Report

Influencing the SPR for storm surge events

A cross-border XBeach application

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Report

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1 Introduction

1.1 Background

1.1.1 Interreg NSR VB Building with Nature project

Building with Nature (BwN) is a phenomenon already known for several decades in which natural forces are used to build, construct or maintain a human intervention. Building with Nature is also known as Natural Flood Management (UK) or Natural and Nature-Based Solutions (USA). In this interregional North Sea project experiences with Building with Nature (BwN) in different countries are shared.

The Interreg VB North Sea Region Building with Nature project (2015-2021) has the overall aim, to make coasts, estuaries and catchments of the North Sea Regio (NSR) more resilient to climate change by both applying and learning from the implementation of Building with Nature (BwN) measures. The project is taking place in the North Sea Region, involving 15 partner organisations from Norway, Sweden, Denmark, Schleswig-Holstein (DE), Niedersachsen (DE), the Netherlands, Belgium and Scotland (UK). The overall objective of the BwN project is to make coasts, estuaries and catchments of the North Sea Region (NSR) more adaptable and resilient to the effects of climate change. The main goal to achieve during the time frame of the BwN project is to create a well-documented evidence base, by transnational knowledge exchange, that allows for policymakers and asset owners to incorporate Building with Nature / Nature Based Solutions and principles in future decision-making processes.

1.1.2 Goal of the current study

Within the BwN project the Source-Pathway-Receptor (SPR) approach is used to understand where sediment originates from (the source), what the general net pathway is and how this affects the receptor (i.e. a coastal function such as safety, recreation etc.). This will provide insight into the smart application of nature-based solutions in the light of the total system change, such as sea level rise.

In the Work Package 3 (WP3) prolongation of Interreg BwN (June 2020 to June 2021), the primary objective of the study is to assess the effect of Building with Nature techniques on influencing the SPR, focussing on dune safety during storm surge events. In this study we will only investigate the main Building with Nature technique for sandy coasts: nourishments. The direct impact of nourishments on dune safety will be tested for different nourishment types and designs under storm conditions. As shown in Wilmink et al. (2021), nourishments can change the coastal profile shape on the long term, which can therefore indirectly affect the dune safety during storm conditions. This effect is included for a couple of cases, but not investigated in detail.

The impact of SLR on the dune safety is also investigated in order to make a first assessment of how future coastal shapes will affect the dune safety. In this SLR-scenario the long-term effect of a structural nourishment strategy is incorporated.

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1.2 Research questions

The main research question is: "*How can Building with Nature techniques, as nourishments, affect dune safety during storm events?*"

To answer the main research question, four sub questions are defined:

1) *Can XBeach be used as a tool to assess the impact of Building with Nature techniques on dune safety?*
2) *What scenarios (e.g. nourishment placement, design, SLR) can be set up to assess the direct impact on dune safety due to storm surges?*
3) *How can nourishments affect the dune safety?*
4) *How will future climate scenarios in combination with different adaptation strategies affect the dune safety?*

1.3 Reading guide

In Chapter 2 the overall methodology for this study is described. Chapter 3 presents the three study sites that were selected, and in Chapter 4 the model (XBeach) is validated for the storm measurements of these study sites. In Chapter 5 the validated model then subsequently used to investigate dune safety under a set of scenarios reflecting different nourishment types, designs, SLR-conditions and adaptation strategies. The report is completed with a discussion on the limitations of the used methodology and putting the results in perspective.

2 Methodology

2.1.1 General approach

Building with Nature techniques aim at influencing the Source-Pathway-Receptor (SPR) for long term sediment processes, but can also have an effect during storm surge events (see Figure 2-1). To assess the impact of nourishments on dune safety during storm conditions, the XBeach model is used in this study. XBeach is a numerical model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and back-barrier during storms, especially focusing on dune erosion during storm conditions. XBeach will be used to assess how (for each selected lab) the Source Pathway and Receptor for water and sediment can be influenced in such a way that benefits the receptors (e.g. flood safety or dune resistance, see Figure 2-2) can be achieved. The aim is to relate the change in dune strength, i.e. resistance against erosion (delta R, in Figure 2-2) to storm surges as a function of nourishment and natural morphological development scenarios. Three tasks are defined:

1) **Select and collect observations of surge events for three study sites**
   For Langeoog (Germany), Sylt (Germany) and Krogen (Denmark) measurements on morphological changes have been conducted after a storm event, and are used in this study.

2) **Validation of the XBeach model**
   The XBeach model is validated using the collected measurements on study sites Langeoog and Sylt. The XBeach model setup applied for Sylt is the Danish calibrated and validated model, validated in Vedersoe, Heatherhill, Havstokken and Marielyst in Denmark. The model is tested by comparing the observed morphological changes of the dune and beach to the model predictions. Both one-dimensional (1D) transect models and two-dimensional (2DH) area models are setup and tested. Goal of this task is to gain confidence in XBeach' capability to reproduce the storm impact on dunes, so it can be used for subsequent task 3.

3) **Testing scenarios for the strategic placement of nourishments to assess the (in)direct effects on dune safety due to a storm event**
   This task involves simulating a set of scenarios to test the impact of Building with Nature techniques on dune safety during storm conditions. A set of scenarios are selected based on different nourishment placement or design, morphological configuration and conceptional climate change profile developments. These scenarios are then applied for all three study sites to cover a range of site-specific conditions. The goal of this task is to support our understanding of the effects of nourishments on coastal behaviour during storm conditions.

Model setup, runs and analysis are performed by DCA for the Sylt and Krogen cases and by NLWKN and Deltares for the Langeoog cases.
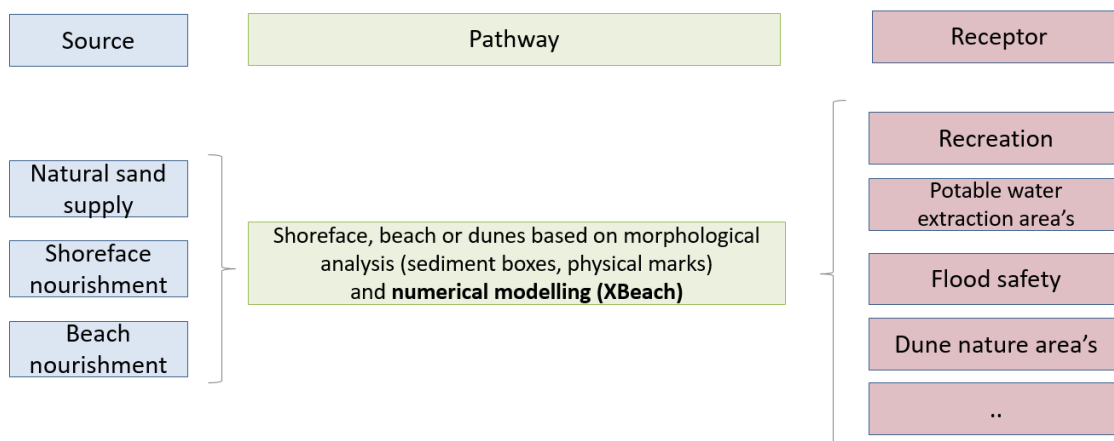
Figure 2-1 flowchart Source Pathway Recepter approach for sediments (nourishments)

SPR flowchart applied to dune resistance to storm surge (Water&Sediment)

R − S = F

$\Delta R = f(\text{Volume}_{nourished}, \text{Position}_{nourished\ Volume}, \text{etc.....})$
$S = f(\text{Sourcing forces [waterlevel, wave, nourishments]})$
F= determined ΔR compared to situation without nourishment by num. simulation software (Xbeach)
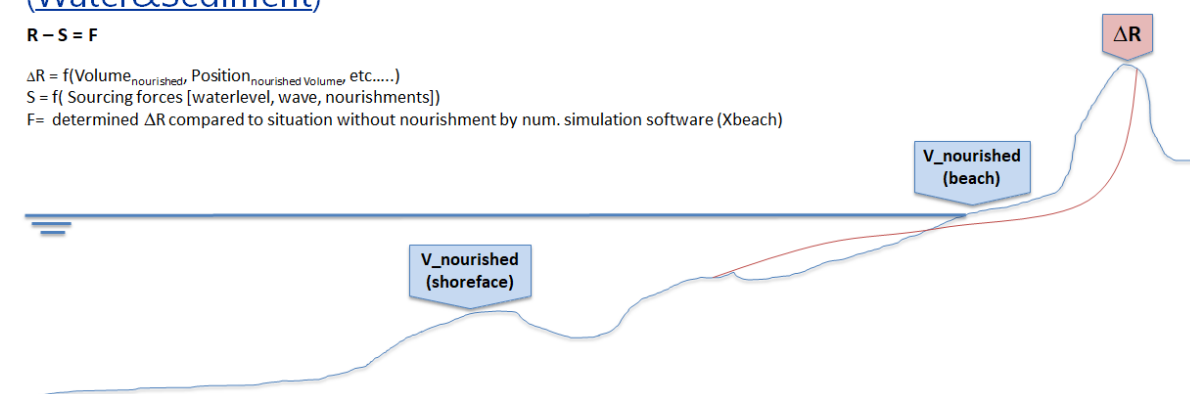

Figure 2-2 Example of SPR approach for flowchart applied to dune resistance storm surges

2.1.2   Quantification of the effects on dune safety

The primary goal of this study is to assess the change in dune resistance (ΔR) during storm conditions using the XBeach model. The impact on the dune resistance is quantified using two morphological indicators: dune erosion volume and dune retreat.

The dune erosion volume is defined as the difference in volume above a vertical datum per meter alongshore between the initial bed level and the bed level at a given time. The maximum storm surge water level is applied as lower vertical datum for this computation, see Figure 2-3.

