for marine and aeolian transport and thus the vertical **erosion/accretion rate** and the transport of organic content to the dunes. Many species on open beaches prefer mobile sand and require a dynamic environment (Brazeiro et al., 2001, McLachlan et al., 1996). Generally, a courser median grain size has negative effects on the burrowing ability of organisms (Brazeiro et al., 2001, McLachlan et al., 1996) and course grained beaches show a tendency to exclude smaller species (McLachlan et al., 1996).

Related to **sediment sorting**, it is likely that homogeneous substrate is preferred as a nursery area (Rogers, 1992).

The degree of **substrate compaction** affects the interstitial spaces, exchange of gases and nutrients, water retention and permeability of the substrate (Defeo et al., 2008, Speybroeck et al., 2006). Due to compaction, the pore space in the soil and the total soil volume reduces. The space between the grains house interstitial organisms and compaction affects the burrowing ability of macrobenthos (Defeo et al., 2008, Speybroeck et al., 2006).

Probably, the most important ecological property of **silt** is that of food carrier (Groenewold and Dankers, 2002). Silt is easily transported by water and contributes to a temporary increase in turbidity in interstitial water and the water mass. This may offer visual protection against predators but can also lead to an oxygen deficit (Speybroeck et al., 2006). Furthermore, a high silt content gives the soil cohesive properties leading to relatively less sediment dynamics (Bouma et al., 2005). Small particles, like silt, will fill up interstitial spaces within the substrate thus affecting interstitial organisms. For some species, a high silt content may have negative consequences while for others silt may be an opportunity. Furthermore, substrates that are rich in silt in the intertidal zone are often covered in a layer of diatoms (micro-algae) on the surface (Bouma et al., 2005). Species communities of ecotopes with a high silt content are likely to be similar to communities with fine grained beds (Bouma et al., 2005).

There is a strong correlation between the **cross-shore slope** and marine species richness and slope and abundance (McLachlan et al., 1996, Schoeman and Richardson, 2002). As wave energy or tidal range increases or median grain size decreases, beaches become more dissipative with a flatter cross-shore slope (Brazeiro et al., 2001). Studies have shown that as a beach becomes more dissipative, species richness increases linearly and abundance exponentially (Brazeiro et al., 2001). Faunal communities experience a change in slope as a change in swash climate on the beach face and sand particle size (McLachlan et al., 1996). Due to increasingly harsh swash conditions and/or coarser sand, species are excluded (Lastra et al., 2005, McLachlan et al., 1996, Schoeman and Richardson, 2002). The cross-shore slope is mainly the result of hydrodynamic forces and it is assumed that the cross-shore slope itself is not of direct influence on the benthos communities.

When a nourishment creates a steeper beach, the **beach width** and habitat area narrows, leading to emigration of some species (Defeo et al., 2008, Fanini et al., 2009). Beach width, as a measure for the distance of the dunes to the water line, is also an important abiotic factor for the composition of sand dune communities (Fenu et al., 2012). A wide dry beach leads to lower dynamics and lower stresses at the upper part of the dry beach, allowing vegetation that cannot cope with these stresses to grow.

The **water depth** in the subtidal zone is relevant for the amount of light penetration in the photic zone and thus for primary production. The depth of the photic zone (depth of 20 m in the North Sea) exceeds the water depth considered at this site, therefore this factor is less relevant in the nearshore (Bouma et al., 2005). According to Bouma et al. (2005), it is likely that the zonation of benthos communities in the highly dynamical subtidal and intertidal zone of the North Sea are more related to the hydrodynamics resulting from currents and wave exposure, than to depth differences.

A short **inundation duration** limits the time for activities of marine organisms. Many benthic organisms rely on sediment-water contact for nutrition, lateral movement and reproduction (Schoeman and Richardson, 2002). Therefore the intertidal zone near the high water line is generally not preferred by benthos and the species diversity is relatively low there, compared to the zone near the low water line (Janssen and Mulder, 2005, Speybroeck et al., 2008). Furthermore, tidal flats are important for foraging wading birds (Speybroeck et al., 2008).

The **inundation frequency** is related to the altitude up to which salt spray reaches. Salt spray is an important factor in vegetation zonation, as vegetation is less salt tolerant when moving up the supratidal zone (Fenu et al., 2012, Speybroeck et al., 2006).

Organic content is generally strongly , inversely correlated to the median grain size, the coarser the sand, the lower the concentration of organic matter (Wijsman and Verduin, 2011). If the nourished sediment has similar sediment properties as the original sediment, the impact on the benthos will be minimized and recovery time will be shortest (Janssen and Mulder, 2005). Quantity of organic matter in sediment is regarded as a critical factor contributing to benthic fauna communities and can be relatively high in sheltered areas (Rodil et al., 2008). However, too much organic material will lead to anoxic conditions for interstitial organisms in lower layers of the substrate if permeability and energy supply by wave action is low, which may occur at sheltered, fine-grained locations (McLachlan and Brown, 2010). The study of Fenu et al. (2012) showed that organic content is closely correlated with the distribution of plant communities (Fenu et al., 2012).

Wrack deposition is an important input of organic material for beach species in the upper intertidal and supratidal zone (Speybroeck et al., 2008). The community of beach invertebrates can be linked to wrack deposits, which provides a food source and a refuge against desiccation (Defeo et al., 2008). Removal of wrack deposits (by grooming) strongly affects wrack associated species (e.g. arthropods) negatively (Speybroeck et al., 2006, 2008). Effects are direct by removing their habitat, or indirect by reducing a food source for predators such as birds (Defeo et al., 2008). Wrack material is also a contributing factor to sand-dune formation (Hanley et al., 2014).

NURSERY

According to Bouma et al. (2005) the most important factors determining the potential for a nursery are the level of **hydrodynamics** and **water depth**. Ecotopes suitable for nurseries are those in the flat, shallow parts of the subtidal and intertidal zone with low dynamics. According to Rogers (1992), in terms of **sediment sorting** and **sediment size**, it is likely that homogeneous fine substrate is preferred as a nursery area for sole (Rogers, 1992) for the food it provides and the protection this type of substrate offers.

INTERRELATION OF THE PARAMETERS

As with the other ecosystem services, the factors influencing the habitat provision service are interrelated. For example, it is more likely that an ecotope with low bed shear stresses has a relatively high silt contents. Silt contents positively correlates to organic contents (Groenewold and Dankers, 2002). The beach state of a shore, resulting in a certain slope and medium grain size, is correlated to the community characteristics of benthos. The question remains whether the benthos respond to the hydrodynamics, the sediment size or the slope. According to Speybroeck et al. (2006) and Bouma et al. (2005), the community structure is mainly regulated by the hydrodynamic forces. Therefore, the conditions that lead to a change in the hydrodynamic forcing (waves and currents), are assumed to have a first order importance and will be used as indicators in the assessment method. This is further described in Section 3.4.

3.3.4. CONCLUDING SUMMARY

In this section, the linkages between the ecosystem services and the abiotic factors that define the potential of the ecosystem to provide ecosystem services are described. The relative importance of the abiotic factors to the service potential is hypothesized, leading to an identification of the indicators of the ecosystem service potential.

Regarding coastal protection, the indicators can be derived from Table 3.1. Under a given storm surge level, the potential for flood protection is predominantly determined by the dune volume. The potential to increase the dune volume is related to the sediment supply in the intertidal zone. An increased intertidal width or flattening of the intertidal slope will lead to a larger intertidal area and therefore to a potentially larger sediment supply. The coastline position is predominantly determined by the volume of the active beach profile, including the subtidal, intertidal and supratidal zone. The curvature of the coastline is important to the gradients in sediment transport, thereby contributing to the position of the coastline in the future.

With respect to the recreation potential, the indicators can be derived from Table 3.2. The kitesurfing potential is related to the low exposure to waves, leading to a flat water surface. The most important abiotic factor for the sunbathing potential is the beach width of the supratidal zone, determining the area available at the dry beach. The abiotic factors that is considered to be most relevant to the strolling potential is the coastline curvature, which influences the length of the strolling route.

Regarding the potential occurrence of habitats, the indicators can be determined from Table 3.3. Factors related to the hydrodynamic forcing (e.g. bed shear stress) within a cross-shore zone, predominantly determine the type of habitat, as they determine the degree of substrate reworking and the mobility of the sediment. The sediment size is also a critical factor in determining the the potential to function as a nursery area.

3.4. QUANTITATIVE MODEL ASSESSMENT METHOD

In the previous section, the indicators for the ecosystem service potential of coastal protection, recreation and habitat provision were identified. This section describes the assessment methods used to quantify the physical potential of the ecosystem services, in which those indicators are incorporated. The quantification method is applied to the morphological model output and the assessment will be made on a yearly basis and compared to the reference situation in 2010.

3.4.1. COASTAL PROTECTION

The assessment is performed at several cross-shore profiles of the model, with a spacing between transects ranging from 200 to 1000 m. At the nourishment section, the resolution is relatively high, because of the strong local variability in the bathymetry. Therefore in the nourishment section 18 transects will be analyzed. At the other Delfland coast sections the resolution is lower at 4 transects per section. The location of the transects is chosen in such a way that they match the coordinates of the JARKUS transects[2]. In Figure 3.3, the locations of the analyzed model transects are visualized. The JARKUS transect numbers and to which coastline section the analyzed transects belong are listed in Table 3.4.

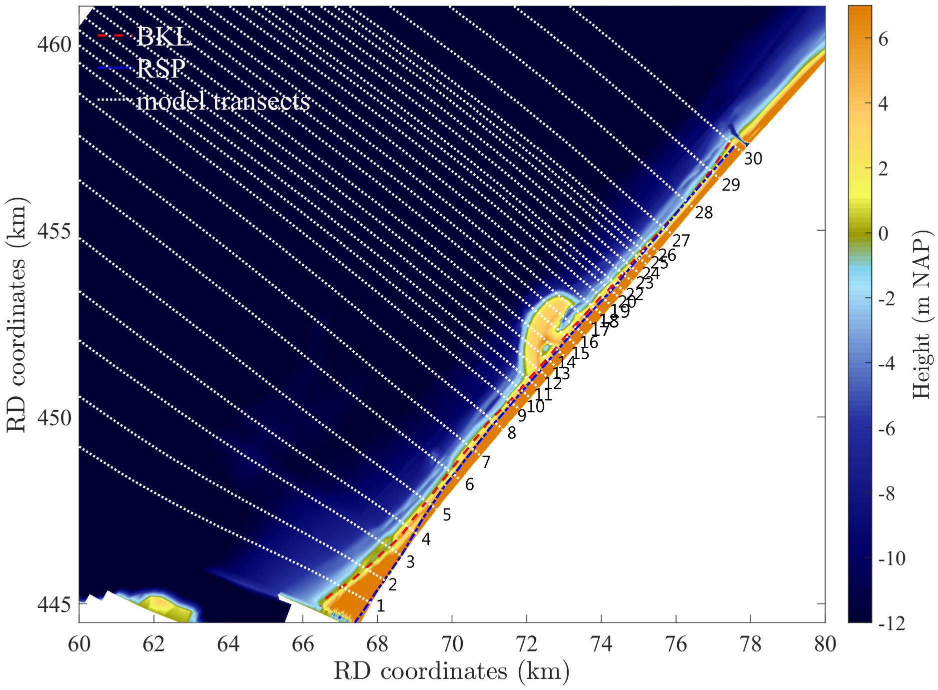


Figure 3.3: The bathymetry (m NAP) of the Delfland coast in 2011 with the locations of the transects used to calculate coastal protection. The Basis Kustlijn (BKL) and (Rijksstrandpalenlijn (RSP) are plotted as well.

Table 3.4: Transects where the coastal protection ecosystem service is assessed per coastline section.

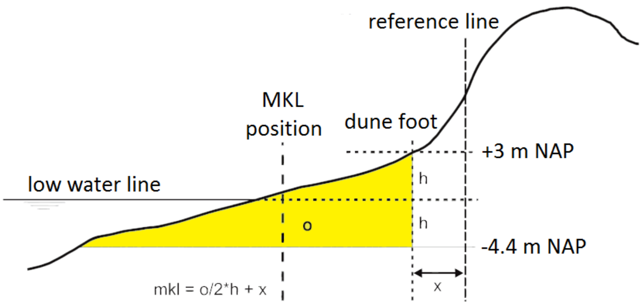
Section	**transect number**	**JARKUS transect number**
Hoek van Holland	1 to 4	11775, 11700, 11611, 11535
's-Gravenzande	5 to 8	11450, 11356, 11263, 11176
nourishment	9 to 26	11109, 11072, 11034, 10996, 10958, 10920, 10883, 10845, 10807, 10773, 10743, 10713, 10683, 10653, 10623, 10592, 10567, 10547
Scheveningen	27 to 30	10488, 10391, 10288, 10200

[2]The Dutch coastal morphology is measured annually and this programme is called the JAaRlijkse KUStmeting (JARKUS). The bathymetry is measured, using laser altimetry, at certain cross shore profiles (JARKUS transects) with an alongshore spacing of approximately 200 to 250 m. The dataset dates back to 1965 (De Vries, 2013)

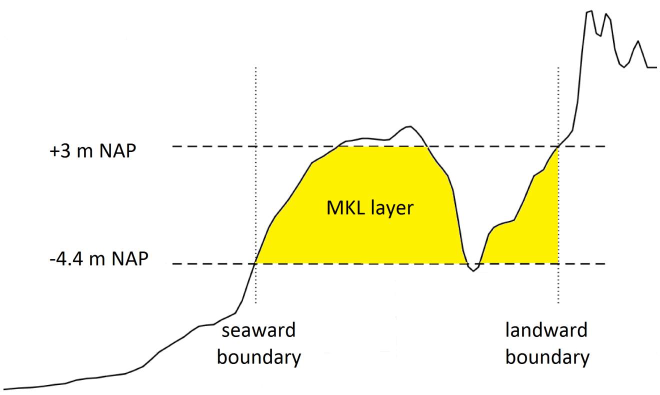
MAINTENANCE OF THE COASTLINE POSITION

The protection of the sandy beach is important to guarantee space for the utilization of the coast and to protect the accommodations and infrastructure present on the beach and near to the dunes. In 1990 the Dutch government decided that the coastline was not allowed to retreat landward of a certain position, the Basis Kustlijn (BKL), and the coast should be preserved by means of nourishment. This coastline position that should be maintained is indicated in Figure 3.3 with a red dashed line. To determine the coastline trend and whether the coastline will remain seaward of the BKL, the momentary coastline position (MKL) is calculated every year. The MKL position is a fictive location and indicated as a distance with respect to a reference line. The calculation procedure is presented in Figure 3.4a. The coastline should remain on the seaward side of the BKL and in case of an expected exceedence of the BKL a nourishment should extend the coastline to an acceptable width.

The MKL procedure calculates the volume between a landward and a seaward boundary. The seaward boundary is defined as the location where the bed level crosses the -4.4 m NAP level and the landward boundary where the bed level crosses the +3 m NAP level. The MKL position is then calculated by dividing the volume by the vertical elevation of the MKL (in this case it is 7.4 m). Figure 3.4a describes the procedure for a standard cross-shore profile, however some parts of the Sand Motor cannot be described by such a profile. Some transects at the Sand Motor have multiple upper and lower boundary crossings due to the low bed level of the lagoon and dune lake and the high bed level at the head of the Sand Motor. The standard procedure of the MKL calculation would assume the most landward upper and lower level crossings, which would lead to a wrong estimation of the coastline position and sudden shifts after some years of morphological development. To overcome this problem, the calculation procedure is adjusted such that the landward boundary is defined as the most landward crossing of the upper boundary level of +3 m NAP and the seaward boundary as the most seaward crossing of the lower level of -4.4 m. This MKL calculation procedure is illustrated in Figure 3.4b.



(a) Standard procedure to determine the MKL position. Adapted from Hillen et al. (1991).



(b) Adjusted procedure to determine the seaward and landward boundary of the MKL zone at Sand Motor transects.

Figure 3.4: Conceptual presentation of the MKL calculation procedure.

For each transect the MKL position is calculated annually. The value of the coastline position is the distance between the MKL position and the BKL of that transect. For each coastline section, the average of the transects will be calculated as well. This is a weighted average, to prevent that the distance between the transects influences the final result. For instance, if there are relatively many transects at the head of the Sand Motor over a certain alongshore distance and only a few at the the sides, this would enlarge the end result of a regular averaged MKL.

Aeolian transport is not incorporated in the model forecast. On the long term, this may significantly influence the volume in the MKL layer. Therefore an additional calculation is made where a yearly volume is extracted from the MKL layer as aeolian transport loss. This is a manual adjustment and therefore the dune foot position (+3 m NAP) will not change. This can be interpreted as manually removing an annual volume from the MKL zone and moving it to the back of the dune, see Figure 3.5.

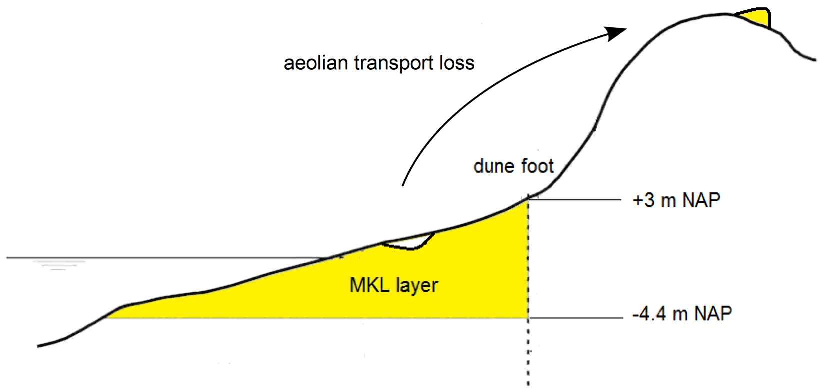


Figure 3.5: Conceptual presentation of the manually corrected MKL volume for aeolian transport loss

FLOOD PROTECTION

Flood protection aims to enhance the safety of the hinterland against flooding. The beach and dune area protect the hinterland against storm erosion. This sub service entails the current state and volume of the sand dunes and the potential for new dune development. In this sub service the aspect of nature development is also very important. The physical factors necessary to create potential for a dune ecosystem must be present in order to enhance this service. Without vegetation such as Sand Couch grass, embryonic dune formation is not initiated. Two methods to assess flood protection are described below. The first is aimed at erosion during storms: DUROS+. The second aims to quantify the potential of future dune development: dune growth potential.

DUROS+

In the Netherlands, flood safety is calculated by calculating the dune retreat (R*) during a design storm, using the DUROS+ calculation. The dune retreat per transect is given as a distance in meters with respect to a certain point, the Rijksstrandpalenlijn (RSP). For a standard beach profile the dune retreat during storms is calculated by means of DUROS+, which is an empirical model based on flume experiments. The DUROS+ model determines a parabolic erosion profile based on hydraulic input parameters such as the initial profile, the storm surge level, significant wave height, wave peak period and median grain diameter, without calculating the underlying physical processes that lead to this post-storm profile. This erosion profile is extended above the water line with a slope of 1:1 and beneath the toe with a slope of 1:12.5. The erosion profile is calculated from the initial profile in such a way that the amount of accretion is equal to the amount of erosion. The input parameters are based on the normative conditions during a storm on the -20 m NAP depth contour (Van Geer, P, 2012).

In the DUROS+ model several assumptions are incorporated, such as a uniform coastline, no interaction between soft and hard elements, no variation in grain diameter in cross-shore and longshore direction, no variation in the initial profile and normal incident waves without directional spreading, one storm surge level, a given storm duration and the effect of vegetation is not taken into account. The calculation method of DUROS+ is not suitable for the Sand Motor, as the initial profile is very different from a standard beach profile and this part of the coast is not alongshore uniform (therefore the erosion equals the accretion assumption cannot be applied) (den Heijer et al., 2012). Furthermore, this method may not compute significant changes in the retreat of the dunes, as aeolian transport is not incorporated and only changes in the subtidal zone of the cross-shore profile will affect the dune retreat. Therefore an alternative assessment method needs to be used that is able to quantify the potential for dune safety at the non-uniform coastline of the Sand Motor and is able to cope with a model that only incorporates marine sediment transport. This method focuses on the potential to develop dunes and is explained in the next paragraph.

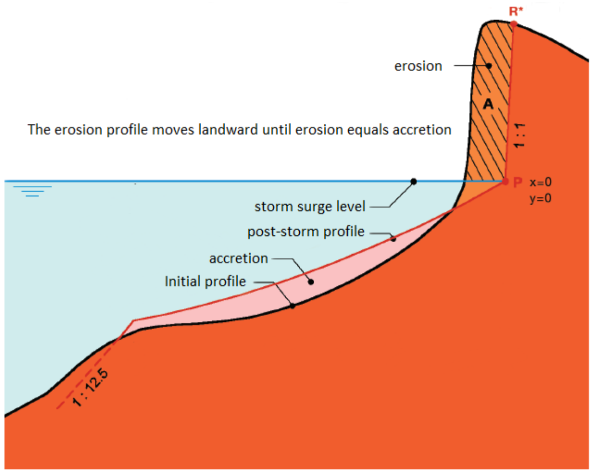


Figure 3.6: Procedure to determine the dune retreat with DUROS+ (Van de Graaff et al., 2007).

DUNE GROWTH POTENTIAL

In the manuscript of De Vries (2013) the hypothesis that the aeolian transport capacity is supply-driven (instead of wind-driven) is discussed. It is suggested that the source of the aeolian transported sediment is located at the intertidal beach. This would mean that in case of a wider intertidal beach, the supply would be larger, leading to an increased transport capacity. The dune volume growth for an accreting coast as found by De Vries lies in the range between 0 - 40 $m^3/m/year$. There is a delay of several years between the construction of the nourishment and the actual increase in dune dimensions (Borsje et al., 2011), but the magnitude of the source could be an indicator of the dune growth potential.

Therefore, as an alternative method to assess flood protection, the intertidal beach width will be used as an indicator for the dune growth potential.

3.4.2. RECREATION

The ecosystem service 'recreation' is subdivided into three different recreation types: strolling, (sun)bathing and kitesurfing. According to McLachlan et al. (2013), there are several factors that determine the potential of an area for recreation. These factors entail the available infrastructure, the safety and health of the beach, the physical carrying capacity, etc. In this thesis, the potential of the recreational ecosystem service will be based on the physical carrying capacity. Or in other words, the available space a site has for a certain activity.

KITESURFING

The potential for kitesurfing is based on the factor that could distinguish this location from other kite surfing spots: the degree of wave exposure. There are only a few sheltered locations at the Dutch sea coast where kitesurfing is possible. The sheltered area available for kitesurfing determines the physical capacity for kitesurfing.

Only the subtidal area is considered in this assessment, because above the low water line, the precondition of the sheltered area might lead to anomelies and faulty results when using the model output. The surface area that is sheltered from waves at a level of -0.95 m NAP is defined as the potential for kitesurfing.

STROLLING

The activity takes place at the dry beach. The physical capacity for strolling is primarily defined by the available length of the strolling route. It is assumed that the most attractive location for walking is along the waterline. The beach length (at the 0 m NAP contour) is defined as the potential for strolling. The potential for strolling will only be calculated at the nourishment section, because the beach length of the adjacent coastline is not significantly influenced by the Sand Motor.

SUNBATHING

The potential for sunbathing is defined by the area physically available for visitors to come to the beach, stay there for some time, go sunbathing and enjoy the surroundings. This area also determines the space available for beach restaurants. The activity is located at the dry beach, between the dune foot and the high water line. The dry beach is available for placing a towel and belongings, etc. There is a minimum dry beach necessary before a beach can be used for this ecosystem service and that minimum is dependent on the recreational pressure of the beach. The first 40 meters from the waterline are used most intensively. During peak days, this may extend up to 50 m from the waterline. Landward of this crowded zone the beach is almost empty. For moderately intensively used beaches, without or with some beach restaurants, the minimum dry beach width is estimated at 60 m. This width accommodates a 50 m crowded zone, lost space due to wind set-up and security services (Broer et al., 2011). The location of the Sand Motor, at Ter Heijde and Kijkduin, is regarded as moderately intensively used and therefore requires a dry beach width of 60 m. This minimum width is also applied to the other sections of the Delfland coast.

In the case of a very wide beach, the potential for sunbathing will be reduced. In case the beach is too wide, the walking distance will be too large and it is assumed the visitors will not take the effort to walk to the waterline. In this assessment, the maximum dry beach width is assumed to be 200 m. In case of a beach width smaller than 60 m, the potential for sunbathing will be minimal.

The dry beach width is calculated between +3 and +1 m NAP. In case the bed level crosses these boundaries more often, the seaward crossing will be used. The potential for sunbathing is calculated by, first of all, determining whether the beach width fulfills the requirements. In the case of a beach width that is too small or too large, the dry beach area will not be taken into account. The sunbathing potential is then calculated by summing the area of 'suitable' beach.

3.4.3. HABITAT PROVISION

The Delft3D model predicts how some of the abiotic factors will evolve after construction of the Sand Motor. Biotic interactions are not incorporated, therefore a method needs to be used that works with abiotic factors only. This will be done according to the ecotope classification hierarchy described in Section 2.4, based on Bouma et al. (2005). The area per ecotope will be calculated on a yearly basis up to 2050. Ecotope maps will be produced, indicating the locations of the ecotopes that are present on the Sand Motor. This method of determining the influence of an anthropogenic measure on the ecosystem by making ecotope maps based on a model forecast is also used in Martin et al. (2005). An ecotope map will be made for every 5 years of morphological development, starting at 2016. The first few years after construction are skipped, because right after construction the ecosystem is buried and needs time to recover. The nine ecotope classes are based on the height and the maximum bed shear stress due to waves and currents. There is no subdivision made between ecotopes in the supratidal zone, because the Delf3D model only calculates stresses in the marine zone. The ecotope class limits are listed in Table 3.5.

The ecotope calculation is made using the dominant wave condition W01, with a significant wave height of 1.48m and a wave direction of $\Theta = 232° N$ (South West). The maximum bed shear stresses are averaged over one tidal cycle, to make a comparison between different time steps possible. More information regarding the reduced wave climate and tidal signal can be found in Appendix C.

Table 3.5: Ecotope classification and limits

	Ecotope	**Height** (m NAP)	**Hydrodynamics** (N/m^2)
1	Surf zone	≤ -0.95	> 4
2	Seaward side of the surf zone	≤ -0.95	2 < and ≤ 4
3	Nearshore	≤ -0.95	1.2 < and ≤ 2
4	Offshore	≤ -0.95	0.3 < and ≤ 1.2
5	Sheltered subtidal	≤ -0.95	< 0.3
6	Exposed lower intertidal	-0.95 < and ≤ 0	> 0.1
7	Exposed upper intertidal	0 < and ≤ 1.2	> 0.1
8	Sheltered intertidal	-0.95 < and ≤ 1.2	≤ 0.1
9	Supratidal zone	> 1.2	-

REFUGE AND FORAGE

For the assessment, the number of ecotopes is determined and the yearly evolution of the ecotope area is calculated. Furthermore, the spatial distribution of ecotope is analyzed using the ecotope maps.

NURSERY

To assess this service, the number and area of the ecotopes that are suitable for the nursery function are determined.

4

VALIDATION OF THE MODEL FORECAST

A Delft3D model was used to forecast the morphological development of the Sand Motor. The model predicts the morphological development forty years ahead and the model output can be used to calculate the evolution of the ecosystem service potential. The Delft3D model was not made with the intention of predicting ecoystem service dynamics. Therefore, to make sure the model accurately predicts the indicators of the ecosystem service potential, the model calculation will be verified according to measured JARKUS data of the past four years at the Sand Motor. The methods used for the ecosystem service assessment are explained in Section 3.4.

The potential of the ecosystem services evolves due to changes in the bathymetry of the Sand Motor. It is assumed that by means of a morphological model, the changes in the ecosystem service potential can be predicted on a long-term scale. The validation provides insight into how the model diverts from reality and in what way this will reflect on the ecosystem service assessment. First of all, an accurate forecast of the morphological changes that occur due to the construction of the Sand Motor is necessary. This will be reviewed in Section 4.1. Secondly, the method determining the potential for coastal protection needs to be validated, by comparing this to the observed situation of the first four years after construction. The method to determine the flood protection during storms is verified in Section 4.2. Two assessment methods are validated regarding the flood protection ecosystem service: the DUROS+ and the dune growth potential method. In Section 4.3 the model output of the MKL procedure will be evaluated. Regarding the recreational ecosystem service, the dry beach width of the model forecast will be compared to the observations in Section 4.4.

The Delft3D model calculates the morphology changes by means of the average climate conditions of the past twenty years and is therefore suitable for a long-term prediction, on a decadal scale. It is not necessarily suitable for predictions on a short-term scale. The wave conditions of the reduced wave climate are listed in Appendix C. These constant averaged conditions are useful for a long-term assessment of the Sand Motor. Stormy or relatively calm years are then averaged out on the longer term. When looking at the first few years of the morphological development, if the storm conditions (angle, storm surge level, etc) deviate from the reduced wave climate, this will have a significant impact on the spreading of the nourishment. Therefore the model is not necessarily suitable for short-term predictions. There only are four years of annual JARKUS observations, which means the short-term observations will probably deviate somewhat from the model prediction. Nonetheless, the model, Shore and the JARKUS data will be compared to check whether the trends correspond to each other. The annual JARKUS measurements were executed around March. The model simulation corresponds to the morphological state in the month of July. The validation results of five transects at the Sand Motor are presented in this chapter. Their locations are visualized in Figure 4.1.

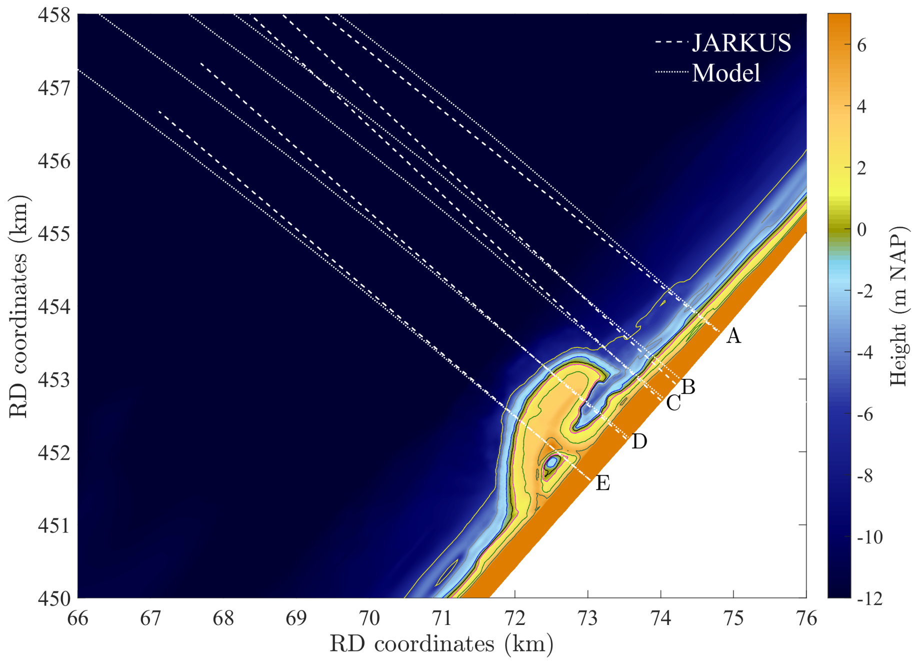


Figure 4.1: The bathymetry (m NAP) of the Sand Motor in 2011 is plotted together with the locations of the analyzed model and JARKUS transects. The JARKUS transects are represented by the dashed line and the model transects by the dotted line. The letters indicate the transect location (A = 10653; B = 10743; C = 10773; D = 10845; E = 10920).

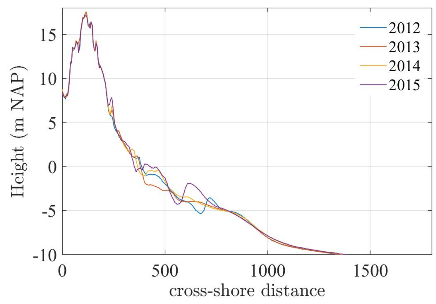
4.1. MORPHOLOGICAL VALIDATION OF THE MODEL

In this section the forecast of bathymetry of the Sand Motor will be compared to the observed bathymetry. In Figure 4.2, the bathymetry development of the selected transects is presented. On the left are the observed bathymetry changes and on the right the modeled bathymetry changes of the same transect location.

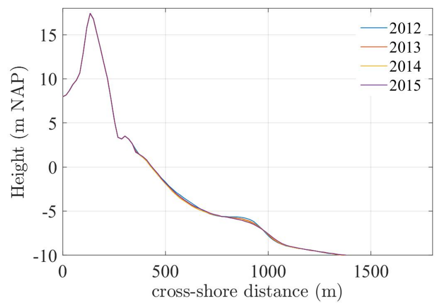
Figure 4.2a depicts the annual observations and Figure 4.2b the bathymetry development of the model forecast for a transect north of the Sand Motor. This transect is in the influence area of the Sand Motor and a distinct difference is that the JARKUS measurement shows a growing spit, while the model does not (yet). In Figure 4.2c the observations at B show that the spit in reality grows above 0 m NAP (which is approximately mean sea level), while in the model it stays below 0 m NAP. Furthermore, the offshore breaker bar which is there in reality is not reproduced by the model in Figure 4.2d. However, the trend of the bathymetry changes is identical for both profiles and the dispersal of the nourished sediment has a clear influence on the bathymetry. As the years progress, the bed level seems to elevate. The Sand Motor is feeding this area sediment. In Figure 4.2e and Figure 4.2f the bathymetry plots clearly show the growing spit. Figure 4.2g and Figure 4.2h are located at the head of the Sand Motor. The model forecast shows no change in bathymetry at the lagoon, while the observations show small bed level changes. However, the trend is identical for both profiles and the erosion at the head of the Sand Motor is clearly visible in both figures. As the years progress, the head of the Sand Motor erodes. The observations in Figure 4.2i show the formation of offshore breaker bars, while the model in Figure 4.2j does not. The erosion trend on the seaward side is identical for both profiles and is clearly visible in both figures.

CONCLUSION

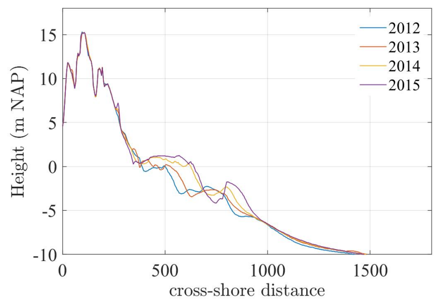
The morphological trends shown by the model forecast fits the development of the JARKUS bathymetry quite well. The exact annual volume changes are not predicted exactly as the observations showed, but the erosion and accretion trends are the same. The cross-shore spreading of the accreted and eroded volume of model forecast differs somewhat from reality and breaker bars are not formed in the model. To make sure the model forecast can be used in the assessment of the ecosystem services, the assessment methods of the ecosystem service potential need to be validated as well.



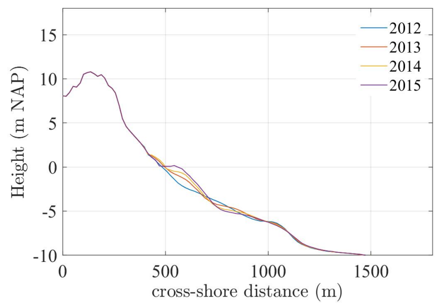
(a) Observations at A.



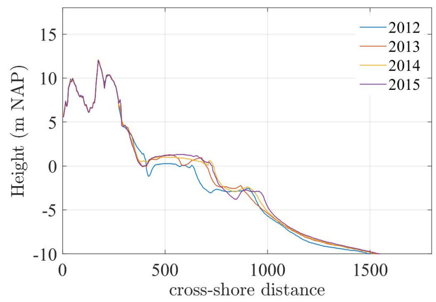
(b) Model forecast at A.



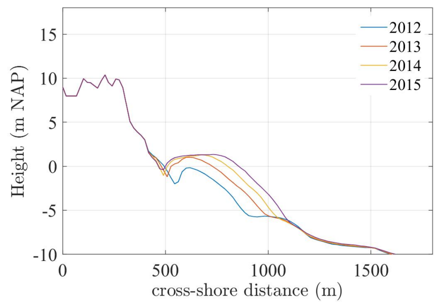
(c) Observations at B.



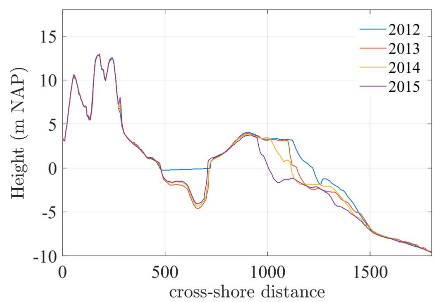
(d) Model forecast at B.



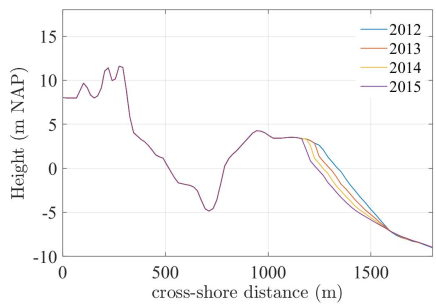
(e) Observations at C.



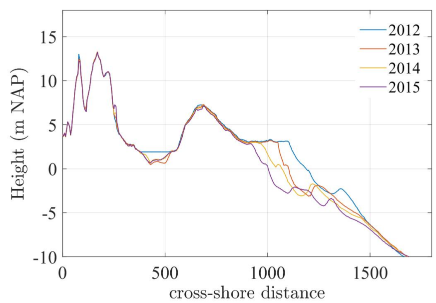
(f) Model forecast at C.



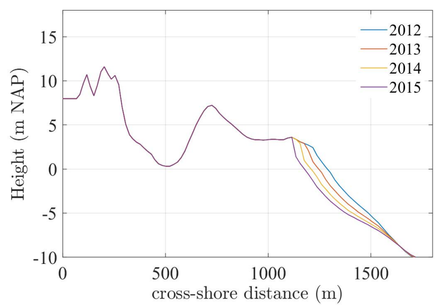
(g) Observations at D.



(h) Model forecast at D.



(i) Observations at E.



(j) Model forecast at E.

Figure 4.2: The figures on the left present the time development of the observed annual bathymetry changes and the figures on the right show the annual bathymetry changes of the model forecast.

4.2. FLOOD PROTECTION

4.2.1. VALIDATION OF DUROS+

The dune retreat at the transects of the Hoek van Holland, 's-Gravenzande and Scheveningen section, defined in Table 3.4, was calculation with DUROS+. The model forecast does not incorporate aeolian transport, which means that the bathymetry above the high water line hardly changes. This was reflected in the results of the DUROS+ calculation. For the first years the change in dune retreat is mostly less than a meter and as the years progress the change in dune retreat decreases to centimeters. The observations of JARKUS show a yearly change in dune retreat in the order of 1 to 70 m.

Aeolian transport and dune volume growth is an important factor in flood protection. This can be illustrated with a simple calculation. If the dunes grow 9 $m^3/m/y$, then in 20 years this is a total volume of 180 m^3. During a 1 in 20 year returning storm the mean erosion that occurred at the Holland coast was 36 m^3/m (De Vries et al., 2012). This is one-fifth of the potential dune volume growth in that period. In the case the model does not incorporate aeolian transport, this will significantly influence the results regarding dune retreat during storms. Therefore it can be concluded that making use of DUROS+ will not give accurate results regarding flood protection. For this reason, an alternative method will tested: the dune growth potential.

4.2.2. VALIDATION OF THE DUNE GROWTH POTENTIAL METHOD

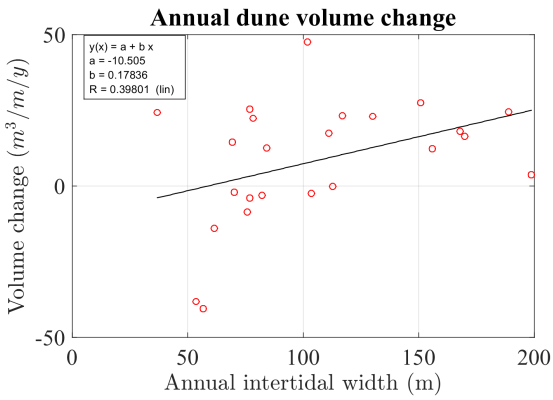
For this assessment method, the hypothesis described in De Vries (2013) will be applied to the Sand Motor. In De Vries (2013) the beach slope is correlated with the annual dune volume growth at the Vlugtenburg coastline. The source of the sediment supply is expected to originate in the intertidal zone. Please note that this is not the case if a storm has just passed. The post-storm profile of the beach has a milder slope than the pre-storm profile. Sand eroded from the dunes during a storm is deposited on the beach, mostly between the dune foot and the low water level. After the storm, when the situation with calmer conditions and lower water levels returns, this deposited sand becomes available for transport again en contributes to dune recovery as well (De Vries, 2013). De Vries (2013) found no consistent spatial lag between dune volume change and bed slope, as a result of oblique winds. This means the correlation in cross-shore direction between dune volume change and slope is the strongest De Vries (2013). This is the case for a standard cross-shore profile and may not apply to the complex three-dimensional system of the Sand Motor.

For the validation of this hypothesis at the Sand Motor the observations at JARKUS transects 10653 up to 11109 (14 transects) are analyzed. The annual intertidal beach width is correlated with the annual change in dune volume. The dune volume is defined as the volume above the dune foot (+3 m NAP) up to a landward point which stays constant in time and is defined to be the location where the vertical variability in the bathymetry over the years is negligible (De Vries, 2013). For the considered transects this landward point is defined at -90 m with respect to the Rijkstrandpalenlijn (RSP), a Dutch reference line. The change in dune volume is considered in this analysis and therefore the exact landward boundary is not relevant for the correlation. The intertidal beach width is defined as the horizontal width between -0.7 m NAP and 1.08 m NAP.

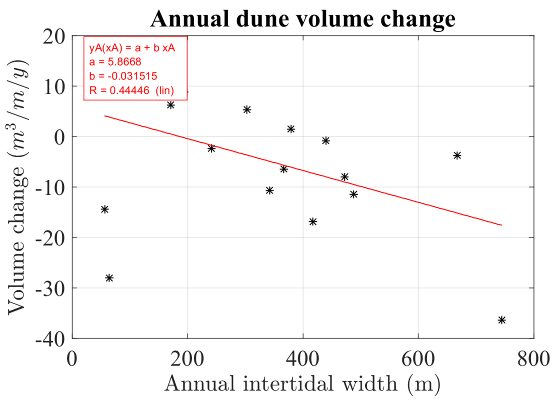
When considering the data of the dune volumes and the intertidal beach width it is important to realize that dune volume change is the cumulative result over a year, while the beach slope is a snapshot taken in time. Therefore the intertidal beach width will be averaged over two consecutive years to find a representative annual value of the intertidal beach width instead of a snapshot (De Vries, 2013).

A correlation is made between the annual representative value of the intertidal beach width and the annual dune volume change. In doing so, a distinction is made between transects that are influenced by the lagoon and the tidal channel (transect 10713 up to 10883) and the other transects. Two methods will be applied to determine the intertidal beach width of the transects at the lagoon. The reason for this is that the transect at the lagoon contains three separate intertidal zones. In theory, this could lead to a drastic increase of the aeolian transport and thus an increase of the dune volume because there is a large intertidal area. However it could also be that the water of the lagoon forms a barrier for aeolian transport and that for this reason the two seaward intertidal zones should be left out. The former theory is investigated with method 1B and the latter with method 1A, which are explained below. For the remaining transects, the beach width between the most seaward low water crossing and the most seaward high water crossing is taken as the intertidal beach width (method 2). To summarize:

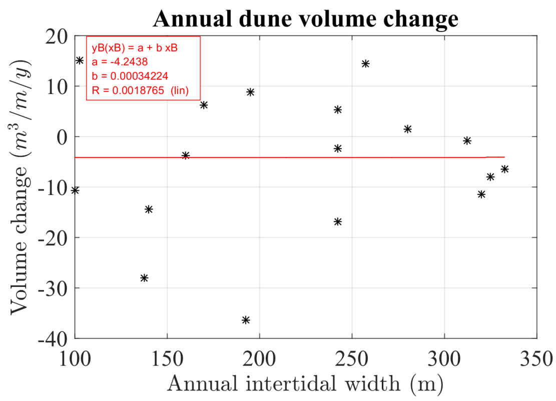
Method 1A For the transects at the lagoon and the tidal channel, the intertidal beach width is defined as the horizontal width between the most landward low water boundary crossing and the most landward high water crossing.



(a) Method 2



(b) Method 1A



(c) Method 1B

Figure 4.3: Correlation of the annual dune growth and the intertidal width per transect, for methods 1A and 1B (transects at the lagoon and tidal channel) and method 2 (remaining transects).

Method 1B For the transects at the lagoon and the tidal channel, the intertidal beach width is defined as the cumulative beach width of all the intertidal zones of this transect. In case of the lagoon this would lead to the sum of three seperate intertidal zones.

Method 2 For the remaining transects with a more standard cross-shore profile, the intertidal beach width is calculated between the most seaward upper and lower boundary crossing.

When only plotting the transects that are not influenced by the lagoon of the tidal channel in method 2, the correlation coefficient of the linear fit is R = 0.40. This is shown in Figure 4.3a, where the annual intertidal beach width is plotted together with the annual dune volume change per transect. The correlation of the transects at the lagoon and tidal channel where the intertidal width is calculated with method 1A is presented in Figure 4.3b and for method 1B in Figure 4.3c. The linear fit of method 1A is 0.56 and of method 1B 0.002. This suggests that method 1A, where only the landward intertidal beach of the lagoon is assumed and the water acts like a barrier, fits better than method 1B. However, there are not enough data points (transects and years) to make a correlation. Figure 4.3b shows a strong negative dune volume change at the Sand Motor on a 2D transect scale, while overall, with a 3D view, the dune volume at the Sand Motor increases.

CONCLUSION

The situation at the Sand Motor is too complex and therefore a simplification like in this method cannot be made. This method focuses on the dune growth on a transect level, neglecting the three-dimensionality of the system at the Sand Motor. This 2D view per transect, instead of an overall 3D view, might also result in negative dune growth on a 2D transect level, while this is not the case in 3D due to an alongshore transport component. Furthermore, there are not enough years and locations with measurements to be able to make a good correlation.

4.3. MAINTENANCE OF THE COASTLINE POSITION

The coastal maintenance ecosystem service evolves due to changes in the bathymetry of the Sand Motor. The MKL distance with respect to the BKL of the first four years of the model forecast will be compared to the JARKUS and the Shore observations. Once more this will be done for the transects presented in Figure 4.1. These short-term comparisons are presented on the left-hand side in figures Figure 4.4a, Figure 4.4c, Figure 4.4e, Figure 4.4g and Figure 4.4i. The Shore project measured the bathymetry at the Sand Motor every month during the first two years after construction. After this the bed level was measured bi-monthly. The higher measurement frequency gives the opportunity to identify seasonal variation. For this reason the winter period (November upto March) is indicated in the figures with a grey area to analyze the impact of the stormy season. Furthermore, the observations are presented together with the 19 year model forecast to see the long-term trend of the MKL positions. The results for the five analyzed transects are presented in Figure 4.4.

CONCLUSION

The trends shown by the observations show in most cases a change in the coastline position that is much larger than those of the model transects, for both erosion and accretion. This phenomenon can be explained by the fact that the Delft3D model is only suitable for long-term prediction due the application of yearly constant, averaged climate conditions. The past years could be regarded as relatively stormy years. This has led to a quicker sediment dispersal than was initially estimated with average storm conditions. This explanation is confirmed by the observation that during the stormy season the largest changes in the MKL values take place.

A drawback of using the MKL procedure for the assessment of the coastal protection is the upper (+3 m NAP) and lower (-4.4 m NAP) level boundaries enforced in the calculation. The model might provide accurate net transports in the southern and northern direction, but might distribute the volumes differently in cross-shore direction, possibly resulting in different MKL volumes.

It can be concluded that given the assumptions made in the model, e.g. no aeolian transport, the results are very promising. Even though the growth factors of the MKL values differ, the accreting or eroding trends are predicted well by the model, especially for the long-term perspective of the model forecast. The model forecast can be used to assess the evolution of the MKL position along the Delfland coast.

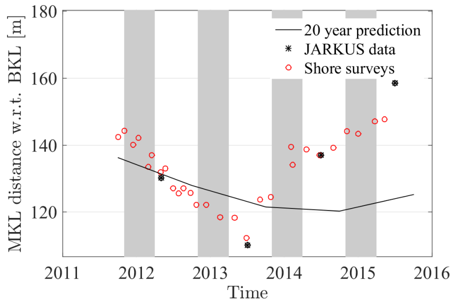
4.4. SUNBATHING

The dry beach width is validated to check whether the cross-shore distribution of the model matches that in reality and to identify shortcomings of the model with respect to the beach width used for recreation. In this validation the most seaward dry beach width is considered. The dry beach width is defined to be the zone between the dune foot (+3 m NAP) and the MHW level (+1 m NAP). The yearly evolution of the modeled dry beach width is presented for the five transects and plotted together with the 4 years of observations in Figure 4.5.

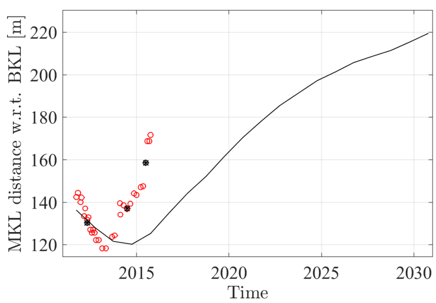
Figure 4.5a depicts the beach width trend of a transect north of the Sand Motor. The model forecast immediately shows an increasing beach width, while the trend of the observations shows a decreasing beach width. This may be related to the calibration of the onshore directed cross-shore sediment transport settings in the model, that may be set too high. This influences the cross-shore distribution of sediment: the cross-shore location where the model deposits sediment is near the high water line and the observed bathymetry of Figure 4.2a at transect A shows an increasing bed level at the shoreface, but not (yet) at the high water line. The beach widths at Figure 4.5b and Figure 4.5c show a growing trend, in both the model forecast and the observations. In Figure 4.5d and Figure 4.5e, the beach width of the model sometimes differs strongly from the observed beach width. The beach width of the observations varies strongly. This may be related to the upper level crossing of +3 m NAP, as can be seen in the observations ofFigure 4.2g and Figure 4.2i. The observed, varying bed level in combination with the +3 m level crossing may explain the sudden jumps in the beach width of the observations. Generally, accreting transects A, B and C will experience an increasing dry beach width and eroding transect D and E show a decreasing beach width.

CONCLUSION

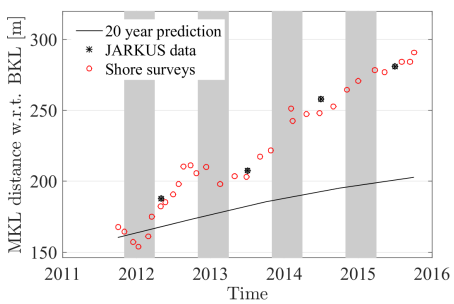
The model deposits sand around the HWL, which is defined as a constant returning high water level of approximately 1.35 m in the Delft3D model. To incorporate this beach growth, the lower boundary of the dry beach is chosen to be just below this level. Therefore in the assessment the zone between +3 m NAP and +1



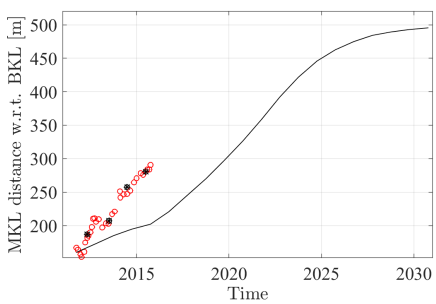
(a) Observations and model forecast at A.



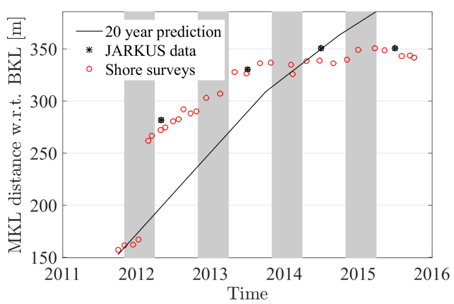
(b) Long-term trend at A.



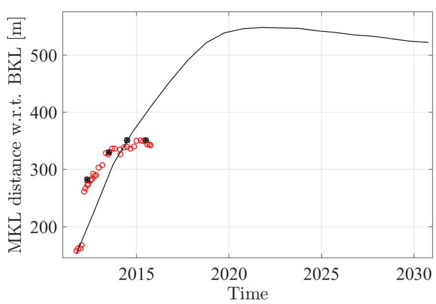
(c) Observations and model forecast at B.



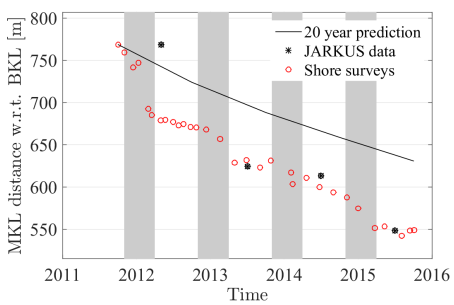
(d) Long-term trend at B.



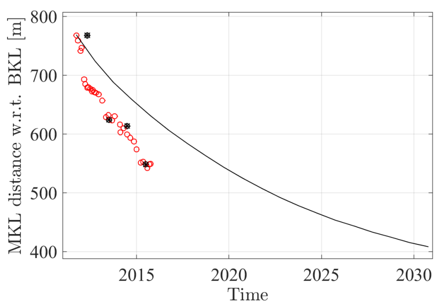
(e) Observations and model forecast at C.



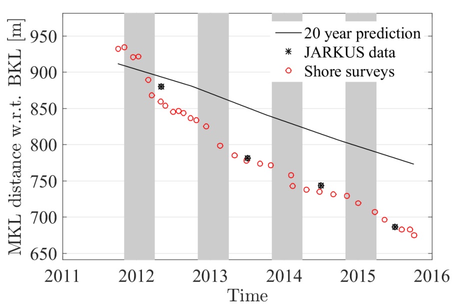
(f) Long-term trend at C.



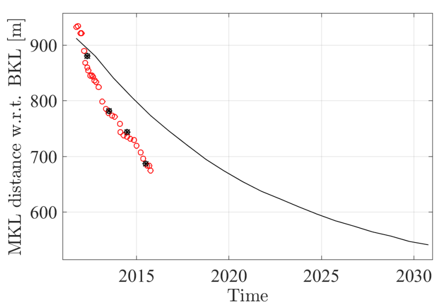
(g) Observations and model forecast at D.



(h) Long-term trend at D.

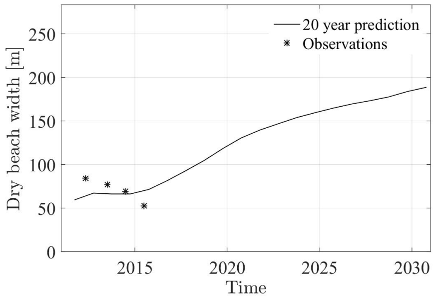


(i) Observations and model forecast at E.

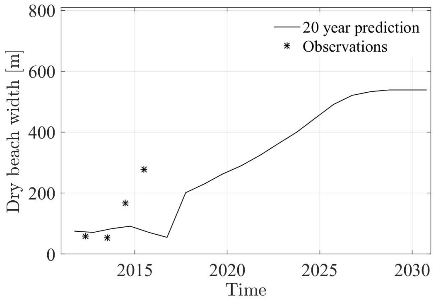


(j) Long-term trend at E.

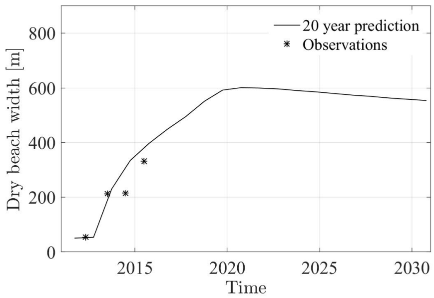
Figure 4.4: The figures on the left present a comparison of the distance between MKL and BKL as observed and predicted by the model for the first 4 years after construction and highlight the winter months (grey). On the right the figures present the observations together with predictions twenty years ahead.



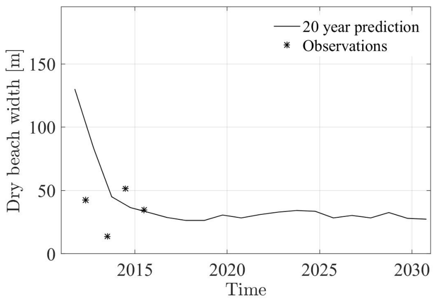
(a) Observations and model forecast at A.



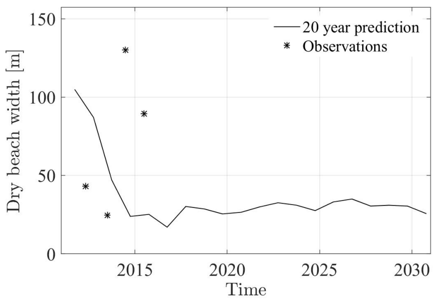
(b) Observations and model forecast at B.



(c) Observations and model forecast at C.



(d) Observations and model forecast at D.



(e) Observations and model forecast at E.

Figure 4.5: At five transects at the Sand Motor the dry beach width of the model prediction is compared to the four years of observations.

m NAP will be considered. However, it reality the sand may be deposited elsewhere in the cross-shore profile, which potentially could lead to differences in the magnitude value of the beach width. Nonetheless, the trend in beach width growth is predicted well. Furthermore, the bathymetry of some locations at the Sand Motor, such as the spit of the lagoon and the dune lake, make it difficult to determine the dry beach width, because there are multiple upper and lower boundary level crossings. For these locations the results must be checked and in case of anomalies or physically strange results, the grid cells must be left out of the assessment.

5

Dynamic ecosystem service assessment: the Sand Motor

In this chapter the results of the ecosystem service assessment of the Sand Motor are presented. The Sand Motor has an impact on the ecosystem services of the sandy shore that varies over time and space. The ecosystem services are assessed from 2011 to 2050 and compared to the situation in 2010, prior to the construction of the Sand Motor.

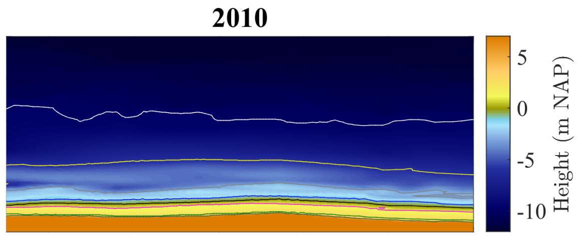
The assessment will be made on two spatial scales: locally at the nourishment section and at a larger perspective of the Delfland coast. To assess the impact of the Sand Motor on the evolution of the ecosystem services of the Delfland coast, the coastline is separately assessed for the nourishment, Scheveningen, 's-Gravenzande and Hoek van Holland section. The locations of the four sections are presented in Figure 2.3 together with the alongshore distance, of which Hoek van Holland is defined as the origin.

For assessments that incorporate bed shear stresses (ecotopes) or wave exposure (kitesurfing), the most dominant wave condition W01 was used. This wave condition was used in the calculation, because it is most representative for the Dutch wave climate. The W01 wave angle is from the South West and the significant wave height is 1.48 m.

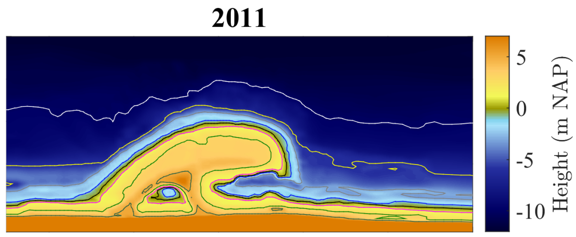
Morphological development of the Sand Motor

To illustrate the morphological development of the Sand Motor forty years ahead, the bathymetry is plotted for at several moments in time in Figure 5.1. Figure 5.1a depicts the reference bathymetry of 2010, one year prior to construction of the Sand Motor and figure Figure 5.1b the bathymetry in 2011, right after construction. The first years after construction, the dispersal rate of the Sand Motor is the highest. As the years progress, the coastline becomes smoother again. However the 'bump' of the shoreline will remain there for at least forty years, according to the model forecast. The hook-shaped peninsula disperses mostly to the North, while simultaneously creating a sheltered lagoon with a tidal channel on the northern side. The surface area of the lagoon decreases and the bed level of the tidal channel elevates over time, partially shutting off the lagoon. The initial bulge of sediment on the shoreface remains there, even after forty years.

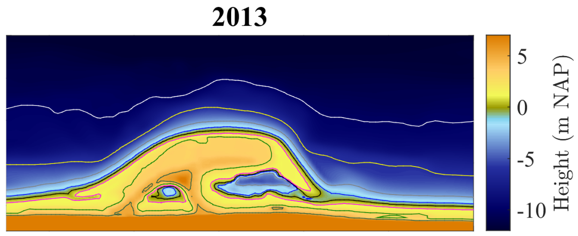
According to the model forecast, the bathymetry of the supratidal area and the dune lake does not change and after forty years there is still quite a substantial lagoon area present. This is because the Delft3D model only incorporates transport in the marine zone and does not include aeolian transport. It is probable that the dune lake and the lagoon will (partially) be filled up with sand due to aeolian transport over the years. Furthermore, in reality the head of the Sand Motor breaches already after 5 years, while the model forecast predicts a first breach only after 28 years. This may related to the way the reduced wave climate is applied in the model, which was intended to make a long-term forecast and does not include inter seasonal variability.



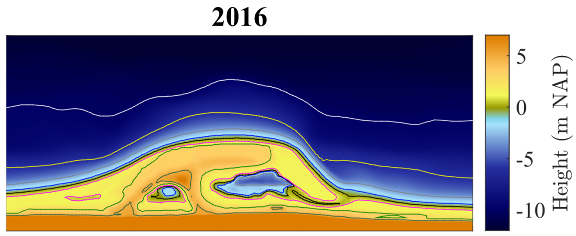
(a) 2010



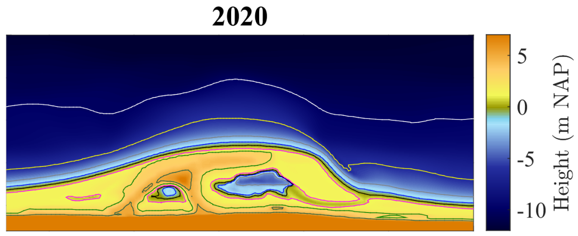
(b) 2011



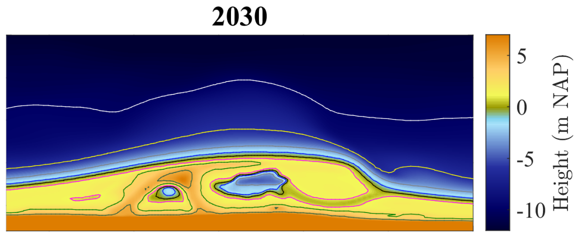
(c) 2013



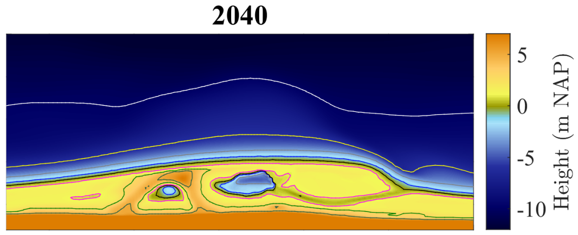
(d) 2016



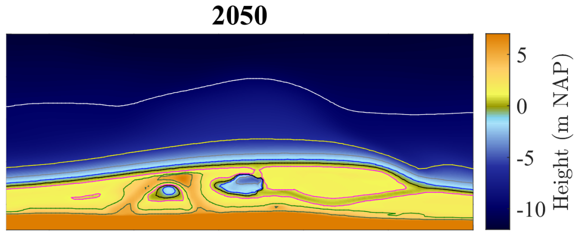
(e) 2020



(f) 2030



(g) 2040



(h) 2050

Figure 5.1: Computed model results of the morphological development at the Sand Motor. The bathymetry is shown for the reference situation of 2010, after construction of the Sand Motor in 2011 and the predicted bathymetry of 2013, 2016, 2020, 2030 ,2040 and 2050.

5.1. ECOSYSTEM SERVICE 'COASTAL PROTECTION'

Coastal protection will only be assessed for the service 'maintenance of the coastline position'. An accurate assessment procedure for 'flood protection' cannot be applied to the current model, as was explained in Chapter 4.

The coastline (i.e. MKL) positions are calculated annually at the transects visualized in Figure 3.3 and listed in Table 3.4. The results of the assessment are presented on two spatial scales. The coastline position of the nourishment section is elaborated first, followed by the assessment of the Delfland coast as a whole.

NOURISHMENT SECTION

The morphological Delft3D model only incorporates sediment transport in the marine zone. On a large temporal scale, sediment loss in de MKL zone due to aeolian transport may add up to significant volumes after forty years. In De Vries et al. (2012), the annual dune volume changes are calculated at transects along the Holland coast from 1977 to 2010. The maximum change in dune volume found at a transect amounted to 29.9 $m^3/m/y$ and the mean of all transects to 8.7 $m^3/m/y$. Aeolian transport will be incorporated in the MKL results during the post-processing of the model output, by a constant and uniform yearly aeolian transport volume.

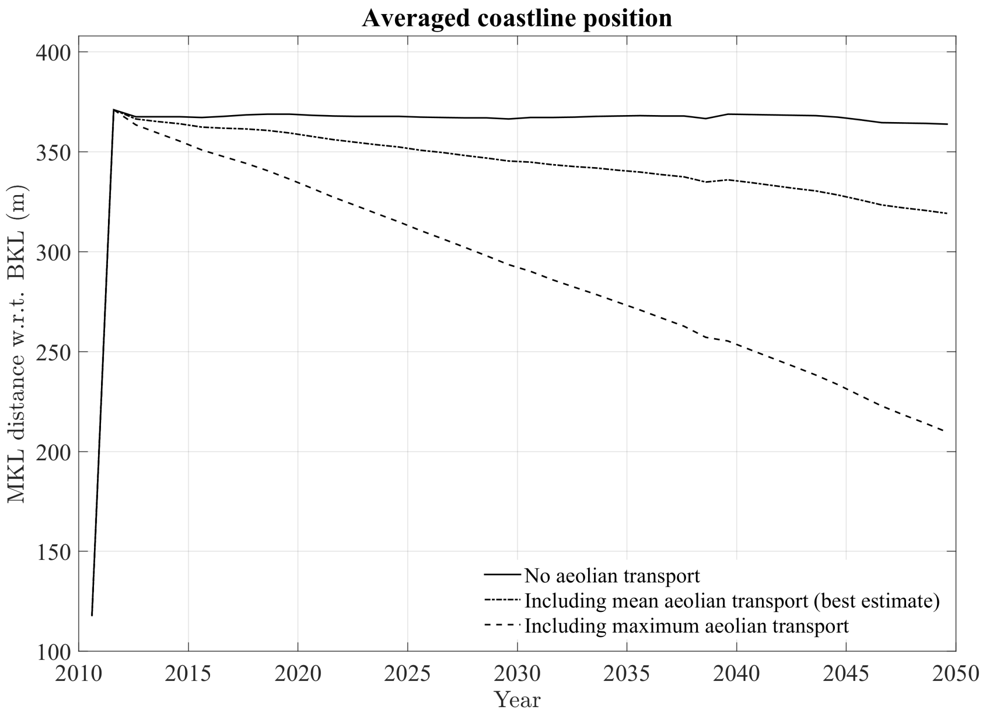


Figure 5.2: The evolution of the weighted, averaged MKL distance with respect to the BKL including no aeolian transport, the best estimate and a scenario including the maximum aeolian transport volume measures at the Dutch coast. The weighted, averaged MKL distance of 2010 is included as well.

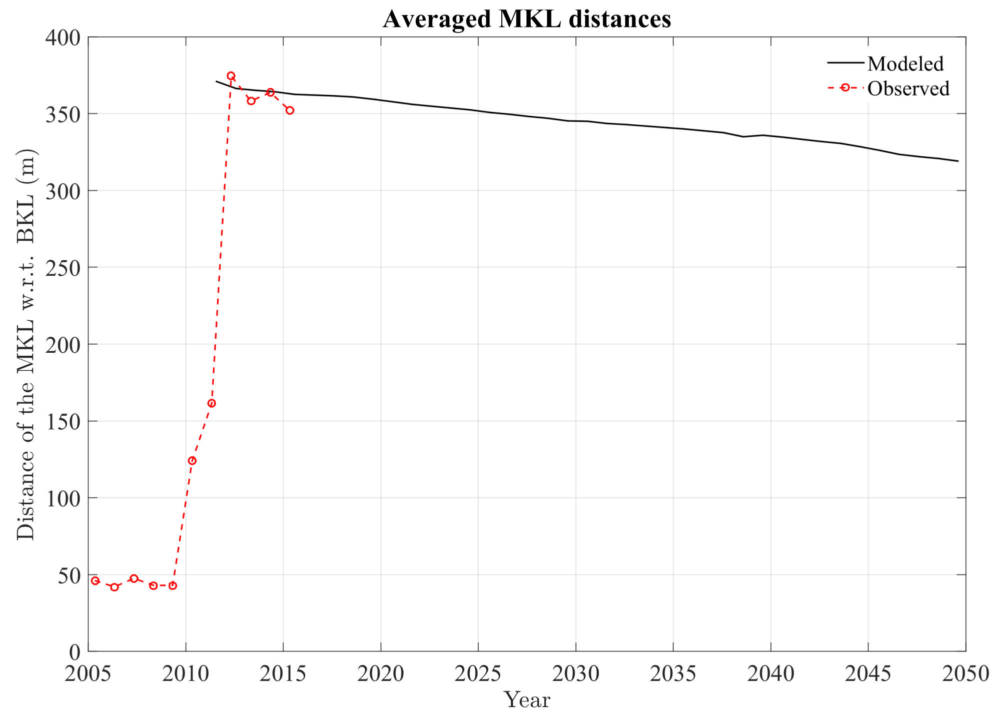
There is great uncertainty in regard to the exact magnitude of the aeolian transport volume. Therefore, in Figure 5.2, three scenarios of the weighted averaged MKL distance have been evaluated. In this calculation, the 18 transects of the nourishment section have been averaged (including a correction for the distance in between the transects). The calculations are presented as an upper limit, a lower limit and a best estimate. The upper limit of the MKL is the direct result of the model forecast, in which no aeolian transport loss is incorporated. The lower limit of the averaged MKL distance is the calculation in which a maximum loss of 29.9 m^3/m each year for each transect is assumed and where the dune foot position cannot shift seaward. The scenario in which an aeolian transport loss of 8.7 $m^3/m/y$ is assumed will be referred to as the best estimate.

Furthermore, in Figure 5.2 the initial MKL distance w.r.t. the BKL in 2010 of 118 m is included. This value is the weighted average of the same 18 transects one year before the construction of the Sand Motor. Comparing the results after construction of the Sand Motor to the situation prior to construction, it can be concluded that the Sand Motor in 2011 led to an immediate, local, substantial seaward shift of the coastline. The Sand Motor initially increased the average MKL distance more than 250 m and tripled the value in comparison to the situation before the nourishment. Moreover, it appears that this substantial gain in the coastal area remains up to 2050. Considering the best estimate, in almost 40 years the coastline only retreats 55 m to a MKL distance of 320 m. In the lower limit scenario, where at each transect a volume of 29.9 $m^3/m/y$ is transferred to the dunes, the coastal area between the BKL and MKL in 2050 is still almost twice the value before construction of the Sand Motor.

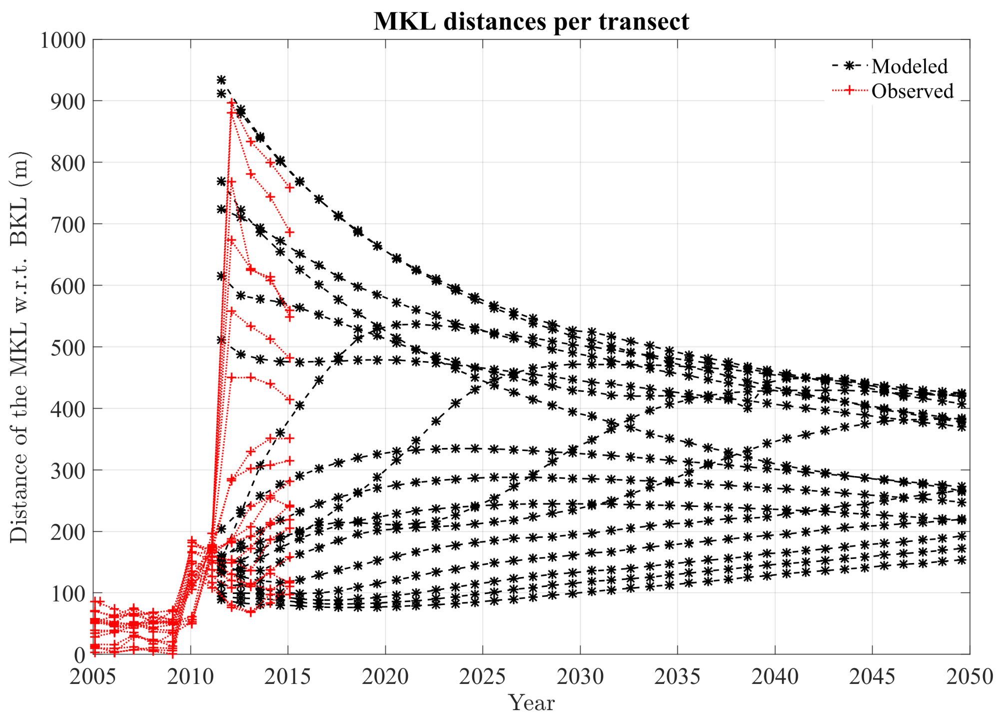
Averaging the 18 transects, the calibrated Delft3D model (no aeolian transport) predicts an averaged MKL distance that stays approximately 370 m seaward of the BKL rather constantly up to 2050. One might expect a decrease in the averaged MKL distance after some years due to sediment transport gradients along the Delfland coast, however this appears not to affect the MKL average. Besides the exclusion of aeolian transport, another phenomenon may contribute to the steady MKL average. This is related to the upper (+3 m NAP) and lower boundary (-4.4 m) of the MKL zone. Initially, the Sand Motor has areas that are higher than +3 m NAP. Once the peninsula erodes, this eroded volume is deposited in the MKL zone. The difference in volume above +3 m NAP initially and after 19 years amounts to approximately 200,000 m^3. Assuming this volume is added to the MKL volume and dividing it by the alongshore distance, it can be concluded that the additional volume per transect in 19 years time is approximately 40 m^3/m. In a MKL volume of 3000 m^3/m, this added volume is negligible.

Over the years, the volume loss due to aeolian transport becomes increasingly relevant. A constant and uniform yearly aeolian transport loss of 30 $m^3/m/y$ is considered to be the upper limit and assuming this magnitude for all transects every year could be regarded as an extreme scenario. Therefore, for the calculation of the coastline position further on, an aeolian transport loss of 8.7 $m^3/m/y$ is assumed, which is the mean volume of all transects of the Holland coast (De Vries et al., 2012). Incorporating a constant and uniform aeolian transport volume of 8.7 $m^3/m/y$ during post-processing of the model results is referred to as the 'best estimate'.

Figure 5.3 displays the evolution of the MKL distance (with respect to the BKL) calculated from the observed data and the best estimate. The best estimated coastline position of the nourishment section is plotted from 2011 to 2050, together with the observations from 2005 to 2015. The best estimated MKL distance corresponds well to the observed coastline evolution measured in the first four years after construction. The evolution of the observed averaged MKL distance (Figure 5.3a) shows that there is a slight retreating trend of the coastline position observed and predicted by the best estimate. In Figure 5.3b, the MKL distances of the individual 18 transect of the nourishment section are shown. Transects at the head of the Sand Motor erode, while the coastline of adjacent transects at the lagoon and the southern side of the peninsula accrete. The observations and the model both show a relatively strong convergence to the MKL average in the first years, when the coastline is most out of equilibrium and the nourishment disperses relatively fast. As the years progress, the nourishment dispersal slows down. According to the model forecast, the alongshore sediment transport gradients decrease as the protrusion of the Sand Motor into the sea retreats.



(a) Weighted, averaged MKL distance



(b) MKL distances of the individual transects

Figure 5.3: Evolution of the modeled MKL distances (w.r.t. the BKL) from 2011 to 2050 and the observed MKL distances of JARKUS from 2005 to 2015, for the nourishment section. In the figures the annual MKL distances per transect and the weighted averaged MKL at the nourishment section are shown.

IMPACT ON THE DELFLAND COAST

The sediment dispersal of the Sand Motor leads to a seaward shift of the adjacent coastline. The magnitude of this shift is shown in Figure 5.4a, where the alongshore development of the best estimated MKL distance is presented for 2010, 2011, 2030 and 2050. The initial location of the Sand Motor in 2011 is indicated in the figures with a vertical dotted line. Once more, the substantial increase in coastal area before the Sand Motor (in 2010) and after the Sand Motor (in 2011) is clearly visible at the nourishment section. Locally at the construction site of the Sand Motor, the coastline abruptly shifts seaward. As the nourishment spreads out, the MKL distance of Scheveningen, 's-Gravenzande and Hoek van Holland will grow and the head of the Sand Motor retreats.

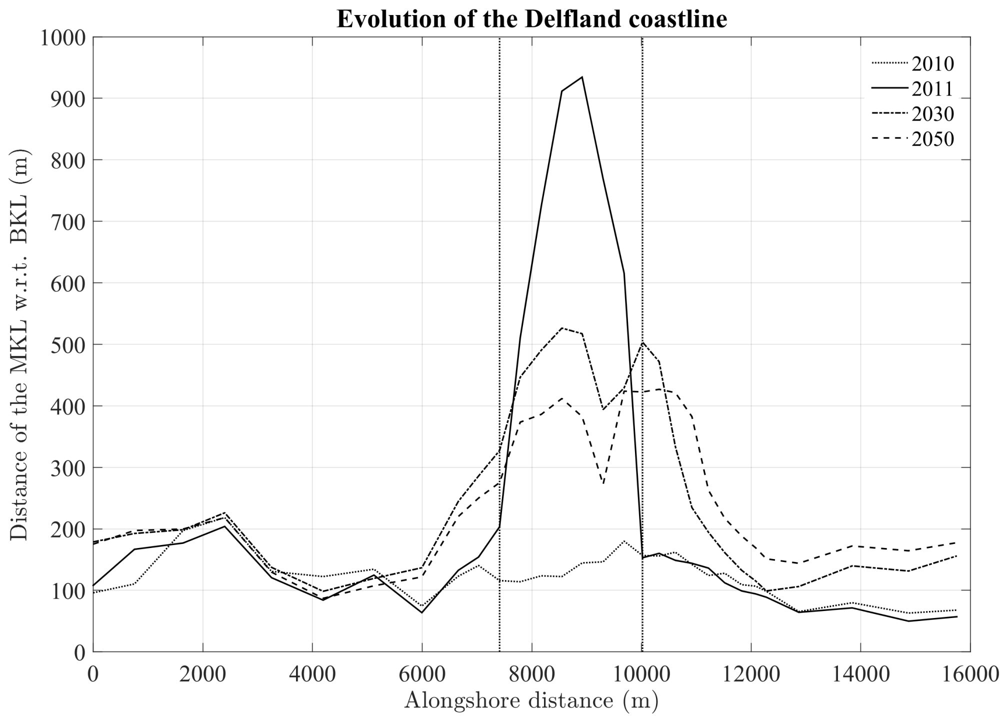
Considering the best estimate in Figure 5.4a, in 2050 the coastline position of the head of the Sand Motor will have retreated to 50% of the initial MKL distance in 2011. The gradient in the coastline change is largest on the northern (Scheveningen) side of the Sand Motor. Until 2030, both coastlines of Hoek van Holland and Scheveningen move seaward. However, between 2030 and 2050, the southern part of the Delfland coast does not experience any accretion anymore. The beach of Scheveningen, on the other hand, is still growing in 2050, even though the accretion is less than the first 20 years. The net alongshore sediment transport in the Netherlands is directed northward, due to the dominant south west wave angle. The results show that the coastline at Scheveningen will advance most in comparison to the other sections, which is in line with the direction of the net sediment transport. The southern breakwater at Scheveningen traps the sediment, leading to rapid sediment accumulation north of the Sand Motor and a change of the coastline orientation towards the most dominant wave direction from the South West. It is likely that this accretion on the northern side will continue until the coastline orientation is perpendicular to the dominant wave angle, leading to an equilibrium situation where there is no gradient in the net sediment transport anymore.

Figure 5.4b shows a comparison between observations (of the NEMO[1] survey) and the best estimate in 2015. The accretion rate on the southern side of the Sand Motor (left side of the figure) corresponds quite well to the observations. On the northern side (right side of the figure), the dispersal rate of the model is somewhat slower than it is in reality. This could be related to the way the reduced wave climate is applied in the Delft3D model, which was intended to make a long-term forecast with a reduced wave climate based on wave conditions of the past twenty years. The retreat at the head of the Sand Motor also agrees well to the observations, comparing it to the initial position in 2011. Four years after construction, the model already predicts a significant coastline advance. This could be related to the model settings of the cross-shore sediment transport component, where the flattening of the cross-shore profile and the breaker bars leads to an immediate coastline advance at the outer end of the profile. Nonetheless, the observations also already show a significant coastline advance at the Scheveningen section.

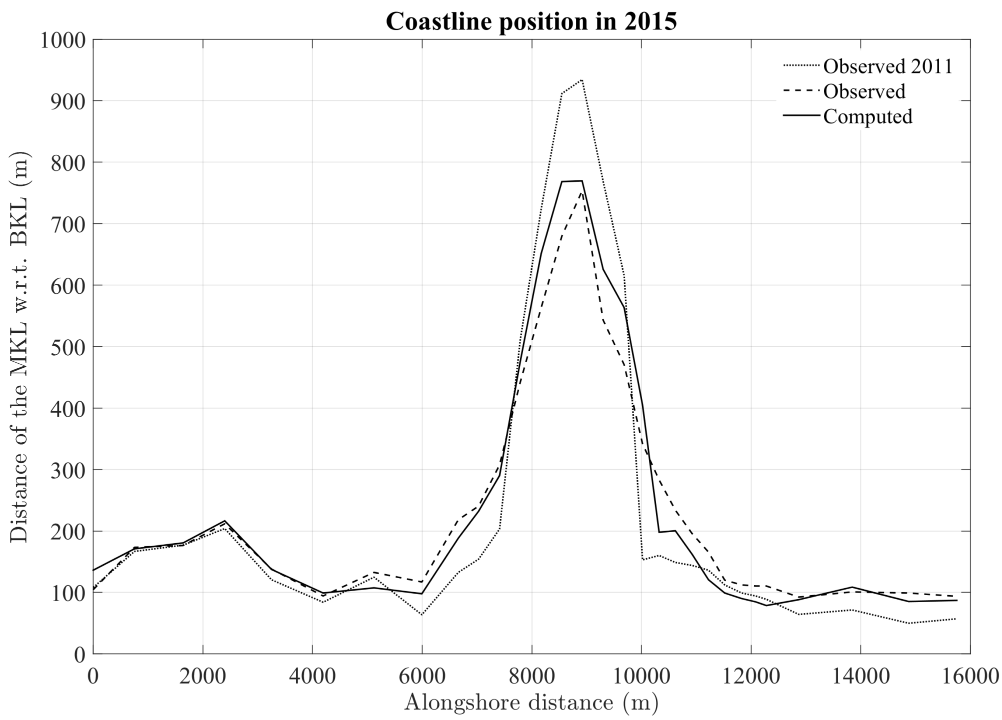
Figure 5.5 shows the annual evolution of the best estimated, averaged MKL distance for the nourishment, the Scheveningen, 's-Gravenzande and Hoek van Holland section. The figure shown that the coastline of Scheveningen and 's-Gravenzande start to advance within year, leading to an immediate seaward growth of the coastline positions. It takes more time before there is an impact on the coastline of Hoek van Holland, where two years after construction the MKL distance starts to grow. This fast coastline advance at the outer ends of the coastline may also be related to the cross-shore sediment transport settings in the Delft3D model.

According to the best estimate of the MKL distance at 's-Gravenzande the accretion stagnates after 12 years and the coastline begins to retreat after 29 years. In 2050 the coastline position is at approximately the same level again as in 2011. At Hoek van Holland, the accretion of the coastline stagnates after 21 years and erosion starts after 32 years. The coastline of Scheveningen is still advancing in 2050, due to the entrapment of sediment at the harbor jetty.

[1]Research project: Nearshore Monitoring and Modelling: Inter-scale Coastal Behavior



(a) Best estimated coastline position



(b) Modeled and observed coastline in 2015

Figure 5.4: Alongshore development of the best estimated MKL distance (including 8.7 $m^3/m/y$ aeolian transport loss). The origin of the alongshore distance is located at Hoek van Holland. The vertical dotted lines indicate the initial location of the Sand Motor in 2011. The upper figure displays the development of the coastline position for the years 2010, 2011, 2030 and 2050. The lower figure shows a comparison of the best estimate to the observations in 2015.

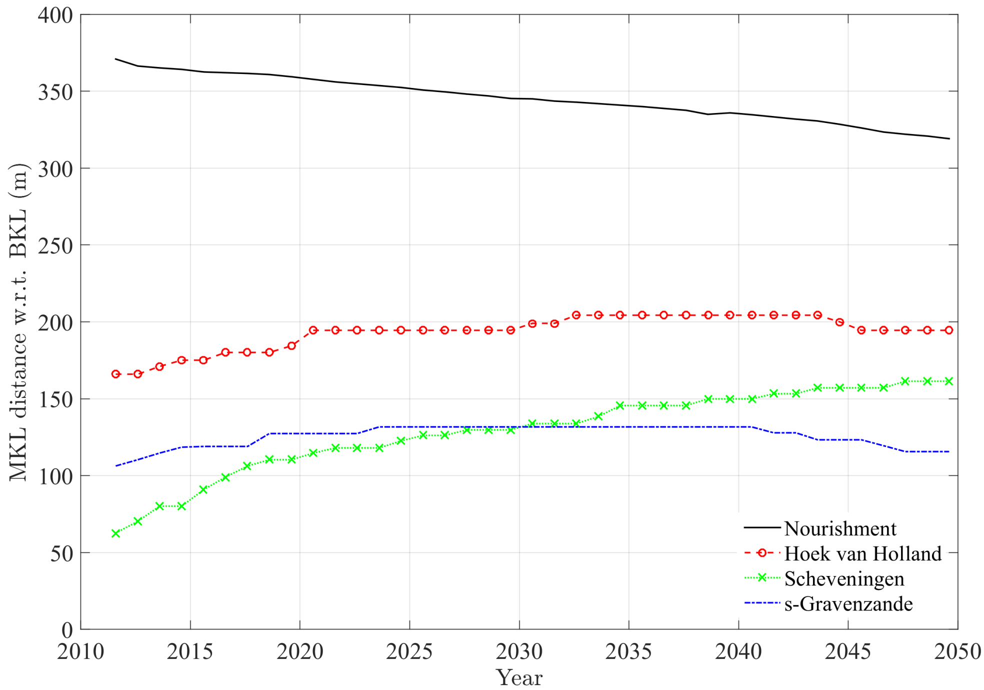


Figure 5.5: The evolution of the best estimated, averaged MKL distance (including 8.7 $m^3/m/y$ aeolian transport loss) for the four Delfland coast sections.