The dune front retreat is the landward migration of the dune front. It is defined as the horizontal displacement at a given reference height in the considered time period. In this study the dune retreat

is determined for four reference levels (i.e. MSL, dune foot, dune face and upper dune face, see Figure 2-3) to make a complete assessment of the profile development.
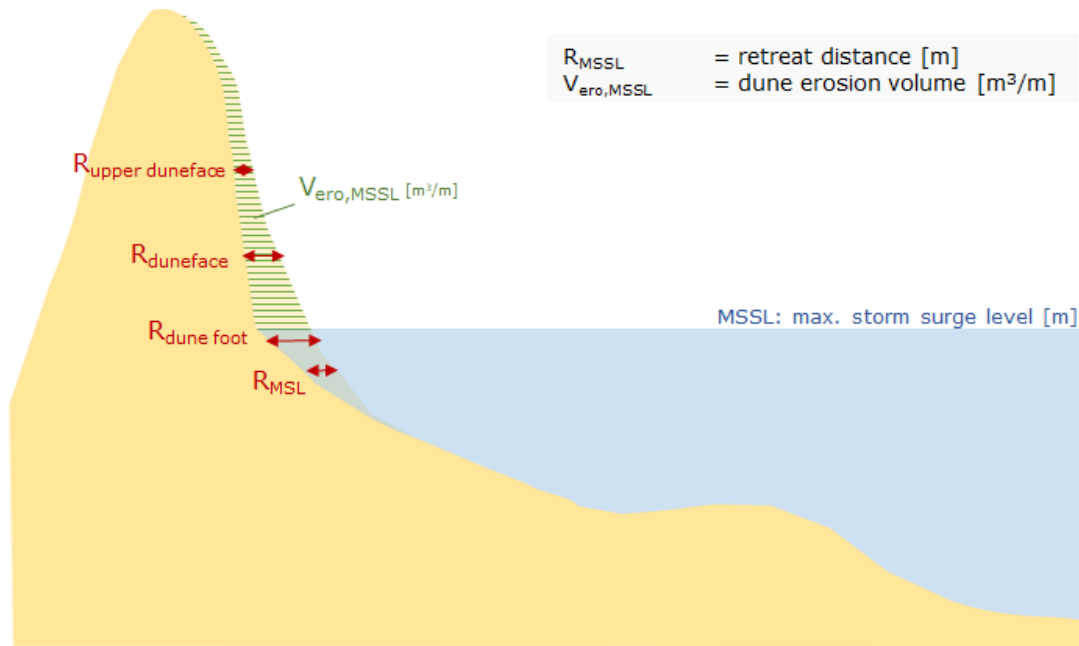

Figure 2-3 Morphological indicators used to assess and compare the model results.

3 Site description and storm measurements

3.1 Langeoog, Germany

The island of Langeoog is one of seven inhabited barrier islands situated along the East Frisian German North Sea coast (Figure 3-1). A detailed description of the study site Langeoog can be found in the National Analysis Report for Lower Saxony of the NLWKN (Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz; Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency) [Interreg VB NSR BwN – NLWKN, 2021].

Figure 3-1 Langeoog (Copernicus Sentinel 2-Image 06.08.2018)

From 5 to 7 December 2013 storm 'Xaver', referring to the name of the low-pressure system, caused an extreme storm surge and significant dune erosion. High resolution measurements of pre- and post-storm bathymetry were collected and Langeoog is therefore selected as a case study for XBeach validation in this study.

A maximum storm surge water level of NHN + 3.95 m was observed at Langeoog gauge station (Figure 3-2) [WSA EMS-NORDSEE]. For the wave input in the XBeach model, a SWAN model was used, created in the EasyGSH project (Plüß et al., 2020 - EasyGSH-DB (baw.de)). The SWAN-datapoint used for XBeach input is located around 10 km in distance from the island and at around 20 m depth. Measurements from the platform FINO1 are compared to the SWAN model regarding hydrodynamic forcing conditions (Figure 3-2).

The used bathymetry for creating the model grid is based on bathymetric and LIDAR-photogrammetric measurements by NLWKN and BSH respectively.
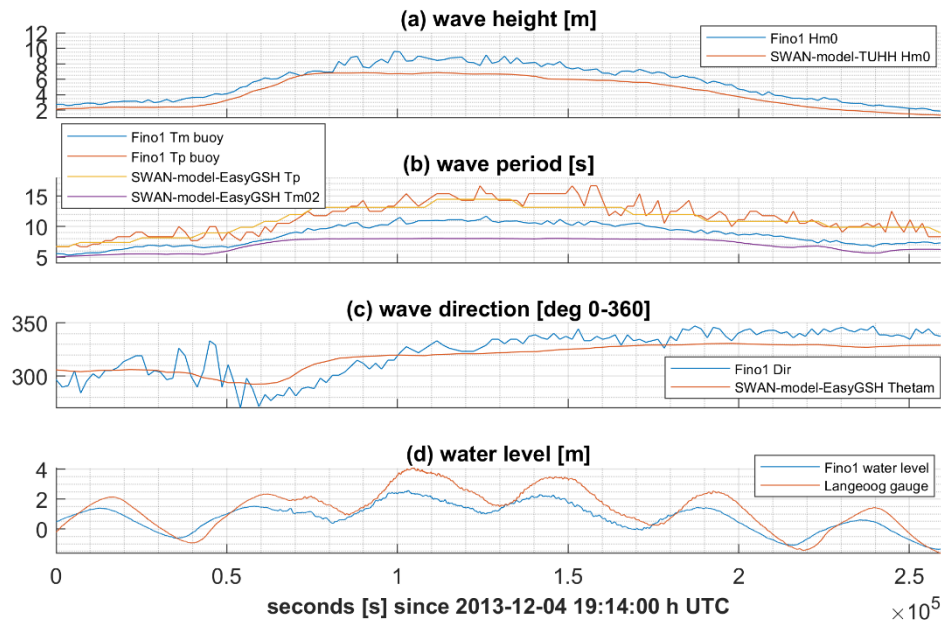
Figure 3-2: Comparison of measured wave data at FINO1-platform (a-d) (BMWi, PTJ) and SWAN model by EasyGSH-project (a-c) (www.easygsh-db.org, https://www.doi.org/10.18451/k2_easygsh_1) and WSA Ems-Nordsee (d)

3.2 Sylt, Germany

The island of Sylt is the northern most of the German Frisian Islands in the Wadden Sea, bordering Denmark to the north (Figure 3-3). It has ~55 km coast exposed to the North Sea, and has an estimated 22.000 inhabitants, of which the majority (~10.000) lives in main town of Westerland, which lies directly exposed to the North Sea, thereby creating a challenge with regards to coastal retreat.

Sylt sees an estimated 1 million m^3 sediment leaving the west coast annually, with the ends (north and south) facing the highest erosion rates. The natural dune retreat rate is 1 to 4 m per year along the west coast of Sylt. Historically the coast has been reinforced with groynes, sea walls, revetments and tetrapod's, all of which fights the symptoms of coastal erosion but not the driving processes.

The first nourishment took place in 1972 with an estimated volume of 1 mio. m^3, and Sylt has subsequently been nourished several times. Until 1996 purely fed on the beach, after which bar- and shoreface nourishments have been carried out with varying effect.

 A detailed description of the study site Sylt can be found in the National Analysis Report for Sylt by LKN.SH (Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein;The Agency for Coastal Defence, National Park and Marine Conservation, Schleswig Holstein) [Interreg VB NSR BwN - LKN-SH, 2019]
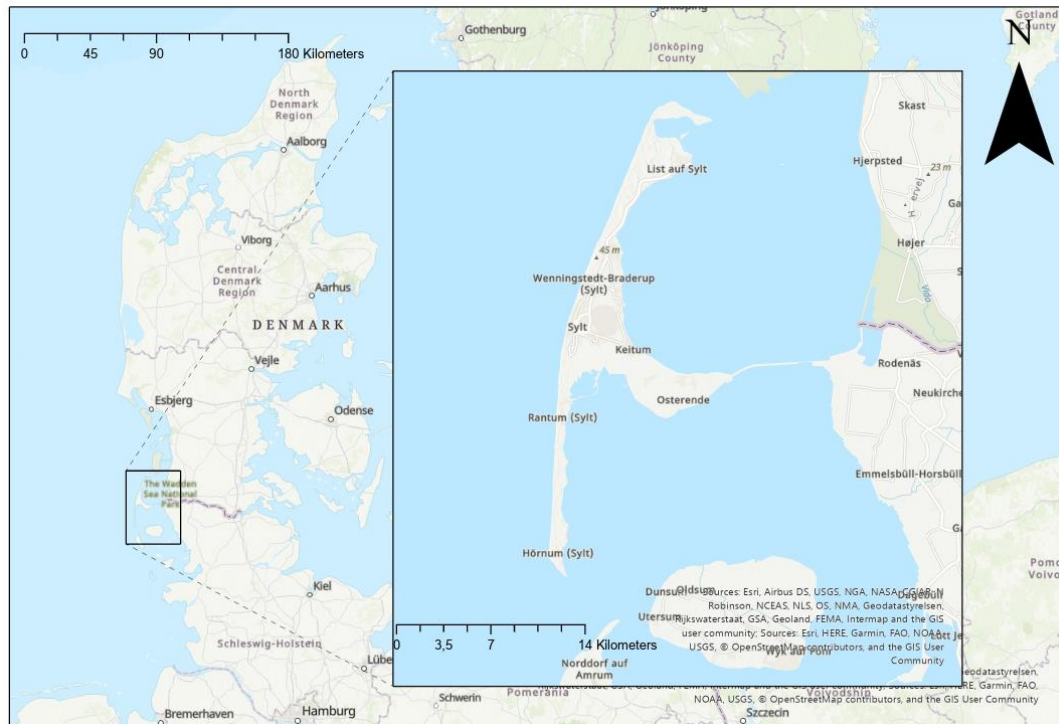
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Figure 3-3   Overview of the model site Rantum on island of Sylt.

The forcing conditions used for the Sylt model are based on a storm on the 3rd of December 1999. The storm was named Adam (or "Decemberorkanen") in Denmark, Orkan Carola in Sweden or Cyclone Anatol given by the Free University of Berlin. The hurricane saw sustained winds of 146 km/h, and maximum water level at Westerland on Sylt of 3.45 m and wave heights exceeding 6 m.

The hydrodynamic data was received from The Agency for Coastal Defence, National Park and Marine Conservation, Schleswig Holstein (LKN.SH) and consists of measured water levels and wave climate during the 1 year period from May 1999 to May 2000 for different measurement sites as seen from Figure 3-4. A complete set of forcing conditions, water level, significant wave height, peak wave period and peak direction was achieved by combining measurements from Westerland with measurements from List. All measurements from List are adjusted for time difference and vertical displacements in all peak levels to match Westerland water levels. Position of water- and wave measurements can be seen in Figure 3-4.