In Section D.1 additional figures can be found that compare the MKL distances of the model forecast and the best estimate of the Delfland coast sections to the first 4 years of observations. Also for the coastline sections of Scheveningen, Hoek van Holland and 's-Gravenzande, the weighted averaged MKL complies to the observations. Unfortunately there are not enough years of data yet to reach a conclusion on the annual volume loss due to aeolian transport.

5.2. ECOSYSTEM SERVICE 'RECREATION'

One of the aims of the Sand Motor is to add attractive nature and recreation areas to the Delfland coast. The main activities that are carried out at the Sand Motor are kitesurfing, sunbathing and strolling. To evaluate recreation, the recreational potential of each activity is estimated by calculating the physical carrying capacity on a yearly basis and comparing it to the situation in 2010, prior to the Sand Motor.

5.2.1. KITESURFING

NOURISHMENT SECTION

The kitesurfing area is defined as the area sheltered from waves. The evolution of the surface area for kitesurfing at the nourishment section is presented in Figure 5.6. The calculation of the sheltered area incorporates the lagoon and the dune lake. The surface area of the dune lake amounts to 1.4 hectare, which is small compared to that of the lagoon.

In 2010 the kitesurfing area was equal to zero. The construction of the Sand Motor in 2011 provided a unique, sheltered area suitable for kitesurfing. In the first year after construction the kitesurfing area increased significantly to almost 14 hectares and increased further in the second year up to the maximum area of 17.5 hectares, due to dispersal of the peninsula that increased the area sheltered from waves. After 2 years the surface area gradually starts to decrease due to sediment import into the lagoon. According to the model forecast, in 2050 the surface area of the lagoon has decreased to 57% of the maximum lagoon area in 2012. It must be noted that the Delft3D model does not incorporate aeolian transport. Over the years the dune lake and the lagoon area may be filled up with sand, decreasing the kitesurfing area much further than is predicted.

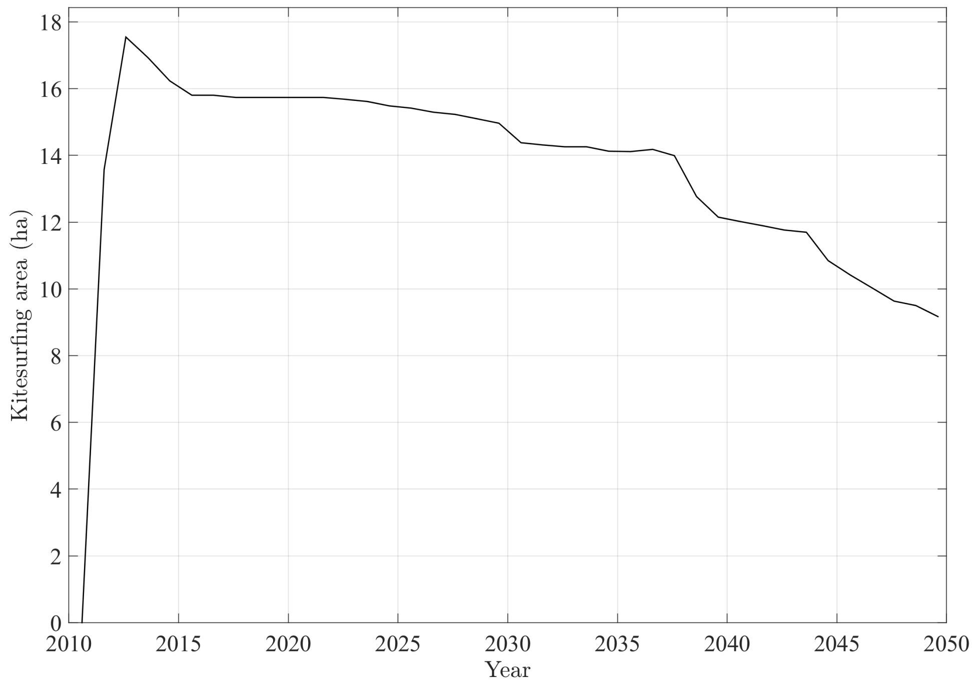


Figure 5.6: Computed evolution of the kitesurfing area at the Sand Motor from 2010 to 2050 at the nourishment section, as predicted by the Delft3D model.

In Section D.2 additional figures are included that visualize the locations of the kitesurfing area.

5.2.2. STROLLING

Figure 5.7 visualizes the evolution of the strolling potential at the Sand Motor. The protrusion of the Sand Motor into the sea increases the beach length along the waterline compared to the situation prior to the Sand Motor. The beach length increases with more than 50% in the first three years after construction. After four years, in 2015, the beach length decreases significantly. This is caused by the fact that the beach length was calculated with the 0 m NAP contour line and due to the dispersal of the Sand motor and the deposition in the mouth of the tidal channel, the bed was elevated to this level. The beach length remains longer than the beach length prior to the Sand Motor, due to the 'bump' of the coastline that, according to the model forecast, remains for at least forty years.

In Section D.2 additional figures are included that visualize the course of the 0 m NAP contourline.

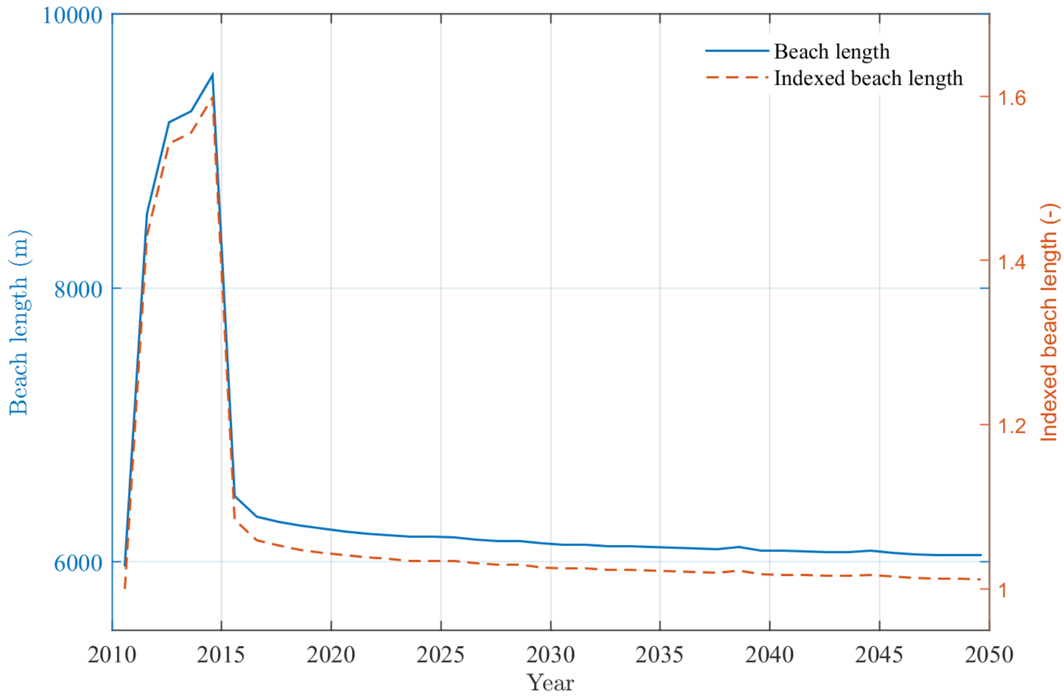


Figure 5.7: Predicted evolution of the strolling potential at the Sand Motor. The strolling potential is defined as the beach length along the water line and is presented as an absolute value (left vertical axis) and an indexed beach length (right vertical axis) where the length of 2010 is taken as the base value.

5.2.3. SUNBATHING

The potential for sunbathing is estimated with the 'suitable'[2] beach area. First, the suitable beach area is presented on a yearly basis for the nourishment section. After this, the impact of the Sand motor on sunbathing is elaborated at the spatial scale of the Delfland coast. The alongshore development of the beach width between Hoek van Holland and Scheveningen is presented at several moments in time and the evolution of the beach area of the different sections is shown.

NOURISHMENT SECTION

The evolution of the area considered to be suitable for sunbathing at the Sand Motor is presented in Figure 5.8. It appears that the suitable beach area at the Sand Motor decreases as the years pass. The beach width either exceeds the maximum width or is smaller than the minimum width, leading to a decrease in the suitable beach area. The cause of the decreasing area is shown in Figure 5.9, 5.10 and 5.11.

[2]A suitable beach is at this location is defined to be minimally 60 m wide (Broer et al., 2011) and maximally 200 m wide. Within this range the beach is 'suitable'.

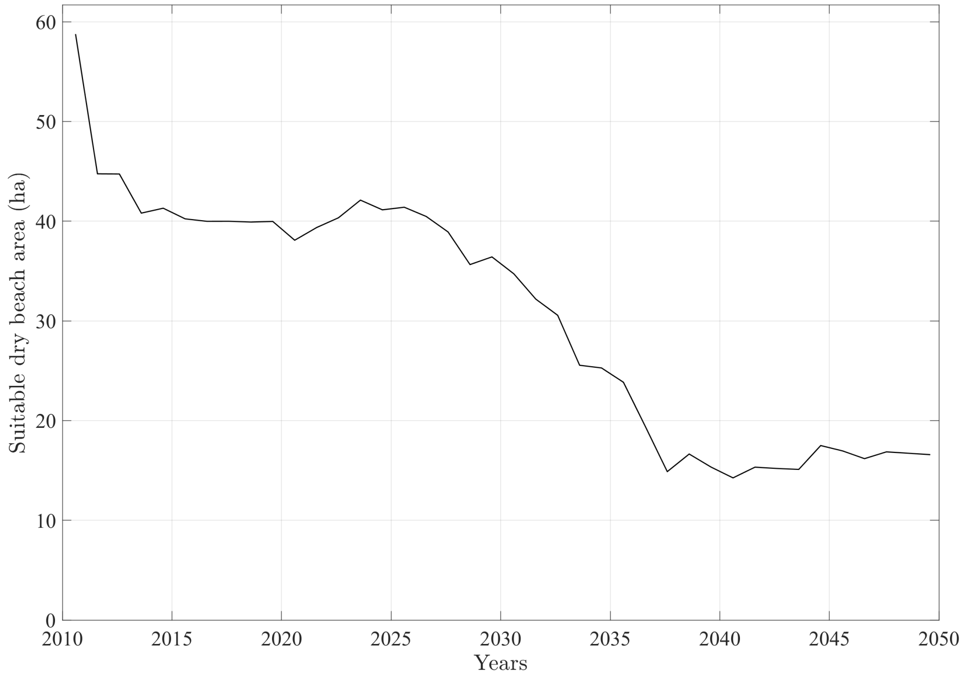


Figure 5.8: Predicted evolution of the sunbathing area at the Sand Motor (nourishment section) that fulfills the requirements of min. 60 m and max. 200 m beach width between +1 and +3 m NAP from 2010 to 2050.

IMPACT ON THE DELFLAND COAST

In Figure 5.9, 5.10 and 5.11 the alongshore development of the beach width is depicted for the years 2011, 2030 and 2050. The initial location of the Sand Motor, between transects 11034 and 10773, is indicated in the figure with dotted vertical lines. Each transect of the Delfland shoreline is color coded. The beach is green in case it fulfills the suitability requirements (min. beach width of 60 m and max. 200 m), red if it is too narrow and yellow in case the beach is too wide. Beaches that exceed the maximum beach width are indicated with a yellow color, because there is a risk the distance to the waterline becomes unattractively large, however the beaches are not necessarily immediately inadequate.

To calculate the dry beach width, the beach between the most seaward crossings was defined to be the sunbathing location. At the tidal channel, this results in a sudden jump of the beach width. This is caused by the multiple +3 m and +1 m NAP crossings, due to the varying bathymetry.

Figure 5.9 shows that initially after construction of the Sand Motor, a large beach area at 's-Gravenzande and Hoek van Holland and a part of the beach at Scheveningen is considered to be too small. At the nourishment section, a part of the beach is too large or too small, however the largest part fulfills the requirements.

Figure 5.10 presents the predicted beach width of the Delfland coast in 2030. The beaches along the entire Delfland coast are predicted to grow tremendously. This would threaten the beach potential because beaches become far too wide. Only at the head of the Sand Motor the dry beach is too narrow. At the eroding head of the Sand Motor, cliff formation leads to a steep profile and a narrow beach between +1 and +3 m NAP. This cliff formation is also visible in the cross-shore profile development at the head of the Sand Motor in Figure 4.2h. Sudden jumps in beach width are caused by the multiple +3 m and +1 m NAP crossings.

Figure 5.11 presents the beach width in 2050, almost forty years after construction. The beach width has increased even further and the largest part of the beach area is considered to be too wide. Only at 's-Gravenzande the beaches remain within the beach width limitations and there is a small area at the lagoon of the Sand Motor that is too narrow.

It must be noted that the model prediction of the beach width is influenced by the model settings of the cross-shore sediment transport. The model deposits sediment around the high water line, while in reality this could be lower in the cross-shore profile as well. This leads to an overestimation of the dry beach width. Nonetheless, observations show a substantial increase of the beach width adjacent to the Sand Motor at Kijkduin. These findings suggest that there is a potential threat of too wide beaches.

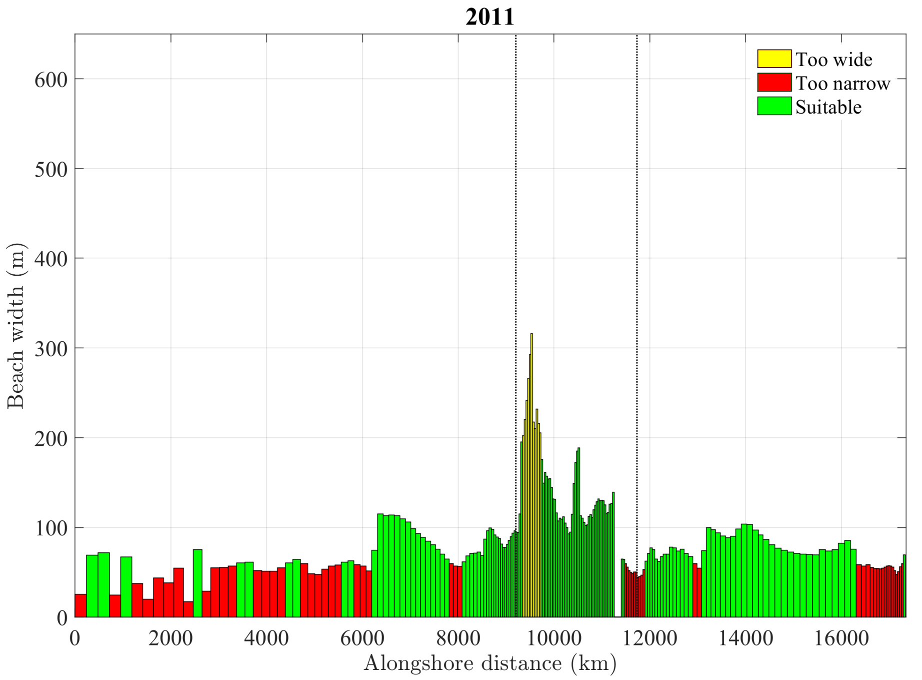


Figure 5.9: Observed alongshore development of the beach width at the Delfland coast in 2011. The green bars fulfill the beach width requirements, the yellow bars are too wide and the red bars indicate the beach that is too narrow. The initial location of the Sand Motor is indicated with the dotted vertical lines.

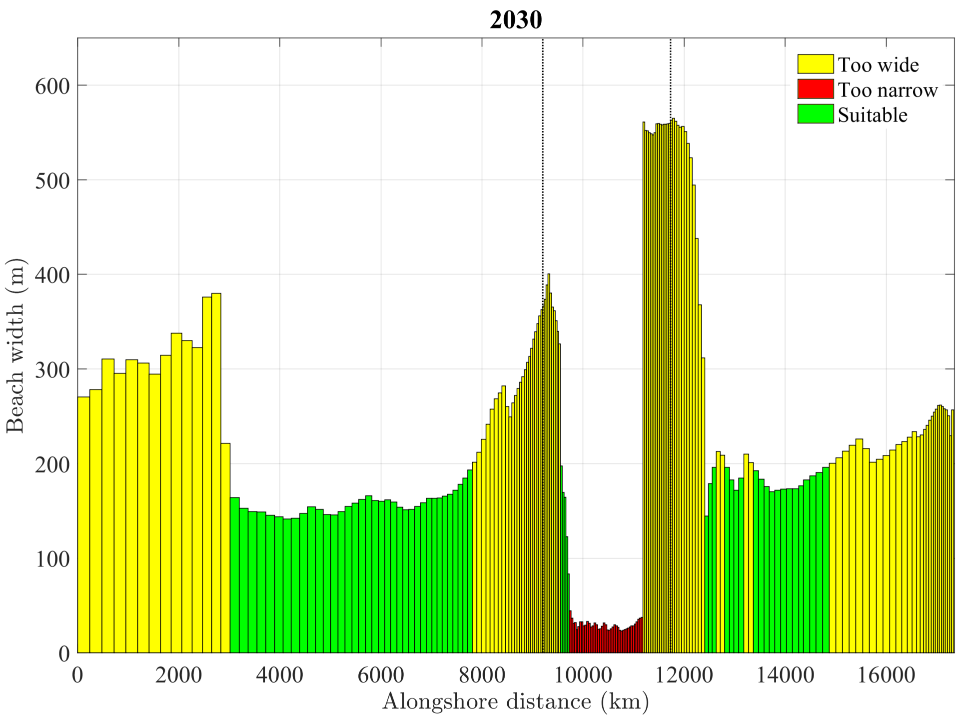


Figure 5.10: Predicted alongshore development of the beach width at the Delfland coast in 2030. The green bars fulfill the beach width requirements, the yellow bars are too wide and the red bars indicate the beach that is too narrow. The initial location of the Sand Motor is indicated with the dotted vertical lines.

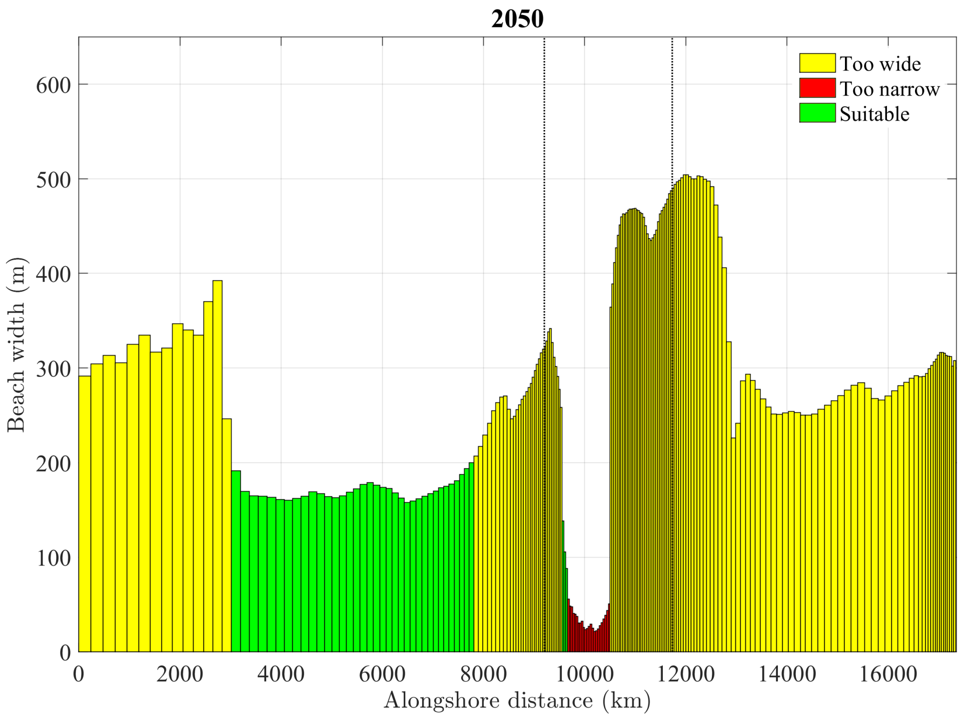


Figure 5.11: Predicted alongshore development of the beach width at the Delfland coast in 2050. The green bars fulfill the beach width requirements, the yellow bars are too wide and the red bars indicate the beach that is too narrow. The initial location of the Sand Motor is indicated with the dotted vertical lines.

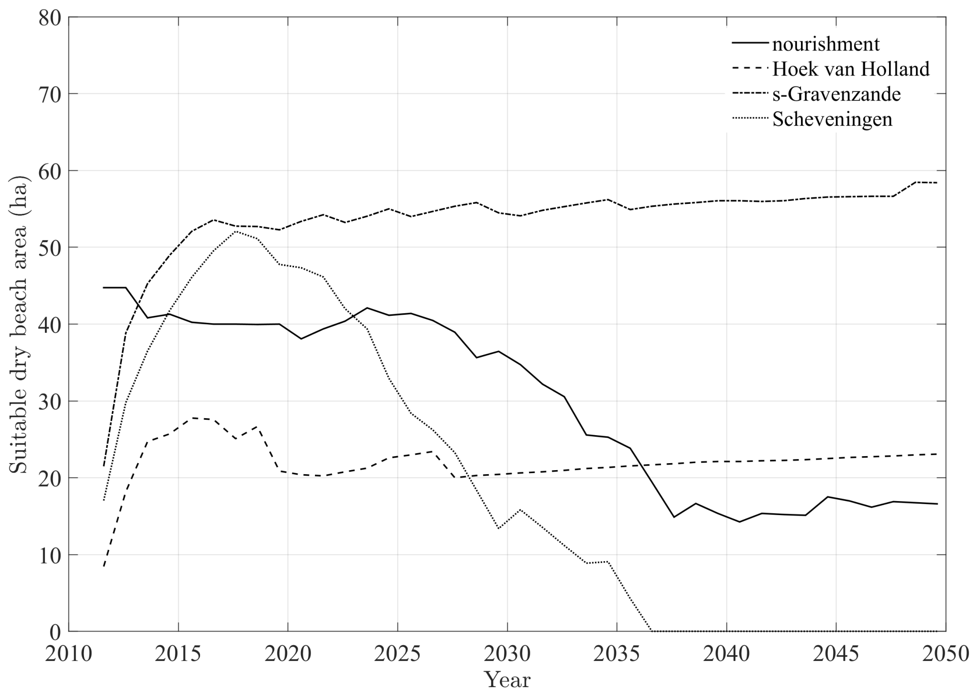


Figure 5.12: Predicted evolution of the sunbathing area that fulfills the requirements of minimum (60 m) and maximum (200 m) beach width at the four sections of the Delfland coast from 2011 to 2050.

In Figure 5.12 the annual evolution of the suitable beach area per coastline section is shown. The evolution of the area at the nourishment section gradually decreases, as was shown earlier in Figure 5.8. The reason for this decrease is partially due to the narrow beach at the head of the Sand Motor, but mostly due to the beach becoming too wide.

The dry beach area of Hoek van Holland first increases due to a widening beach. After a few years, the beach area decreases and the area remains at a constant level, due to beaches that have grown too wide (beyond 200 m).

The dry beach area of 's Gravenzande starts with a quick increase the first few years after construction of the Sand Motor and as the years progress the beach area gradually increases further.

Up to 2017 the dry beach area area at Scheveningen increases to its maximum value of 52 hectares. Beyond 2017 the suitable bathing area quickly decreases because the beaches become too wide. In 2036 the Scheveningen beach has become so wide that there is no beach anymore that fulfills the requirements.

5.3. ECOSYSTEM SERVICE 'HABITAT PROVISION'

The maintenance of healthy habitats is essential for the provision of ecosystem services (De Groot et al., 2002, van Wesenbeeck et al., 2010). Habitat provision entails the adding of new habitats and maintenance of existing habitats that are crucial for the successful life cycle of species. Habitat maintenance can be split into two sub functions, 'refuge and forage' and 'nursery'. The physical potential to accommodate certain species in the future must be determined in order to evaluate habitat provision. This will be done according to the method of ecotope classification described in Subsection 3.4.3.

To evaluate the ecosystem service of 'Habitat provision' nature objectives have to be assigned to the impact area of the mega-nourishment. The aim here is to increase the nature diversity on a spatial scale of the Delfland sandy shore and to enlarge the nursery area of fish species. The nature objectives of the Sand Motor for this assessment are:

1 Increasing the number of occuring ecotopes, thereby increasing the diversity of habitats on a spatial scale.

2 Increasing the area of ecotopes that potentially enhance coastal protection or recreation.

2 Provide ecotopes suitable for nurseries.

Increasing the supratidal area (ecotope 9) could potentially enhance flood safety and increasing the diversity of habitat types may potentially enhance the recreation service.

The ecotopes that are expected to be relevant for the nursery sub service are the seaward side of the surf zone (ecotope 2), the sheltered subtidal (ecotope 5) and the sheltered intertidal (ecotope 8).

ECOTOPE CLASSIFICATION

In Section 2.4 the ecotope classification of the Sand Motor is elaborated. To assess the evolution of the ecotopes, class limits have to be assigned to the hydrodynamic and altitude classes. The level of hydrodynamics is based on the maximum bed shear stress (τ_{max}) due to waves and currents[3]. In Table 3.5 the applied class limits during the post-processing of the model data are listed per ecotope. The ecological composition of the ecotopes is elaborated in Appendix A.

For the ecotope calculation the dominant wave condition W01 was used, with a significant wave height of 1.48 m and a wave direction of $\Theta = 232° N$ (south-west). This wave condition is most representative for the Dutch wave climate. The morphological tide was reduced to a constant signal with a high water level near the shore of approximately 1.4 m NAP and low water level of -0.9 m NAP. More information regarding the reduced wave climate and tidal signal can be found in Appendix C.

To be able to compare the ecotopes between different time steps, the bed shear stresses in the marine zone need to be averaged over one tidal cycle. The comparison between time steps would otherwise lead to differences in the ecotope prediction due to a varying water level. The class limits of the subtidal, intertidal and supratidal zone were defined in such a way that the combination of the height and the bed shear stress in the model leads to an ecotope forecast that matches the expected ecological composition of that area. The decreasing shear stress towards the supratidal zone must not lead to physically strange results, therefore the boundaries between the subtidal, the intertidal and the supratidal zone are slightly above or below the modeled high and low water line. To prevent the prediction of sheltered ecotopes at the open sea, the upper boundary of the intertidal zone is set at 1.2 m NAP, which is 20 cm below the high water level near the shoreline and the upper boundary of the subtidal zone is set at -0.95 cm, just below the low water line.

5.3.1. ECOTOPE MAPPING

The ecotope maps are made on two spatial scales: one locally of the nourishment section and one on a larger Delfland scale. The contour lines of the 6, the 9 and the 12 m depth contour are depicted in the maps as well, to indicate the relation between depth, bed shear stress and species composition. The ecotope maps are made every 5 years, starting at 5 years after construction (2016). An ecotope map of the situation right after construction is not presented, because after the nourishment the ecosystem needs 2-5 years to recover (Baptist et al., 2008). The ecotope map of the initial situation would definitely not correspond to the ecological composition of the ecotopes described in Appendix A.

[3]When combining waves and currents, the bed-shear stresses are non-linearly enhanced due to a non-linear relationship between velocities and shear stresses. The formulation for the enhanced bed shear-stress is based on a 2D (depth-averaged) flow field, generated from the velocity near the bed using a logarithmic approximation (**?**).

NOURISHMENT SECTION

In Figure 5.13, 5.14 and 5.15 the ecotope maps at the location of the Sand Motor of 2010, 2016 and 2050 are presented. For these maps the number of occurring ecotopes and the spatial distribution is analyzed. Furthermore, the area per ecotope is quantified in Subsection 5.3.3. The results are compared to the reference situation of 2010. In Appendix D, the ecotope maps of '21, '26, '31, '36 and '41 are displayed as well.

At this spatial scale, the impact of the Sand Motor is significant. The protrusion has led to a harsher climate seaward of the peninsula. At the head of the Sand Motor a bulge came into existence that locally enlarged the highly turbulent surf zone (ecotope 1). On both sides of the Sand Motor the cross-shore width of the surf zone appears to be smaller, making these areas milder. This may partially be caused by the wave angle of the dominant wave condition. The northern side of the Sand Motor is sheltered due to the incident wave from the south west. Due to construction of the Sand Motor, the subtidal ecotopes have been relocated seaward compared to the situation in 2010.

The lagoon and the dune lake of the Sand Motor have added sheltered areas to the beach ecosystem, both in the subtidal (ecotope 5) and the intertidal (ecotope 8) zone. The hydrodynamic conditions in these ecotopes are very low. Mild climates are associated with a higher species diversity and biomass than harsh climates. An increase in the benthos abundance and diversity may also attract birds that forage on those individuals, which potentially could be interesting for the recreation service. The tidal channel connecting the lagoon and the sea has a high level of hydrodynamics (ecotope 6 and 7) as a result of the high current velocities due to ebb and flood. Sedimentation at the mouth of the tidal channel has elevated the bed level to above 0 m NAP, partially shutting off the lagoon and leading to the classification of the exposed upper intertidal zone in the mouth of the channel.

The supratidal area (ecotope 9) has increased significantly after construction of the Sand Motor. The enlarged dry zone gives space for (embryonic) dune formation (potentially enhancing flood protection) and the large beach width in combination with the sheltered zones in the lagoon and on the sides of the peninsula may give an opportunity to develop a green beach.

Gradients in the ecotope progression in cross-shore direction has changed significantly at the peninsula. This might attract new species that need larger areas in the surf zone of species that need a habitat completely sheltered from waves. The addition of ecotopes increased the diversity of physical conditions and habitats on a spatial scale.

Figure 5.15 present the ecotope map of 2050, almost 40 years after construction. According to the morphological model, the bulge of the surf zone and the seaward side of the surf zone are still present while the supratidal and intertidal zone have spread out. This is due to the fact that the majority of the bed level changes happens landward of the closure depth (approximately -6 m NAP). The dispersal of the nourishment after 40 years has led to an increased supratidal area along the entire coastline, which gives potential for dune formation and the development of green beaches. After 40 years the lagoon area has decreased due to sediment import into. The sediment dispersal has led to an increased length of the tidal channel. The tidal range in the lagoon changes due to the elevated and lengthened tidal channel and in the future the lagoon may even be closed off entirely. (partially) shutting off the lagoon will have a major impact on the benthos communities in the lagoon, due to salinity changes and anoxic conditions. According to the model forecast, the ecotopes at the dune lake will not change over the years. This is related to the fact that there is no aeolian transport incorporated in the Delft3D model. Over time, the dune lake may be filled up and may even have disappeared in forty years. This also applies to the lagoon. The model prediction shows a substantial area of the lagoon in 2050, however it is likely this area will be a lot smaller due to aeolian transport filling up the lagoon.

Referring to the nature objectives and comparing the situation prior to and after construction of the Sand Motor, the diversity of ecotopes has increased. In the reference situation of 2010, 7 ecotopes were present. The Sand Motor has added new sheltered ecotopes in the subtidal and intertidal zone and increased the number of ecotopes to 9. The sheltered subtidal and the sheltered intertidal ecotopes are known as potential nursery areas. Furthermore, the areas of the ecotopes have changed. The evolution of the ecotope areas from 2010 to 2050 is analyzed in Subsection 5.3.3.

IMPACT ON THE DELFLAND COAST

In Figure 5.16, 5.17 and 5.18 the ecotope maps of 2010, 2016 and 2050 of the Delfland coastline are displayed. Besides the Sand Motor, there are other perturbations along the Delfland coast, e.g. by harbors, a river and breakwaters. At the southern end of the Delfland coast the Nieuwe Waterweg flows into the sea. This channel is an important shipping route to the harbor of Rotterdam and occasionally needs to be dredged for depth maintenance. The dredged sand is dumped offshore from 's-Gravenzande, leading to a locally increased bed

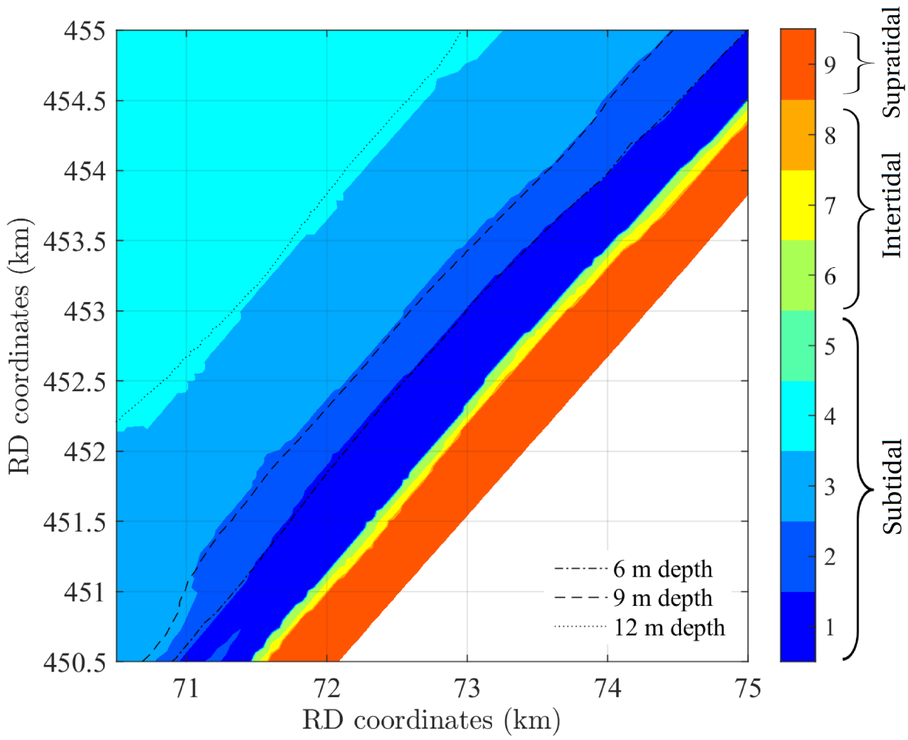


Figure 5.13: Ecotope map at the location of the Sand Motor in 2010, one year prior to the construction of the Sand Motor

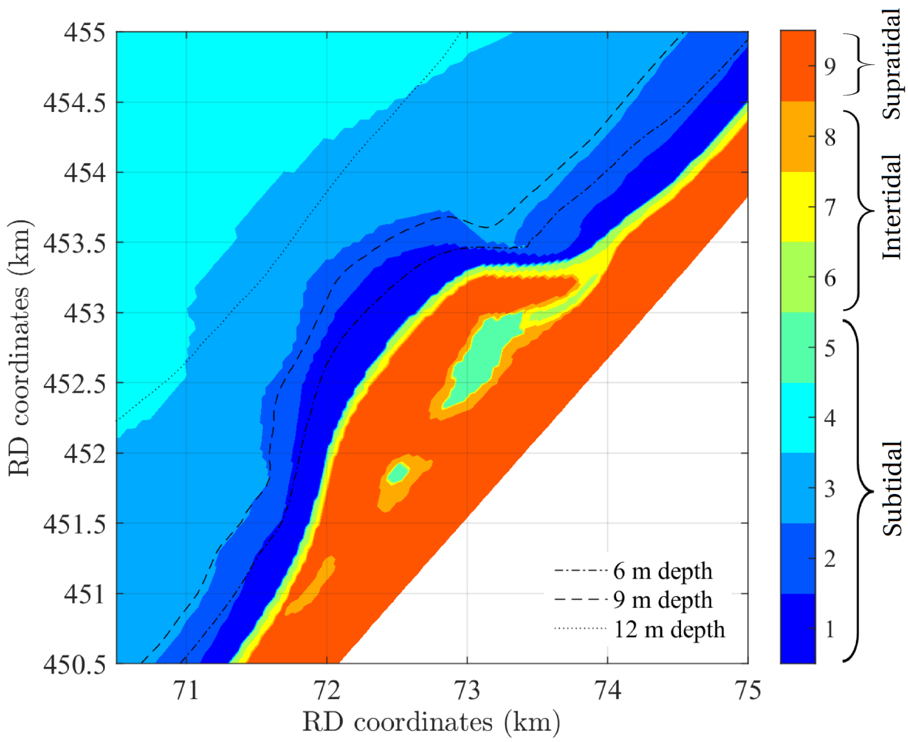


Figure 5.14: Ecotope map of the Sand Motor in 2016, 5 years after construction of the Sand Motor.

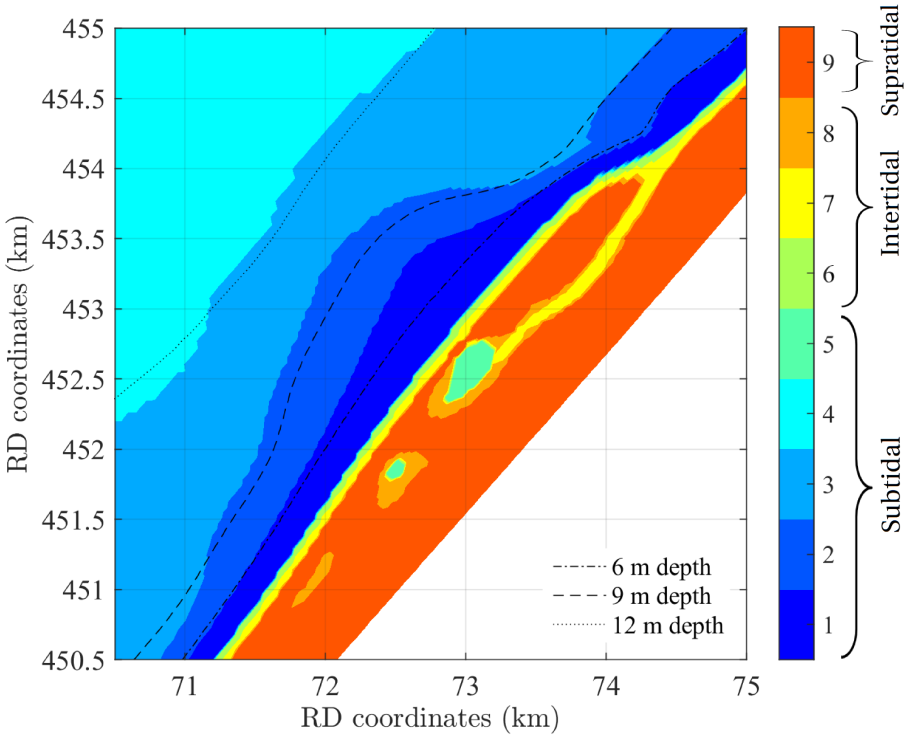


Figure 5.15: Ecotope map of the Sand Motor in 2050, almost 40 years after construction of the Sand Motor.

level. This has led to the large offshore patch of nearshore ecotope (ecotope 3). Please note that wave condition WC01 was used while calculating the ecotope occurrence. This wave comes from the south west, leading to a large sheltered area down drift from the breakwater of the Nieuwe Waterweg. In reality, this sheltered area may not exist or may be smaller because waves can come from many directions. At the northern end of the Delfland coast the breakwaters of the Scheveningen harbor are visible. The breakwaters perturb the littoral drift and create a sheltered area in the harbour and at the lee side of the breakwaters.

Comparing Figure 5.16 and Figure 5.17 at the scale of the entire Delfland coastline, the disturbance of the Sand Motor is smaller than at the nourishment scale. The Sand Motor has retracted an area of the moderately exposed subtidal area in the near shore (ecotope 3) and the offshore zone (ecotope 4) and has replaced it with a harsher subtidal area at the head of the peninsula. The surf zone at the head of the Sand Motor is wider compared to the cross-shore width of the surf zone along the rest of the Delfland coast. On the northern side of the Sand Motor, at the tidal channel, the protrusion of the Sand Motor leads to a relatively narrow surf zone compared to the rest of the Delfland coast and the situation in 2010. On the scale of the Delfland coast in Figure 5.17, the increase in supratidal area and dry beach width in 2016 at the Sand Motor becomes evident. This provides space for embryonic dunes and dune growth. Furthermore, the Sand Motor has added a sheltered lagoon and dune lake. Due to the chosen wave condition, there is a large area at Hoek van Holland assigned to this ecotope, however this would not have been there in case the incident wave angle comes from the North. The two dominant wave directions are North North West (WC07) and South West (WC01), of which WC01 is used in this case.

In Figure 5.18, the ecotope map of the Delfland coast in 2050 is shown. 40 years after construction of the Sand Motor, the supratidal area has increased along the entire Delfland coast. This increases the potential of embryonic dune growth across the entire Delfland coast, leading to an increased level of flood protection from Hoek van Holland to Scheveningen. In comparison to the situation in 2010 and 2016, the seaward side of the surf zone (ecotope 2) has widened at the head of the peninsula. This ecotope is associated with the potential to be a nursery area for flatfish.

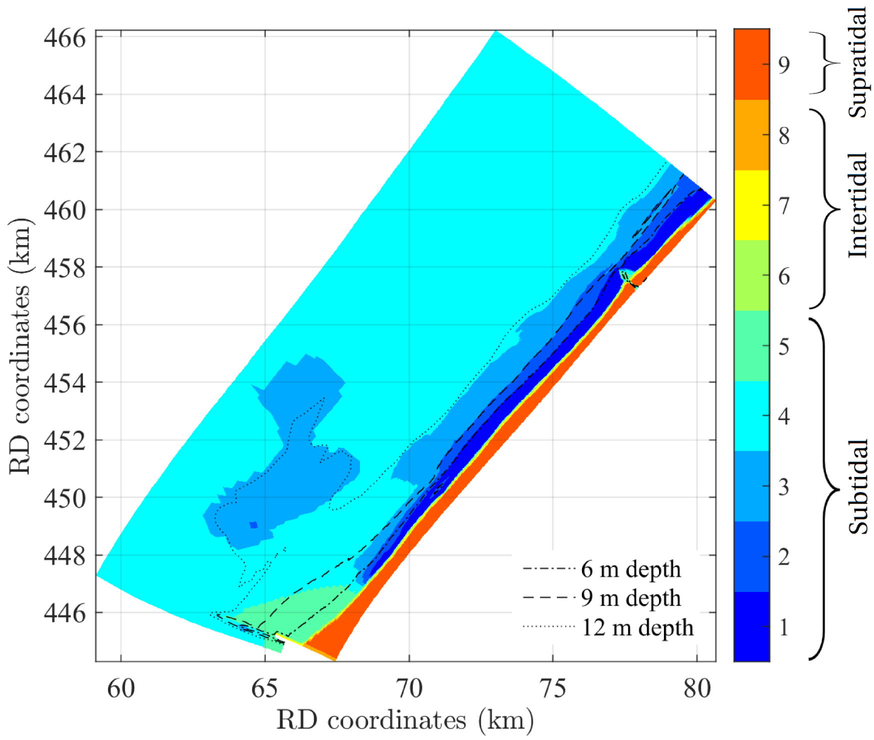


Figure 5.16: Ecotope map of the Delfland coast in 2010, prior to the Sand Motor.