The storm duration is chosen to 12 hours prior and post the peak water level, in total 25 hours. The forcing conditions are linear interpolated to match a sea state of 15 min throughout the storm. Water level and wave data can be seen in Figure 3-5 and Figure 3-6.
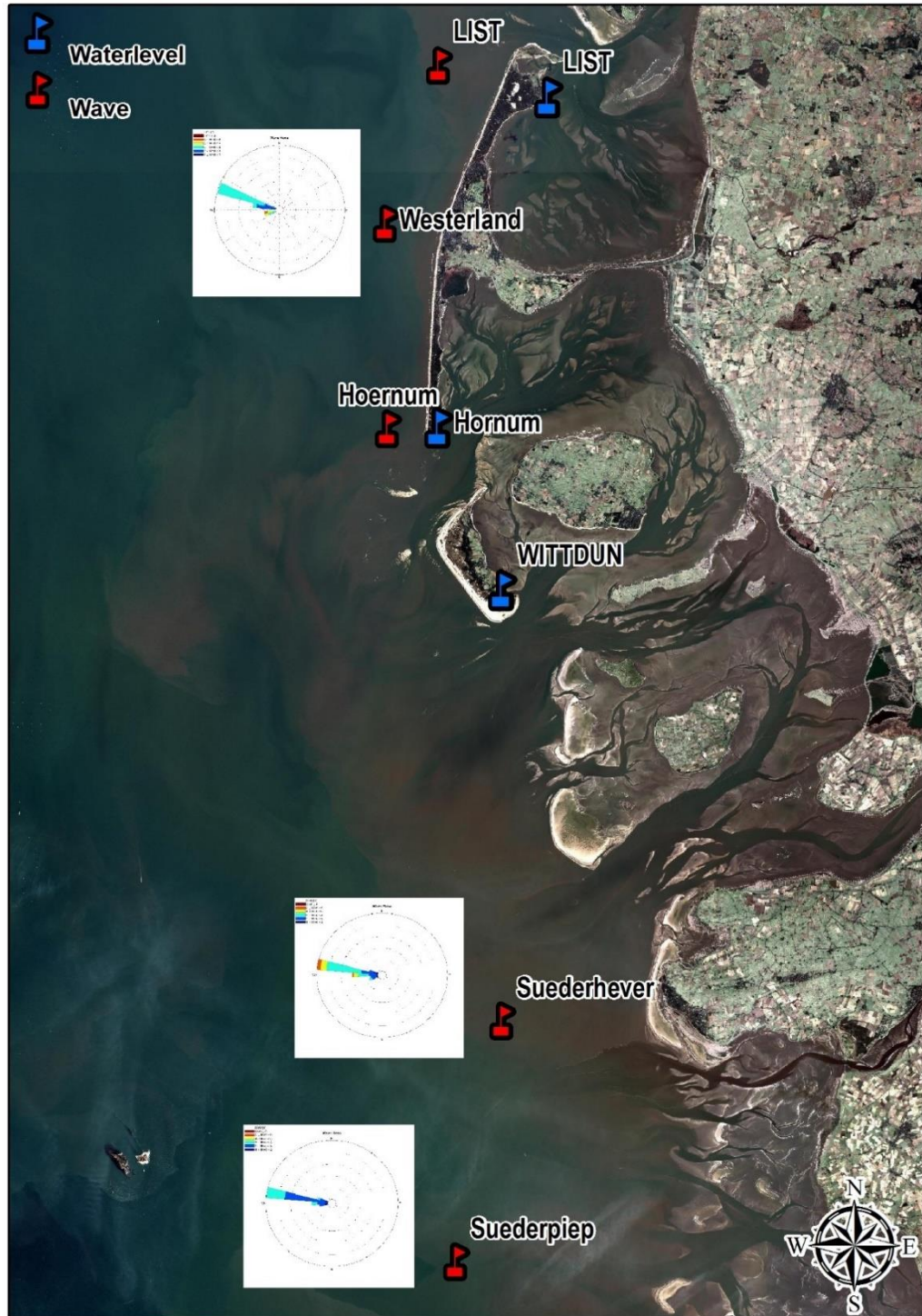
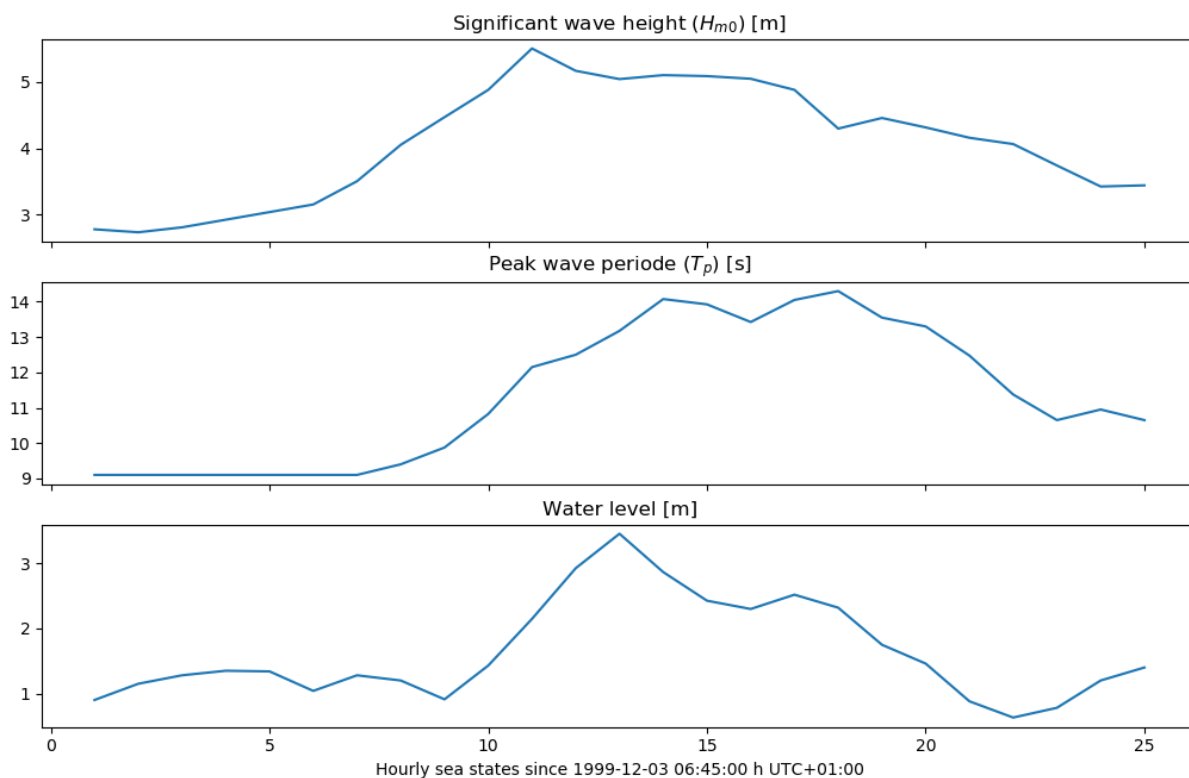*Figure 3-4 Overview of available data for the Sylt model.*

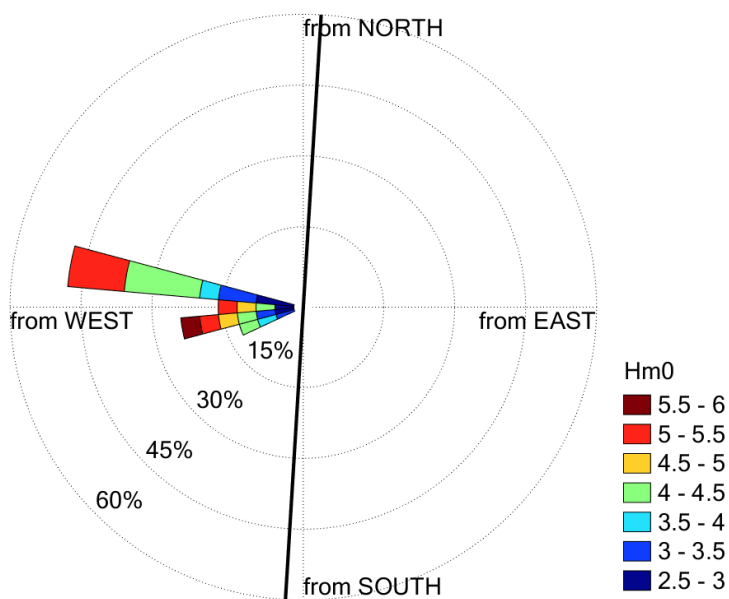*Figure 3-5 Forcing conditions of the December 1999 design storm applied for the Sylt model*

Figure 3-6 Wave rose of the December 1999 design storm applied for Sylt.

3.3 Krogen, Denmark

Krogen is situated on the west coast of Jutland, which is a micro tidal wave dominated sandy coastline. It sees high variations of the coastline and is quite dynamic. Krogen is not a town, but the name of the road which runs through the area. The location of Krogen and a close-up of the area can be seen in Figure 3-7.

A WWII bunker at Krogen was protected with a short rock revetment in 1944, but it collapsed in a storm in 2007. A comparatively low 1 m chronic erosion per year occurs at Krogen, but severe erosion during a storm surge of 46 m has been recorded just 10 km north of it. To compound this, WWII era bunkers still exists in the dunes, which tends to exacerbate the acute erosions problem, when they eventually topple from the dunes onto the beach. The coastal erosion at Krogen has since the 1990'es been compensated for, by regular shoreface and beach nourishments

This paired with narrow dunes and vast, low lying hinterlands makes for a great potential for flooding. The hinterlands of Krogen are varied in use; it contains a lot of farmland, towns, industry and many vacations homes, making flooding potentially very costly and potentially dangerous.