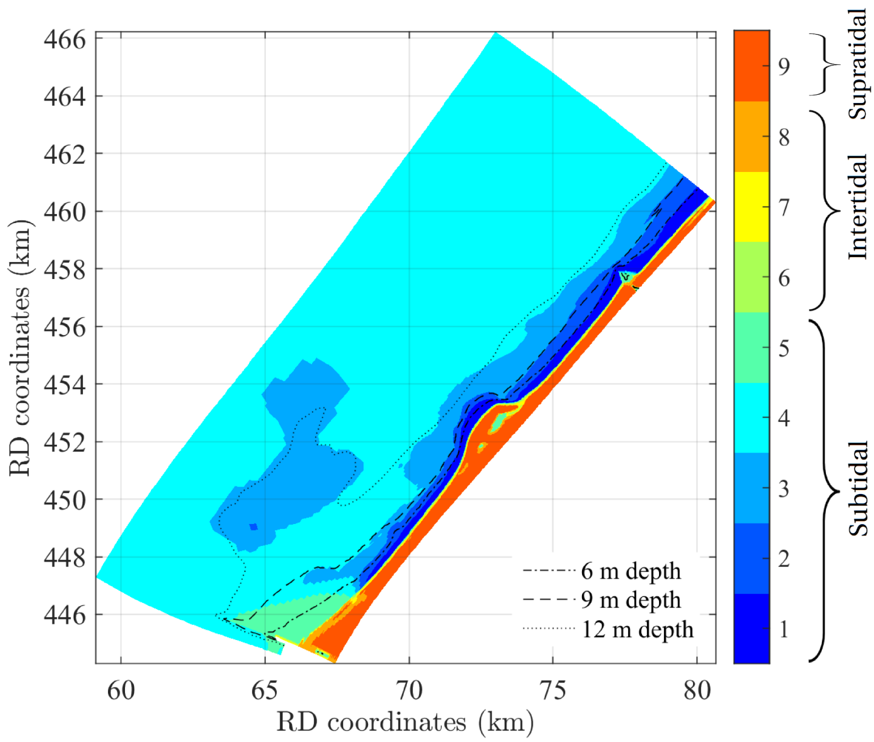


Figure 5.17: Ecotope map of the Delfland coast in 2016, 5 years after construction of the Sand Motor.

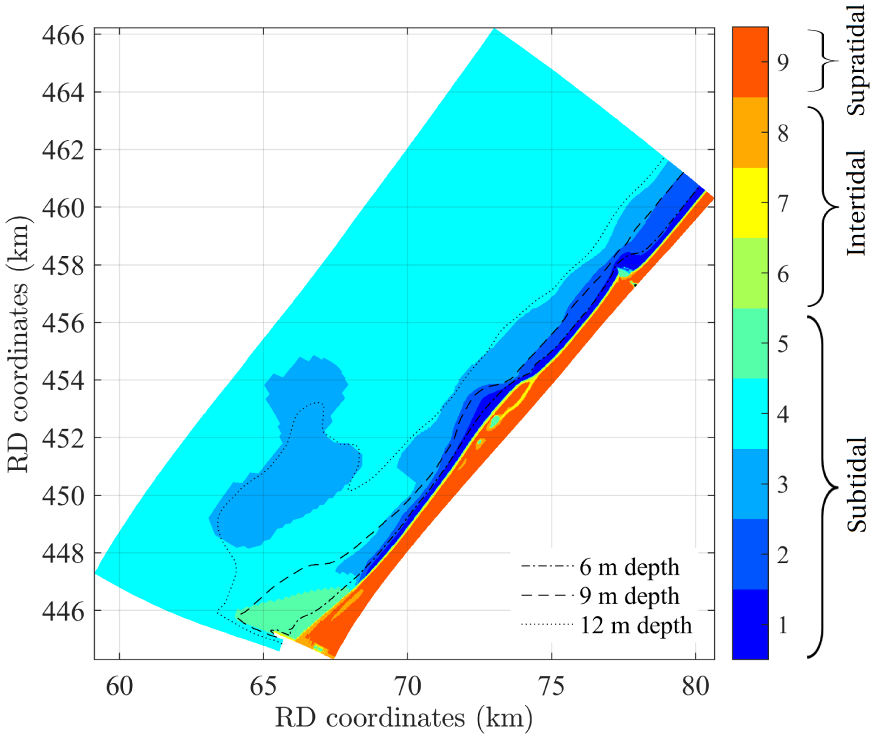


Figure 5.18: Ecotope map of the Delfland coast in 2050, almost 40 years after construction of the Sand Motor.

5.3.2. Dynamic ecotope analysis

The presented ecotope maps are based on the W01 wave condition, with waves from the South West and a significant wave height of 1.48 m. This is the dominant wave direction and the probability of occurrence of this condition within the reduced wave climate is 12,24 %. Inter annually the wave conditions will differ, leading to a change in the wave direction and the magnitude of the maximum bed shear stresses. To demonstrate the inter annual variability of the ecotopes at specific locations, the probability of occurrence of the ecotopes during the year is presented for five locations, of which the coordinates are shown in Figure 5.19. The ecotope dynamics were analyzed at an offshore location (location 1), at Hoek van Holland (location 2), at the head of the Sand Motor (location 3), far into the lagoon (location 4) and at the transition from the tidal channel to the lagoon (location 5).

In Figure 5.20 the predicted occurrence of the ecotopes at location 1 to 4 are presented for the year 2016. Pie charts in which the expected percentage of time during the year a certain ecotope is present at a specific location are shown, based on the wave conditions and the probability of occurrence per wave condition. The probability of occurrence of the reduced wave climate does not add up to a 100%, only to 53%. During the remaining conditions, a low level of hydrodynamic forcing with bed shear stresses due to currents (induced by waves) only is assumed. The probability of occurrence of W01 is also indicated in the figures. Far offshore, presented in Figure 5.20a, most of the time during the year the predicted hydrodynamic conditions are relatively mild (ecotope 4). At Hoek van Holland (Figure 5.20b), W01 predicts a large sheltered subtidal area (ecotope 5). This was also visible in the Delfland coast ecotope maps of Figure 5.16, 5.17 and 5.18. The model predicts a sheltered area because of the South West wave direction, causing a sheltered area on the lee side of the breakwater. The probability that this location is characterized by a highly dynamic environment like the surf zone (ecotope 1) is high at 80%. The head of the Sand Motor is characterized by highly dynamic conditions (ecotope 1) during all levels of hydrodynamic forcing. Inside the lagoon, the predicted conditions are sheltered during all conditions. Further analysis showed that the probability certain ecotopes will occur at these four locations does not change throughout the years.

The inter annual occurrence of ecotopes does change at the transition between the tidal channel and the lagoon. The probability that certain ecotopes will occur at this location is shown for the years 2016 and 2030 in Figure 5.21. Sediment import into the lagoon causes an elevation of the bed level. This changed the

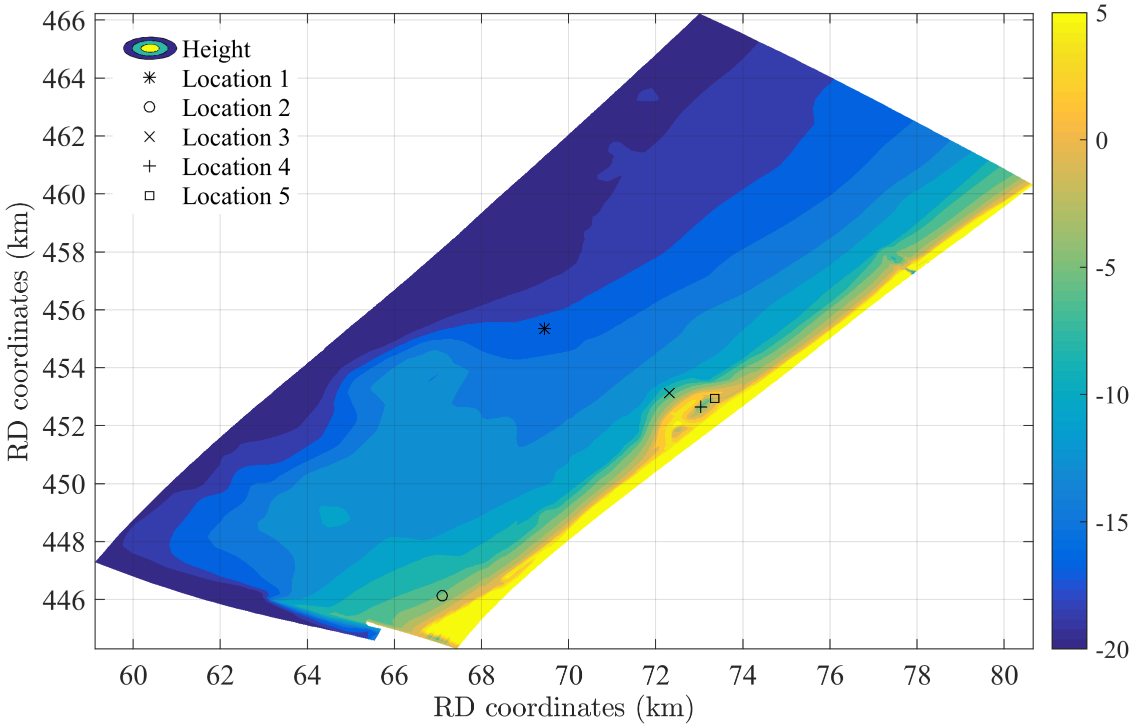
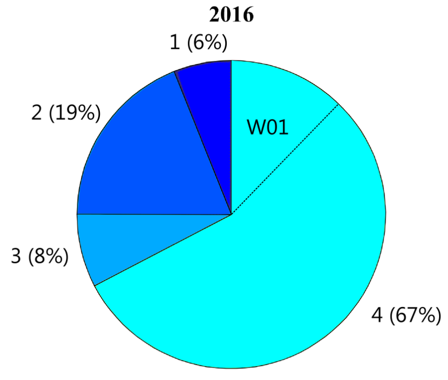
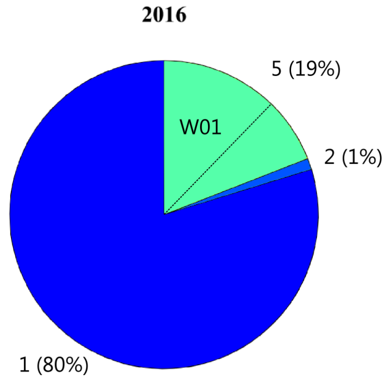


Figure 5.19: The five analyzed locations, plotted onto the bathymetry (m NAP) of the Delfland coast.

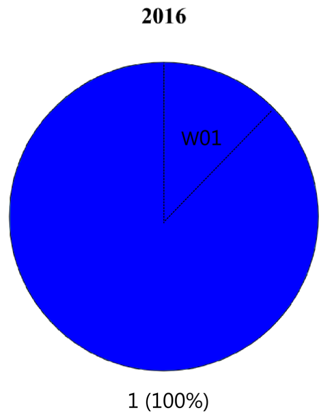
occurring ecotope from the lower intertidal (ecotope 6) to the upper intertidal (ecotope 7) and the changing morphology caused an increase of the probability that the location is sheltered (ecotope 8).



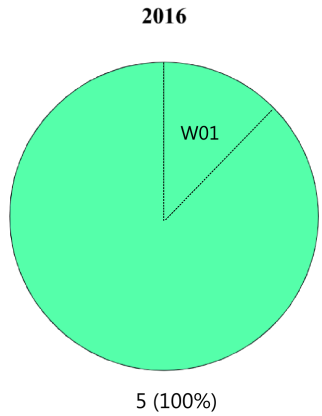
(a) Location 1: offshore.



(b) Location 2: Hoek van Holland.

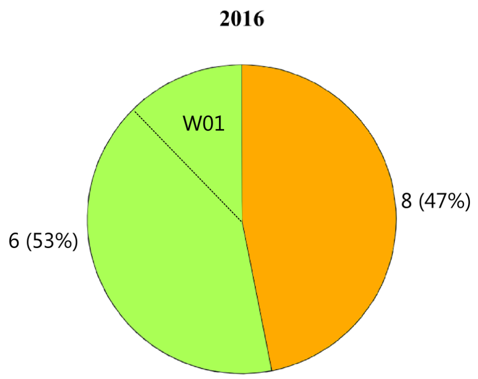


(c) Location 3: head of the Sand Motor.

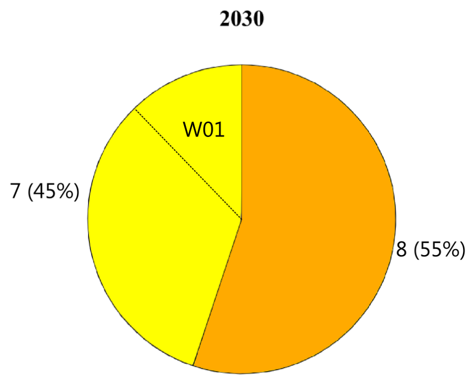


(d) Location 4: inside the lagoon.

Figure 5.20: Predicted inter annual variation of ecotopes at specified locations at the Delfland coast, as a result of the variations within the Dutch wave climate. The pie charts present the predicted occurrence of ecotopes as a percentage of time in 2016. The probability of occurrence of W01 within a year is 12,24 %.



(a) Location 5



(b) Location 5

Figure 5.21: Predicted inter annual variation of ecotopes at the transition from the tidal channel to the lagoon, as a result of the variations within the Dutch wave climate. The pie charts present the predicted occurrence of ecotopes as a percentage of time in 2016 and 2030 (probability of occurrence of W01 within a year is 12,24 %).

5.3.3. AREA ANALYSIS

NOURISHMENT SECTION

In Figure 5.22a to 5.22i the evolution of the ecotope areas are plotted from 2010 to 2050 for the nourishment section. Comparing the evolution of the ecotope areas prior to and after the construction of the Sand Motor, some ecotopes show significant variability over the years.

Regarding the subtidal zone, the 'surf zone', the 'seaward side of the surf zone' and the 'sheltered subtidal' shown an interesting development. In Figure 5.22a the evolution of the surf zone area is shown. It appears that the surf zone area overall decreases from 2010 to 2011. Even though the peninsula creates a relatively harsh climate at the head, the sides of the Sand Motor appear to be milder. In total this has led to a reduction in the surf zone area. After construction of the Sand Motor, the area of the 'seaward side of the surf zone' decreased, most likely due to the steeper profile of the Sand Motor. The area of the seaward side of the surf zone (ecotope 2) shows a gradual increase again over the years, as can be seen in Figure 5.22b. This is a positive development for the nursery function, as this zone is an important nursery for flatfish. Another ecotope that is relevant to the nursery function is the sheltered subtidal, of which the evolution of the area is presented in Figure 5.22e. There was no sheltered subtidal zone present prior to the Sand Motor. The sheltered subtidal has a very mild climate which is associated with a high biodiversity, abundance and biomass and is a suitable area for nurseries of fish and benthos. In 2011 the area increased to 18 hectares and over the years it will gradually decrease due to sediment import into the lagoon. Once more, it must be noted that there is no aeolian transport incorporated in the Delft3D model. Over time, it is likely that the sheltered subtidal area will decrease due to sand deposition by wind. The area of the offshore ecotope in Figure 5.22d hardly changes over the forty year period. The area of the nearshore ecotope shows a variability over the years, but does not show a significant change as a result of the Sand Motor in Figure 5.22c.

In the intertidal zone, the upper intertidal ecotope (Figure 5.22g) gradually increases. This is probably caused due to the accretion at the intertidal beach, causing a milder slope and hence an increased area. The sheltered intertidal ecotope (Figure 5.22h) was not present prior to the Sand Motor. After construction of the Sand Motor the area of this ecotope starts to increase. This is probably also caused by accretion inside the lagoon at the high water level, causing milder slopes and an increased area. The evolution of the area of the lower intertidal ecotope in Figure 5.22f does not display significant changes as a result of the Sand Motor.

To conclude, the area of the supratidal ecotope is presented in Figure 5.22i. Due to the Sand Motor the supratidal area increases with more than 50 % of the area in 2010, providing an increased potential for dune growth. The area remains at a steady level during the forty years of the model forecast. According to the model, the added volume of sand in this zone remains there and the increase in the area of this habitat is robust. Also for this ecotope, aeolian transport will influence the evolution of the the supratidal area in reality, which is not taken into account in the model.

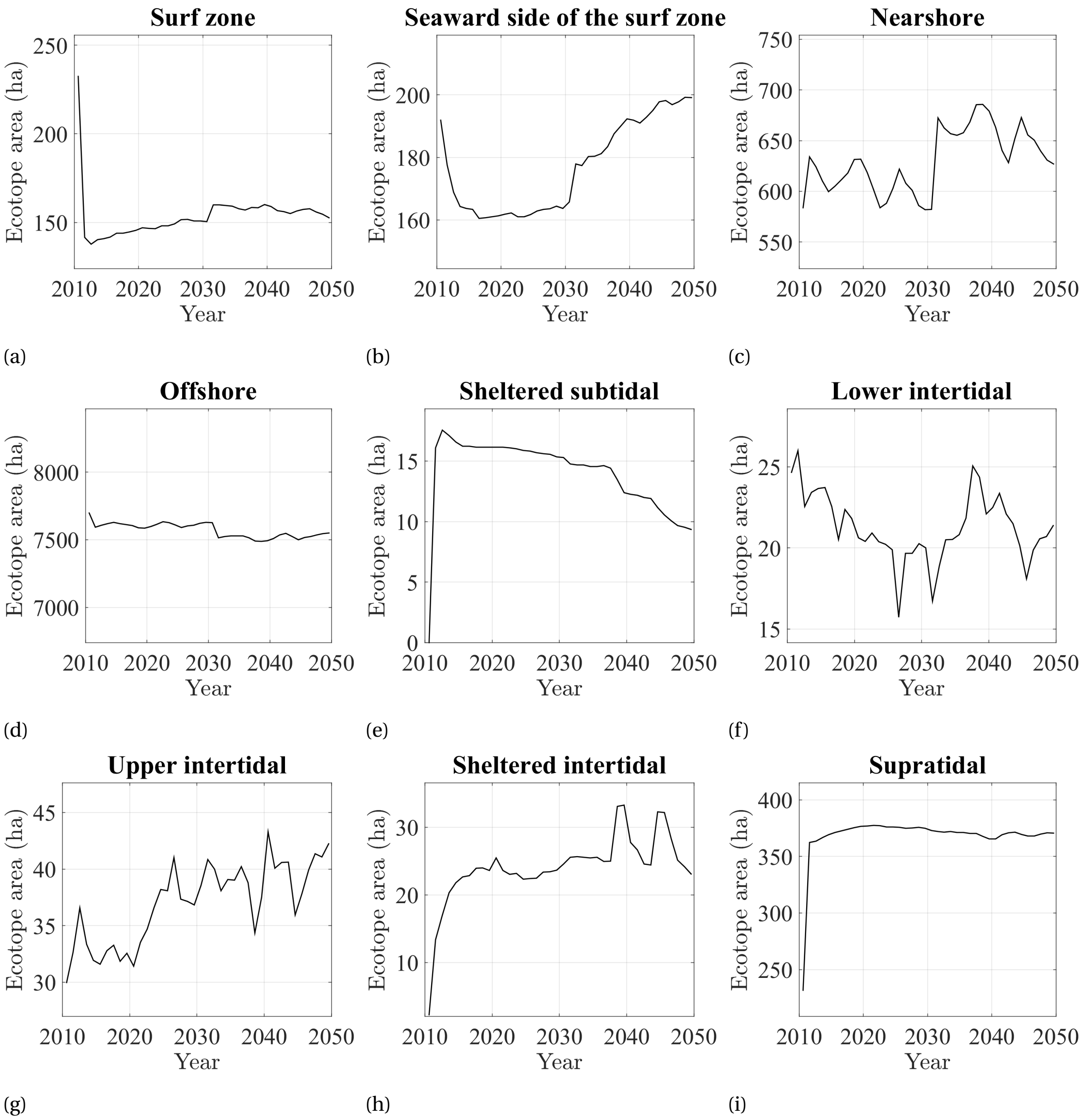


Figure 5.22: Predicted evolution of the ecotope areas in the nourishment section from 2010 (prior to construction) to 2050.

6

DYNAMIC ECOSYSTEM SERVICE ASSESSMENT: THE NOURISHMENT ALTERNATIVES

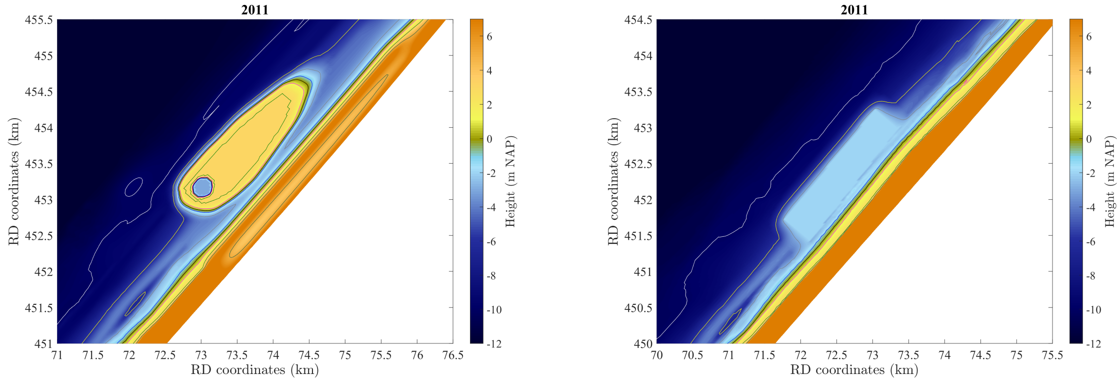
In this chapter the Sand Motor will be compared to two alternative shapes of a mega-nourishment. The two alternative scenarios are an offshore island and an upscaled traditional nourishment that is implemented every four years. The morphological forecast of the alternatives resulted in the morphological behavior twenty years ahead. A comparison is made between the alternatives for the coastal protection, recreation and habitat provision ecosystem service until 2030.

THE ALTERNATIVES

To take a step towards enhancing the ecosystem services of a mega-nourishment, the ecosystem service dynamics of the Sand Motor will be compared to two alternative designs. These will be the offshore Island and an upscaled 'traditional' foreshore nourishment. The initial bathymetry of the nourishment design alternatives, right after construction in 2011, are displayed in Figure 6.1. Further details on the alternatives and a visualization of the bathymetry development of the alternatives are presented in Appendix C.

The Island was analyzed, because this design was a serious option during the Environmental Impact Assessment of the Sand Motor. The Island is a scenario where the same volume as at the Sand Motor is shaped like an island just offshore the coastline of Kijkduin. Onshore directed sediment transport causes the Island to move towards the shore. The model predicted that the southern end of the Island becomes attached, while on the northern end a tidal channel was formed. This results in a peninsula shape, that has a relatively smaller protrusion and a larger alongshore length than the Sand Motor peninsula. This results in the formation of a lagoon that is larger than that of the Sand Motor. For a visualization of the morphological development of the Island in twenty years time, see Figure C.1.

The traditional nourishment scenario was chosen as a design alternative, because this is the more common way of nourishing in the Netherlands and it would be valuable to analyze the difference between a mega-nourishment and a more frequent, smaller sized nourishment. The traditional nourishment scenario in this study is upscaled, to be able to compare the ecosystem services without the different volume being a factor. It is the impact of a higher nourishment frequency that is considered here. The traditional nourishment is a scenario that contains in total the same volume as the Sand Motor, but where the volume is split up into five partial foreshore nourishments of approximately 4 Mm^3 implemented every 4 years. The minimum depth of the foreshore nourishment is 2 m NAP. The upscaled nourishment is a fictive scenario, because usually a 'traditional' nourishment takes place when the BKL threatens to be exceeded by a retreating MKL. Once this BKL exceedence is imminent, a nourishment is implemented locally at that part of the coast that requires it. This is not yet the case after implementation of the partial nourishment in this study. This results in an increasing protrusion of the shoreface after every partial nourishment. Onshore directed sediment transport processes bring the sediment to the shore over time. A visualization of the morphological development is shown in Figure C.2.



(a) The Island (b) The traditional nourishment

Figure 6.1: Initial bathymetry of the fictive nourishment design alternatives in 2011.

6.1. ECOSYSTEM SERVICE 'COASTAL PROTECTION'

6.1.1. MAINTENANCE OF THE COASTLINE POSITION

The results of the best estimated MKL distance, with 8.7 $m^3/m/y$ aeolian transport volume loss, are presented and discussed on two spatial scales: the nourishment section and the entire Delfland coast.

NOURISHMENT SECTION

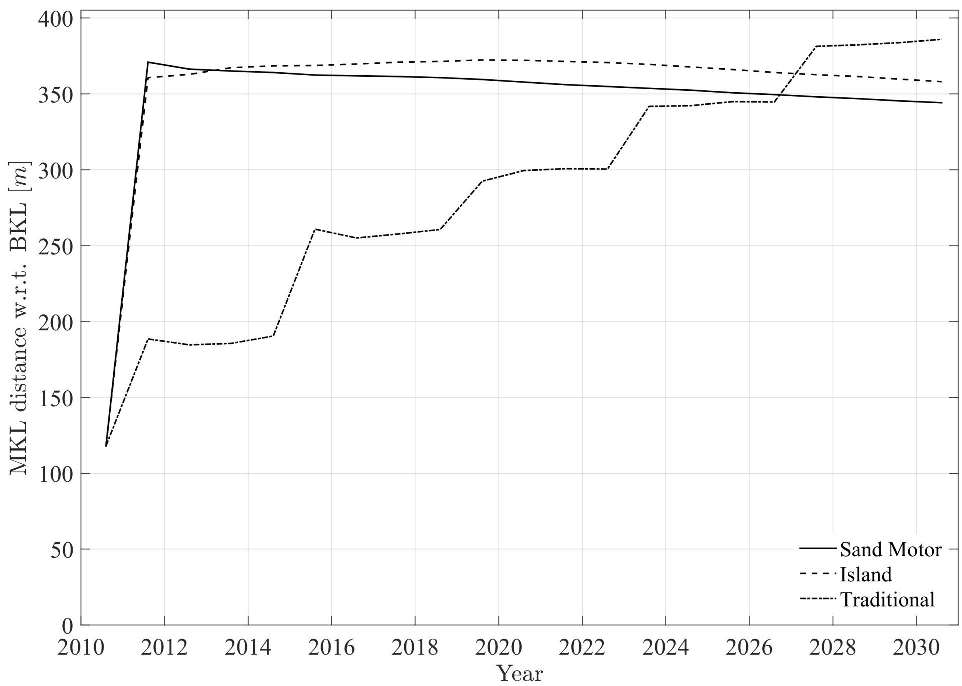


Figure 6.2: Predicted evolution of the best estimated, weighted, averaged MKL distance of the Sand Motor, the Island and the traditional nourishment. The averaged MKL distance is calculated with the transects of the nourishment section.

In Figure 6.2, the evolution of the coastline position within the nourishment section is shown. The MKL distances of the 18 transects of the nourishment section are averaged, also taking into account the distance in between two transects. The locations of the 18 transects of the nourishment section are listed in Table 3.4 and visualized in Figure 3.3. The evolution of the weighted, averaged MKL distances of the Sand Motor, the

Island and the traditional nourishment upto 2030 are compared. The evolution of the coastline position of the Island and the Sand Motor are approximately at the same level, however the Sand Motor is on average just landward of the Island. The trend of the traditional nourishment is typical: the MKL distance shows a sudden increase every four years, after a partial foreshore nourishment. After the partial nourishment the averaged MKL distance increases somewhat, as the sand is transported into the MKL zone by onshore sediment transport processes.

DELFLAND COAST

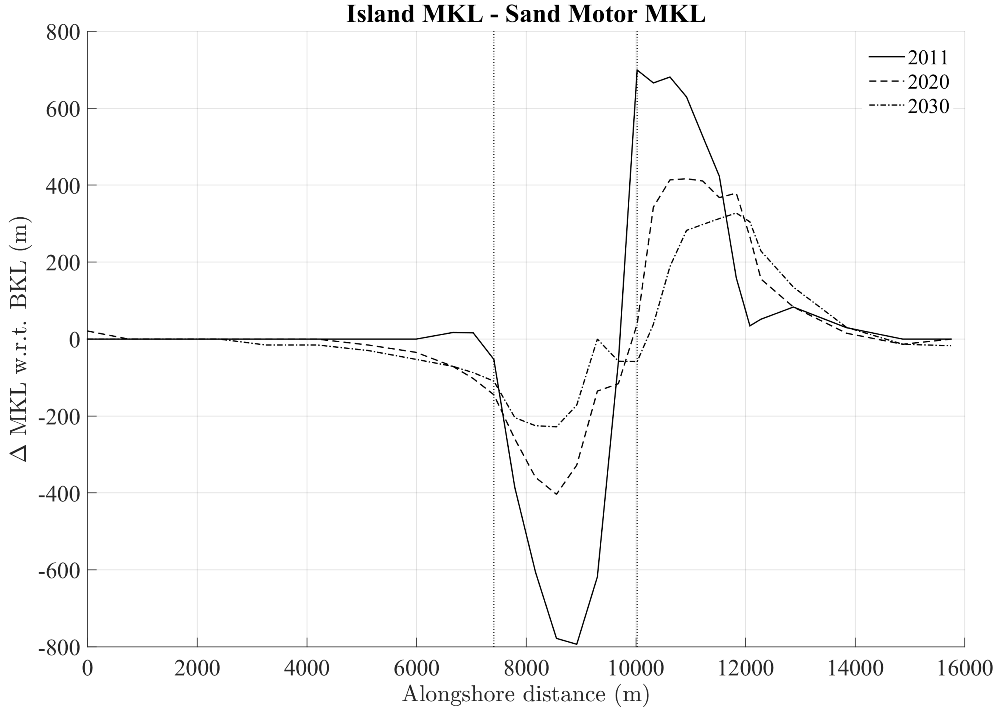
The alternatives may lead to a different long-term impact on the rest of the Delfland coast. To analyze this, the Delfland coastline positions of the alternatives are compared to the Sand Motor. The MKL distances per transect of the Sand Motor are subtracted from those of the alternative, resulting in a Δ MKL distance per transect. The results of the comparison between the Island and the Sand Motor and the traditional nourishment and the Sand Motor are presented in Figure 6.3, where Hoek van Holland is defined as the origin of the alongshore distance and the initial location of the Sand Motor is indicated (between transects 11034 and 10773). A positive Δ MKL distance means that the MKL distance of the alternative is larger than that of the Sand Motor for that transect, while a negative value means the Sand Motor has a larger MKL distance. The individual alongshore development of the best estimated Delfland coastline position of the alternatives is presented in Section E.1.

Integration of the Δ MKL distance over the alongshore distance from Hoek van Holland to Scheveningen results in a coastal area difference between the nourishment alternative and the Sand Motor. Looking at Figure 6.3a, the MKL area of the Island in 2011 was 1,3 % larger than the MKL area of the Sand Motor. In the best estimate MKL calculation of 2030, the MKL area of the Island has grown to be 4% larger than the Sand Motor.

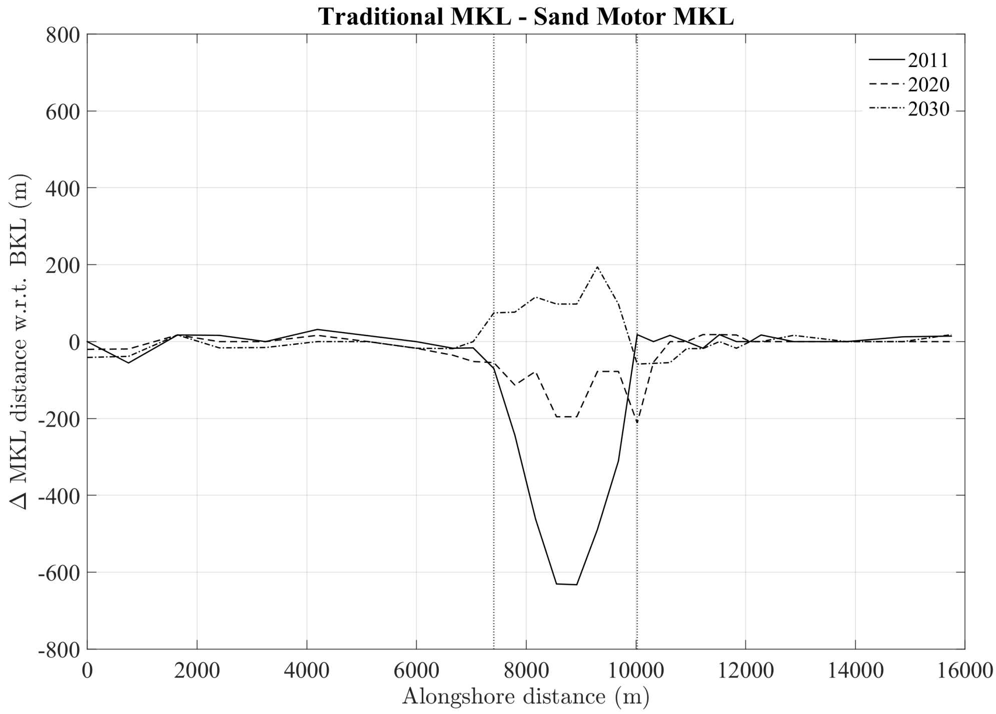
In the case of the traditional nourishment scenario, the sediment volume is gradually added every four years. For the first years, this results in a significant larger coastal area for the Sand Motor scenario, as can be seen in Figure 6.3b. Initially in 2011, the coastal area of the Sand Motor over the entire Delfland coast is 31% larger than the traditional nourishment. This difference decreases to 12% in 2020, after three out of five partial nourishments are added. In 2030, the coastal area of the traditional nourishment is 4.3 % larger than the Sand Motor.

From Figure 6.2 and Figure 6.3 it can be concluded that the Sand Motor and Island provide an immediate, substantial gain in coastal area, due to a seaward movement of the coastline position, is not enhanced by the traditional nourishment scenario. From the dynamic assessment can be concluded that an immediate implementation of the total nourishment volume results in an overall enhancement of this ecosystem service that is robust and holds for the first twenty years after construction. The traditional nourishment gradually increases the MKL distance and eventually will reach the same gain in coastal area, however this takes many years.

To investigate the dispersal rate of the Sand Motor towards the northern and southern parts of the Delfland coast, the evolution of the best estimated MKL distances of the design alternatives are plotted at plotted together in a figure for the nourishment section, the coast north of the nourishment (Scheveningen) and the coast south of the nourishment (Scheveningen and 's-Gravenzande together). The averaged MKL of Scheveningen appears to be larger for the Island. This is likely the result of the more northern position of the Island, which influences the coastal section of Scheveningen. The increase of the MKL distance at Scheveningen is also the largest for the Island, due to the fact the Island is located closer to Scheveningen than the Sand Motor or the traditional foreshore nourishments. The increase of the MKL distance at the southern part of the Delfland coast is the largest for the Sand Motor scenario. This is probably related to the more southern location of the Sand Motor compared to the Island. The traditional nourishment shows the smallest seaward shift of the southern and northern Delfland coastline, due to the phased nourishment. It is likely that the sediment of the foreshore nourishments have not fully reached those parts of the coast yet.



(a) Difference between the MKL distance of the Island and the Sand Motor.



(b) Difference between the MKL distance of the traditional nourishment and the Sand Motor.

Figure 6.3: Difference between the predicted MKL distances of the nourishment alternatives and the Sand Motor, based on the best estimate calculation. The difference is calculated per transect for the years 2011, 2020 and 2030 for the entire Delfland coastline between Hoek van Holland and Scheveningen, where Hoek van Holland is defined as the origin. The initial location of the Sand Motor in 2011 is indicated with the vertical dotted line.

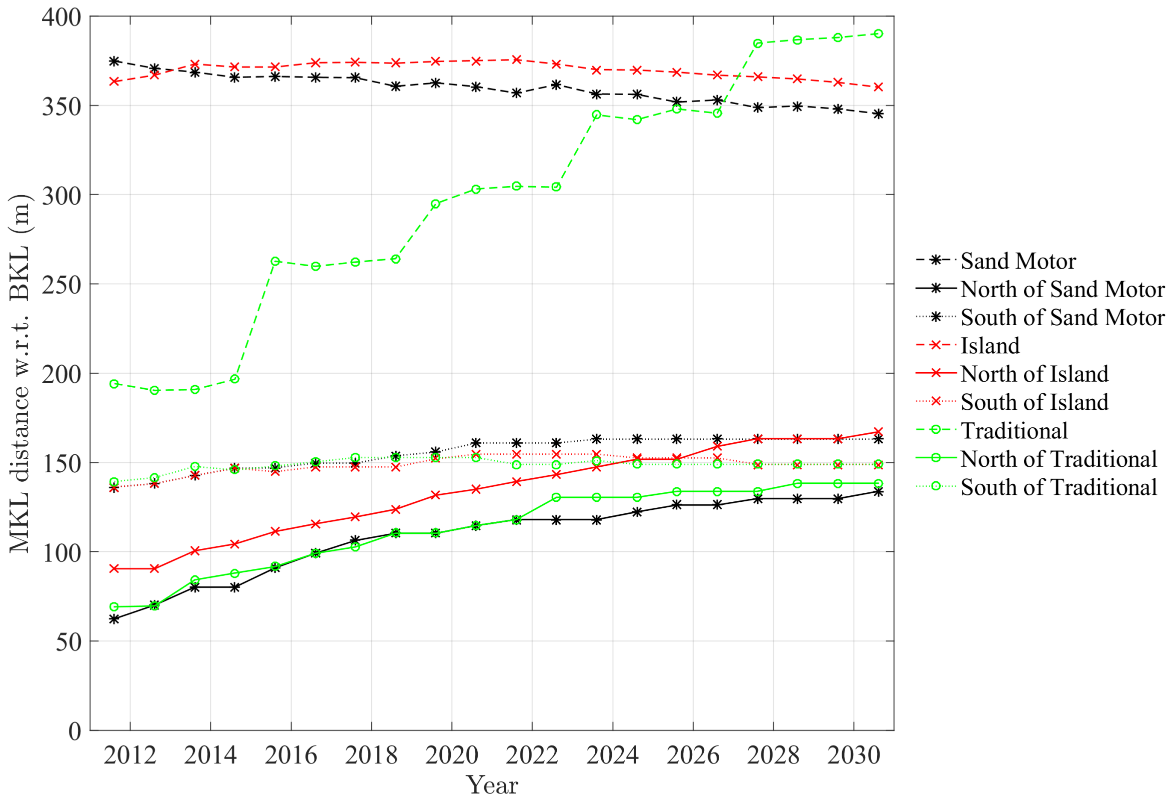


Figure 6.4: Predicted evolution of the best estimated MKL distances of the Sand Motor, the Island and the traditional nourishment. The evolution of the averaged MKL distances are shown for the nourishment section, the transects north of the nourishment and the transects south of the nourishment.

6.2. ECOSYSTEM SERVICE 'RECREATION'

6.2.1. KITESURFING

NOURISHMENT SECTION

The predicted evolution of the kitesurfing area of the Sand Motor, the Island and the traditional nourishment have been depicted, starting in the reference situation of 2010 (see Figure 6.5). The sheltered areas are calculated with the representative dominant wave condition with waves from the South West and a $H_s = 1.48m$ (the W01 wave condition). In the case of the Island, for the first year after construction, the island provided a small sheltered area on the landward side. Due to onshore directed sediment transport processes, the southern end of the Island was predicted to attached to the shore after two years and the alternative also became peninsula shaped. This resulted in a predicted lagoon area that is 75% larger than the lagoon of the Sand Motor. Thus the model forecast of the Island predicts a larger kitesurfing area, see for a visualization of the location of the kitesurfing area at the Island Figure E.2 in Section E.2. The filling up of the Island lagoon happens faster than the filling up of the Sand Motor lagoon, resulting in a quicker decrease of the kitesurfing area than at the Sand Motor.

The traditional nourishment also develops a kitesurfing area according to the model calculation. The extended foreshore results in a sheltered area at the north of the traditional nourishment. This can be seen in the visualization of the kitesurfing spot of 2015 in Figure E.3a of Section E.2. This sheltered area is present in the case waves come from the South West, which is not representative for the entire year. As the years progress at the traditional nourishment, an interesting bed level pattern develops. This results in a highly variable, shallow subtidal area that is sheltered from waves. The location of the kitesurfing area in 2030 is visualized in Figure E.3b of Section E.2. The kitesurfing area is scattered over the nourishment, making the potential for kitesurfing questionable.

The lagoons that result from the Sand Motor and the Island provide a uninterrupted area that is suitable for kitesurfing, no matter the wave direction. This is not the case for the traditional nourishment. The area for that nourishment alternative may seem significant in Figure 6.5, however this area is scattered and not robust because it is dependent on the wave direction.

Once more, it must be noted that the Delft3D model does not incorporate aeolian transport. Over the years the lagoons of the Sand motor, the Island and the traditional nourishment may be filled up with sand, decreasing the kitesurfing area much further than is predicted.

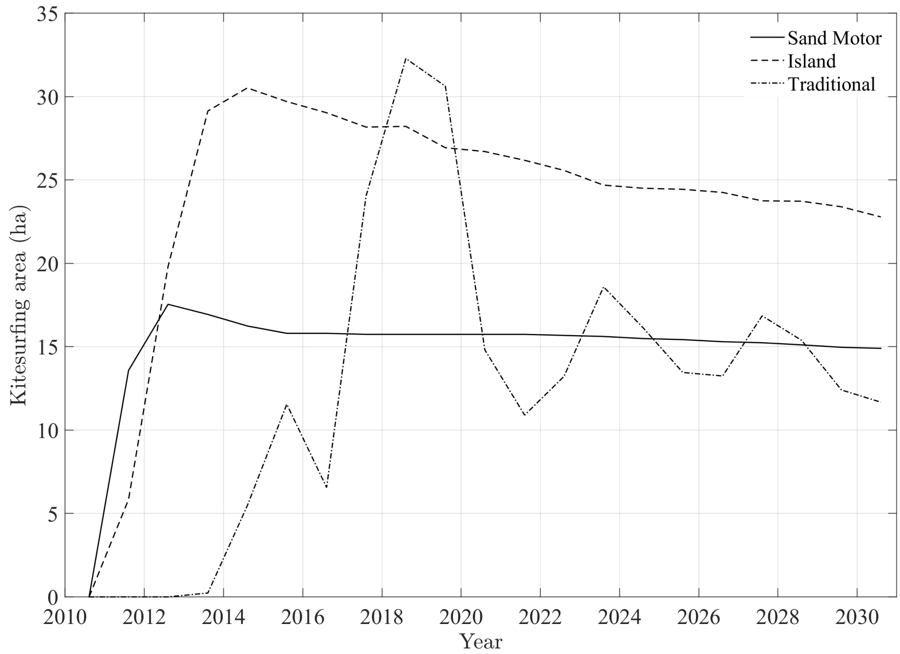


Figure 6.5: Predicted evolution of the kitesurfing area at the nourishment section, for the Sand Motor, the Island and the traditional nourishment. The kitesurfing area is calculated annually from 2010, prior to construction, to 2030.