A detailed description of the study site Krogencan be found in the "Shoreface Nourishment effects- An analysis of the 2016 nourishment at Krogen by DCA (Kystdirektoratet; Danish Coastal Authority) (Interreg VB NSR BwN – DCA, 2020)
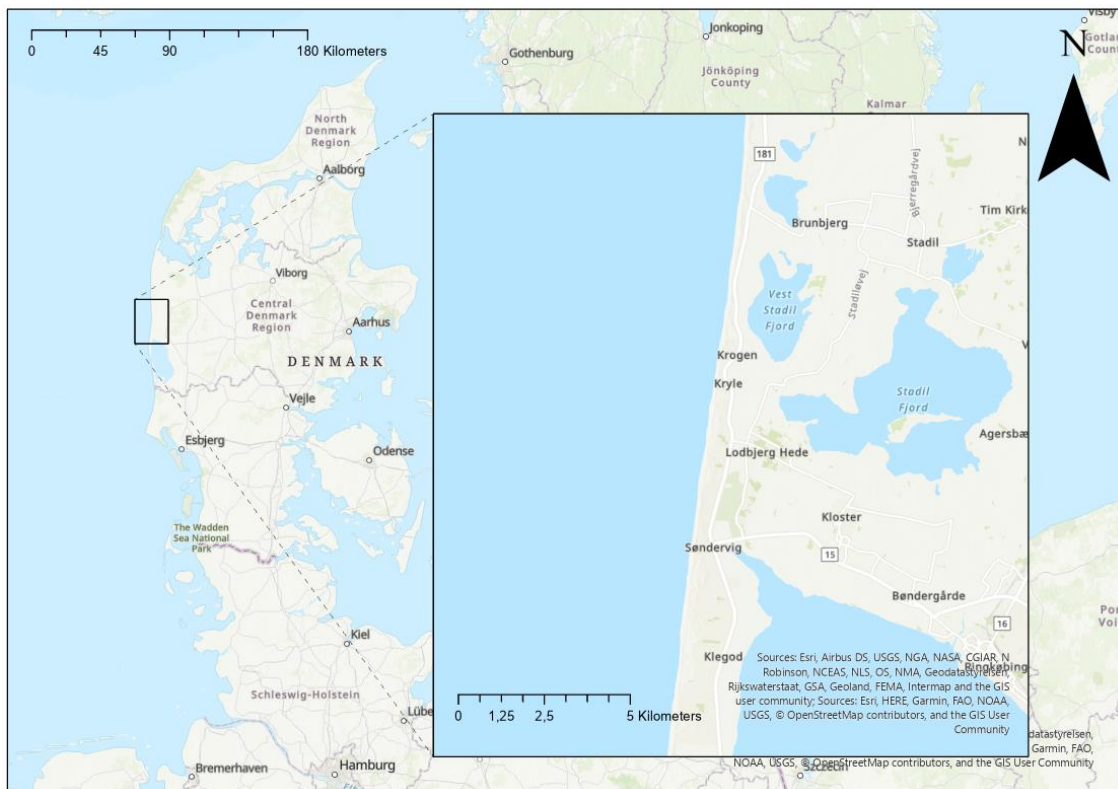
Figure 3-7 Overview of the model site of Krogen.

The forcing conditions used for the Krogen model are based on a storm on the 8th of January 2005. The storm was named Gudrun in Denmark (or "Januarorkanen"), Norway and Sweden, Cyclone Erwin given by the Free University of Berlin. The water level data was measured at Ferring, roughly 40 km north of Krogen. The maximum storm surge level was measured to 313 cm during the storm. The wave data used is measured at Nymindegab, which is approximately 40 km south of Krogen. The maximum wave height was measured to exceed 6 m during the storm. Based on the Danish national storm surge statistics, a design storm of 100 years return period is determined for Krogen by linear interpolation between a 100-year water level estimated for Thorsminde and Hvide Sande. The 100-year storm surge level is determined to 290 cm for Krogen. All measured water levels are adjusted, such that the peak of the design storm matches the 100 years storm surge level for Krogen. The wave conditions are kept as measured.

Water level and wave data for the synthetic design storm for Krogen can be seen in Figure 3-8 and Figure 3-9.

Figure 3-8 Forcing condition for the 100 years design storm applied in the model for Krogen

Figure 3-9 Wave rose of the 100 years design storm applied for the model of Krogen.
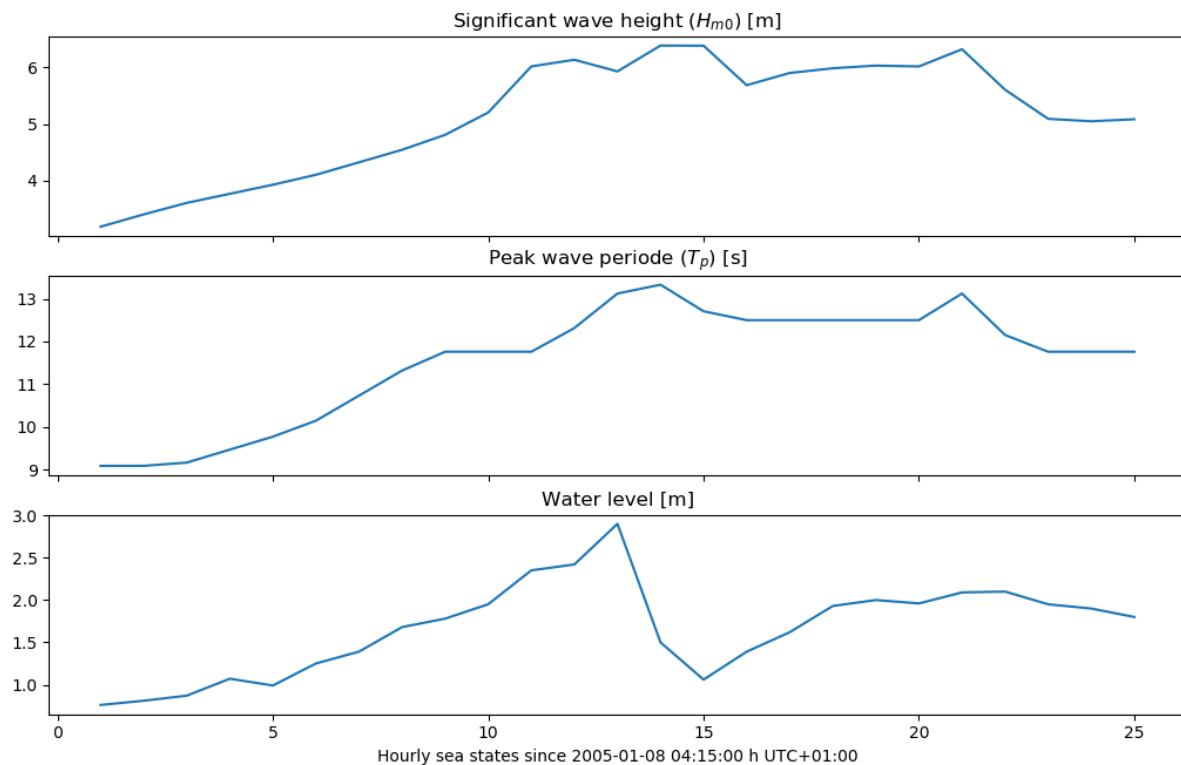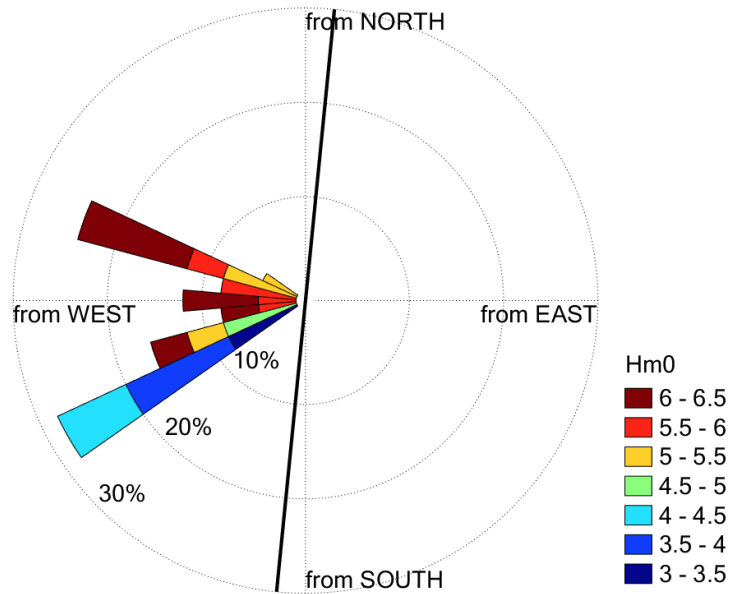
4 Model validation

In order to use XBeach to assess the effects of nourishments on short-term reduction of dune erosion due to storm events, the accuracy of the model must be evaluated. In this chapter, XBeach models are setup and validated for the three study sites in Germany and Denmark. The XBeach predictions on dune erosion are compared to the observations of a storm event, as described in Chapter 2.

4.1 Model description

Infragravity waves dominate nearshore hydrodynamics on dissipative beaches under storm conditions and play a key role in the dune erosion process. XBeach is a process-based 2D numerical model for the nearshore and coast (Roelvink et al., 2009, 2018), and is specifically developed to predict dune erosion during extreme events. The XBeach surfbeat mode resolves the variation of short-wave energy on the wave-group scale, which drives lower frequency motions (infragravity waves) that are fully resolved in the model. The hydrodynamic processes are fully coupled with sediment transport, avalanching of dune faces and the resulting bed level changes. XBeach model skill has been demonstrated for dune erosion, overwash and breaching (e.g. McCall et al., 2010 and van der Lugt et al., 2019).

Within this study two different versions of the XBeach software have been applied. For the Sylt and Krogen study sites the XBeachX release version has been used as for the Krogen site a calibrated XBeach model already existed (Kystdirektoratet, 2021). For the Langeoog case the BOI version of XBeach (1.23.5741) has been used. This is first beta-release version of the XBeach model for (internal) use in the BOI program, including all code developments made in the BOI Zandige Keringen Fase 0 project. The BOI project is a program of Rijkswaterstaat to develop a new methodology for the dune safety assessment in the Netherlands of 2023. It focusses on the development and validation of the XBeach model and a redefinition of the assessment methodology using the new modelling approach. The Langeoog case study was selected to be tested with the beta-release BOI version and corresponding settings.

As two different versions of XBeach are used, both models applications were also calibrated to different model settings. For the Langeoog case, the BOI settings as derived in Deltares (2020a) were used. For the Sylt and Krogen cases, the settings as derived in (Kystdirektoratet, 2021) are used. In Table A1 in Appendix A an overview of the most relevant XBeach settings are listed for both model applications. Other free model parameters were kept at their default values.

4.2 Langeoog, Germany

4.2.1 Model setup and methodology

For the Langeoog island in Germany both a 2D and 1D transect models are setup and validated for the 2013 storm "Xaver". The 2D model domain is 4km in longshore and 4.5km in cross-shore direction, and covers the area where the storm resulted in significant dune erosion. Two months prior to the storm, October 2013, a beach nourishment was deployed on the North-Western part of the island (km 4.005 to 4.020 in Figure 4-1 left panel). From the 2D-model domain 6 transects are used to setup 1D XBeach models, of which transect A to C are located at the beach nourishment and transect D to F are located East of the nourishment.

A cross-shore varying grid is setup for both 1D and 2D models, with grid sizes varying from 2m on the beach/dune and 30m offshore. For the 2D model a uniform alongshore grid size of 5m was applied. The bathymetry is created using a combination of the measurements of the shoreface in August 2013 and beach/dune (dry area) on October 18th, 2013. The shoreface of Langeoog is wide and shallow shelf due to the ebb-tidal delta. Using the complete shoreface data would result in a large model domain in the cross-shore direction, as for XBeach the offshore boundary needs to be at deep water to avoid any boundary effects in the model results. Therefore, the model bathymetry is cut-off at -12m and extended with a steeper slope to an offshore depth of -23m, based on the criteria as described in Deltares (2020b) and shown in Figure 4-1 right panel. Forcing conditions are based on observations (tidal + surge elevation) and SWAN model simulations (wave conditions, see section 3.1). The models are run for a total simulation period of 30h, indicted by the red line in Figure 4-2.

The model results are validated using the topography measurements of the beach and dunes, collected on December 13th, 2013 for the area around the beach nourishment and April 30th, 2014 for the Eastern part of the island. The modelled bed level changes of the beach and dunes are compared to the observations.
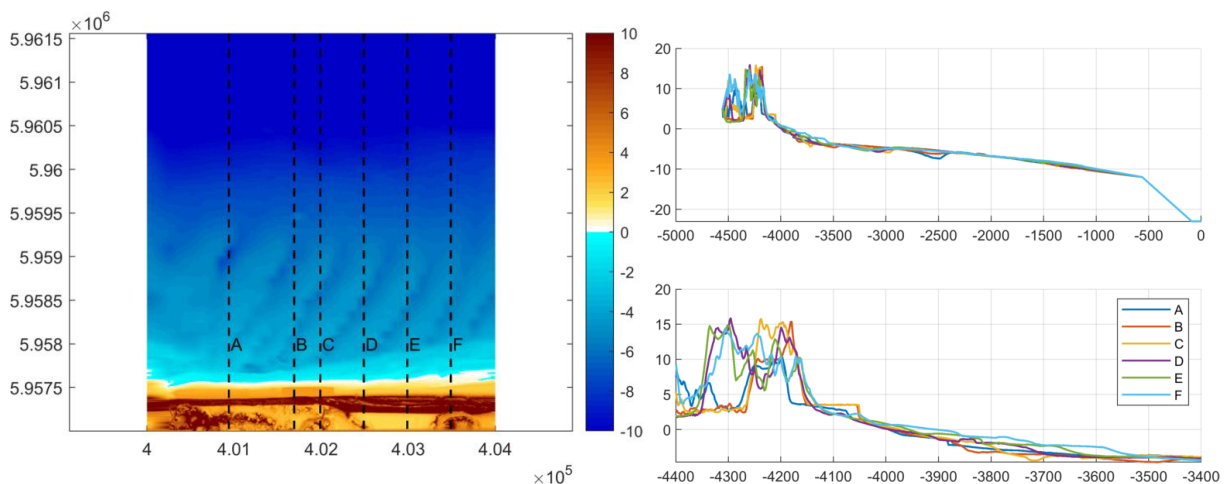

Figure 4-1 Model bathymetry Langeoog 2D model, including locations of the 1D transect models A to F.
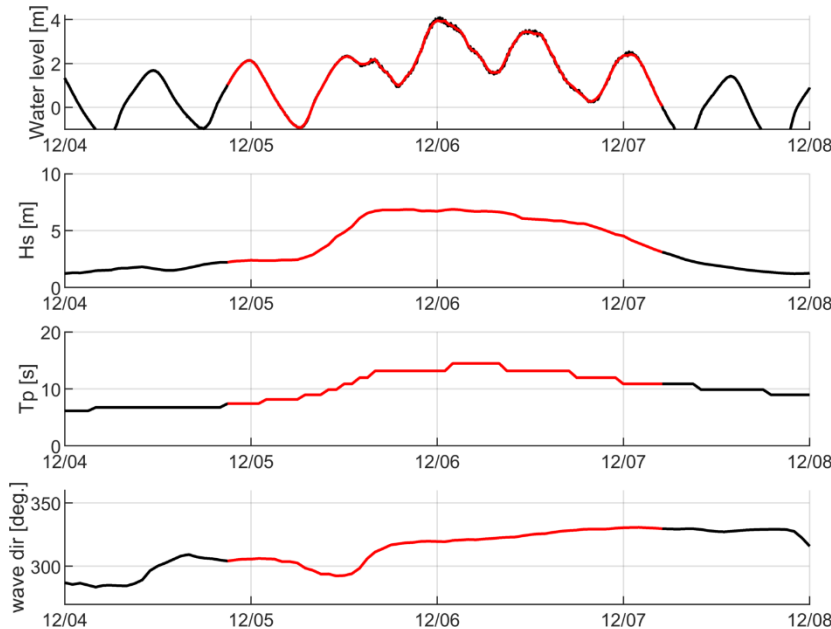
Figure 4-2 Forcing conditions used for the XBeach model of Langeoog. Simulation period is shown in red.

4.2.2 Results

Measurements of the pre- and post-storm topography (Figure 4-3) show that a large part of the beach nourishment was eroded by the storm. Also notable is that the dune erosion in the measurements is larger for the eastern area without beach nourishment. The predictions by the XBeach 2D model are shown in Figure 4-3 (right panels), and show that XBeach underestimates the erosion of the beach nourishment. But the larger dune erosion on the eastern side of the nourishment is well reproduced by the model.

In Figure 4-4 the resulting profiles are shown in more detail for transects A to F for both 2D and 1D models. Transects A to C are located at the beach nourishment, and show that XBeach underestimates the erosion of the beach nourishment, and subsequently underestimates the dune erosion and retreat landward of the nourishment. For transects D to F it can be concluded that XBeach predicts the post-storm dune profile well for the area East of the nourishment. In addition, the 2D and 1D model results correspond well and show no significant deviations.

The storm impact is quantified by calculating the dune erosion/deposited volume and retreat distances and its alongshore variation is shown in Figure 4-5. Again, it is visible that the erosion volume and retreat distances are larger east of the nourishment, and is well represented by the 1D and 2D models. Also, is becomes clear that the model underestimates the erosion of the beach nourishment and subsequent dune retreat, but mostly only for the eastern 2/3 part of the nourishment. In the pre-storm measurements (and thus input bed level

for the model) it is visible that the beach nourishment is higher compared to the rest of the nourishment.