6.2.2. STROLLING

NOURISHMENT SECTION

Initially, the Island is not attached to the shore and recreationists cannot reach the Island. After two years, the southern side of the Island becomes attached to the shore, due to onshore directed transport. This attachment results in a peninsula shaped nourishment, making the Island accessible and thereby increasing the potential for strolling as the length of the waterline becomes longer. Visualizations of the course of the waterline in the Island scenario can be found in Figure E.4 of Section E.2. As soon as the bed level of the tidal channel has elevated to 0 m NAP, the length of the waterline decreases. This happens in 2030 for the Island, decreasing the physical potential of this ecosystem service. Nonetheless, as long as there is a protrusion of the coastline at the nourishment, the beach length is larger than the base value of 2010.

Regarding the traditional nourishment, with every partial nourishment the protrusion into the sea increases. This leads to a stepwise increase of the beach length along the waterline. Visualizations of the course of the waterline for the traditional nourishment can be found in Figure E.5 of Section E.2.

6.2.3. SUNBATHING

NOURISHMENT SECTION

The evolution of the suitable dry beach area at the nourishment section is calculated from 2010 to 2030 for the Sand Motor, the Island and the traditional nourishment scenario and is presented in Figure 6.6. All nourishment scenarios show a decreasing trend of the suitable sunbathing area. In Chapter 5, it appeared that the beach became too wide at the accreting coastline and too small at the eroding head of the Sand Motor, resulting in a decrease of the suitable dry beach area at the Sand Motor. In the Island and traditional nourishment scenario, this decrease in suitable dry beach area at the nourishment section is even larger. For the alternative scenarios, a smaller beach area fulfills the requirements of the minimum and maximum width.

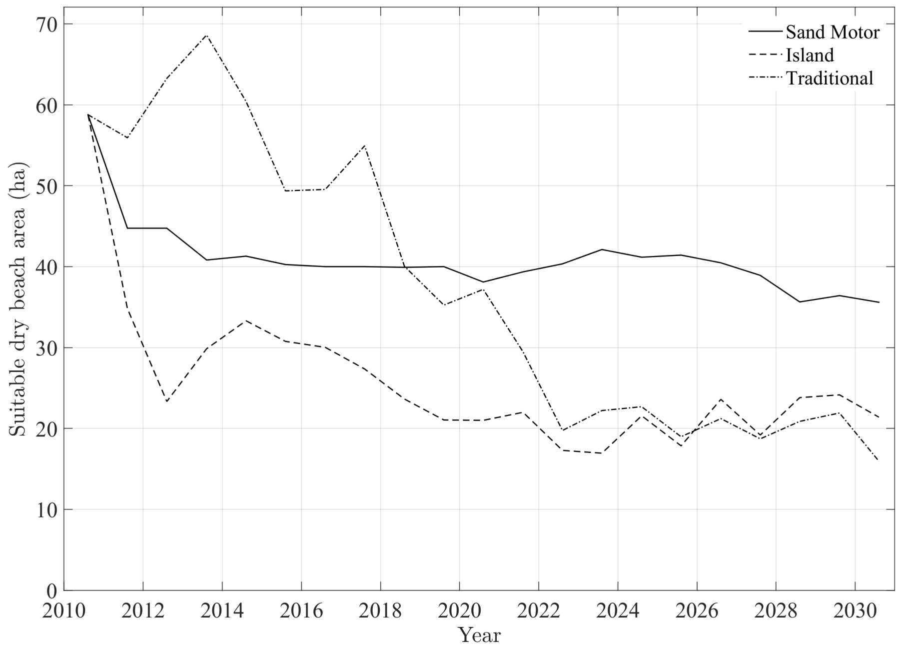


Figure 6.6: Predicted evolution of the suitable dry beach area at the nourishment section, for the Sand Motor, the Island and traditional nourishment scenario. The suitable dry beach area is calculated annually from 2010, prior to construction, to 2030.

Delfland coast

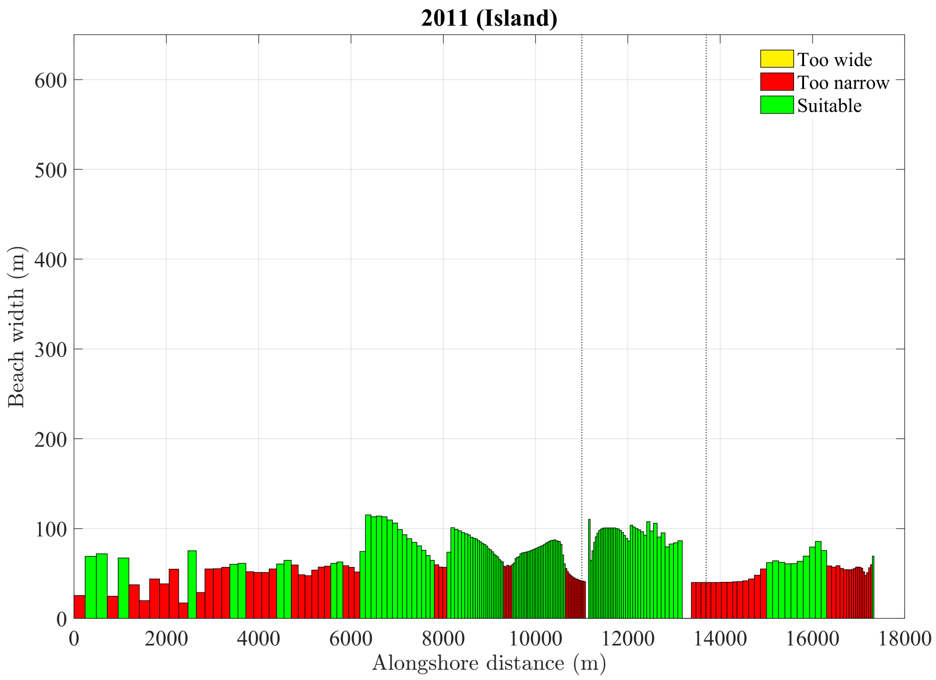
In Figure 6.7 the alongshore dry beach width of the Island scenario is displayed for 2011 and 2030. The initial location of the Island in 2011 is indicated in the figure as well. Sudden shifts in the beach width of Figure 6.7a are caused by the multiple upper and lower crossings of the +1 and +3 m NAP level. The most seaward crossings are taken to be the dry beach width used for recreation and at a lagoon this may lead to sudden shifts in the width due to a varying bed level. This phenomenon is also explained in Section 4.4. Figure 6.7b shows the situation of the Island scenario in 2030. The dry beach width has increased substantially along the entire Delfland coast. At many parts of the coast this has increased to beyond the maximum beach width. The decrease in suitable dry beach area at the nourishment section of the Island can mostly be explained by a beach width that is too large. A small area of the beach is too narrow.

The Island and the Sand Motor give comparable results regarding the beach width of the Defland coast after twenty years. The beach width increases substantially along the entire coastline. For many areas the beach width is beyond the maximum width of 200 m, making the suitability for sunbathing near the waterline questionable due to the long walking distance. Only locally at the eroding transects of the nourishment site, the beach width is too narrow.

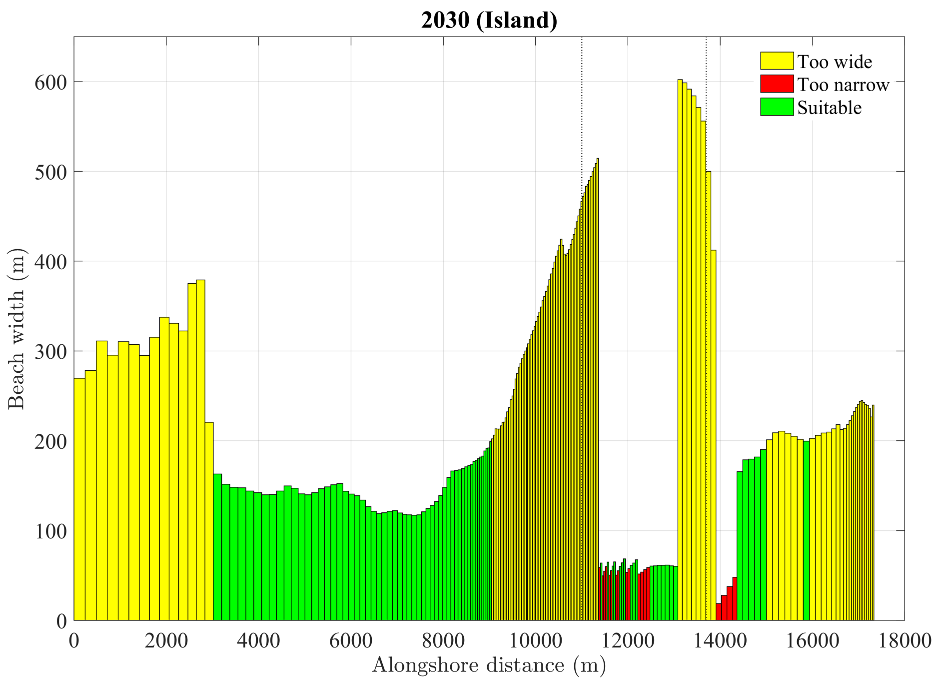
In Figure 6.8, the alongshore beach width of the traditional nourishment is displayed. The initial location of the first foreshore nourishments is indicated in the figure as well. Initially in 2011 almost the entire Delfland coast was suitable for sunbathing. The initial beach width at Hoek van Holland and 's-Gravenzande deviates from the Sand Motor and the Island. This is related to the reference bathymetry used in the traditional nourishment model, which was from a different period than the initial bathymetry of the Sand Motor and the Island. This gives a difference in initial results. Nonetheless, the trend of the beach width can be used to draw conclusions on the assessment of the ecosystem service. In 2030, just like for the Sand Motor and Island, the beach width has increased substantially for the entire Delfland coast. Especially locally at the nourished site, the beach width has increased tremendously to almost 900 m.

The traditional nourishment scenario results in a large area at Hoek van Holland and 's-Gravenzande that is suitable for sunbathing. This is probably caused by a delay in beach width growth, as it takes time before the nourished sand reaches Hoek van Holland and a large volume is nourished at a later time. Only locally at the nourishment site and Scheveningen, the suitability for sunbathing is questionable due to the large beach width.

The Delft3D models of the Island and the traditional nourishment predict substantial beach widths. The predictions of the beach width are influenced by the model settings of the cross-shore sediment transport. The model deposits sediment around the high water line, while in reality this could be lower in the cross-shore profile as well. This leads to an overestimation of the dry beach width.

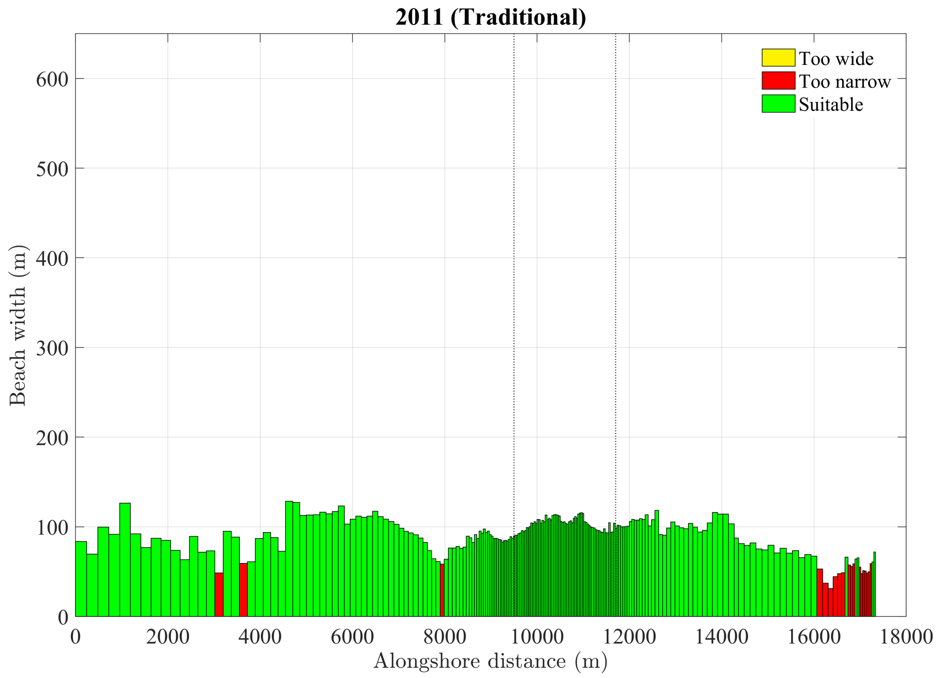


(a) Modeled alongshore development of the beach width at the Delfland coast for the Island scenario in 2011.

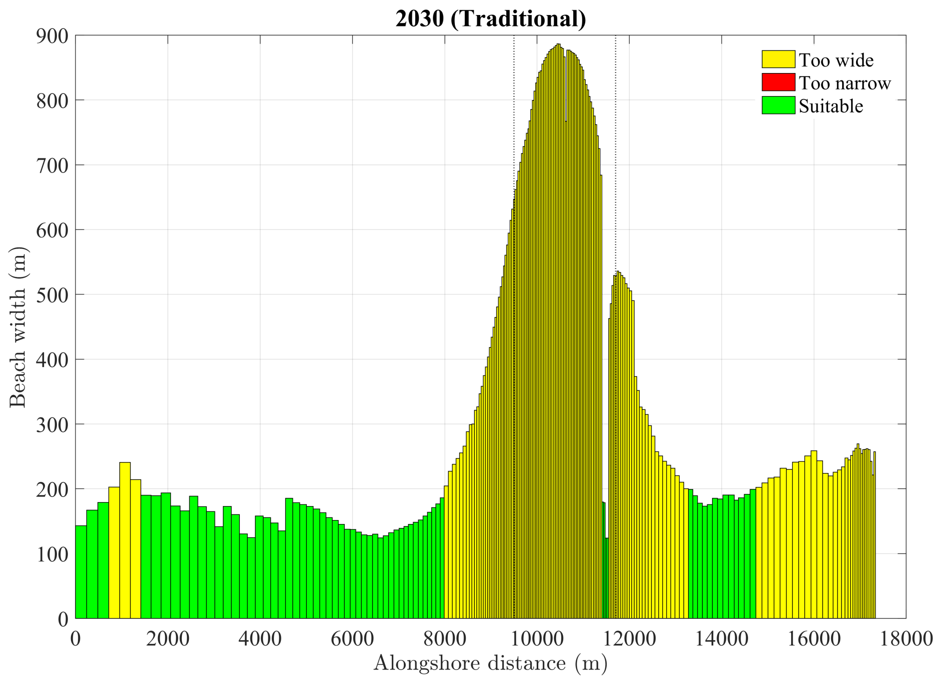


(b) Predicted alongshore development of the beach width at the Delfland coast for the Island scenario in 2030.

Figure 6.7: Predicted alongshore development of the beach width at the Delfland coast for the Island scenario. The green bars fulfill the requirements of a minimum (60 m) and maximum beach width (200 m), the yellow bars are wider than the maximum width and the red bars indicate the beach that is too narrow.



(a) Modeled alongshore development of the beach width at the Delfland coast for the traditional nourishment scenario in 2011.



(b) Predicted alongshore development of the beach width at the Delfland coast for the traditional nourishment scenario in 2030.

Figure 6.8: Predicted alongshore development of the beach width at the Delfland coast for the traditional nourishment scenario. The green bars fulfill the requirements of a minimum (60 m) and maximum beach width (200 m), the yellow bars are wider than the maximum width and the red bars indicate the beach that is too narrow.

6.3. ECOSYSTEM SERVICE 'HABITAT PROVISION'

The ecotope class limits of Table 3.5 are applied to the model output of the Island and traditional nourishment, resulting in the area per ecotope on the spatial scale of the nourishment section and the visualization of the ecotopes with maps. Once more, the model output of the dominant wave condition W01, with waves from the South West and a significant wave eight of 1.48 m, was used. This wave condition is the most representative of the wave climate. The Sand Motor and Island alternatives are scenarios where the total volume is implemented at once, giving the benthos communities time to recover and develop. The higher nourishment frequency of the traditional nourishment has consequences for the recovery of the biota. Because of the addition of a large sand volume every four years, the benthos communities need to recover five times, instead of only once after the nourishment of 2011.

6.3.1. ECOTOPE MAPPING

The ecotope maps of the Island and traditional nourishment are made on two spatial scales: one locally of the nourishment section and one on a larger Delfland scale. The contour lines of the 6, the 9 and the 12 m depth contour are depicted in the maps as well, to indicate the relation between depth, bed shear stress and species composition. The ecotope maps are made every 5 years, starting in 2016 (5 years after construction of the Island and more than a year after construction of the second partial foreshore nourishment). Ecotope maps of the situation right after construction of the Island and the first partial foreshore nourishment are not presented, because after the nourishment the ecosystem needs some years to recover. The ecotope map of the initial situation would definitely not correspond to the ecological composition described in Appendix A. The traditional nourishment is implemented every 4 years, resulting in a frequent disturbance. Because the nourishment volume is smaller, it is expected that the benthos community will recover relatively faster in this scenario. In this chapter, only the ecotope maps of 2016 and 2030 are displayed for the Island and traditional nourishment alternative. The ecotope maps of the nourishment section in 2021 and 2026 can be found in Section E.3.

NOURISHMENT SECTION

In Figure 6.9, the locations of the ecotopes of the Island are visualized for the years 2016 and 2030 on the scale of the nourishment section. These maps can be compared to the ecotope maps of the Sand Motor in Section 5.3. In 2016, the Island has become a peninsula that is more streamlined than the Sand Motor peninsula. This has resulted in a flatter bulge of the surf zone (1) and the seaward side of the surf zone (2) at the head of the Island compared to the the Sand Motor. Furthermore, the lagoon is significantly larger than the Sand Motor lagoon and thus the Island has a larger sheltered subtidal (5) ecotope. A larger lagoon surface area increases the tidal prism of the Island lagoon and may also increase the current velocity in the tidal channel. The tidal channel that develops over time on the north side of the Island gives room for a large intertidal zone with a large sheltered intertidal area. The supratidal zone (9) has increased significantly in the Island scenario compared to the reference situation of 2010.

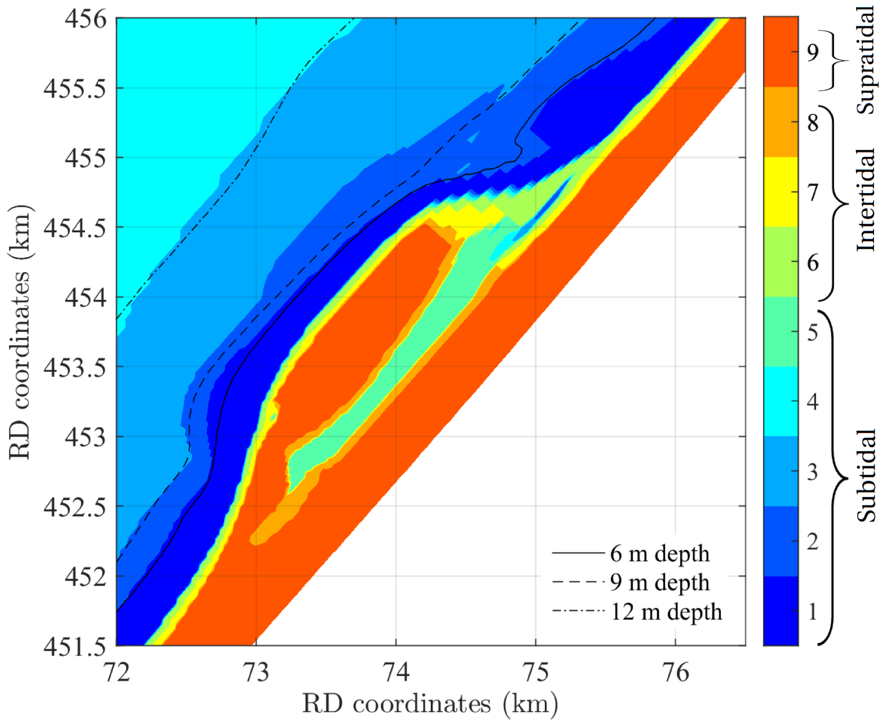
In Figure 6.10, the locations of the ecotopes of the traditional nourishment are visualized for the years 2016 and 2030. The map of 2016 is made more than a year after the second partial nourishment and the map of 2030 is made of a situation almost 4 years after the fifth partial nourishment. In the situation of 2016, the benthos community may not have fully recovered yet. The foreshore nourishment results in a sudden seaward extension of the nearshore (3) and the surf zone (1) ecotopes, especially in 2030 of Figure 6.10b. The sediment transport at the nourishment site leads to an interesting ecotope pattern. In Figure 6.10a, some sort of lagoon formation is already visible in 2016. Sediment transport processes have led to a varying bed level and a sheltered area. In Figure 6.10b, the ecotope map of 2030 shows a larger lagoon-like formation with a short tidal channel, a small sheltered subtidal area and a relatively large sheltered intertidal area. In 2030, the supratidal zone (9) has increased substantially compared to the reference situation of 2010.

All nourishment scenarios lead to an increased area of the supratidal zone. The Sand Motor and the Island lead to an immediate increase ecotope 9 and the traditional nourishment will eventually lead to a comparable area, after the same volume has been nourished. This enhances the potential of dune formation and a green beach. Furthermore. all alternatives are predicted to develop a lagoon-like shape with sheltered ecotopes.

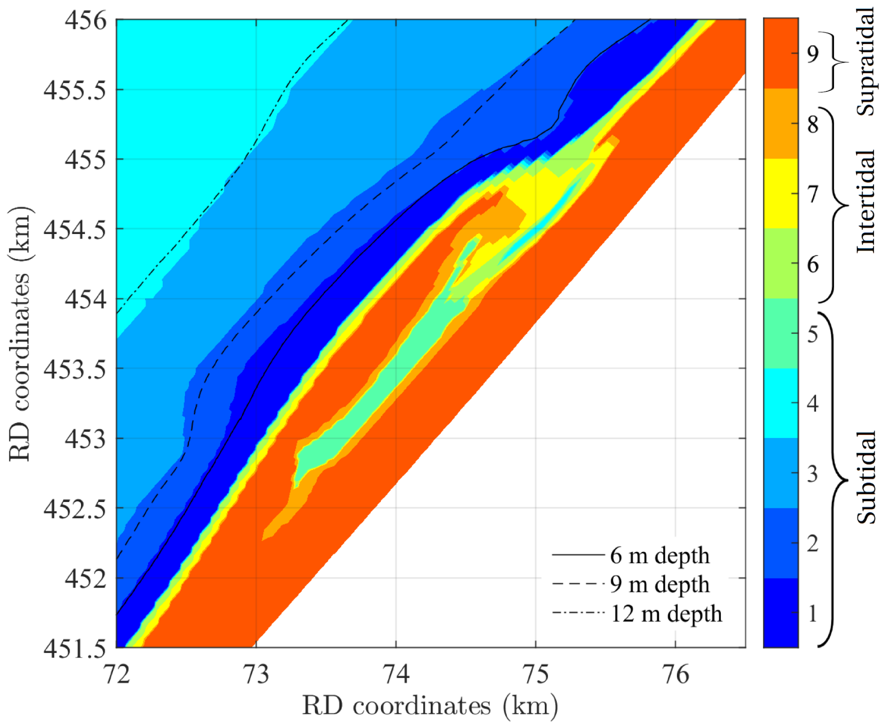
DELFLAND COAST

In Figure 6.11, the ecotope maps of the Island on the scale of the Delfland coast are shown. The streamlined shape of the Island results in a smaller bulge of the surf zone at the head of the nourishment and thus in a local situation that is less harsh, compared to the Sand Motor and the traditional nourishment. On the ecotope map of the Sand Motor in Figure 5.17 a bulge of the surf zone (1) is more distinct than on the map of Figure 6.11a. Even though the Sand Motor disperses, this bulge of the surf zone is still present after 40 years. The relatively small bulge of the island is also still present in 2030, as can be seen in Figure 6.11b. Sediment transport into the lagoon has decreased the sheltered subtidal area (5), but increased the area of the sheltered intertidal (8) and upper intertidal (7) ecotopes at the mouth of the lagoon in 2030.

In Figure 6.11, the ecotope maps of the traditional nourishment scenario are presented on the scale of the Delfland coast. There is a distinct increase of the surf zone (1) ecotope in 2030 (Figure 6.12a) compared to 2016 (Figure 6.12b), due to the added partial nourishments. The increase of the supratidal zone (9) area in twenty years is also clearly visible. This strong increase of the supratidal zone may be related to the defined height boundary in the ecotope classification between the intertidal and supratidal zone of 1.2 m NAP. This level is 20 cm below the modeled high water level and together with the storm surge of the wave conditions, the model was able to deposit the sediment near the high water line. In the area where the dredged sand of the Nieuwe Waterweg is dumped, a patch of ecotope 2 is visible. This may be related to the initial bathymetry of the traditional nourishment model that is not dated from the exact same period.

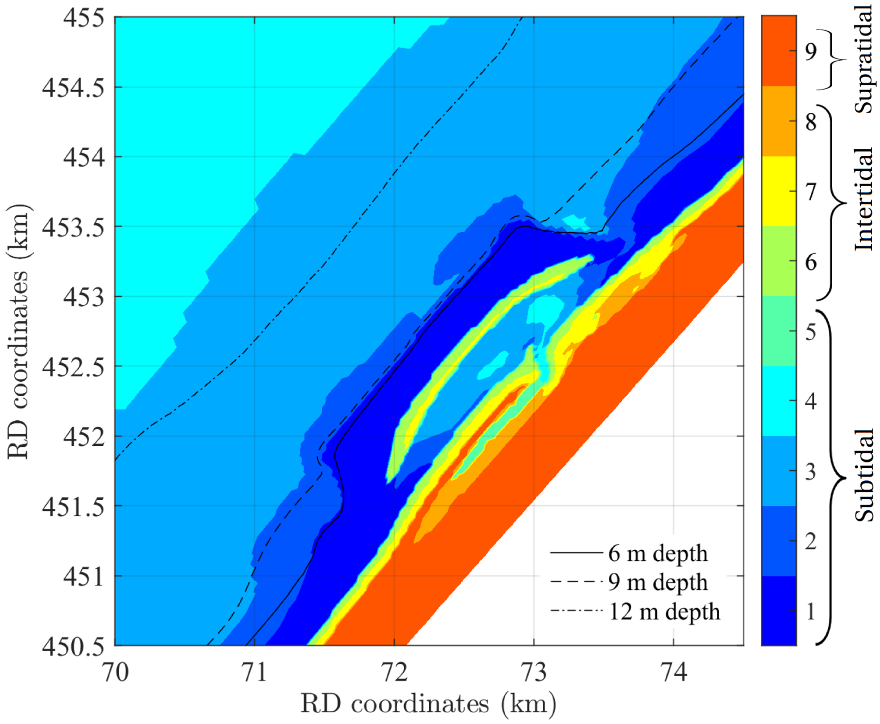


(a) Ecotope map of 2016.

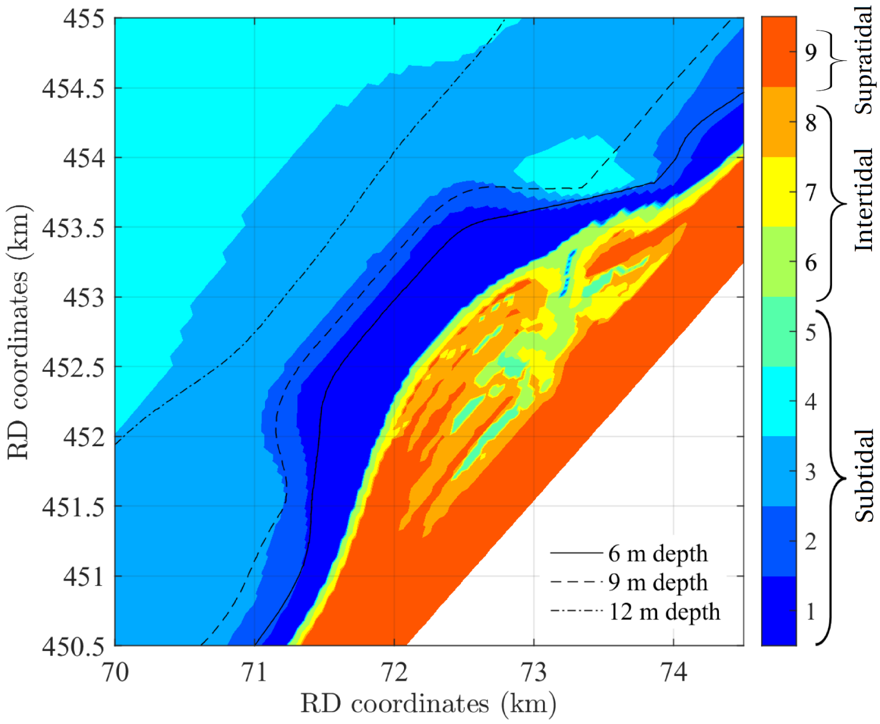


(b) Ecotope map of 2030.

Figure 6.9: Computed ecotope map of the Island on the spatial scale of the nourishment section. The contour lines of the 6, the 9 and the 12 m depth contour are depicted in the maps as well.

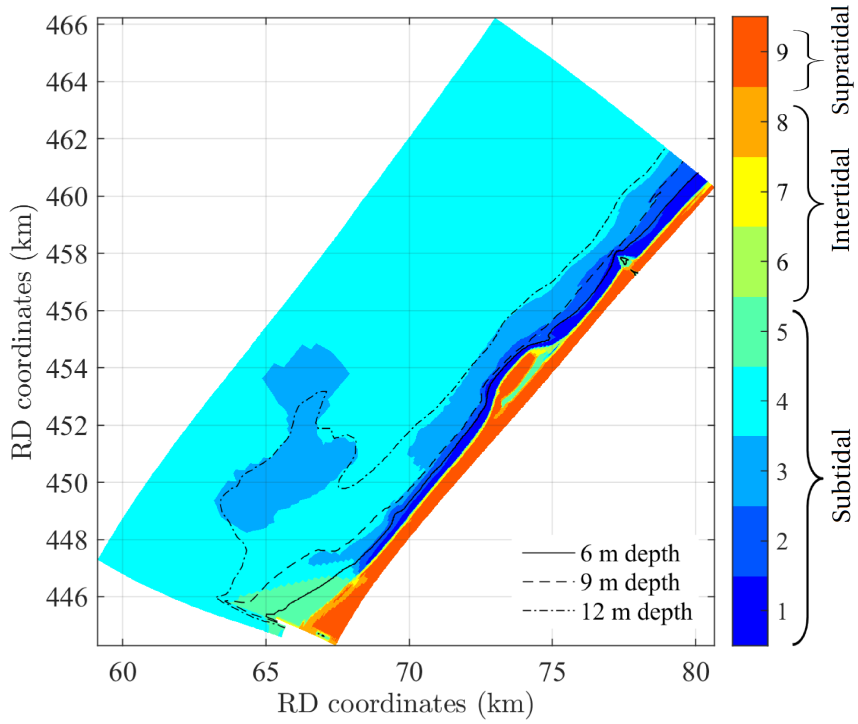


(a) Ecotope map of 2016.

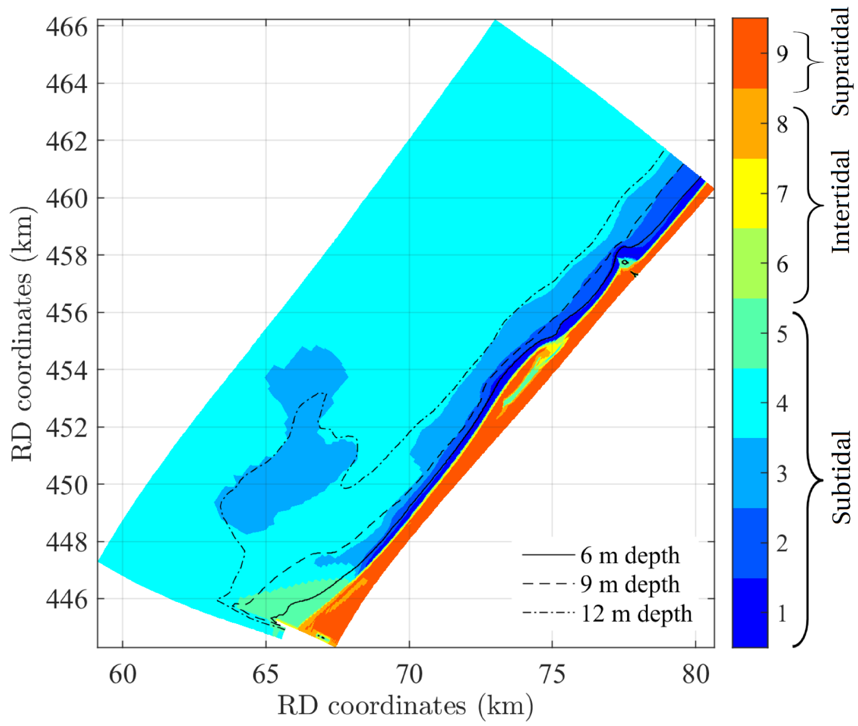


(b) Ecotope map of 2030.

Figure 6.10: Computed ecotope map of the Island on the spatial scale of the nourishment section. The contour lines of the 6, the 9 and the 12 m depth contour are depicted in the maps as well.

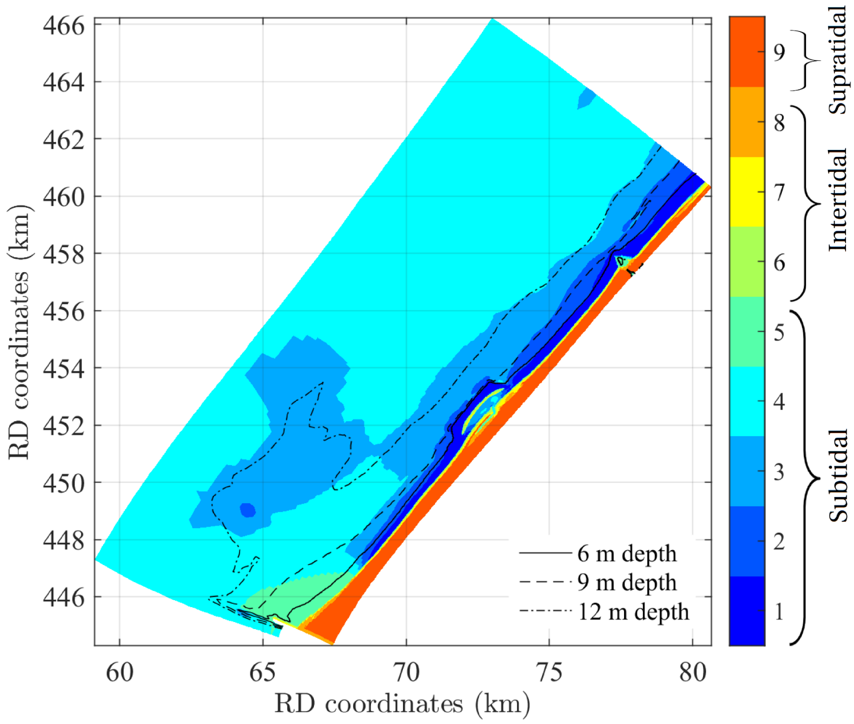


(a) Ecotope map of 2016.

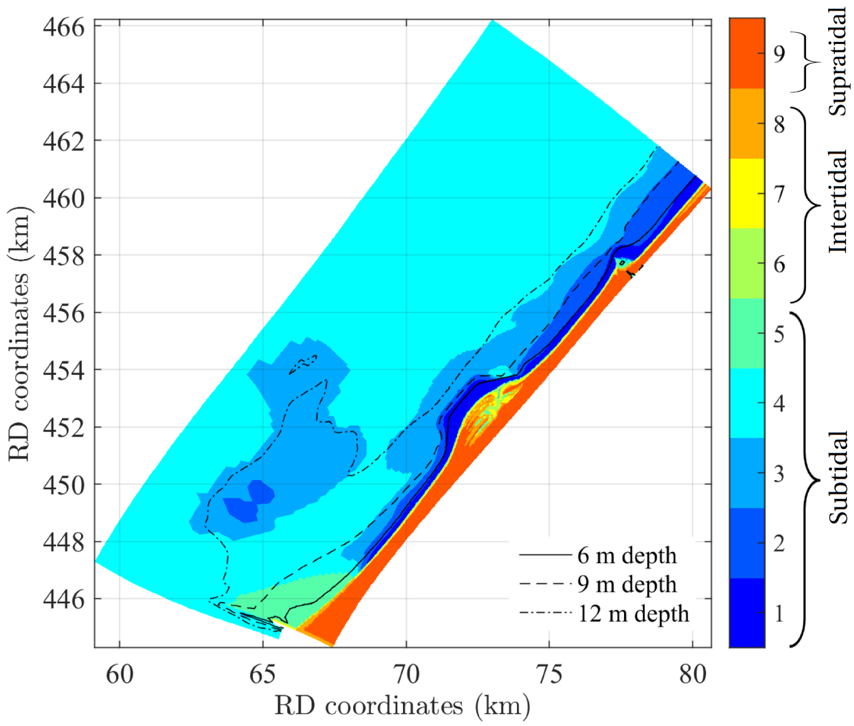


(b) Ecotope map of 2030.

Figure 6.11: Computed ecotope map of the Island on the spatial scale of the Delfland coast. The contour lines of the 6, the 9 and the 12 m depth contour are depicted in the maps as well.



(a) Ecotope map of 2016.



(b) Ecotope map of 2030.

Figure 6.12: Computed ecotope map of the traditional nourishment on the spatial scale of the nourishment section. The contour lines of the 6, the 9 and the 12 m depth contour are depicted in the maps as well.

6.3.2. AREA ANALYSIS

NOURISHMENT SECTION

Figure 6.13 displays the evolution of the nine ecotopes for the Sand Motor, the Island and the traditional nourishment on the spatial scale of the nourishment section.

The surf zone (1) is relatively large at the traditional nourishment scenario, as can be seen in Figure 6.13a. After construction of each partial foreshore nourishment, the area of the surf zone peaks. After a foreshore nourishment the slope is relatively mild, resulting in a more dissipative beach and an increase of the highly turbulent surf zone area. The area of the surf zone of the Sand Motor and the Island instantly decrease after construction. This may be related to the steepness of the cross-shore profile at the nourishment section. The steepening of the cross-shore slope after construction of the Sand Motor is also visualized in Figure B.4. The initial cross-shore slopes of the Island and the Sand Motor are steeper than the slope in the reference situation of 2010, resulting in a more reflective beach and a relatively narrow surf zone. In comparison to the Sand Motor, the area of the surf zone is 30% larger at the traditional nourishment and 17% smaller at the Island in 2030.

The area of the seaward side of the surf zone (2) is shown in Figure 6.13b. The area peaks after the first two partial nourishments in the traditional nourishment scenario and decreases as the years progress. The area of ecotope 2 in the Island and Sand Motor scenario is somewhat smaller than the area in 2030, which also may be related to the steepening of the cross-shore slope.

Figure 6.13c displays the evolution of the area of the nearshore (3) ecotope and Figure 6.13d the area of the offshore (4) ecotope. The area at the Sand Motor and the Island nourishment remain at approximately the same level after construction in 2010 and remain rather constant throughout the years for both ecotopes. The areas of the nearshore and offshore ecotopes at the traditional nourishment are highly variable as a results of the partial extension of the foreshore nourishment every four years.

In Figure 6.13e the evolution of the sheltered subtidal ecotope area is presented. Initially in 2010, the area of this ecotope was zero. After construction of the Island, there is an immediate increase of the area, however it also decreases rather quickly due to filling up of the lagoon. The area and of the Island lagoon is initially substantially larger than that of the Sand Motor and the tidal range inside the Island lagoon remains larger over time resulting in a larger tidal prism at the Island[1]. The water level variation and the morphological development of a specific location inside the lagoon is presented in Figure E.8 for both the Sand Motor and the Island. The surface area of the Island lagoon is larger, increasing the time until the lagoon fills up with sediment and silt (leading to the possibility of anoxic soil in the lagoon). A larger tidal prism may also result in a larger current velocity in the tidal channel at the mouth of the lagoon. After construction of the Sand Motor the area also displays an immediate increase and remains constantly at this level throughout the years. During the first years after the first partial foreshore nourishment of the traditional scenario, there is no sheltered area and the area of this ecotope remains zero. Only after the second partial nourishment, the protrusion of the shallow foreshore results in a sheltered area that increases over the years after more partial nourishments are implemented. Once more, it must be noted that there is no aeolian transport incorporated in the Delft3D model. Over time, it is likely that the sheltered subtidal area will decrease further due to sand deposition by wind.

Figure 6.13f and Figure 6.13g display the exposed lower (6) and upper intertidal (7) ecotopes. In the traditional nourishment scenario the areas of these ecotopes are highly variable throughout the years. The peaks in the ecotope areas over time at the upscaled traditional nourishment scenario are characteristic for the highly frequent traditional way of implementing nourishment at the Dutch coast. Benthos communities are disturbed frequently then.

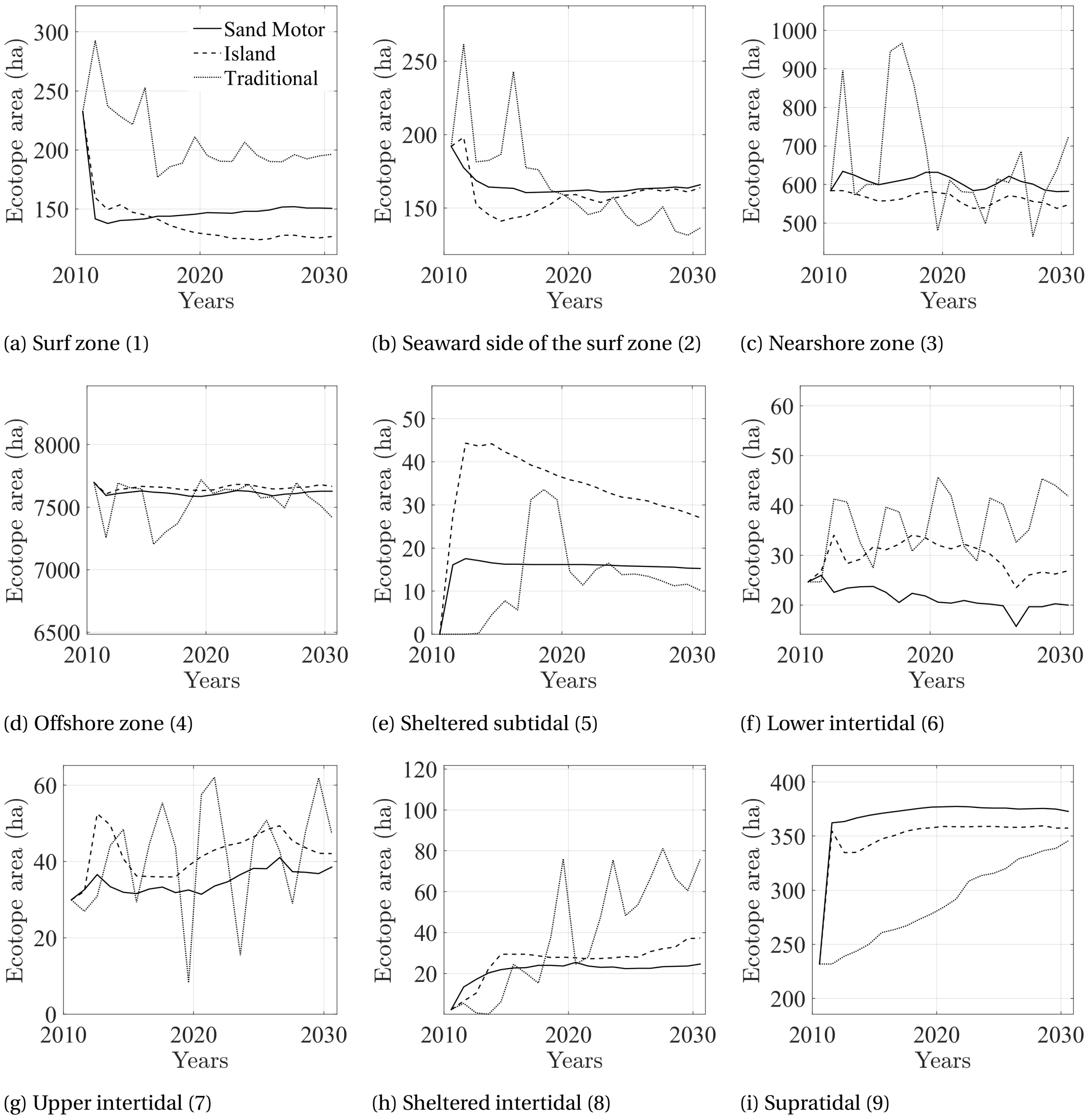
In Figure 6.13h the evolution of the sheltered intertidal ecotope is shown. In the reference situation of 2010 this ecotope is not present. After construction of the Island and the Sand Motor, the area of the sheltered intertidal immediatly increases due to the lagoon. The area of this ecotope at the traditional nourishment increases over time, as added partial nourishments create the bed level pattern shown in Figure 6.10. This eventually leads to a relatively high sheltered intertidal ecotope area that is predicted to be three times larger than it will be at Sand Motor in 2030.