An possible explanation for the underestimation of the erosion of the beach nourishment is that the pre-storm observations were collected on the day the beach nourishment was placed, October 18th 2013, almost two months prior to the storm event on December 6th. In that period the shape of the beach nourishment may have changed due to natural processes (e.g. aeolian- or wave-induced). Therefore, the underprediction of the erosion of the beach nourishment may be due to the initial shape of the beach nourishment in the input model bathymetry, as that may have been different (less steep) in reality.
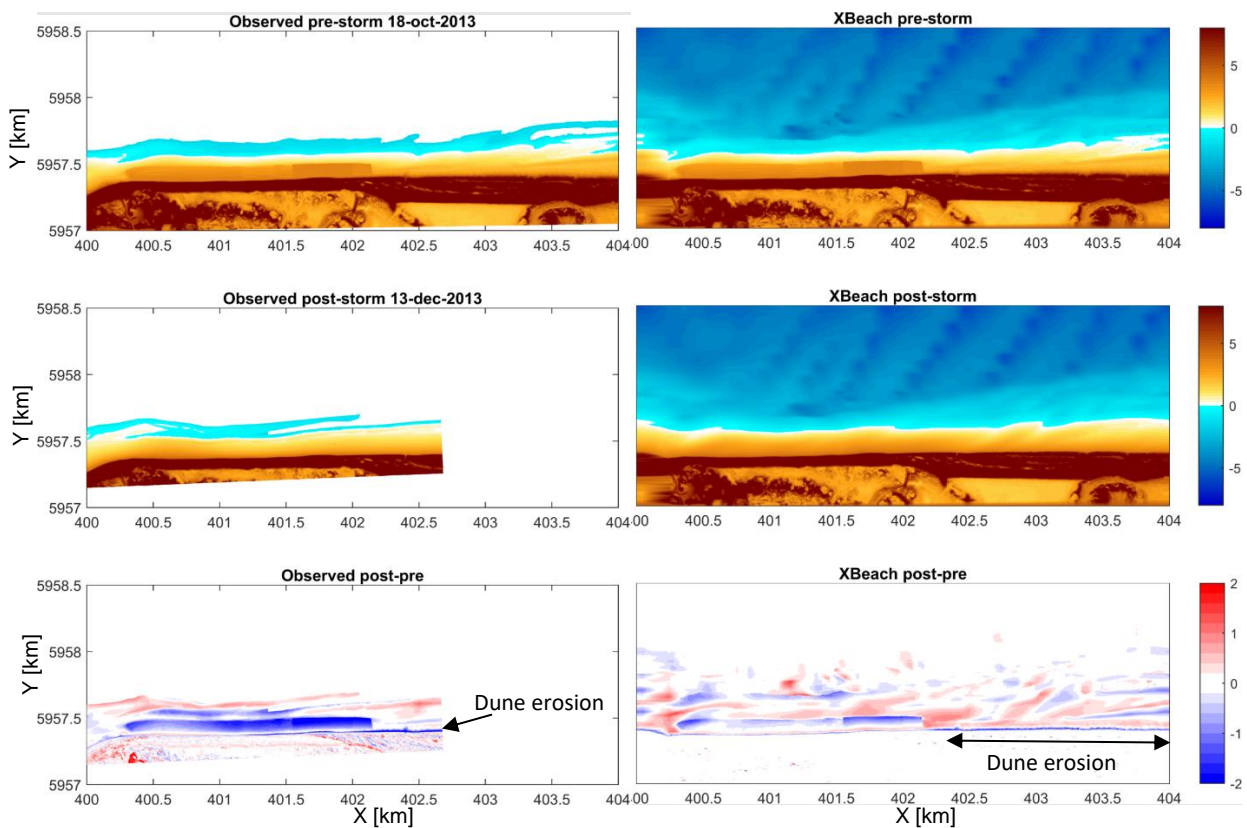
Figure 4-3 Observed (left) and modelled (right) bed levels. Bottom panels show the difference between post and pre bed levels, where blue indicates erosion and red accretion.
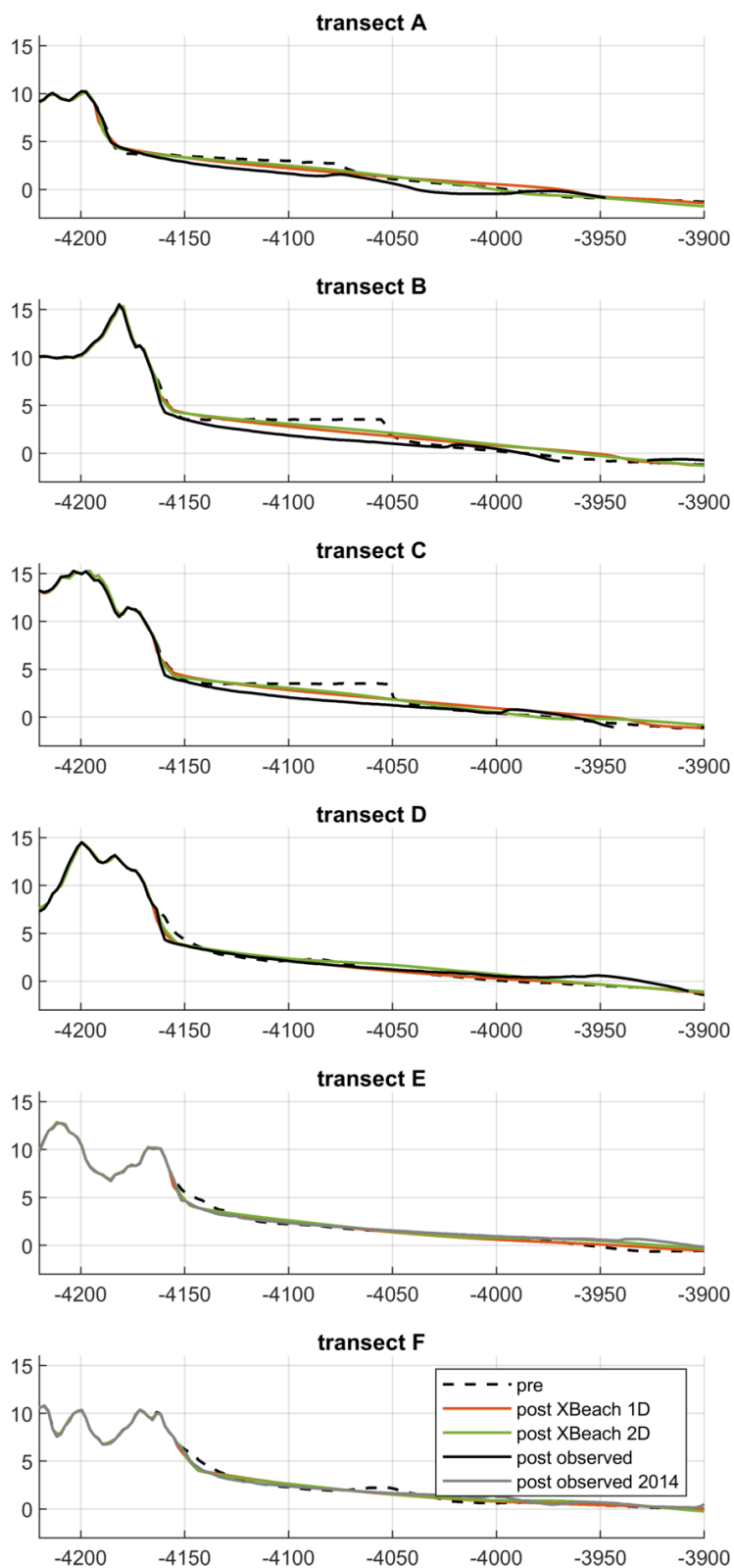
Figure 4-4 Pre-(dotted line) and post (solid line)-storm bed levels for transects A to F. Measured data is shown in black (2013 data) and grey (2014 data), XBeach results for the 1D model in orange and 2D model in green.
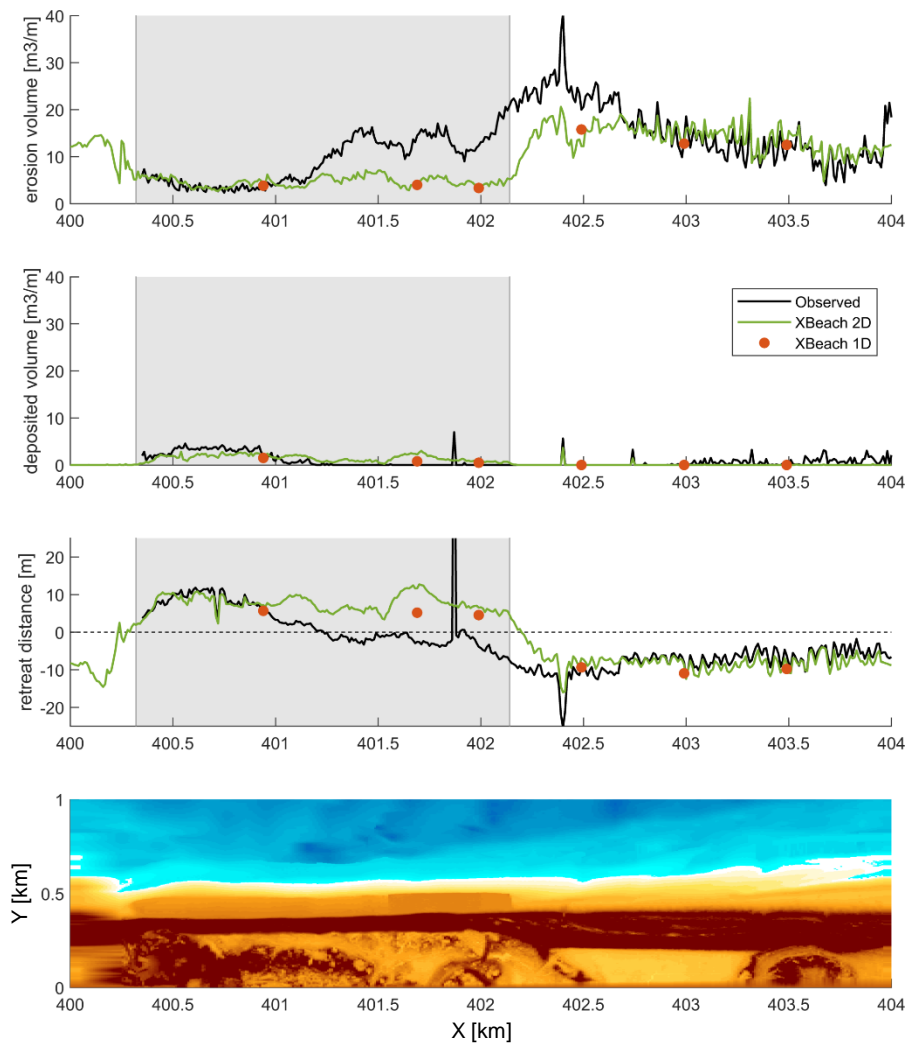
Figure 4-5 alongshore variation in dune erosion volume (top), deposited volume (middle) and retreat distance at maximum storm surge level + 3.95m (bottom). The grey area denotes the location of the beach nourishment. Measured values are represented by the black lines, modelled 2D results by the green line and modelled 1D results by the orange dots.

4.3   Sylt, Germany

Model validation work on Sylt, is conducted by applying a calibrated and verified Danish XBeach model setup as described in (Kystdirektoratet, 2021). The Danish model setup is calibrated and validated to reproduce the storm erosion, during a storm on three different coasts, west coast, east coast and north coast, representing levels of coastal exposure ranging from low to very high. The model validation work on Sylt, will test if the Danish XBeach model setup is able to reproduce the storm erosion on Sylt.

4.3.1   Model setup and methodology

The model validation of Sylt is performed in 2D, based on 82 coastal transects, with 50 m in between each transect, measured during a beach-shoreface measurement campaign in May 05, 1999 at Rantum and composes the before storm bathymetry. The model results are compared with the post storm observation, measured 13 days after the storm, December 16, 1999. Within the timespan, of nearly 6 months, between the measurements are collected before and after the storm, it is uncertain which process the beach and shoreface undergoes and is not covered by the XBeach simulation. Based on retreat maps, see
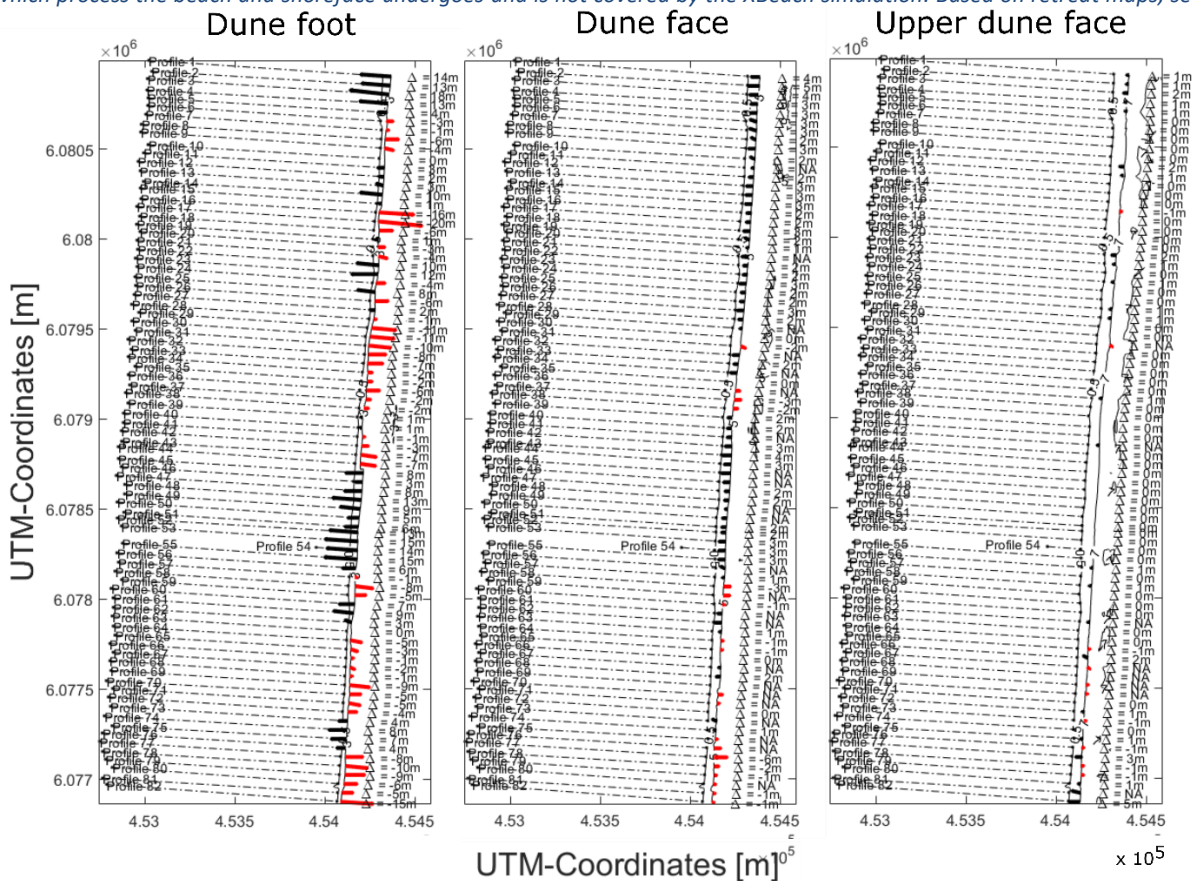
Figure 4-6, generated from the before and after storm observations, it seems that sediment has deposited significantly along the coast in all three morphological reference levels (3 m, 5 m and 7 m) between May 1999 and December 1999.
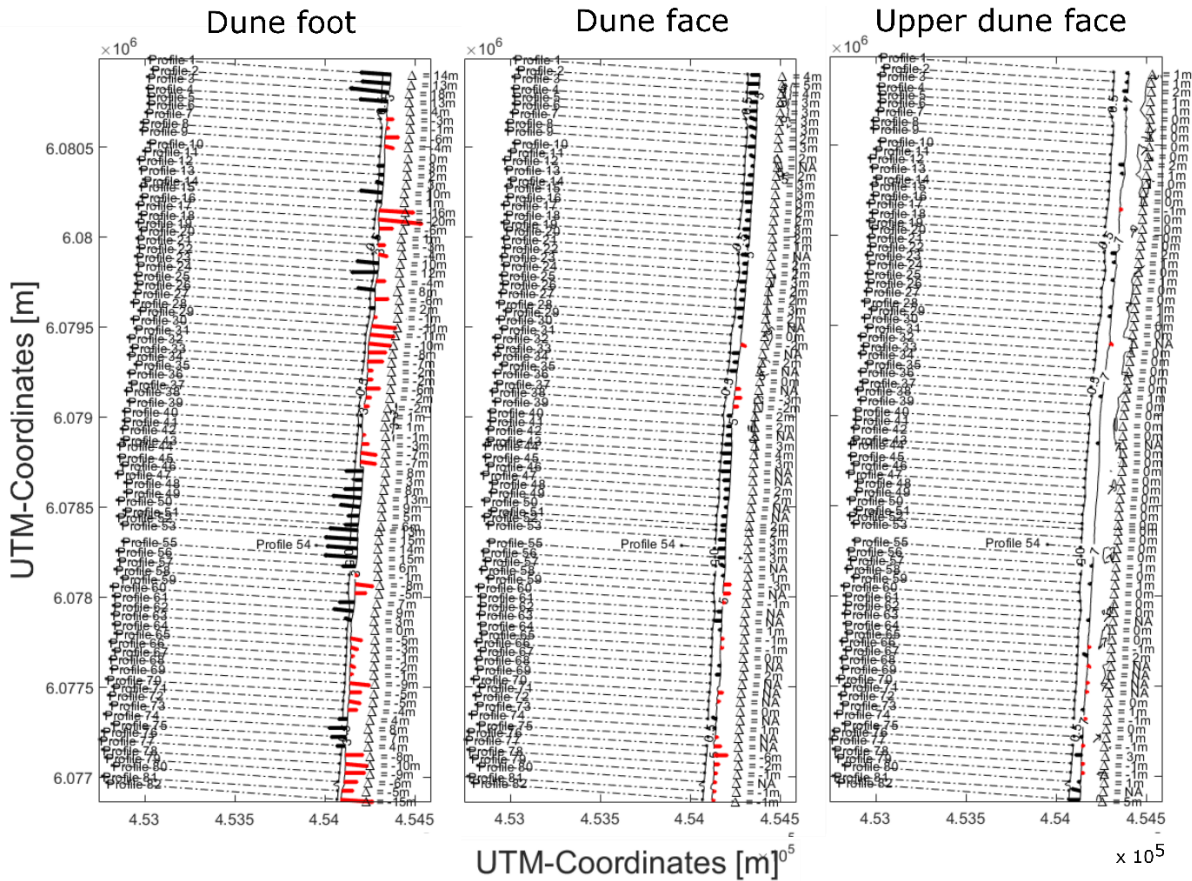
Figure 4-6 Retreat maps for the morphological reference levels dune foot (3 m), dune face (5 m) and upper dune face (7 m) determined from observation from 05 May 1999 (pre storm) and 16 Dec. 1999 (post storm).

The 2D model bathymetry is covering most of the measured transect lines, where a rectilinear 2D grid, with cells sizes varying along the x-direction. The largest cells are located offshore and minimum cell sizes closest to the shore, as seen from Figure 4-7. Further, the grid varies along the y-direction with largest cell sizes along lateral boundaries and minimum cell sizes in the centre of the model. In total 414 cells in x-direction and 280 cells in the y-direction, with cell sizes ranging from (45x50) m to (2x10) m in the centre of the model closest to the beach, as can be seen from Figure 4-7.
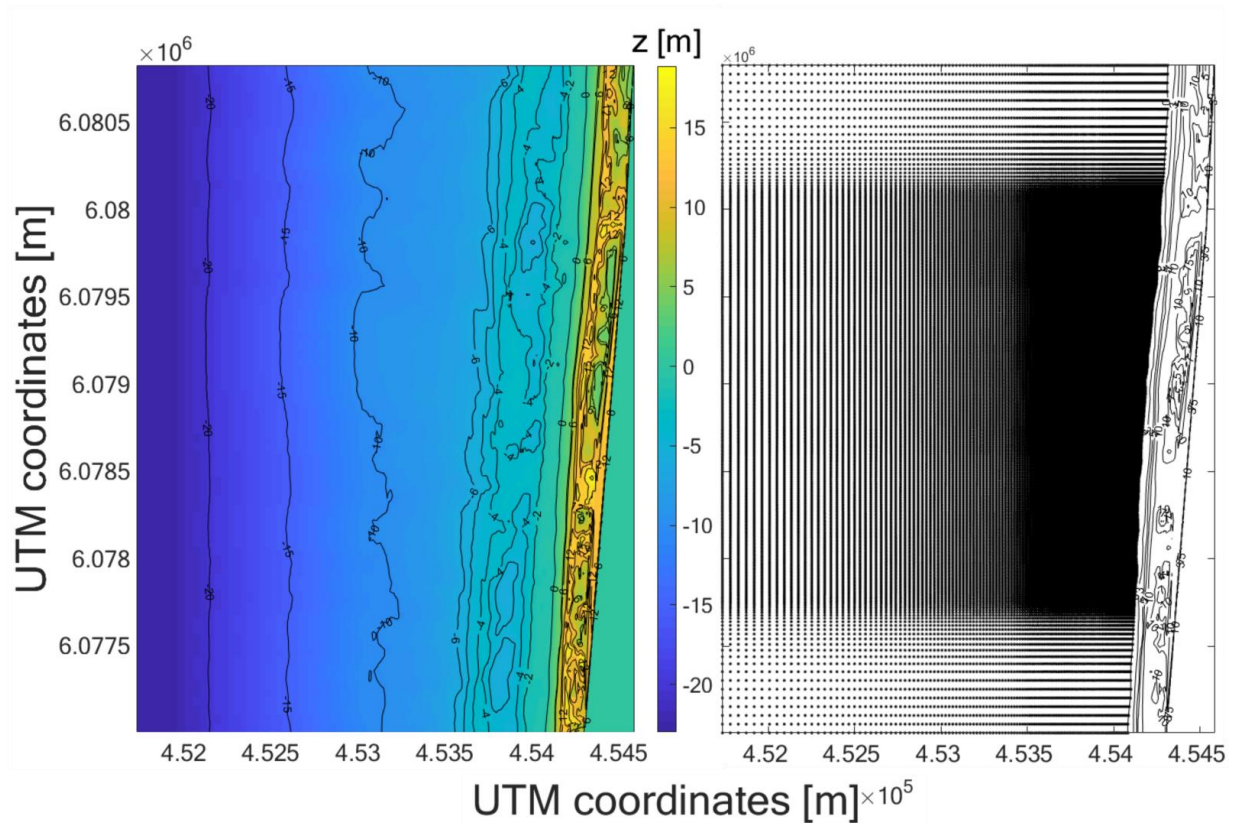
Figure 4-7 2D model setup for Sylt. The bathymetry is plotted with colour plot and contour lines are added (left). Further, the computational resolution of the model is represented by a plot of the location of computational cell centers (right)

To lower the number of cells and decrease computational time of the model, the bathymetry was cut of close to the depth of closure (–11 m) and extended to sufficient deep water (–23m) with a slope of 1/50 m.