Figure 6.13i shows the evolution of the supratidal ecotope (9) area. The Sand Motor and the Island both show an immediate increase in this area after construction in 2011 and stay constantly at this level for the next 20 years. The traditional nourishment reaches this level after 20 years, due to onshore directed sediment transport that brings the nourished sediment from the foreshore to the supratidal zone. A traditional scenario

[1] the volume of water that has to flow in and out of the lagoon through the tidal channel.

will have a delayed effect on the potential for dune formation. Also for this ecotope, aeolian transport will influence the evolution of the the supratidal area in reality, which is not taken into account in the model.

To summarize the most important developments, the area of the surf zone (1) decreases after construction of the Island and the Sand Motor. This is most likely due to the steeper shoreface profile after construction. The surf zone area is significantly increased by the foreshore nourishments of the traditional nourishment scenario. In all nourishment scenarios, a sheltered subtidal (5) ecotope will develop. The area of the sheltered subtidal (5) will become the largest at the Island scenario, due to the relatively large lagoon formation. In the traditional nourishment scenario, a sheltered subtidal ecotope develops only after the second partial foreshore nourishment, when the protrusion into the sea becomes large enough. The partial foreshore nourishments develop an interesting bed level pattern in the traditional nourishment scenario. The very mild slope in this scenario leads to a relatively large sheltered intertidal (8) ecotope. Furthermore, the traditional foreshore nourishment is implemented frequently, disturbing the benthos communities more often, which is also visible in the peaks of the ecotope area evolution of the alternative. To finalize, the Sand Motor and the Island both show a significant sudden increase of the supratidal ecotope (9) immediatly after construction. This area stays constant throughout the forecasted period and provides space for dune formation. In the traditional nourishment scenario, this area gradually increases over time, as sediment transport processes bring the sediment towards the high water line.



(a) Surf zone (1)

(b) Seaward side of the surf zone (2)

(c) Nearshore zone (3)

(d) Offshore zone (4)

(e) Sheltered subtidal (5)

(f) Lower intertidal (6)

(g) Upper intertidal (7)

(h) Sheltered intertidal (8)

(i) Supratidal (9)

Figure 6.13: Predicted evolution of the ecotope areas in the nourishment section from 2010 to 2030, for the Sand Motor, Island and traditional nourishment.

7

DISCUSSION

During the formulation of the research objective, the conceptualization of the approach and the specification of the ecosystem service assessment, several choices and assumptions were made. In this chapter, these choices and assumptions will be discussed. The discussion will be structured on three levels. Firstly, on a more aggregated level, the choices regarding the research objective and how this research adds to the aim of engineering the ecosystem services will be discussed. After this, the conceptualization of the ecosystem service approach will be reviewed. To finalize, the specification of the assessment method and the effect of the model uncertainty on the results will be discussed.

FORMULATION OF THE RESEARCH OBJECTIVE

The research objective contains several components: to perform a *dynamic* assessment of the *ecosystem services* of the Sand Motor and to make a *comparison* between nourishment designs. This will take a step towards *engineering* the ecosystem services of a mega-nourishment.

Firstly, the decision was made to analyze the Sand Motor's effectiveness using an ecosystem services approach. The concept of ecosystem services is increasingly used as a framework for analyzing and comprehending the nature-society relationship (Schröter et al., 2014). It considers human activities, habitats, species and physical processes and integrates them, allowing the wide impact of decisions to be assessed. This research focuses on some of the ecosystem services of the Sand Motor, namely coastal protection, recreation and habitat provision. These services contribute to human well-being, by maintaining quality of life and contributing to health, safety, etc. Habitat services create added value both directly and indirectly. Providing a habitat for (embryonic) dunes enhances flood protection and habitats with a diversity and abundance are likely to attract birds, enhancing recreation. The habitat service is able to assess contributions to policy objectives related to protected species and nature conservation areas. Habitats also add direct societal value by providing nursery areas that maintain (commercial) fish species.

Secondly, the dynamics are evaluated in this research. The sandy shore is a dynamic environment, especially at the Sand Motor. It was expected this would affect the long-term response of the ecosystem services. To assess this, the ecosystem services of the Sand Motor are analyzed on a large spatial scale and on a yearly basis, predicted forty years ahead. According to literature, a Delft3D model has not been used previously in dynamic ecosystem service assessments. A dynamic assessment using a model forecast has proven to be valuable to Building with Nature solutions. For example, the coastline advance at Scheveningen South and the change in coastline orientation would not have been found in a short-term, static analysis of the 2012 situation. The dynamic assessment provided insight into the ecosystem services response and trends and the effects further away from the Sand Motor.

This research aims to take a step towards 'engineering' the ecosystem services of a mega-nourishment. It is assumed that by developing a set of abiotic indicators that create potential for a specific ecosystem service, a design approach can be determined that optimizes the desired ecosystem services of a mega-nourishment. The possibilities of engineering the ecosystem service potential are explored by comparing the potential between different nourishment designs. Analyzing the Delft3D predictions of the nourishment alternatives suggests that varying design parameters affects the physical potential of the ecosystem services. For example, the Delft3D models predict a robust enhancement of the coastline position if the total volume is implemented at once. Furthermore, the alternative nourishment designs lead to different effects on the ecosystem service of habitat provision. First of all, the traditional nourishment disturbs the ecosystem frequently by adding a large volume of sand every four years, which was clearly visible in the evolution of the ecotope areas. A smooth coastal outline leads to a smaller surf zone 'bulge' and a less harsh, dynamic situation for benthos locally. The area of the highly dynamic surf zone is relatively large at the traditional foreshore nourishment, due to the mild cross-shore slope as a result of the foreshore nourishments. These findings suggest that the combination of the protrusion of the nourishment into the sea, the water depth and the coastline curvature play a role in the level of hydrodynamics that is created after construction.

The practical application of ecosystem service optimization would also require knowledge on trade-offs and synergies between ecosystem services. This study analyzes the dynamics of coastal protection, recreation and habitat provision at the Sand Motor, capturing some of the ecosystem services of the Sand Motor. The occurrence of trade-offs and synergies between ecosystems services should be studied with more detail for a wide range of services, before the ecosystem services of a mega-nourishment can be engineered.

CONCEPTUALIZATION OF THE ECOSYSTEM SERVICE APPROACH

In conceptualizing the ecosystem service approach, a distinction was made between the potential of the ecosystem to provide a service and the actual use of the ecosystem service. The results of this study are a forecast of the physical capacity of the ecosystem to provide a service, incorporating the abiotic factors that influence the physical potential. There are many factors that play a role in the actual use of an ecosystem service, such as accessibility to the site, safety of the surroundings, the weather and the infrastructure at the beach. The factors necessary for the actual use of ecosystem services differ per ecosystem service and it is a complicated system to capture into a prediction. For an accurate forecast of the actual use of ecosystem services, these factors should be evaluated and the relationship to the service should be validated.

A component of the ecosystem service approach used in this study, was the comparison of the post Sand Motor situation to the situation prior to construction of the Sand Motor (in 2010). After construction, many observations on the number of visitors at the Sand motor, morphology surveys and benthos samples are made, which can be used to validate the model prediction. Unfortunately, there are only few observations made of the situation prior to construction. This makes it difficult to draw conclusions on the exact effects of the Sand Motor on the ecosystem services.

In conceptualizing the ecosystem, the prediction of nature was based on the development of abiotic factors. It is hypothesized by several studies, mentioned in Section 2.2, that the zonation of benthic communities at sandy beaches is primarily controlled by abiotic factors and by physical processes. Another school of thought suggests that the zonation of biota results from the interaction between biotic (e.g. food availability) and abiotic factors. By studying the abiotic factors that define the preconditions of the biotic system, an important contribution to the potential occurrence of nature can be made. It is however recommended to incorporate biotic interaction if possible, as the actual ecological composition of the ecotope is determined by abiotic and biotic conditions on site.

SPECIFICATION OF THE ASSESSMENT METHOD

For the prediction of the ecosystem service potential, one of the most advanced, state-of-the-art tools available in forecasting long-term morphology was used. The long-term intention of the model is emphasized: the hydrodynamic forcing in the model is based on averaged climate conditions and is therefore suitable for predictions on a decadal scale. It should make an accurate forecast of the morphology after a decade, when relatively stormy or calm years are averaged out. These constant averaged conditions are useful for a long-term assessment of the ecosystem service potential of the Sand Motor, but not necessarily for a short-term prediction.

In specifying the assessment method of the potential of the studied ecosystem services, the most important abiotic factors were used as indicators. The findings of the dynamic ecosystem assessment and how these relate to the model limitations will be discussed per ecosystem service.

ASSESSING COASTAL PROTECTION

Coastal protection can be divided into two sub services: maintenance of the coastline position and flood protection during storms. This study focused on the assessment of coastline maintenance. The coastline position was based on the volume of the active beach profile.

The construction of the Sand Motor led to an immediate, substantial, local, seaward shift of the coastline. The lifetime of the Sand Motor was expected to be approximately twenty years. According to the best estimated coastline position, the Sand Motor exceeds this lifetime substantially. The dispersal rate of the Sand

Motor decreases over the years as the outline of the Sand Motor becomes smoother with respect to the adjacent coastline. According to the best estimate of this service, the seaward shift of the coastline is robust and remains far beyond the initial position of 2010 for over 40 years. Over the years the sand of the Sand Motor disperses, leading to accretion of the adjacent coastline. The adjacent coastline on the northern side of the Sand Motor, towards Scheveningen, experiences the largest advancement. The breakwater of the Scheveningen harbor blocks the alongshore transport, leading to accumulation of sand and a change of the coastline orientation. Between Kijkduin and Scheveningen South the large nourished volume develops a coastline orientated towards the dominant South West wave direction.

The used Delft3D model is a depth-averaged model. The model settings of the cross-shore sediment transport need to be specified to balance the onshore directed transport of wave skewness with the compensating offshore directed undertow current. The model settings of the cross-shore sediment transport cause an uncertainty with respect to the location where the sediment is deposited in the cross-shore profile. Different settings may affect the MKL volumes. A calculation where the cross-shore transport was diminished to a minimum, led to a retreat of the MKL distance that was in the order of 50 m in twenty years. The loss of MKL volume over the years due to aeolian transport towards the dunes also brings an uncertainty into the MKL calculation. The model forecast does not include aeolian transport, therefore during the post-processing of the results this component was incorporated by a constant and uniform yearly aeolian transport volume loss from the MKL zone. This volume loss was based on calculations of the dune volume change in De Vries et al. (2012). The mean of the annual dune volume change calculated at transects along the entire Holland coast was used for the aeolian transport loss correction. In the best estimate of the MKL position, this value amounted to 8.7 $m^3/m/y$ and was applied annually to all analyzed transects. There is an uncertainty to this parameter and the aeolian transport volume may vary alongshore and over time. To check what the impact of aeolian transport on the coastline position is, a calculation was made that ranged from no aeolian transport loss to a maximum aeolian transport loss of 30 $m^3/m/y$ in Chapter 5. The difference between the averaged coastline position of this calculation amounted to approximately 70 m after twenty years. The uncertainty associated with the aeolian transport loss is of the same order as the modeled cross-shore transport. The best estimated coastline position (with a uniform and constant aeolian transport volume) is predicted to remain beyond the initial position of 2010 for forty years, including the uncertainty associated with the cross-shore distribution of sand.

The validation of the MKL forecast with the JARKUS and Shore surveys showed that the model prediction corresponds to the first years of observations, especially when some transects are averaged to calculate the shoreline position of a smaller coastline section. The model forecast is able to predict the coastline position reasonably well in the first years after construction, giving confidence in the long-term model forecast.

ASSESSING RECREATION

Regarding recreation, the model forecast was used to calculate the evolution of the potential of the kitesurfing, the strolling and the sunbathing ecosystem service.

For the assessment of the sunbathing potential, the dry beach area was the indicator of the ecosystem service capacity. A minimum beach width was defined that incorporates enough space for crowds and beach facilities. A maximum beach width was defined to take into account the effects of a walking distance to the waterline that is too large, increasing the possibility that visitors will not take the effort to walk to the water. The results of the ecosystem service assessment show a widening trend of the dry beach width due to dispersal of the Sand Motor, threatening the recreational potential at the adjacent beaches. While interpreting the beach width calculated by the model forecast, it is important to realize that the model settings of the cross-shore directed transport have a large influence on the predicted beach width. Currently, the model deposits sediment up to the high water line. In reality, the sand may be deposited lower in the cross-shore profile, resulting in a dry beach width that is less wide than predicted. The model cross-shore transport settings affect magnitude of the dry beach width and therefore the substantially large beach width predicted by the model should be interpreted with caution. Nonetheless, observations of the past years do show a substantial increase of the beach width adjacent to the Sand Motor. These findings suggest that there is a potential threat of too wide beaches in the future. The long-term model results of the widening beaches adjacent to the Sand Motor are therefore a possible scenario.

In assessing the kitesurfing potential, absence of waves was preconditional to the potential, because it distinguishes the Sand Motor of alternative kitesurfing spots at the Holland coast. The construction of the Sand Motor provided an attractive kitesurfing area. The kitesurfing area decreases over time due to filling up of the lagoon. According to the model forecast, in forty years time the physical capacity has decreased to almost half of the initial kitesurfing area. It is important to note that this finding is based on morphology as a result of marine transport. In reality, aeolian transport is expected to partially fill up the dune lake and the lagoon. This will affect the area of the lagoon and dune lake over time, resulting in a smaller available area and possibly the disappearance of the kitesurfing area in a few decades.

The abiotic factor that determines the physical potential for strolling at the beach is length of the strolling route along the waterline. The protrusion of the Sand Motor into the sea has led to a significant, initial increase of the beach length. After a few years the bed level of the tidal channel has elevated, leading to a decrease of the beach length along the water line. Due to the protrusion of the Sand Motor into the sea that is preserved according to the morphological model, the length of the strolling route will remain larger than prior to the Sand Motor.

ASSESSING HABITAT PROVISION

Translating abiotic parameters to ecotopes and finally to ecological composition is a difficult task, due to the varying characteristics among species and the complexity of the relationships between abiotic parameters and species. On a large spatial scale, the zonation of species in the marine zone is predominantly related to height and the level of hydrodynamic forcing that affects the reworking of the bed. In specifying the classification of ecotopes with the model output, height and bed shear stresses (due to waves and currents) were used.

The ecotope maps show that the Sand Motor has led to a local increase of the relatively harsher ecotopes at the head of the Sand Motor (the local bulge of the surf zone). At the head of the Sand Motor, the width of the surf zone is wider than at the adjacent coastline and this roughening of the conditions at the head of the Sand Motor is still noticeable after forty years. These highly dynamic ecotopes are associated with a lower species diversity and biomass. Implementation of the Sand Motor has added new ecotopes: the sheltered subtidal and intertidal ecotopes. These low dynamic ecotopes are associated with a high biodiversity, a high biomass and could potentially function as a nursery. The Delft3D model predicts a decreasing sheltered subtidal area as the years progress due to the filling up of the lagoon. In reality, aeolian transport is expected to partially fill up the dune lake and the lagoon, leading to a smaller sheltered subtidal area than was predicted. Immediately after construction, the supratidal ecotope has increased substantially at the Sand Motor. Dispersal of the Sand Motor leads to a widening of the adjacent beaches. This provides space for dune formation and the increased, sheltered beach width at the Sand Motor may potentially lead to the formation of a green beach.

On a small spatial scale, there are additional factors important to the zonation of benthic communities and nurseries, for example sediment size. The information regarding sediment size and sorting is not produced by the model and therefore this specification within the ecotopes cannot be made. The ecotope on the seaward side of the surf zone and the sheltered subtidal ecotope are valued as an important nursery area. There are substrate samples taken at the Sand Motor that show a coarsening of the sediment size at the head of the Sand Motor, which affects the local potential to function as a nursery. Sampling has also found a high silt contents in the lagoon and a decrease of the benthos abundance, most likely due to the anoxic conditions in the substrate that arise from the high silt content. This illustrates the complexity of the ecosystem: there are many factors and processes important to the occurrence and abundance of specific species. The ecotope maps computed in this thesis focus on a large spatial scale, where the ecotopes predict a potential niche. In the case the occurrence and abundance of specific species need to be predicted, other factors relevant to those species need to be incorporated as well.

Another example of a model limitation that influences the ecotope mapping is salinity. At a standard sandy shore, the water is saline. However, the Sand Motor has distinct features. The closed-off dune lake is in reality a brackish lake, that has different ecological characteristics compared to a saline environment. In this study with the current ecotope classification, this ecosystem is viewed as a sheltered ecotope. At some point, the lagoon may also be closed off for some time, possibly resulting in a large brackish lake. This would instantly affect the benthic community in the lagoon, because there are no species present that can both live in a saline and brackish environment. Furthermore, the depth-averaged model is not able to create breaker bars, which are a characteristic feature in the surf zone and of which the trough has distinct ecological value.

Usually, ecotope maps are validated using benthos samples. As a part of the Monitoring and Evaluation Program (MEP), benthos sampling is done on a yearly basis at the Sand Motor. The ecotope maps produced with the model output are not yet validated with these samples. This is related to the fact that it is still too early to draw conclusions from the benthos sampling, because the community characteristics appear to be highly variable. The dynamic state of the marine zone leads to spatial variability and natural year-to-year changes in species composition, making it difficult to assess the impact of the nourishment on the marine ecosystem. Four years of benthos samples are not enough to exclude the natural variability of biota in the coastal zone and to draw conclusions on the change in benthic communities purely as a result of the Sand Motor.

8

CONCLUSIONS AND RECOMMENDATIONS

8.1. CONCLUSIONS

To assess the impact of a nourishment on the coastline, an ecosystem service approach was followed. Ecosystem services are increasingly used to analyze the relation between humans and nature and to support utilization of ecosystems in a sustainable way. It considers human activities, habitats, species and physical processes and integrates them, allowing the wide impact of decisions to be assessed. Ecosystems services are often mentioned in Building with Nature projects, where natural processes are used to develop hydraulic infrastructure. However, in those projects ecosystem services are not yet explicitly incorporated into the designs.

The aim of this research is to take a step towards engineering the ecosystem services of a mega-nourishment. This is achieved by assessing and predicting the evolution of the ecosystem service potential of a mega-nourishment, using state-of-the-art morphological modeling. According to literature, the Delft3D model has not been used previously in (dynamic) ecosystem service assessments. This study was a useful exploration of the opportunities of using a Delft3D model for ecosystem service prediction. The findings contribute to knowledge on the effects of varying nourishment design parameters on the evolution of the ecosystem service potential.

Sandy shores are complex systems that show a high variability with respect to morphology and nature. Therefore a dynamic assessment was performed, evaluating the ecosystem services potential over time and space, using critical abiotic factors. The long-term response of the mega-nourishment on the ecosystem services was studied using morphological Delft3D models. A dynamic assessment in which the long-term response is evaluated annually, on a large spatial scale, has proven to be valuable to Building with Nature solutions.

From the literature study of the sandy shore ecosystem and the analysis of the model forecasts, several conclusions can be drawn. In this chapter the objectives of the research are recalled and answered and recommendations are given.

1. WHAT ARE THE ECOSYSTEM SERVICES OF THE SAND MOTOR?

The ecosystem services of the Sand Motor can be subdivided into sub services. The services that contribute to human well-being are:

1. Coastal protection with sub services 'flood protection' and 'maintenance of the coastline position'.
2. Recreation with sub services 'kitesurfing', 'strolling' and 'sunbathing'.
3. Habitat provision with sub services 'refuge and forage' and 'nursery'.
4. Fresh water provision

2. WHICH ABIOTIC FACTORS DESCRIBE THE PRECONDITIONS OF THE BIOTIC SYSTEM AND THE POTENTIAL OF THE STUDIED ECOSYSTEM SERVICES AT THE SAND MOTOR?

This research focuses on the ecosystem service potential of coastal protection, recreation and habitat provision.

- The potential for coastal protection is determined by the coastline position.
- The potential for kitesurfing is determined by the size of the area that is sheltered from waves.
- The potential for sunbathing is determined by the dry beach area available for this activity.
- The strolling potential is based on the length of the strolling route along the waterline.
- The abiotic factors that describe the preconditions of the marine biotic system on a large spatial scale are water depth and bed shear stresses (due to waves and currents).

3. ACCORDING TO THE MORPHOLOGICAL MODEL FORECAST, HOW DOES THE ECOSYSTEM SERVICES POTENTIAL EVOLVE AT THE SAND MOTOR?

The evolution of the ecosystem services potential of the Sand Motor, predicted by the Delft3D model, is analyzed for the coastal protection, recreation and habitat provision ecosystem service, forty years ahead. The conclusions of the assessment are summarized per ecosystem service.

- The construction of the Sand Motor led to an immediate, substantial, local, seaward shift of the coastline. For at least forty years, the Sand Motor has a significant positive effect on the maintenance of the coastline position that is substantial and robust locally at the Sand Motor and also affects the coastline position positively towards Scheveningen and Hoek van Holland. Towards the north, at Scheveningen South, the coastline advances more than at Hoek van Holland.
- The sunbathing potential at Scheveningen South, Kijkduin and Hoek van Holland may be threatened in the future by too wide beaches, increasing the risk that the walking distance to the waterline becomes too large.
- The Sand Motor provides potential for kitesurfing. In a few decades the kitesurfing area will have decreased substantially.
- Initially, the Sand Motor enhanced the strolling potential with a lengthy strolling route. This is expected to decrease after a few years, however it remains enhanced in comparison to the situation prior to construction.
- Distinctive ecotopes are added, increasing the diversity of habitats on a spatial scale, and are preserved over time. Gradients in the physical conditions are changed locally at the Sand Motor and an extensive supratidal area develops increasing the potential for dune formation.

4. IS A MORPHOLOGICAL MODEL FORECAST QUALIFIED TO MAKE A PREDICTION OF THE ECOSYSTEM SERVICES POTENTIAL AND WHAT ARE ITS LIMITATIONS?

Validation of the model performance with observations show that the model prediction is qualified to predict the ecosystem service potential based on morphology and hydrodynamic forcing (waves and currents). The predicted coastline position corresponds to the morphological surveys of the first four years. The beach width as predicted by the model is slightly overestimated, but the widening and narrowing trends agree with the observations. The computed increase of the highly dynamic ecotopes at the head of the Sand Motor and the sheltering effect on the sides corresponds to the first impression from the benthos samples.

Moreover, using a morphological model adds value to the long-term assessment of the ecosystem service response. The large nourishment volume changes the coastline orientation between Kijkduin and Scheveningen towards an orientation perpendicular to the dominant South West wave direction. This reduces alongshore sediment transport gradients and the magnitude of the transport, increasing the lifetime of the Sand Motor well beyond the envisaged lifetime of twenty years. This robust enhancement of coastal protection could only have been predicted using a morphological model forecast, leading to the conclusion that it is beneficial to use it for ecosystem service dynamics analyses.

However, the morphological model has limitations which are summed below:

- Aeolian transport is not incorporated in the morphological model, leading to a minimal variability of bed level in the supratidal zone. This means the evolution of flood protection cannot be assessed and a distinction between ecotopes in the supratidal zone cannot be made.
- Not all potentially relevant abiotic factors are predicted by the morphological model, such as sediment size and salinity.

5. IS IT POSSIBLE TO ENHANCE THE ECOSYSTEM SERVICE POTENTIAL OF A MEGA-NOURISHMENT BY ADJUSTING THE SHAPE?

The evolution of the ecosystem services potential of the Sand Motor is compared to two alternative nourishment designs twenty years ahead. A comparison is made between the coastline maintenance, recreation and the habitat provision potential. This study shows that it is possible to enhance the potential of certain ecosystem services, by changing nourishment design factors such as nourishment frequency and shape. The ecosystem service dynamics of the Sand Motor was compared to a prediction of an offshore Island and an upscaled traditional shoreface nourishment. This resulted in the following findings:

- A robust enhancement of the coastline maintenance ecosystem service if the total mega-nourishment volume (21 Mm^3) is implemented at once.

- The nourishment protrusion, size and coastline curvature affect the hydrodynamics at the head of the nourishment. A large protrusion combined with a strong curvature of the coastline increases the level of dynamics at the head of the nourishment, affecting the habitats.

- A mega-nourishment with a smooth coastal outline and a large lagoon enhances the potential for kitesurfing and habitat provision.

- A frequent nourishment, as with the traditional shoreface nourishment, leads to a highly variable evolution of the ecotope areas, disturbing the habitats.

8.2. RECOMMENDATIONS

In this thesis a first step towards engineering the ecosystem services is taken. While exploring the opportunities of ecosystem service prediction with morphological models, several recommendations could be made.

VALIDATION OF THE ABIOTIC FACTOR- ECOSYSTEM SERVICE RELATIONSHIP

This research describes the relationships between abiotic factors and ecosystem services qualitatively. The Delft3D model makes a forecast of the morphology, but does not make a prediction of all relevant abiotic factors, such as sediment size and sorting. On a small spatial scale, e.g. a tidal flat, sediment size is one of the most relevant factors to the response of macrobenthoc species and the potential for a nursery for flatfish. These factors are monitored in the substrate samples of the Monitoring and Evaluation Program (MEP) of the Sand Motor, together with visitor counts, morphological surveys and yearly benthos samples. This data of the first years can be used for the validation of the relationship between ecosystem service potential and the abiotic factors, which are described qualitatively in this study using literature.

POTENTIAL VERSUS ACTUAL USE OF THE ECOSYSTEM SERVICE

This study distinguishes between the potential of an ecosystem to provide an ecosystem service and the actual use of the service. The potential of the ecosystem to provide ecosystem services is analyzed using morphological models. The next step in analyzing ecosystem services would be to model the actual use of ecosystem services at the Sand Motor. There are many complexities involved in such an assessment, where aspects, such as weather, infrastructure and crowdedness of the beach, need to be included that influence the actual use of services. This goes beyond analysis of physical indicators. The integrated ecosystem service approach needs to be validated. This includes monitoring of a wide range of factors that influence the actual use (e.g. sunny weather and infrastructure) and monitoring of the use of the services (e.g. visitor count data). A research that incorporates the actual use of services would add clarity to the existence of the actually used ecosystem services versus the potential that the ecosystem provides.

ASSESSING ECOSYSTEM SERVICE DYNAMICS

In this study a dynamic assessment is performed that assesses ecosystem service potential on a yearly basis and on a large spatial scale of the Delfland coast. A sandy shore is a dynamic environment and findings of this study found that this influences ecosystem service potential over time. It is therefore recommended that future studies regarding ecosystem services in dynamic environments perform a dynamic analysis as well.

AEOLIAN TRANSPORT

This research focused on the ecosystem services of a sandy shore. The morphological model incorporates marine sediment transport, but no aeolian transport. In the case an aeolian transport module could be added to the morphological model, a more realistic future topography of the supratidal zone would be generated with (embryonic) dune formation. After a calibration of the aeolian transport settings and a validation of the model performance, the model would then be able to predict the potential of flood protection and the development of supratidal habitats.

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ECOLOGICAL COMPOSITION PER ECOTOPE

The Delfland coast is regarded as highly dynamic. The level of hydrodynamics, due to waves and currents, is considered to be the dominant factor for the faunal response in the nearshore. High current speeds and/or significant wave impact lead to high bed level dynamics and result in a relatively low biodiversity, abundance and biomass. The currents are an important transport mechanisms for benthos, fish, juveniles and larvae (Bouma et al., 2005).

THE SUBTIDAL ZONE

Based on the magnitude of the bed shear stress five ecotopes are distinguished in the subtidal zone.

ECOTOPE 1. SURF ZONE

The surf zone is characterized by very high bed shear stresses due to breaking waves and a low species diversity and abundance. The Dutch coast has two breaker bars (an intertidal bar and a surf zone bar) with a sheltered trough in between where locally the species diversity can be high and the abundance very high. Sampling studies in the surf zone have found a strong increase in benthos abundance in this trough due to the presence of juvenile Sand Mason (Lanice conchilega), indicating that the abiotic conditions in the trough differ strongly from the rest of the surf zone (Janssen and Mulder, 2005). Unfortunately, the Delft3D model does not produce these breaker bars in cross-shore direction. Generally, species richness in the surf zone is low, except for the local increase at the trough. Fishes, such as sole, sand eel, Atlantic herring and plaice are most abundant in the surf zone, followed by crustaceans like hermit crabs and brown shrimp (Janssen et al., 2008). Several bird species may forage at the surf zone (Bouma et al., 2005). The surf zone generally entails water depths up to -6 m NAP approximately.

ECOTOPE 2. SEAWARD SIDE OF THE SURF ZONE

This ecotope is characterized by relatively lower, but still quite significant bed shear stresses. Beyond the -6 m NAP depth contour (approximately the seaward boundary of the suf zone), the number of species increases with increasing depth (Baptist et al., 2008). Sampling studies found a high abundance of juvenile sole just seaward of the surf zone. The abundance of the juveniles was equal to or even higher than was found in the Wadden Sea, making this zone an important nursery area (Janssen et al., 2008). Generally, this zone can be found approximately at -6 to -9 m NAP.

ECOTOPE 3. NEARSHORE

The bed shear stress decreases further with increasing water depth. This ecotope is characterized by bed shear stresses milder than the bed shear stress seaward of the surf zone and thus the species diversity increases. The bed beyond the surf zone is primarily inhabited by amphipods, bivalves and enchinoderms of which the bristle worm Spiophanes bombyx is the most abundant species (Janssen and Mulder, 2005). Generally, this zone can be found approximately at -9 to -12 m NAP.

ECOTOPE 4. OFFSHORE

This ecotope is located far offshore and is characterized by large water depths and low bed shear stresses. The species richness increases, more or less linearly, with the water depth and it is unknown at what water depth or distance from the Dutch shore the species richness will have its peak or when the increase stabilizes (Janssen et al., 2008). Generally, this ecotope would occur beyond the 12 m depth contour. At water depths large than 30 m, factors like stratification of the water column will play a more important role in the zonation of species (Bouma et al., 2005).

ECOTOPE 5. SHELTERED SUBTIDAL

This ecotope is characterized by extremely low bed shear stresses. Low dynamic ecotopes are generally more diverse than highly dynamic ecotopes. Locally the number of species and the biomass can be relatively high. A large number of molluscs (e.g. Ensis Directus, Spisula subtruncata) may appear in this ecotope. These species form an important food source for certain bird species. Furthermore, this ecotope can function as a nursery for benthos and flatfish species, such as sole, flounder and plaice (Bouma et al., 2005).

INTERTIDAL ZONE

This zone is highly dynamic and is submerged with every tide. Birds forage on the benthos species that are present in this ecotope. Some species, such as Scolelepis squamata, can be found across the entire intertidal zone. However, most species are confined to the upper or lower intertidal (Baptist et al., 2008). The intertidal zone is split up into a sheltered and exposed zone according to the bed shear stresses. Subsequently, the exposed intertidal zone is classified into an upper and a lower intertidal zone. The distinction between the upper and lower intertidal zone is made to incorporate two important factors: the increase in mechanical disturbance due to waves from the high water line to the low water line and the concurrent decrease in inundation duration. In the middle, around mean sea level, there is an optimum where species number, biomass and abundance peak (Janssen and Mulder, 2005).

ECOTOPE 6. EXPOSED LOWER INTERTIDAL

This ecotope is located between mean sea level and the low water line. At the low water line, the water content is high, the sediment is well sorted and the median grain size is relatively large compared to the high water line. This means the substrate is more easily penetrable and thus more favourable for interstitial organisms. Near the low water line the species number abundance and biomass is generally lower than near mean sea level, but higher than near the high water line. A possible explanation for the decrease in species richness near the low water line may be the high mobility of the sediment and the high predation pressure on macrobenthos from shrimps, crabs and juvenile fish (Janssen and Mulder, 2005).

ECOTOPE 7. EXPOSED UPPER INTERTIDAL

This ecotope is located between mean sea level and the high water line where the median grain size is relatively smaller, the water content lower, the sediment sorting poorer and the penetrability of the substrate lower, making it more difficult for interstitial organisms to bury themselves into the soil (Janssen and Mulder, 2005). The upper intertidal zone is characterized by terrestrial species and drift line fauna. The abundance is relatively low in this zone and combined with the low penetrability of the sediment it is more difficult for birds to find food and to penetrate the soil with their bills. A possible explanation for the lower biomass and abundance around the high water line is the short immersion period and the strong fluctuations of factors like temperature (Janssen and Mulder, 2005).

ECOTOPE 8. SHELTERED INTERTIDAL

This ecotope can function as a nursery area for flatfish and crustaceans, with a potentially high number of juvenile benthos mostly in the middle of the intertidal zone. Near the high water line, the submergence time is minimal, the biomass is lower, the benthos species are mostly crustaceans and polychaetes and filter feeders are absent. In the case of a silty substrate, the combination of low dynamics and a large silt content can lead to low oxygen levels in the substrate and even anoxic layers close to the bed surface. Biomass and diversity and can be large at this ecotope. A very high silty content generally leads to a very low diversity and abundance. The number of juveniles can be relatively high. This ecotope can be a potentially important foraging area for birds (Bouma et al., 2005).

SUPRATIDAL ZONE

This zone above the high water level is the habitat of air-breathing terrestrial species, such as insects, and vegetation. In this ecotope classification no distinction is made between ecotopes in the supratidal zone. Within the supratidal zone there could potentially be several ecotopes present which are described below.

ECOTOPE 9. THE SUPRATIDAL ZONE

Dry beach Exposed, highly dynamic supratidal zone that are mostly devoid of vegetation due to the high stresses. Pioneer plants, such as Sea Rocket (Cakile maritime) and Sand couch (Elytrigia juncea) are able to withstand relatively stressful conditions, but do not survive wave impact. A polychaete such as Scolelepis squamata may be expected here (Bouma et al., 2005).

Embryonic dunes On the higher parts of the dry beach embryonic dune formation starts with pioneer plant sand couch, which is taken over by Marram grass. Marram grass cannot handle regular salt pray and is therefore only found at the higher parts of the dry beach where the stresses are very low.

Green beach In the case of beaches that are flooded only during unusually high water levels, microbial mats and algae may develop that will form a so-called 'green beach'. To grow a potential green beach, the bed shear stress must be low and the bed must be covered with a new layer of silt and sediment that has settled during extremely high water levels. In the case of beaches that are flooded on a daily basis, the algae mats cannot develop. On a green beach specific vegetation can be initiated due to the entrapment of silt (Wesenbeeck van et al., 2008). Silt is therefore a precondition of this habitat type. In the case of a lower bed level on the landward side of the high supratidal beach, silt is trapped and microbial and algae mats may form giving the area a brownish-green color. In the Netherlands, green beaches can be found at the Wadden Islands where wash-over complexes provide areas that are rarely flooded, leading to relatively static beds covered with silt on which microbial mats and algae can grow (Löffler et al., 2008).

Stagnant brackish This ecotope can be found in the dune lake. Unfortunately there are no samples taken at the dune lake, so information on the ecosystem is missing. The stagnant brackish ecotope can also be found at the shallow parts of the Veerse Meer in the Netherlands. This ecotope is characterized by a low biodiversity. In the Veerse Meer molluscs and worms make up the largest part of the ecosystem. Fields of Seagrass (Zostera marina) could potentially develop in a stagnant brackish ecotope (Bouma et al., 2005).

B

Characterization of the abiotic parameters

Sediment size

The sediment size is reviewed as the median grain diameter, which is the midpoint of the grain size distribution where 50% of the grain sizes are smaller and 50% are larger than the median grain diameter.

At the Sand Motor

This parameter is relevant for all the ecosystem services. Before construction of the Sand Motor, it was decided that the medium grain diameter of the nourished sand should be between 200 μm and 300 μm (www.zandmotordata.nl).

Spatial characterization

The median grain diameter differs spatially over the Sand Motor, in cross-shore and alongshore direction. Within a cross-shore zone, there are differences in the energetics of an area. For instance, the north and south sides of the Sand Motor are less energetic than the head of the peninsula and therefore transport of finer sediment to these location will occur (Huisman et al., 2015).

Temporal characterization

The time scale of the change in particle size differs per location. At the energetic swash zone the response is almost instantaneously, in the order of days, while more offshore the time scale is in the order of weeks. Storms cause rapid coarsening of the swash zone and forces fine sediment offshore and to less energetic areas at the sides of the Sand Motor (Van der Zwaag, 2014). It is expected that the time scale of change of the grain size on the supratidal zone will be longer. This also implicates that unnaturally large or small imported sediment will have a long-lasting, large impact on the supratidal beach ecosystem.

Sediment sorting

Sediment sorting particularly occurs at the subtidal and intertidal zone due to water transport processes, but may also occur at the supratidal due to aeolian transport (Arens et al., 2002). Well sorted sand can be described as homogeneous sand with a narrow distribution, see Figure B.1. The degree of sorting can be expressed as the standard deviation of grain size (Fenu et al., 2012) or by the steepness of the sieve curve.

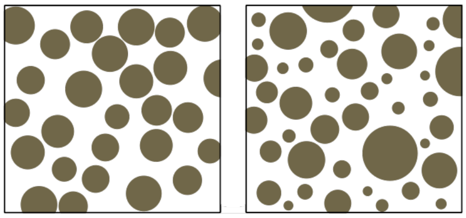


Figure B.1: On the left an example of well sorted sand with a narrow distribution. On the right an example of poorly sorted sand.

SAND MOTOR

After construction of the Sand Motor wave, wind and tidal action rearrange the spatial pattern of the sediment and sort the sediment size according to the energetics of the surroundings, leading to a change in the grain size distribution. For example, at the head of the Sand Motor the median grain size is gradually coarsening after flushing the finer sediment. A possible explanation for this could be the occurrence of winnowing, which is a process that contributes to sediment sorting (Kaji, 2013).

SPATIAL CHARACTERIZATION

The elaboration of this parameter on the spatial scale is comparable to the spatial scale of the parameter 'grain size'. The median grain diameter differs spatially over the Sand Motor, in cross-shore and alongshore direction. The bed of the intertidal zone is stirred up during every high water, while the supratidal zone is only affected during storms.

TEMPORAL CHARACTERIZATION

The time scale of the change in sorting differs per location. At more energetic areas the response time is much shorter than at more sheltered areas. Storms can accelerate the sediment sorting process (Van der Zwaag, 2014). In the cross-shore direction during storms, the time scale of the sorting process is in the order of hours to days. The time scale for sediment spreading alongshore during storms is somewhat larger, in the order of months (Huisman et al., 2015).

SUBSTRATE COMPACTION

Nourishment can cause a compaction of the substrate. Figure B.2 shows a conceptual representation of substrate compaction. Due to compaction, the pore space in the soil and the total soil volume reduces (Leung and Meyer).

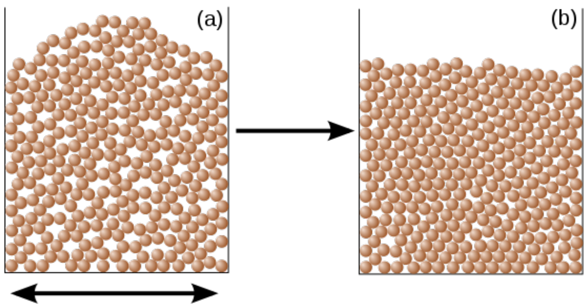


Figure B.2: Conceptual representation of substrate compaction (Ouyang, 2015)

SAND MOTOR

There have been incidents on the Sand Motor where people got stuck in soft soil, like drift sand. This soft soil is a mixture of sand and water where the proportion of water to sand is larger than in normal situations. It is probable that this drift sand is formed by sand blown on sheltered areas with a shallow water depth. The sand forms a layer on top of the water column and the water slowly mixes with the sand. The time it will take before the soil returns to a stable state depends on the weather conditions. In january 2015 more warning signs were placed on the locations represented in Figure B.3.

Figure B.3: Sketch made in 2011 of the locations where drift sand was expected shaded in red (www.dezandmotor.nl, 2015c)

SPATIAL CHARACTERIZATION

The degree of compaction differs on the Sand Motor. Interesting patches on the Sand Motor with respect to soil compaction are the patches where the compaction is very low and strolling recreationists sink away in the soil.

TEMPORAL CHARACTERIZATION

The rate of compaction differs on the Sand Motor. On patches that have experienced higher vertical forces, for instance due to a water layer or trampling by foot, a faster compaction of the substrate occurs. The dispersion of the sediment of the Sand Motor is also a factor in the temporal scale. The top layer of patches with a strong sedimentation rate will need time to compact (e.g. the spit of the Sand Motor), while it is expected that eroding patches have a higher compaction due to the weight of the original soil.

SILT CONTENT

A sediment particle between 2 - 63 μm falls within the category of silt. Relatively sheltered areas with low energetic conditions generally have larger silt contents.

SAND MOTOR

SPATIAL CHARACTERIZATION

Fine sediment like silt will generally settle at areas with low energetic conditions. At the Sand Motor, this will particularly be at the lagoon. Along the lagoon, there are also differences in energy due to the tidal flow, being stronger at the inlet than at the outer end of the lagoon. The inlet of the lagoon will be flushed with every tide, while at the outer end of the lagoon silt can accumulate. Furthermore, between the breaker bars in the subtidal zone, relatively higher silt contents are expected to be found.

TEMPORAL CHARACTERIZATION

The catchment of silt in the lagoon will cause a gradual increase in silt content if the lagoon is not flushed or cleaned. The silt contents often shows a seasonal variation, where the levels are highest during the summer and fall (Bouma et al., 2005).

CROSS-SHORE SLOPE

The cross-shore slope is a a linear line that fits the vertical elevation and the horizontal cross-shore width.

SAND MOTOR

After construction of the Sand Motor, the slope of the new beach profile was steeper than the original slope. This change in slope is visualized in Figure B.4.

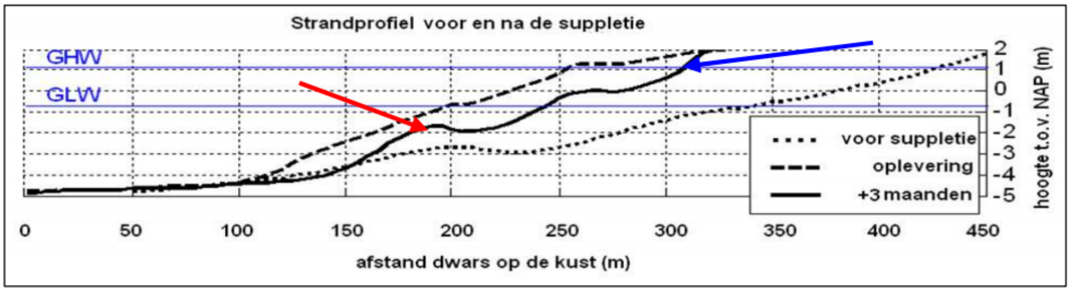


Figure B.4: Slope of the original profile, slope directly after construction and slope after three months at the Sand Motor. In the picture the levels of MHWL (GHW) and MLWL (GLW) are indicated by the blue lines (van Ettinger and de Zeeuw, 2010)

The beach slope of the Sand Motor varies in alongshore and cross-shore direction. A regular sandy shore will have a gradual slope up from the subtidal to the supratidal zone. However, the Sand Motor has a typical profile with a varying gradient.

SPATIAL CHARACTERIZATION

The cross-shore slope varies in alongshore and cross-shore direction. Generally, accreting beaches will have a more gentle slope while eroding beaches have steeper slopes. The nourishment has been constructed with a certain slope, and therefore the beach slope of the Sand Motor will differ from adjacent beaches.

TEMPORAL CHARACTERIZATION

Directly after construction of the Sand Motor, the cross-shore slope was most out of equilibrium. Tidal regime and wave action have stayed constant and therefore the Sand Motor will be slowly formed towards the dynamic equilibrium of the original shoreface profile. The cross-shore profile will form towards an equilibrium corresponding to the coinciding forcing. The wave forcing varies over the year, leading to a different beach slope in the summer and winter period (Bosboom and Stive, 2013).

WATER DEPTH

The water depth is directly related to the bathymetry in combination with the water level.

SAND MOTOR

The morphological development of the Sand Motor changes the bathymetry and the water level at the Sand Motor varies with the tide. The only exception to this is the dune lake, where the water level depends on the evaporation, rainfall and ground water table.

SPATIAL CHARACTERIZATION

The bathymetry varies in alongshore and cross-shore direction. Within the subtidal zone, the bathymetry varies due to the breaker bars, and in the deeper and relatively sheltered troughs the local diversity and abundance increases (Janssen et al., 2008, Janssen and Mulder, 2005). The lagoon is a special case on the Sand Motor. The water depth in the lagoon is influenced by a combination of tide and the development of the morphology at the Sand Motor (De Vries et al., 2015). During high water, the crest of the lagoon inlet is submerged, the water flows in over the spit and the water level in the lagoon follows the sea level. During low water, the outflow of the lagoon decreases significantly due to the decreased cross-sectional area of the channel. This leads to a different tidal range inside the lagoon, compared to the sea (De Vries et al., 2015).

TEMPORAL CHARACTERIZATION

The water level varies with the semi-diurnal tidal regime.

BEACH WIDTH

Beach width affects the ecosystem services in various ways. The underlying factor of beach width is the amount of space which is available for the several functions (McLachlan et al., 2013), e.g. habitat availability, space for strolling routes and the distance a recreationist has to walk to reach a specific point near the waterline.

Sand Motor

The beach width is drastically extended at the location of the Sand Motor.

Spatial characterization

The beach width is split up into two parts: the wet beach width of the intertidal zone and the dry beach width of the supratidal zone. The wet beach and the dry beach each have their specific functions. Most recreational activities (sunbathing, strolling) make use of the dry beach (Broer et al., 2011), while the biota mainly live on the wet beach. The beach width varies alongshore due to the shape of the Sand Motor and will therefore be analyzed per transect. For a conceptual representation of the beach widths, see Figure B.5. An interesting detail is that on some transects the wet beach and dry beach consists of multiple parts across the shore. For example, near Kuikduin the dry beach consists of a part between the sea and the lagoon, and a part from the lagoon up to the dunes. This is visualized in Figure 2.5. The adjacent beaches next to the Sand Motor accrete and thus the beach width will increase over time.

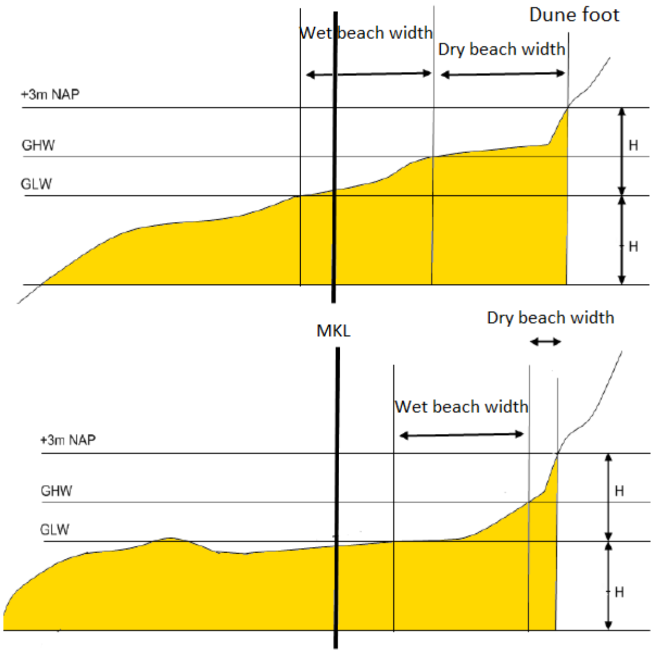


Figure B.5: Example of two profiles that have different dry and wet beach widths, but have the same sand volume. GHW (MHW), GLW (MLW), MKL and the dune foot position are indicated in the figure (Broer et al., 2011)

Temporal characterization

The temporal characterization of the beach width is related to the time scale of the sediment dispersal. This time scale varies per transect and the dispersal rate decreases over time as the outline of the Sand Motor becomes smoother. The beach width also has a seasonal variability due to the different winter and summer profiles. It is expected that the variability due to sediment dispersal is dominant at the beginning, however as time passes seasonal variability could start to play a more important role.

Inundation duration of the intertidal zone

This parameter is applicable to the intertidal zone.

Sand Motor

On the Sand Motor several incidents occurred where recreationists were surprised by the upcoming tide and were isolated from the main land during high water. The area which is inundated for a particular duration might be interesting for the habitat provision ecosystem service.

Spatial component

The different patches in the intertidal zone experience a different inundation duration.

TEMPORAL COMPONENT

The time scale of this parameter relates to the semi-diurnal tidal regime.

INUNDATION FREQUENCY OF THE SUPRATIDAL ZONE

During storms, the water level reaches far up the supratidal zone. The probability of exceedance of extreme water levels directly relates to the safety of the hinterland.

SAND MOTOR

The inundation frequency is relevant for the coastal protection ecosystem service. At the location of the Sand Motor, the dunes must be able to withstand a probability of exceedance of the water level of $1 * 10^{-4}$ (Ministerie van Verkeer en Waterstaat, 2007). The effect of a storm surge level on the dunes is represented in Figure B.6, where a strong undertow during storms deposits sand in the nearshore. Note that this probability of exceedance of the design water level is not equal to the failure probability of the dunes. This allowed failure probability is set by the Delta Committee at a factor 10 smaller than the exceedance probability of the design water level (den Heijer et al., 2012).

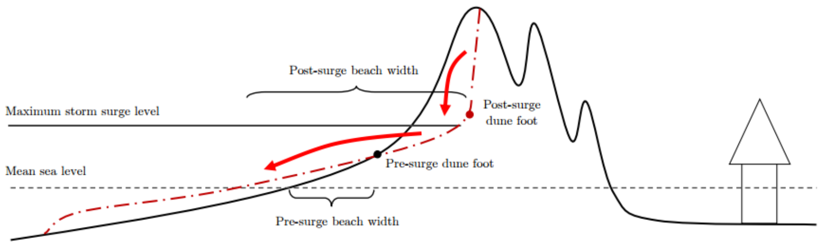


Figure B.6: Representation of the effect of storm surge on the dunes (Bosboom and Stive, 2013)

SPATIAL COMPONENT

The inundation frequency decreases as the elevation of the beach increases.

TEMPORAL COMPONENT

During storm surges the waterline reaches onto the supratidal zone. The frequency of storms is season dependent, with an increased number of storm events in winter.

CURRENTS

Currents are a crucial hydrodynamic factor on a sandy shore. The currents are driven by waves and tide and can be split up into cross-shore currents and longshore currents.

SAND MOTOR

Currents influence the ecosystem services in several ways. In the subtidal zone, the occurrence of tidal contraction (Van der Zwaag, 2014) and rip currents strongly affect swimmer safety (Van Der Moolen, 2015). Alongshore transport, induced by waves and tide, determine the dispersion of the sand. In the intertidal zone the horizontal tidal current generates in- and outflow of water in the lagoon. On the tidal flats the currents are induced by tide and waves. The dune lake, with its stagnant water, is a special case on the Sand Motor.

SPATIAL CHARACTERIZATION

Currents are the driving factor behind the spatial distribution of the imported sand. The shape of the Sand Motor in combination with the wave climate leads to a strong variability in the current patterns.

TEMPORAL CHARACTERIZATION

A significant change in shape of the Sand Motor over time, such as the decreasing protrusion, increasing length and formation of the lagoon strongly affects current velocities and patterns.

Vertical erosion/accretion rate

For a conceptual illustration of this parameter, see Figure B.7.

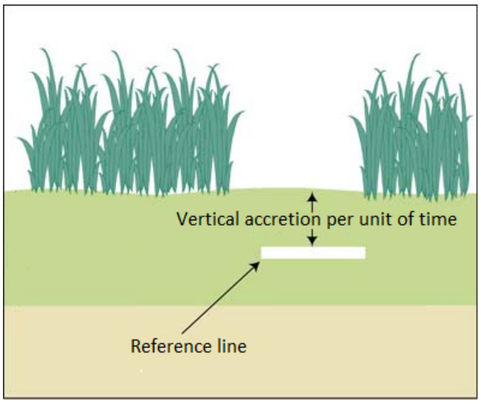


Figure B.7: Conceptual representation of the vertical accretion rate (figure adapted from (USGS, 2015))

Sand Motor

Due to the dispersal of sediment, at some locations the bed level is elevated while other parts are deepened. Initially, when the slope and curvature of the Sand Motor were most out of equilibrium, the gradients in sediment transport rates were highest (Kaji, 2013).

Spatial characterization

Per transect the average erosion and accretion rate differs.

Temporal characterization

In case of a gradient in sediment transport, sediment will erode or accrete. This gradient depends, among others, on the curvature of the coastline. As the curvature of the coast evolves, the erosion/accretion rate will also change over time. It is likely that the rate is also linked to the seasonal cycle (see Section 4.3).

Beach and dune volume

A sand volume is calculated between an upper and a lower boundary. On a transect level, where the profile is viewed in 2D, the volume is expressed as a volume per running meter.

Sand Motor

The ebach and dune volume change, as transects accrete or erode.

Spatial characterization

Per transect the average erosion and accretion rate differs. Therefore the volume which erodes or accretes per unit of time will be investigated for each transect separately. It is important to define the upper and lower boundary which are taken into account.

Temporal characterization

The beach profile experiences seasonal variability, due to a changing wave climate. To exclude the seasonal variability, the volumes per transect must be assessed on a yearly basis in the same season. This can either be a summer or a winter profile, as long as it is taken consequently to be able to follow the development.

Curvature of the coast

This parameter is a combination of curvature of the coast and the protrusion into the sea relative to the original coast. In this parameter the scale of the nourishment is an underlying factor, combining protrusion, length and curvature of the coastline at the nourishment.

SAND MOTOR

At the Sand Motor, the wide mega-nourishment protrudes approximately a kilometer into the sea with a strong curvature, inducing tidal contraction, eddies and rip currents. Initially, when the Sand Motor is most out of equilibrium these phenomena are most intense (Kaji, 2013). For example, in Figure B.8 the observed bathymetry in August 2011 is displayed. A year later, the Sand Motor has dispersed significantly as can be seen in Figure B.9.

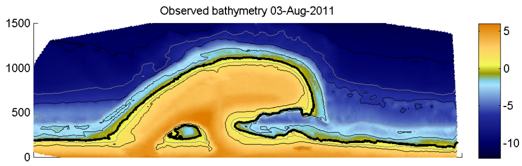


Figure B.8: Observed bathymetry of the Sand Motor in August 2011

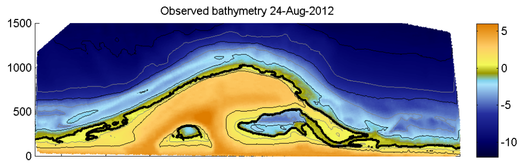


Figure B.9: Observed bathymetry of the Sand Motor in August 2012

SPATIAL CHARACTERIZATION

For this parameter, it is important to define the spatial scale in combination with the curvature. A blunt, but small protrusion will have different hydrodynamic effects than a smooth profile with a larger cross-shore protrusion. The curvature and the protrusion of the Sand Motor change over time to a smoother profile.

TEMPORAL CHARACTERIZATION

The development of this parameter is linked to the dispersion of the nourishment. Initially, as the peninsula is most out of equilibrium the rate of change is the largest. Furthermore, it is expected that during the winter period the nourishment will disperse more than during summer.

WRACK MATERIAL DEPOSITION

Wrack material is present on the boundary between the intertidal and the supratidal zone, see Figure 2.1 for an indication on the location. At many beaches used for recreation, unwanted material (such as wrack line deposits) is removed during maintenance cleaning. The removal of wrack material has significant consequences for beach ecology (Defeo et al., 2008). In Figure B.10 a picture of a drift line is depicted.

Figure B.10: Picture of a wrack line composed mainly of small sticks (Morey, 2015)

SAND MOTOR

SPATIAL CHARACTERIZATION

The wrack material will be located at the HWL.

TEMPORAL CHARACTERIZATION

The composition of the wrack varies over time. The wrack line is influenced by the seasons and by the neap/spring cycles, as the high water line varies and high waves take wrack accumulation further up the beach (Rodil et al., 2008).

Availability of organic matter in sediment

Nourishment imports exotic sediment, which may lead to an altered percentage of organic matter in the substrate and thus a change in food availability.

Sand Motor

In the subtidal zone, troughs between bars are expected to accumulate organic matter and thus support more species with a higher density than the surrounding sand banks (Speybroeck et al., 2008). In the intertidal zone, the lagoon is expected to accumulate organic matter as well.

Spatial characterization

The organic content in the substrate varies spatially in alongshore and cross-shore direction (Rodil et al., 2008). The different areas on the Sand Motor (e.g. the lagoon, tidal flats, dune lake) have different exposure levels and therefore it is expected the spatial variation of this parameter is strong. Organic content accumulates at the troughs of sand banks and at other sheltered locations.

Temporal characterization

Organic matter in the sediment shows seasonal variability, where lower values generally occur in summer (Rodil et al., 2008). This may be due to less energetic sea conditions, higher temperatures and more solar radiation during this season (McLachlan and Brown, 2010).

Wave exposure

Exposure to wave action has a strong influence on the morphological and ecological dynamics. The overall rate of exposure to waves on the Dutch western beaches can be regarded as moderately exposed (Janssen and Mulder, 2005). Changes alongshore in the level of wave exposure can lead to rapid changes in sediment characteristics, morphology and species communities.

Sand Motor

The lagoon is a sheltered area within the peninsula. This results in large variations in exposure to wave action on the Sand Motor and gives opportunities for different species communities and recreational activities.

Spatial characterization

The lagoon is sheltered from sea waves and is only influenced by the tide. The dune lake is not in connection to the sea and is therefore sheltered from wave and tidal influence.

Temporal characterization

Wave action is related to the seasons. During winter the wave conditions may be more energetic.

Bed shear stress

The level of hydrodynamics has a major influence on the species community distribution. The bed shear stress, due to waves and currents, is a measure of the level of hydrodynamics. A bed shear stress that is higher than the critical bed shear stress mobilizes sand grains and causes significant reworking of the bed (Van Rijn, 2007). Both waves and currents affect the bed shear stress, and therefore in theory it is the best parameter to describe the hydrodynamics (Vlaams Nederlandse Schelde Commissie, 2014).

Sand Motor

Spatial characterization

Currents and waves affect the magnitude of the bed shear stress (Bosboom and Stive, 2013). As the magnitude of the currents and wave characteristics differs along the Motor, the bed shear stress will show a variation in space as well.

Temporal characterization

The magnitude of the bed shear stress differs per phase in the spring/neap tidal cycle. During spring tides the bed shear stress will be maximal (Bouma et al., 2005).

C

THE DELFT3D MODELS

The process-based numerical Delft3D model is used to calculate the morphological changes under the influence of waves, tides and winds. The model is depth-averaged and contains a curvilinear computational grid that extends from the Nieuwe Waterweg at Rotterdam to the north beyond Scheveningen harbor. The resolution of the grid near to the nourishment is approximately 35 m and increases with distance from the nourishment to approximately 135 m.

The tidal conditions have been reduced to a single cyclic morphological representative tide that leads to the same long-term averaged residual transports. Near the coastline the constant modeled high water level (excluding surge) is approximately 1.4 m and the low water level approximately -0.9 m. The wave climate at the Dutch coast has been reduced from 116 to 10 wave conditions to reduce the computation time of the model. Calculations with the reduced wave climate result in a similar morphological development as would be the case for calculations with all the wave conditions. The reduced wave climate is shown in Table C.1. The two dominant wave conditions with respect to the probability of occurrence are conditions 1 and 7. An extensive explanation on how the wave and tidal conditions have been reduced is explained in Tonnon et al. (2009).

The parallel-online method is applied to the morphological model calculation. This method calculates the bottom changes for all wave conditions simultaneously, while using the same initial bed. After every time step the bed level change is weighted per wave condition and summed in a merging process. The weighted average bed level change is applied to the initial bathymetry and the new bathymetry is used as the initial bed for the new time step.

The model is calibrated for the first year after construction with regard to waves, currents, bed level changes, etc. The settings that resulted from this calibration with the first year changes are also applied to the island model and 'traditional' nourishment model.

Table C.1: Reduced wave climate (Tonnon et al., 2009)

Condition	$H_{1/3}$ (m)	$T_{1/3}$ (m)	Θ_{wave} ($°N$)	V_{wind} (m/s)	Θ_{wind} ($°N$)	surge (m)	weighting factor (-)
WC01	1.48	5.34	232	9.97	231	0.04	0.1224
WC02	2.46	6.34	232	13.37	227	0.12	0.0685
WC03	1.97	5.99	246	11.09	210	0.20	0.0118
WC04	1.48	5.45	261	8.24	197	0.16	0.0006
WC05	2.47	6.53	277	11.44	175	0.42	0.0460
WC06	2.97	7.00	277	13.30	171	0.59	0.0109
WC07	1.97	6.59	322	8.65	126	0.22	0.1206
WC08	2.96	7.71	322	11.93	127	0.53	0.0036
WC09	1.47	6.07	337	5.69	107	0.02	0.0652
WC10	0.96	5.63	352	3.62	73	-0.08	0.0823

C.1. THE MEGA-NOURISHMENT ALTERNATIVES

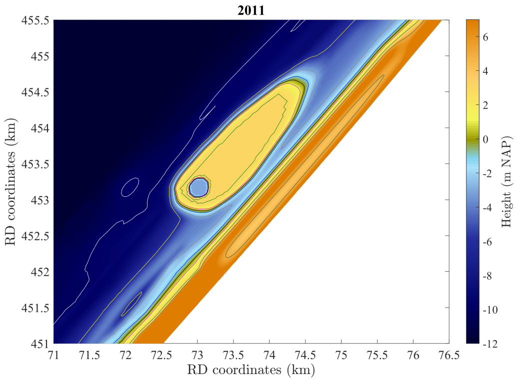
To test whether it is possible to enhance the ecosystem services provided by a mega-nourishment, the Sand Motor is compared to two alternatives: an island and a traditional nourishment. For each nourishment alternative a morphological model was made, giving a morphological prediction twenty years ahead. The same calibrated settings as in the Sand Motor model were used in these models. Please note that these are fictive scenarios and the models are not validated.

THE ISLAND

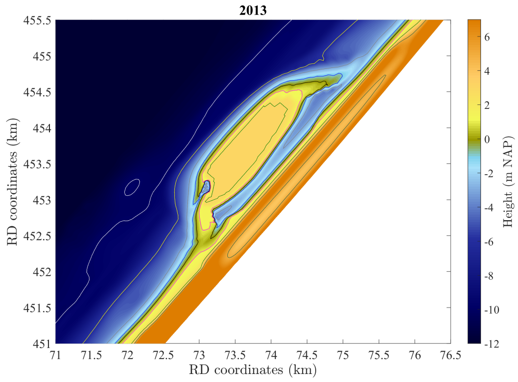
In this model, an offshore island is constructed that contains the same volume of sand as the Sand Motor. The island is located just offshore the coast of Kijkduin. In Figure C.1, the morphological development of the Island alternative is presented.

THE TRADITIONAL NOURISHMENT

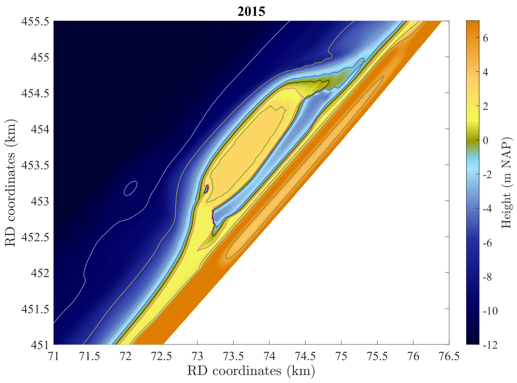
The traditional nourishment represents a shoreface nourishment that is repeated every four years. To be exact, every 3.8 years a volume is added at the exact same location upto a depth of -2 m NAP. This is a fictive scenario, because usually a 'traditional' nourishment takes place when the BKL threatens to be exceeded by a negative MKL trend. Once this BKL exceedence is imminent, a nourishment is implemented locally at that part of the coast that requires it. The scenario used for this study is not likely, for the reason that four years after a foreshore nourishment of more than 4 Mm^3, the BKL will not be exceeded yet at this location. Nonetheless, this scenario shows the effect of nourishing with a higher frequency on the ecosystem service potential. In Figure C.2, the morphological development of the traditional nourishment scenario is presented.



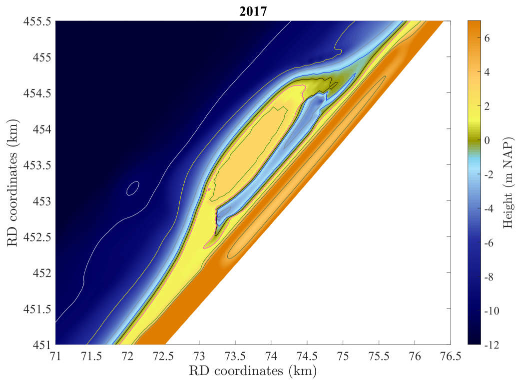
(a) 2011



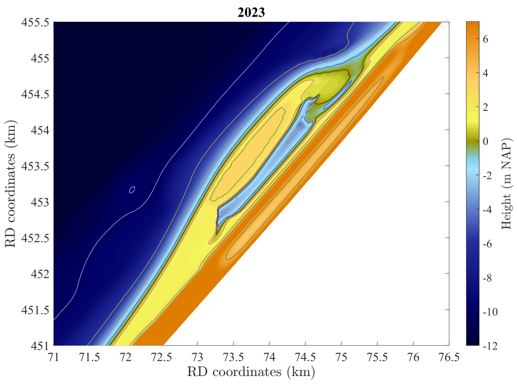
(b) 2013



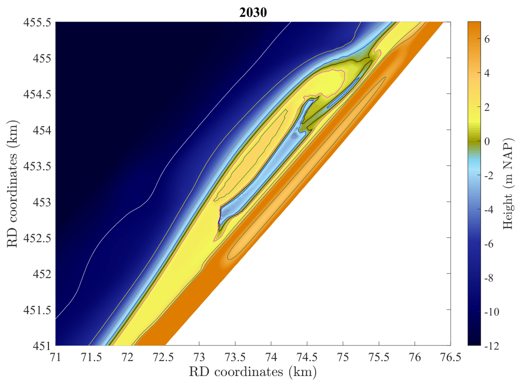
(c) 2015



(d) 2017

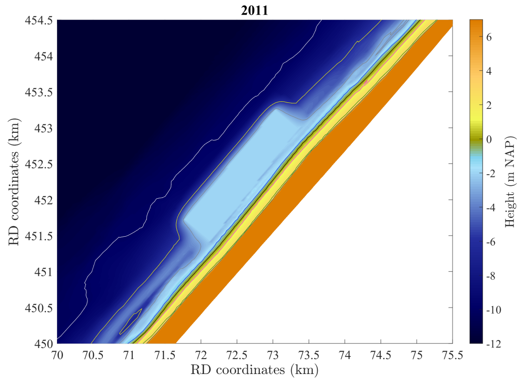


(e) 2023

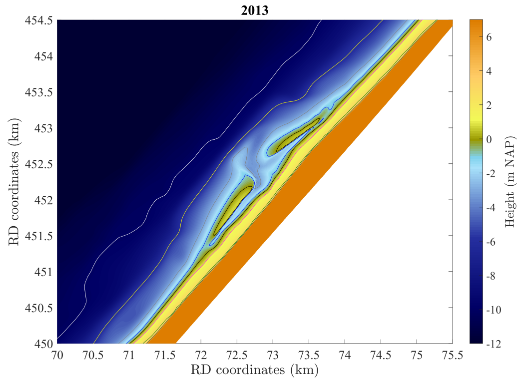


(f) 2030

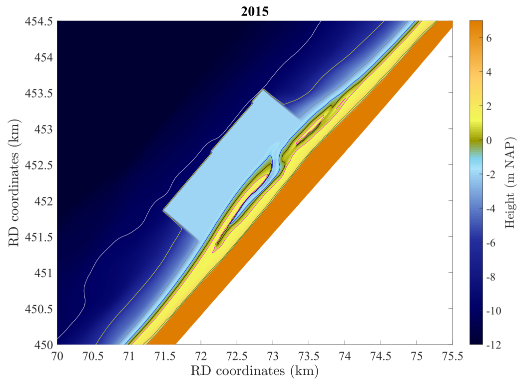
Figure C.1: Morphological development of the Island.



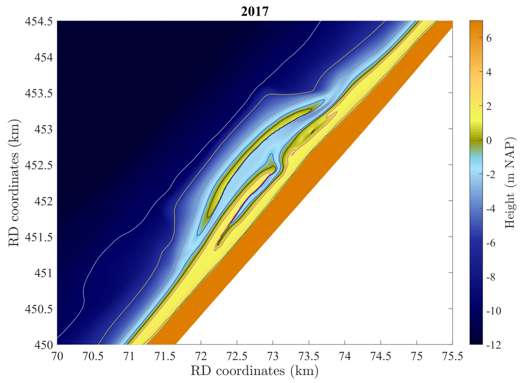
(a) 2011, after one nourishment



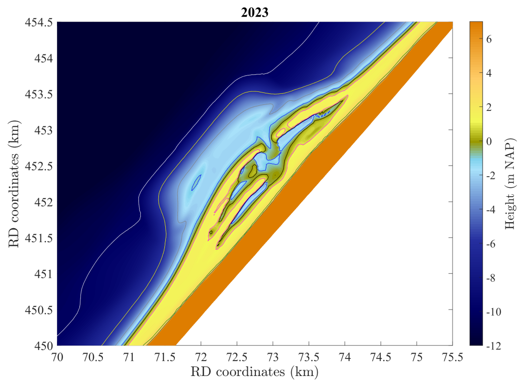
(b) 2013, after one nourishment



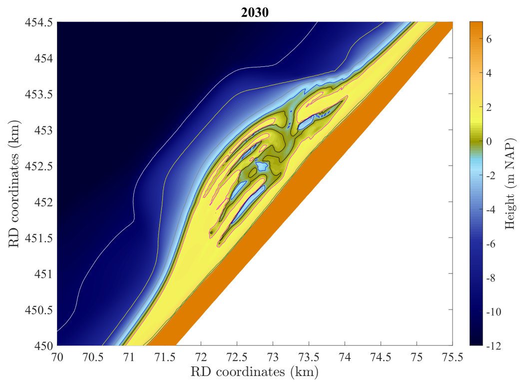
(c) 2015, after two nourishments



(d) 2017, after two nourishments



(e) 2023, after four nourishments



(f) 2030, after five nourishments

Figure C.2: Morphological development of the traditional nourishment.

D

ECOSYSTEM SERVICE ASSESSMENT: ADDITIONAL FIGURES OF THE SAND MOTOR

In this appendix additional figures are presented for further elaboration on the results of the ecosystem service assessment of the Sand Motor.

D.1. COASTAL PROTECTION

In Figure D.1 the evolution of the MKL distance per transect and the averaged MKL distance are shown for the sections of Scheveningen, Hoek van Holland and 's-Gravenzande. The model forecast, the best estimate and the observations are plotted together to check whether the forecast and the observations agree. The weighted average calculated with the measured JARKUS data matches the calculation of the model and best estimate well. Unfortunately there are not enough years of data yet to reach a conclusion on the annual volume loss due to aeolian transport

D.2. RECREATION

KITESURFING

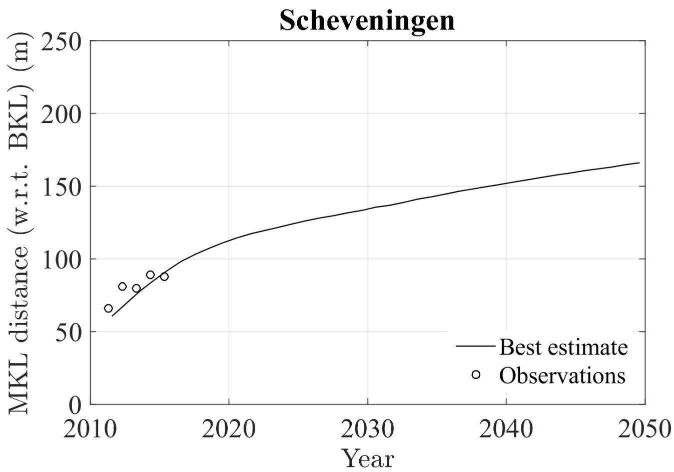
As an example, the location of the potential kitesurfing area for the situation 1 year and 5 years after construction is mapped in Figure D.2a and Figure D.2b.

STROLLING

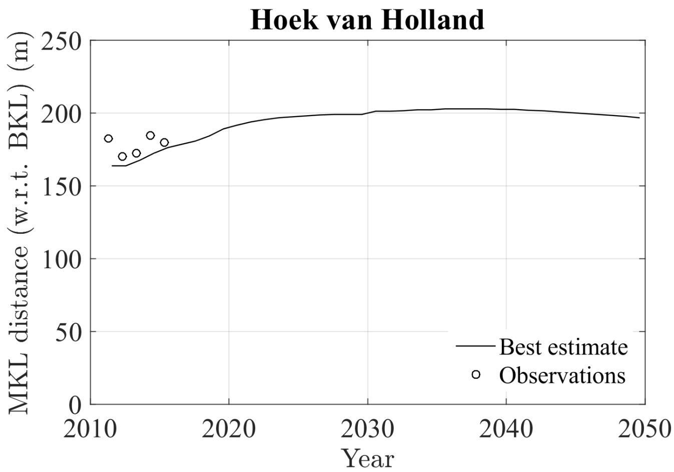
In Figure D.3 a spatial presentation of the 0 m NAP contour line is shown for 2011, 2016, 2030 and 2050. The outer, largest contour line is taken as the beach length. The small circle on the south-eastern side of the Sand Motor is the contour line of the dune lake and the northern circle is the lagoon. Those lengths are neglected in the calculation.

D.3. HABITAT PROVISION

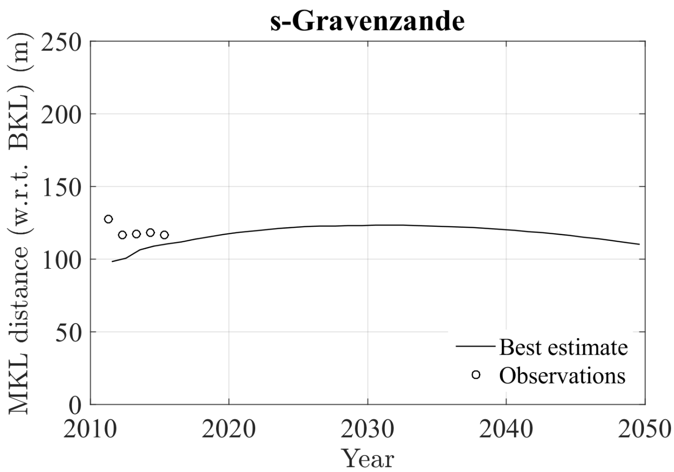
Every 5 years an ecotope map is made visualizing the location of the ecotopes at the nourishment section. In Figure D.4, D.5, D.6, D.7 and D.8 the maps of respectively 2021, 2026, 2030, 2036 and 2041 are presented.



(a) Evolution of the MKL at Scheveningen

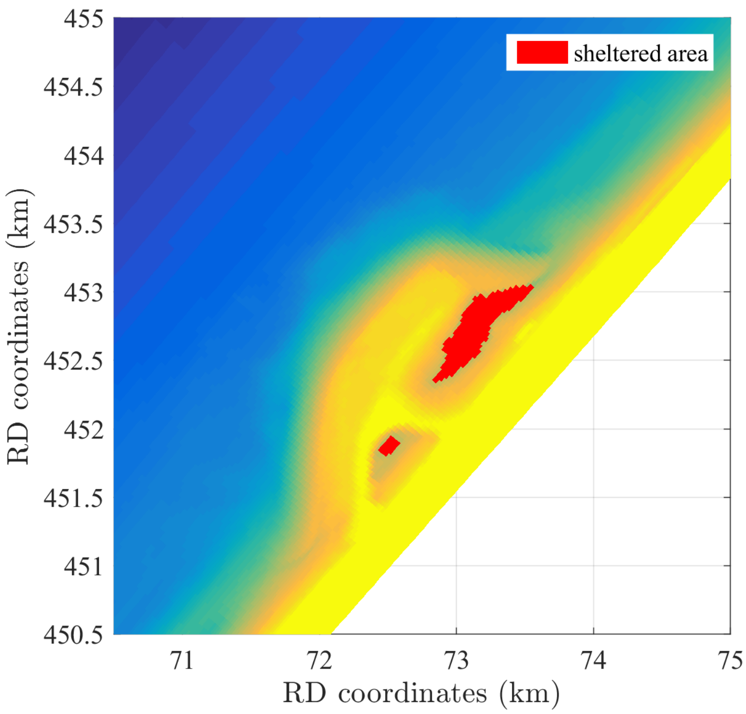


(b) Evolution of the MKL at Hoek van Holland

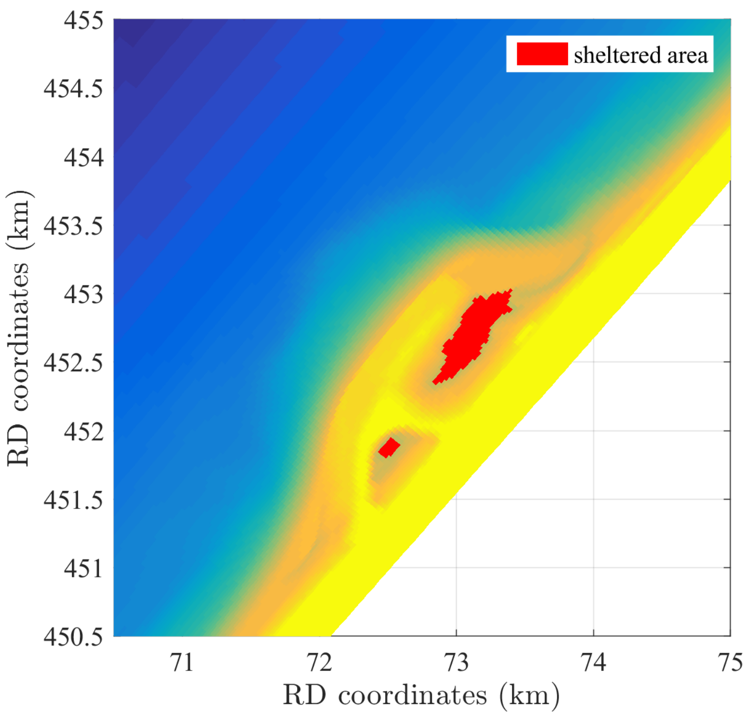


(c) Evolution of the MKL at 's-Gravenzande

Figure D.1: The predicted evolution of the weighted, averaged MKL distance with respect to the BKL for the Delfland coast sections. The best estimated coastline position (incl. an aeolian transport volume of 8.7 $m^3/m/y$) and the observations (JARKUS) are plotted together.

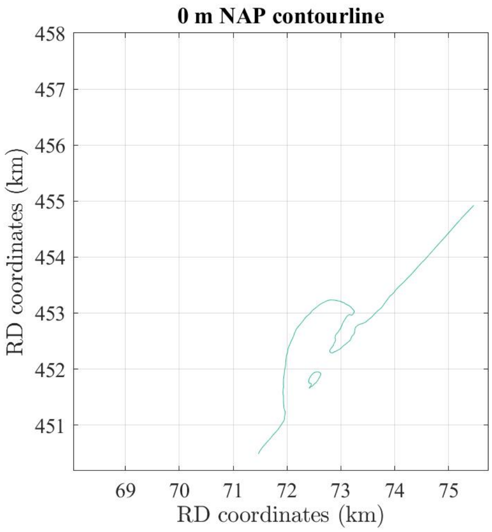


(a) In 2012, 1 year after construction.

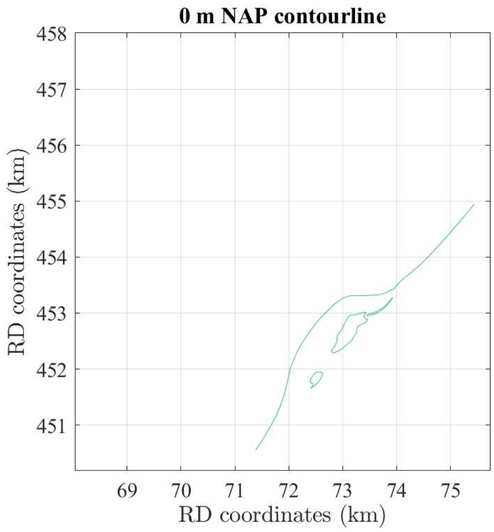


(b) In 2016, 5 years after construction.

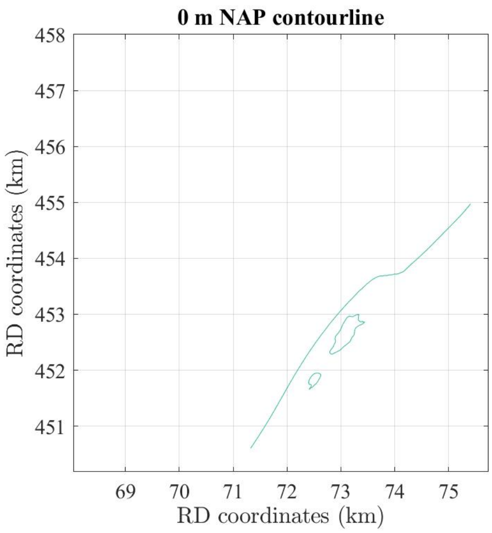
Figure D.2: Visualization of the predicted area suitable for kitesurfing



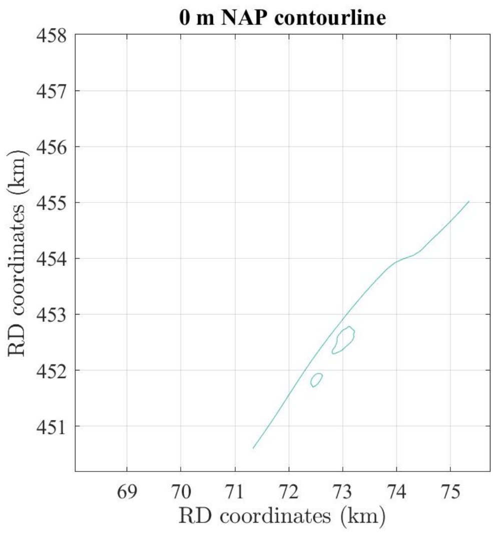
(a) Contour line in 2011, right after construction



(b) Contour line in 2016



(c) Contour line in 2030



(d) Contour line in 2050

Figure D.3: The predicted course of the 0 m NAP contour line throughout the years

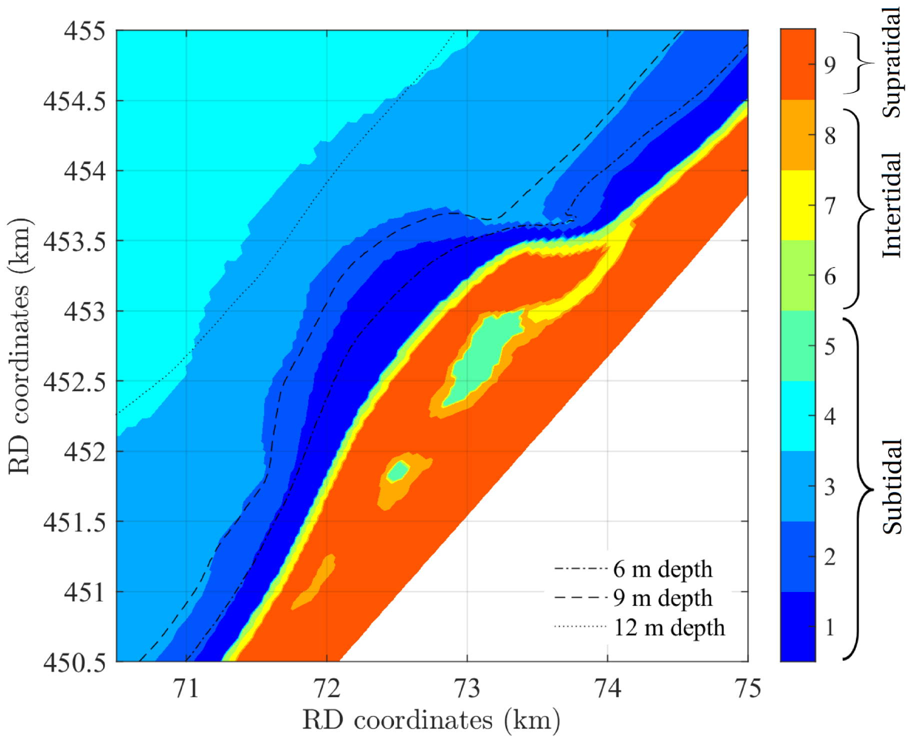


Figure D.4: Ecotope map of the Sand Motor in 2021, 10 years after construction.

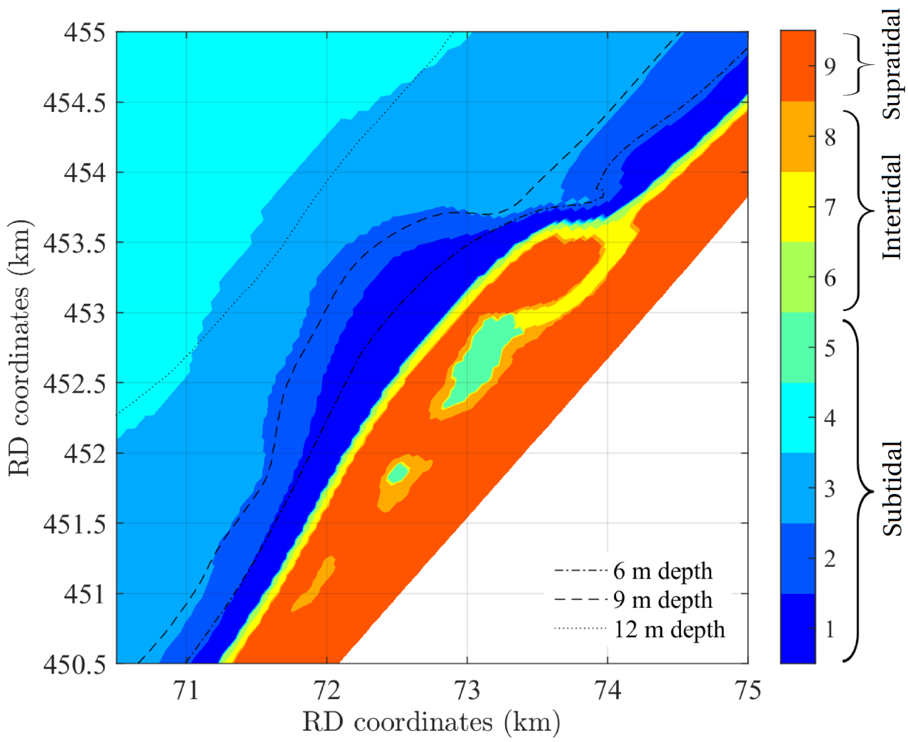


Figure D.5: Ecotope map of the Sand Motor in 2026, 15 years after construction.

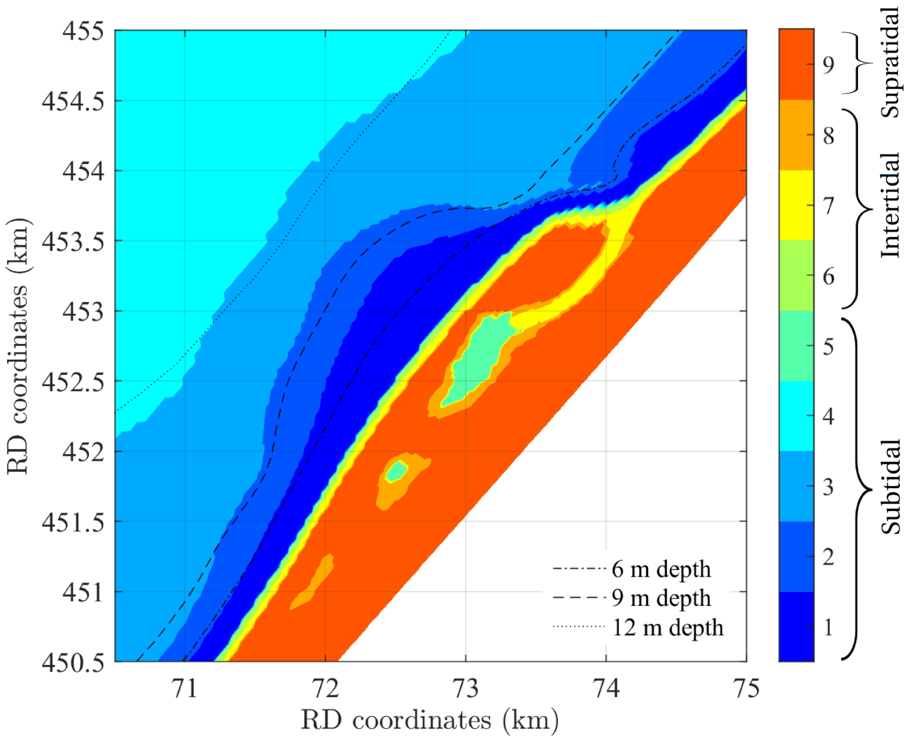


Figure D.6: Ecotope map of the Sand Motor in 2030, 19 years after construction.

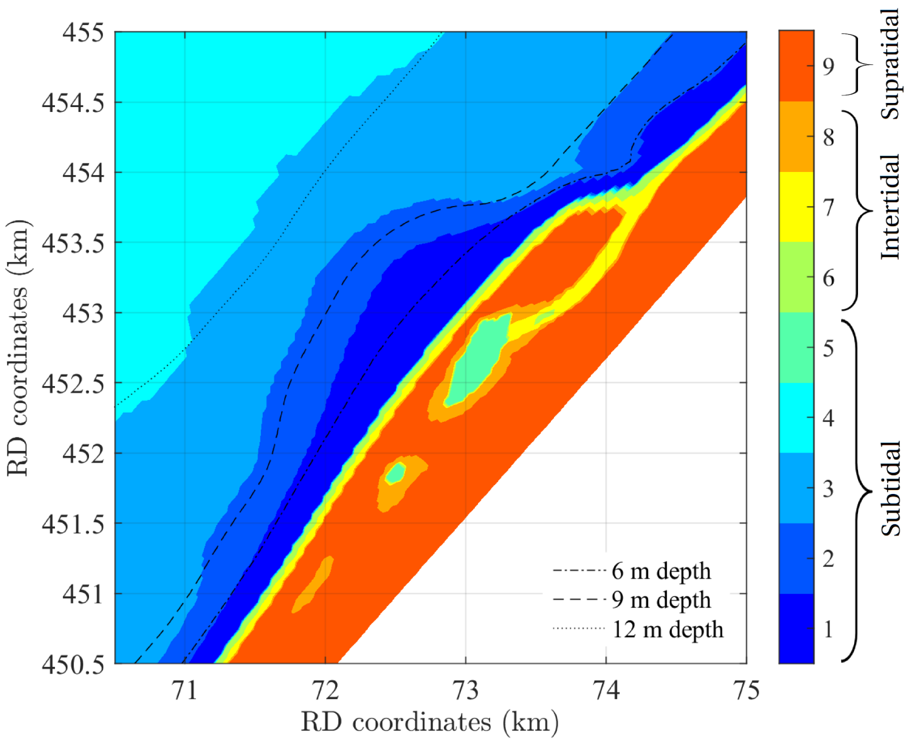


Figure D.7: Ecotope map of the Sand Motor in 2036, 25 years after construction.

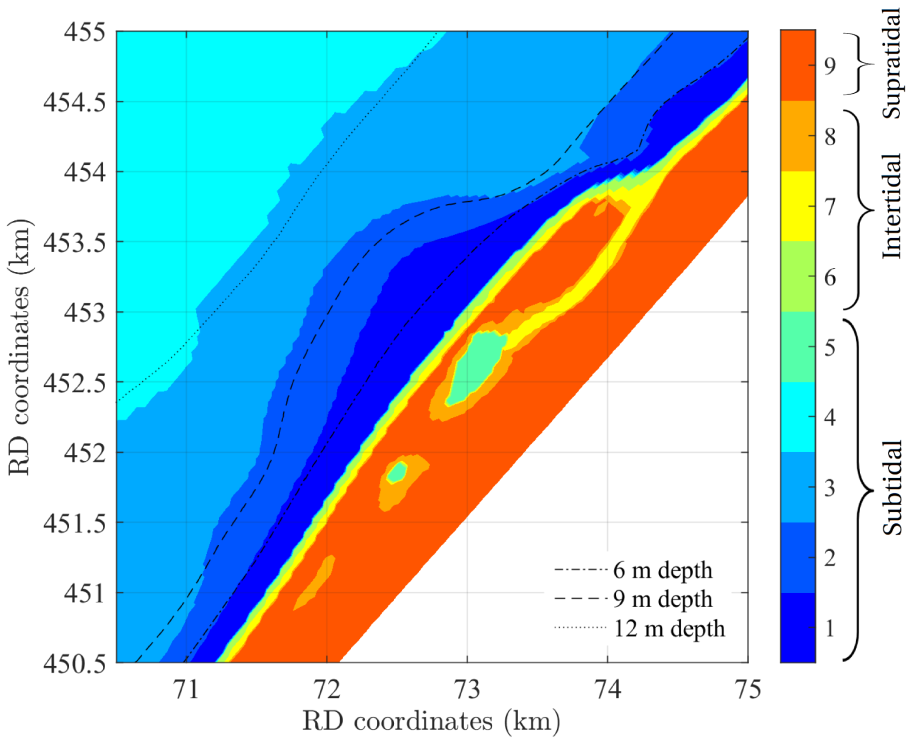


Figure D.8: Ecotope map of the Sand Motor in 2041, 30 years after construction.

E

Ecosystem service assessment: additional figures of the alternatives

In this appendix, additional figures are presented for further elaboration on the results of the ecosystem service assessment of the Sand Motor.

E.1. Coastal Protection

In Figure E.1, the alongshore development of the MKL distance with respect to the BKL is shown for the Sand Motor, the Island and the traditional nourishment for 2010, 2011, 2020 and 2030. The best estimate is presented, incorporating an aeolian transport loss of $8.7 m^3/m/y$ in the calculation of the MKL distance. Hoek van Holland is defined as the origin of alongshore distance.

E.2. Recreation

Kitesurfing

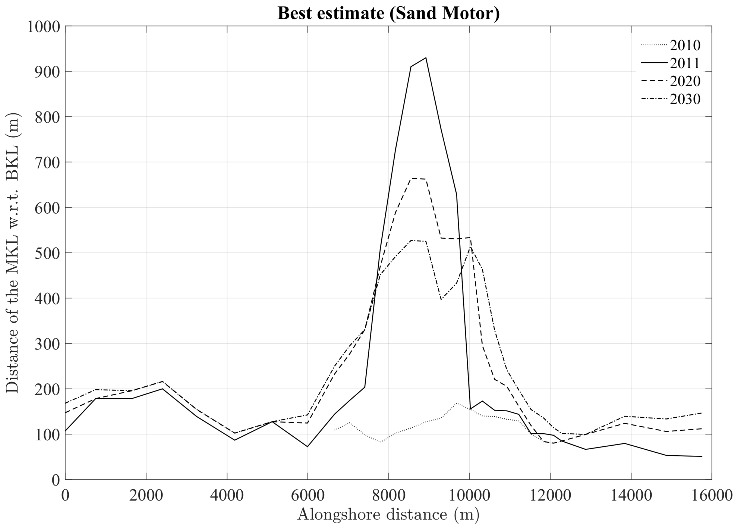
The locations of the kitesurfing spots are visualized for the Island in Figure E.2 and for the traditional nourishment in Figure E.3 for the years 2015 and 2030.

Strolling

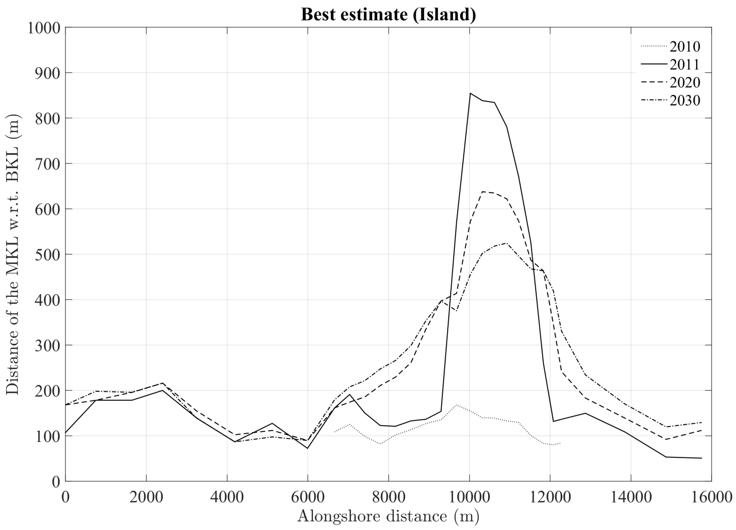
In Figure E.4 and Figure E.5 a spatial presentation of the 0 m NAP contour line is shown for 2011, 2013, 2020 and 2030 for the Island and the traditional nourishment. The largest contour line is taken as the beach length.

E.3. Habitat Provision

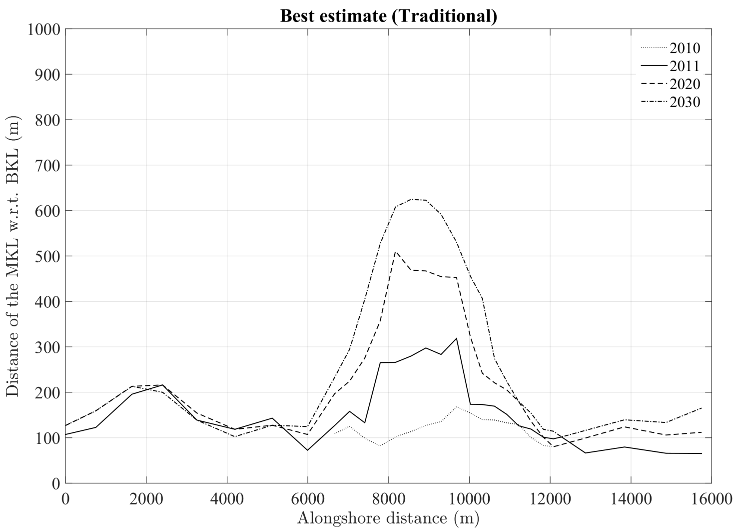
Every 5 years an ecotope map is made visualizing the location of the ecotopes at the nourishment section of the Island and the traditional nourishment scenario. In Figure E.6, the ecotope maps of the Island are presented for 2021 and 2026.Figure E.7 depicts the maps of the traditional nourishment in 2021 and 2026.



(a) Sand Motor.

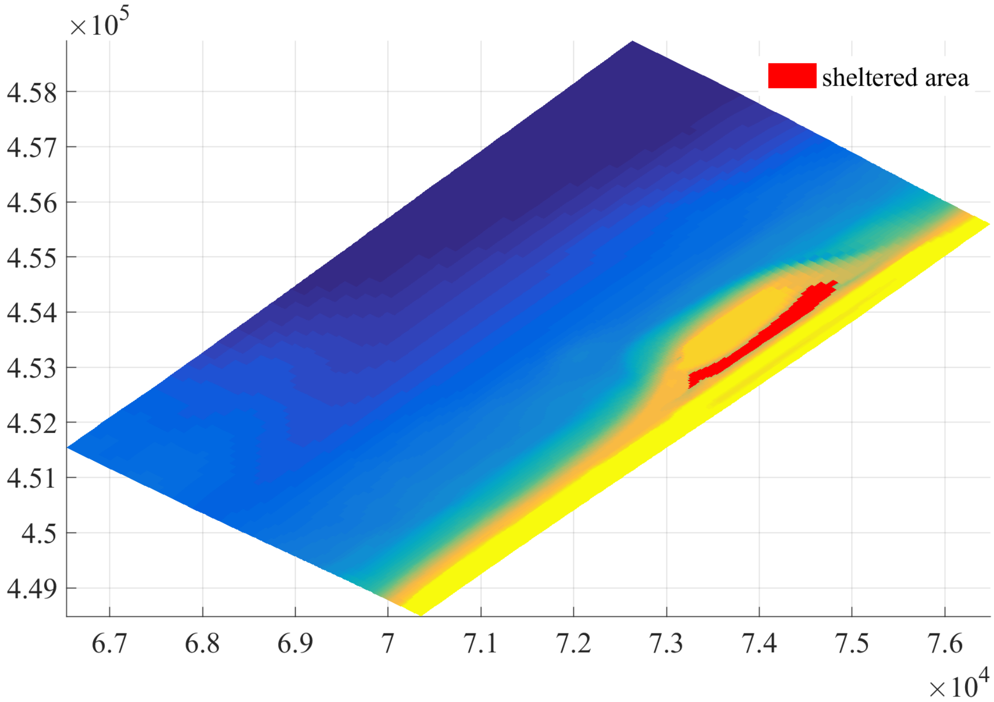


(b) Island

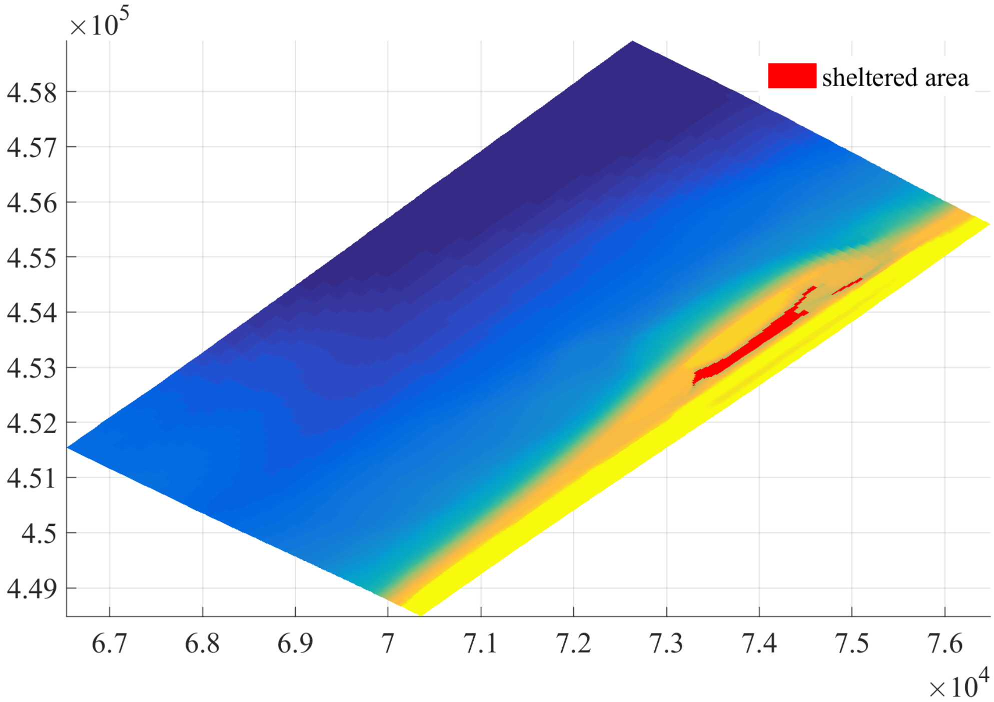


(c) Traditional nourishment

Figure E.1: Alongshore development of the best estimated MKL distance with respect to the BKL for the years 2010, 2011, 2020 and 2030. The origin of the alongshore distance is located at Hoek van Holland.

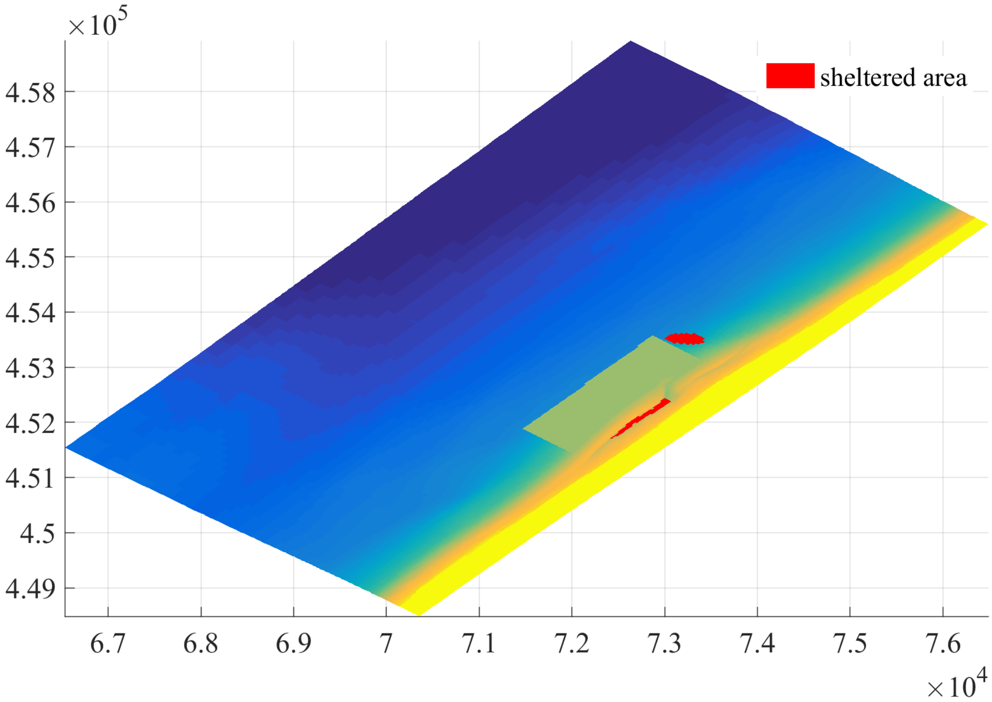


(a) 2015

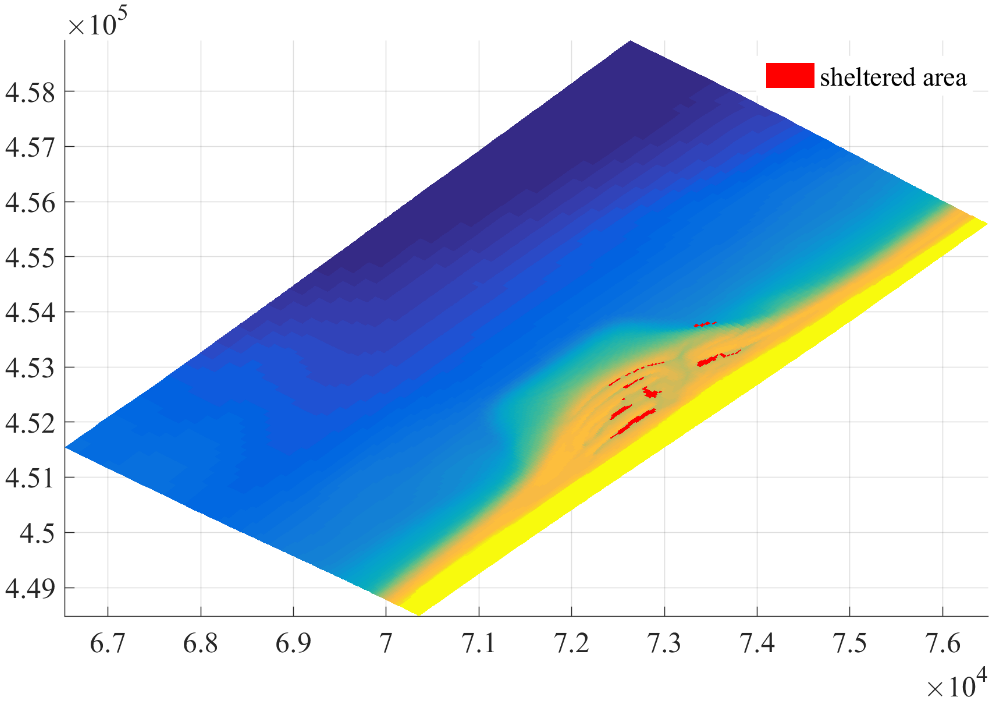


(b) 2030

Figure E.2: Vizualization of the area suitable for kitesurfing at the Island for the years 2015 and 2030.

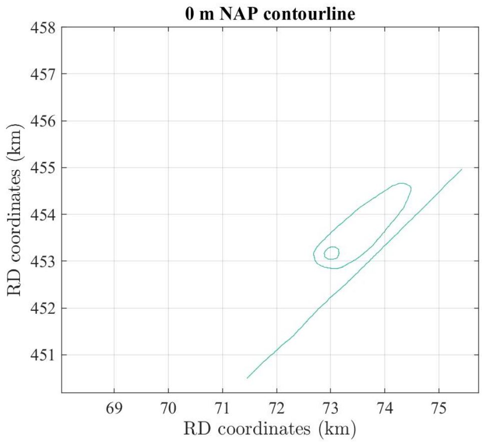


(a) 2015

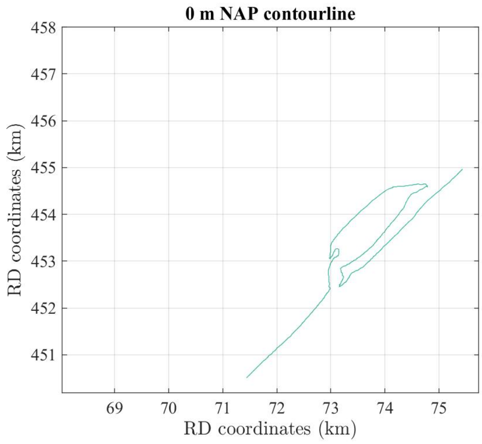


(b) 2030

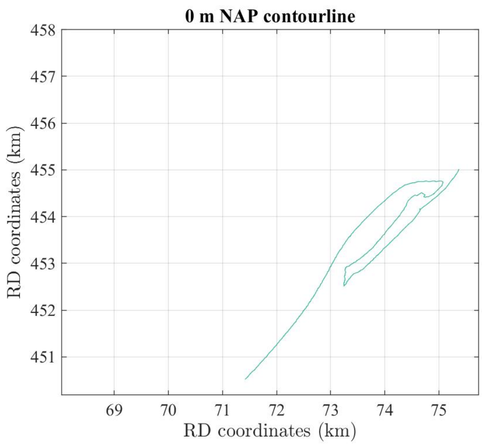
Figure E.3: Vizualization of the area suitable for kitesurfing at the traditional nourishment for the years 2015 and 2030.



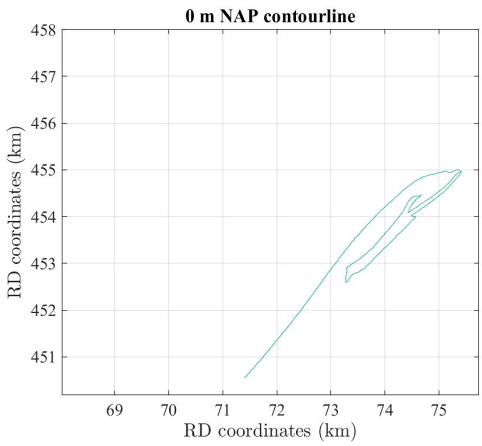
(a) 2011



(b) 2013

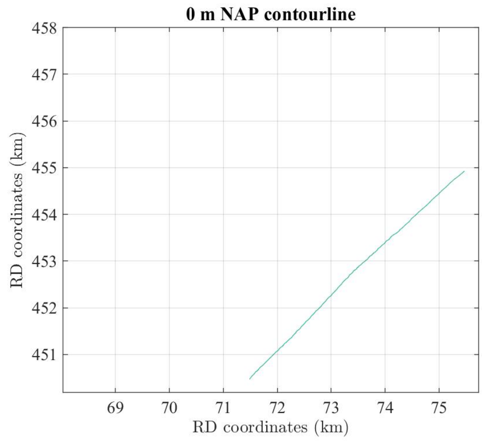


(c) 2020

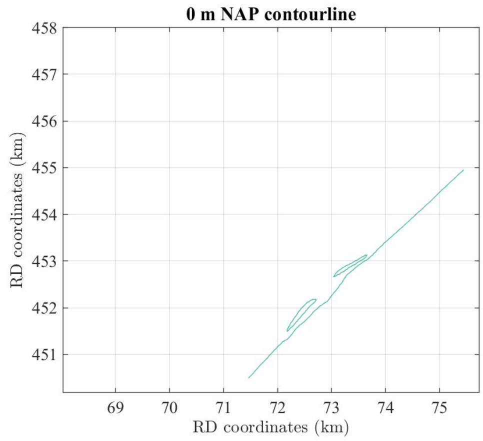


(d) 2030

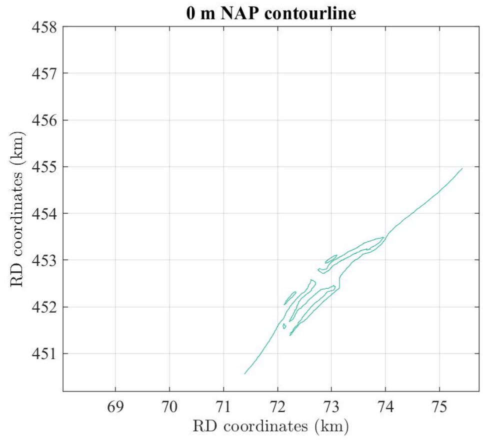
Figure E.4: The course of the 0 m NAP contour line throughout the years at the nourishment section of the Island.



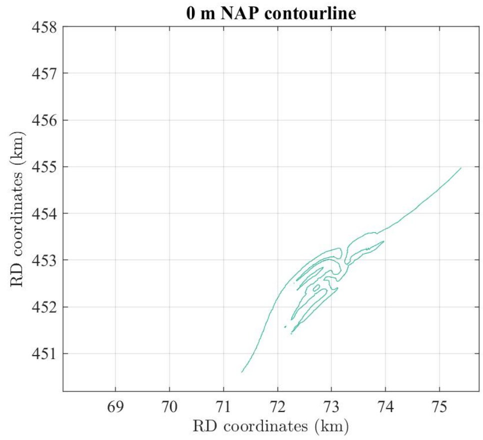
(a) 2011



(b) 2013

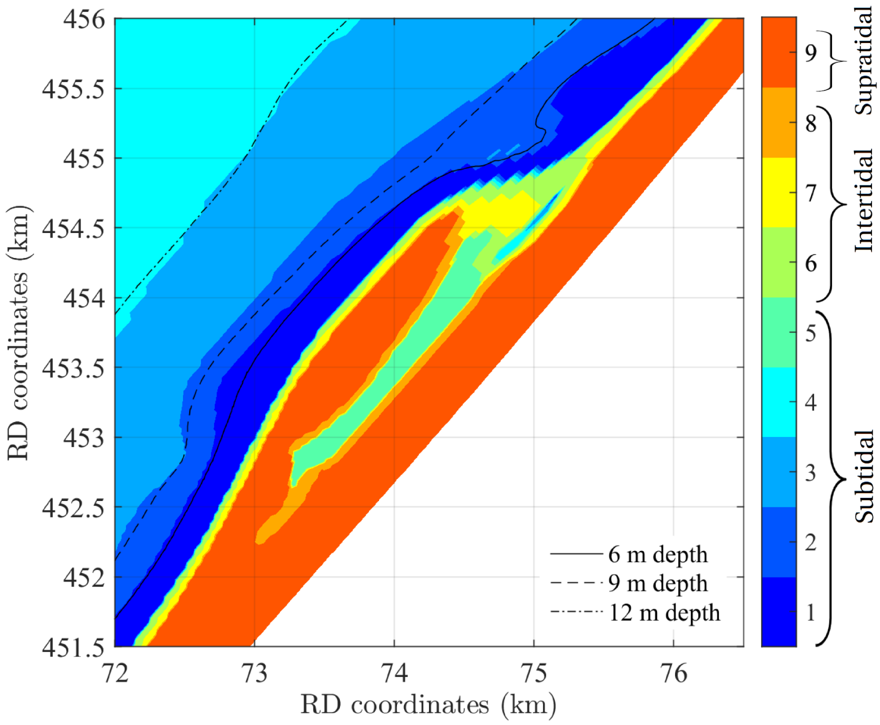


(c) 2020

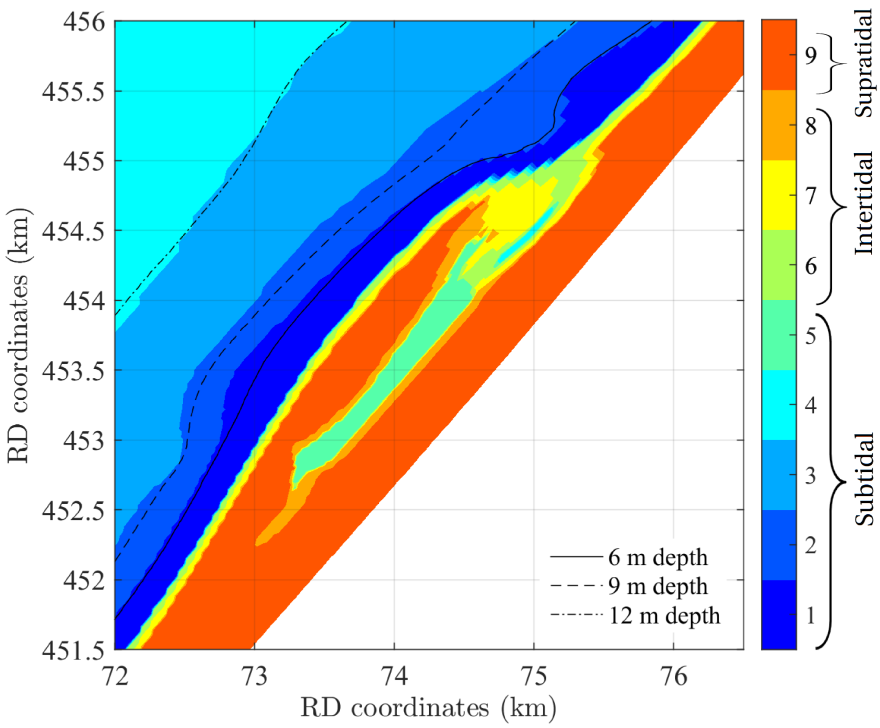


(d) 2030

Figure E.5: The course of the 0 m NAP contour line throughout the years at the nourishment section of the traditional nourishment scenario.

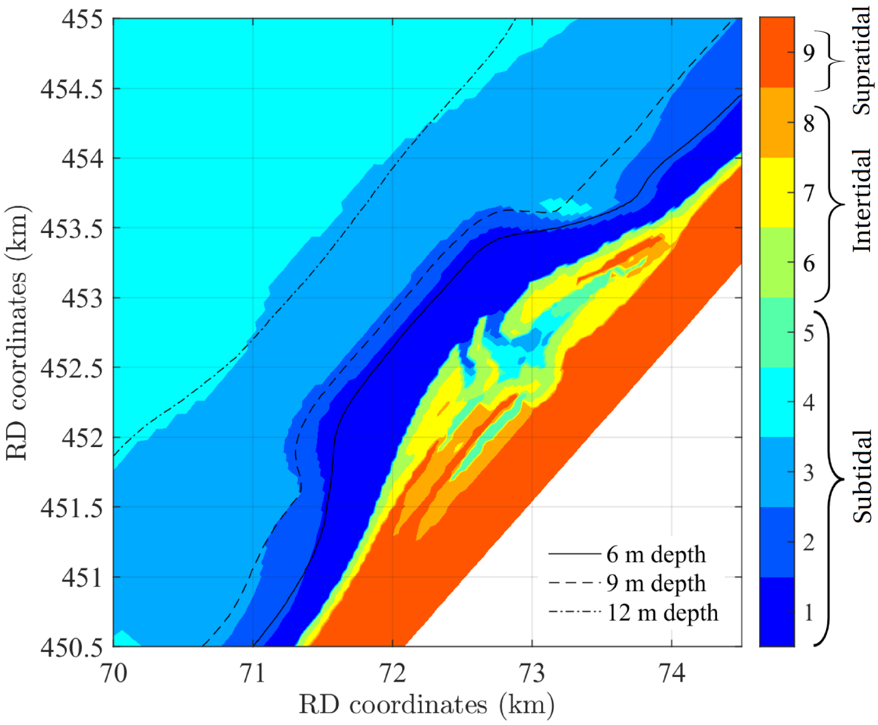


(a) Ecotope map of 2021.

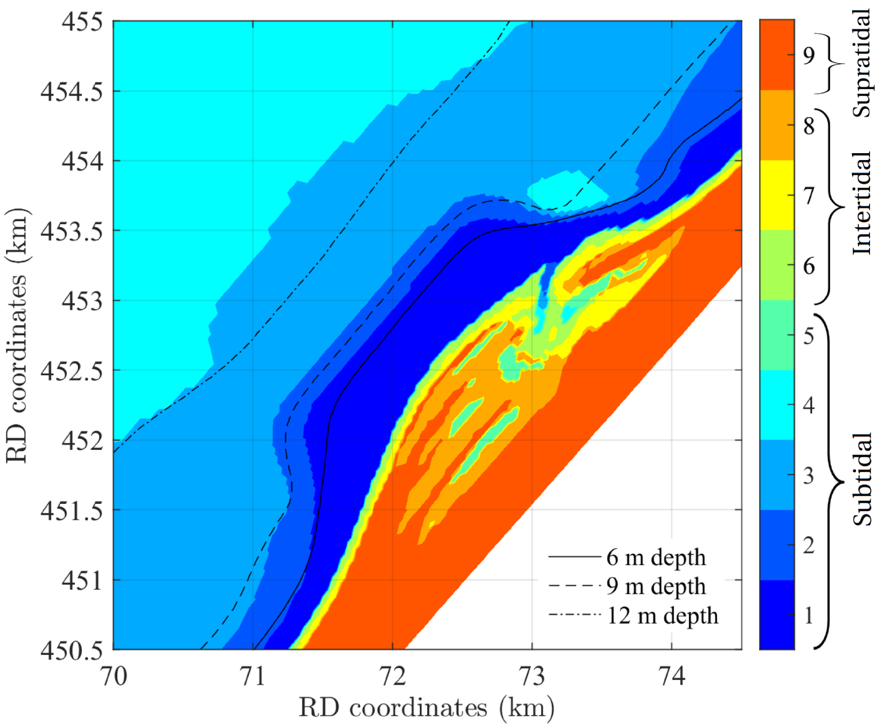


(b) Ecotope map of 2026.

Figure E.6: Ecotope map of the Island for the years 2021 and 2026. The contour lines of the 6, the 9 and the 12 m depth contour are depicted in the maps as well.

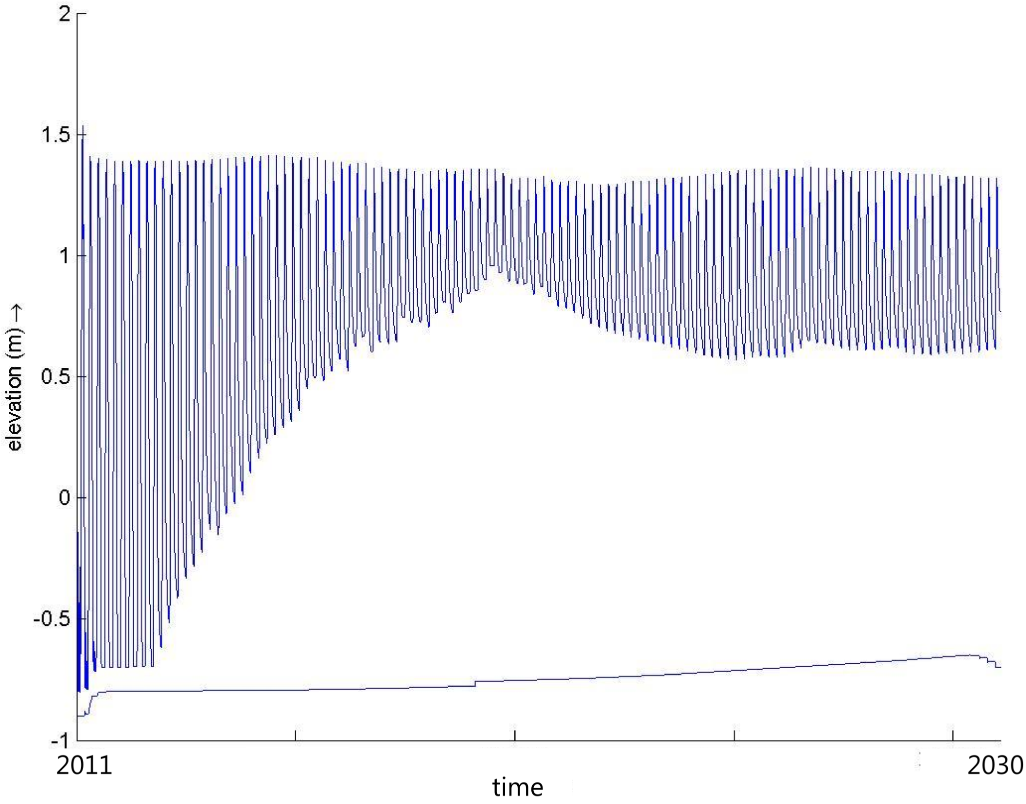


(a) Ecotope map of 2021.

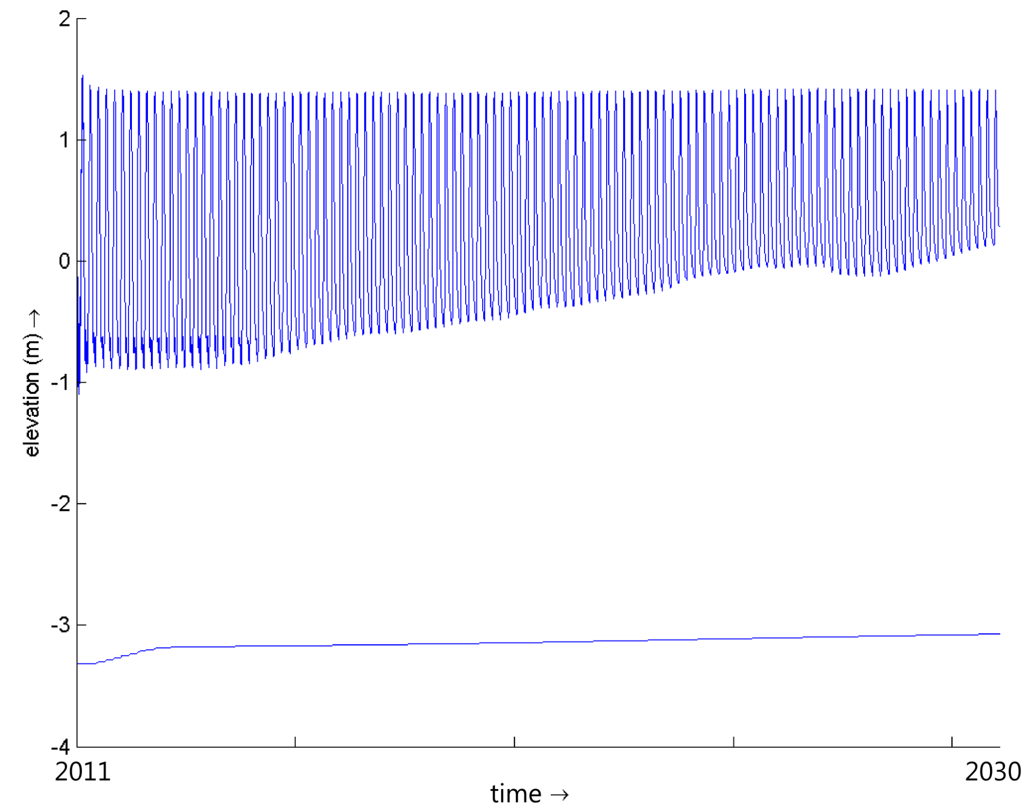


(b) Ecotope map of 2026.

Figure E.7: Ecotope map of the traditional nourishment for the years 2021 and 2026. The contour lines of the 6, the 9 and the 12 m depth contour are depicted in the maps as well.



(a) Sand Motor



(b) Island

Figure E.8: Water level and bed level variation of time of the Sand Motor and the Island.