4.3.2   Results

To assess the performance of the XBeach model, the erosion and the deposited volumes above 3 m reference contour levels are determined, along the coast, for both the model and observations and compared in Figure 4-8. Further the retreat distance along the coast, is determined based on model result and observation. As seen From Figure 4-8 and Figure 4-9, sand is deposited during the storm, based on the pre and post observational coastal data (black line), above the 3 m (NN +3 m) contour level, while XBeach predict no deposition of sand (green line) above this reference level during the storm. It is to the author, not clear how this large deposition volume above the 3 m (NN +3 m) contour level occurs during the storm. Based on the determined erosion volumes and retreat distances, XBeach predicts somehow the longshore variations on Sylt.
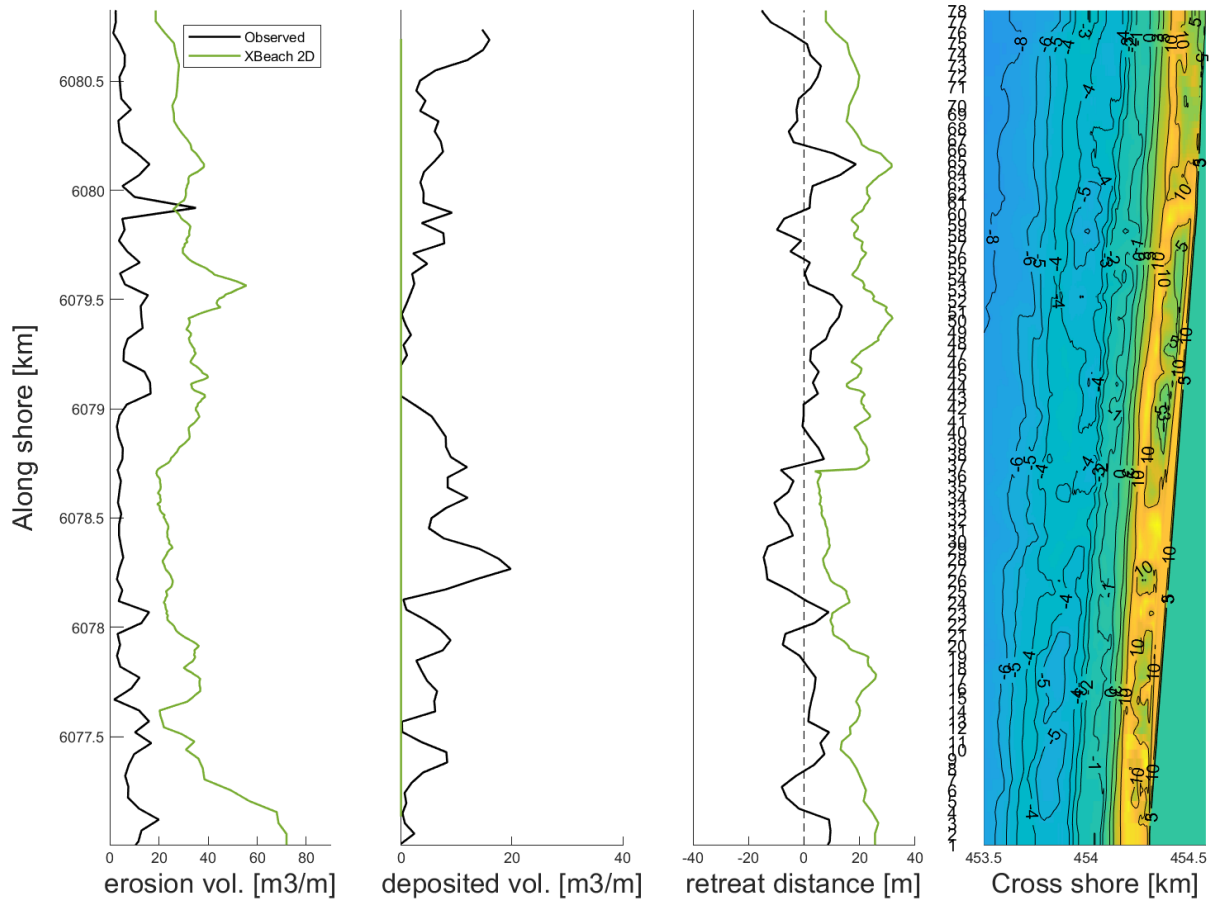
Figure 4-8 Map of coastal state indicators as the erosion volume, the deposited volume and the retreat distance related to NN + 3 m along the coastline. Transect numbers are listed along the y-axis of the colour plot of the interpolated raw observational data to indicate where 1D comparison transects as shown in Figure 4-9 are located.

Based on the map of the coastal state indicators, Figure 4-8, three transects are selected to visualize the difference between pre and post observational coastal data and the XBeach simulation and in Figure 4-9. For the results of all transects, see Appendix B.
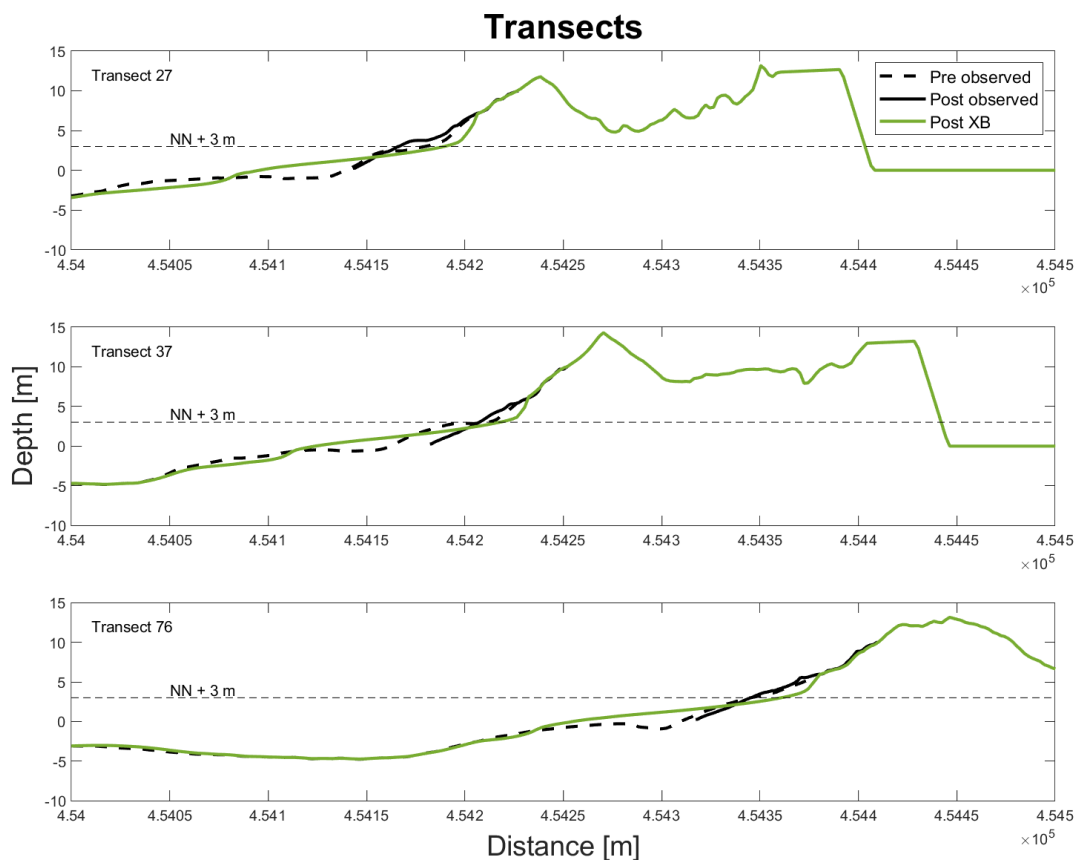
Figure 4-9 Plot of measured transect 27, 37 and 76 before the storm (black line) and after the storm (dashed black line). XBeach post storm profile is included, as the green line, to assess the performance of the model. Transects numbers shown link to the transect numbers from Figure 4-8. Results for all transects are shown in Appendix B.

4.4 Krogen, Denmark

Based on the XBeach work in Denmark, (Kystdirektoratet, 2021), the Danish XBeach model was calibrated and validated in a coastal area (Vedersoe) close to Krogen, hence the Danish XBeach model set-up is assumed applicable for Krogen and therefore Krogen is not a validation case. Krogen is included as the Danish study site in this investigation of how to influence the pathway to enhance the safety of the receptor. The Krogen XBeach model, is generated from coastal transect measurement collected in autumn 2020. The model bathymetry is based on 25 coastal transects with 100 m in between. The coastal transects are merged with a national terrain model to generate the inland elevation.

The 2D grid is generated using the same procedure as for the Sylt model grid and consists of the same grid resolution of (45x50) m as maximum cell size and (2x10) m as minimum cell size in the centre of the model closest to the beach, as can be seen from Figure 4-10. In total, the model grid of Krogen consist of 591 cells along the x-direction and 330 cells along the y-direction.

The bathymetry was cut at the depth of closure and extended to sufficient water depth with a slope of 1/50 m to increase computational times.

Figure 4-10 2D model setup for Krogen. The bathymetry is plotted with colour plot and contour lines are added (left). Further, the computational resolution of the model is represented by at plot of the location of computational cell centers (right)

5 Scenario modelling

This Chapter involves simulating a set of scenarios to test the impact of Building with Nature techniques on dune safety during storm conditions. First a set of scenarios are sele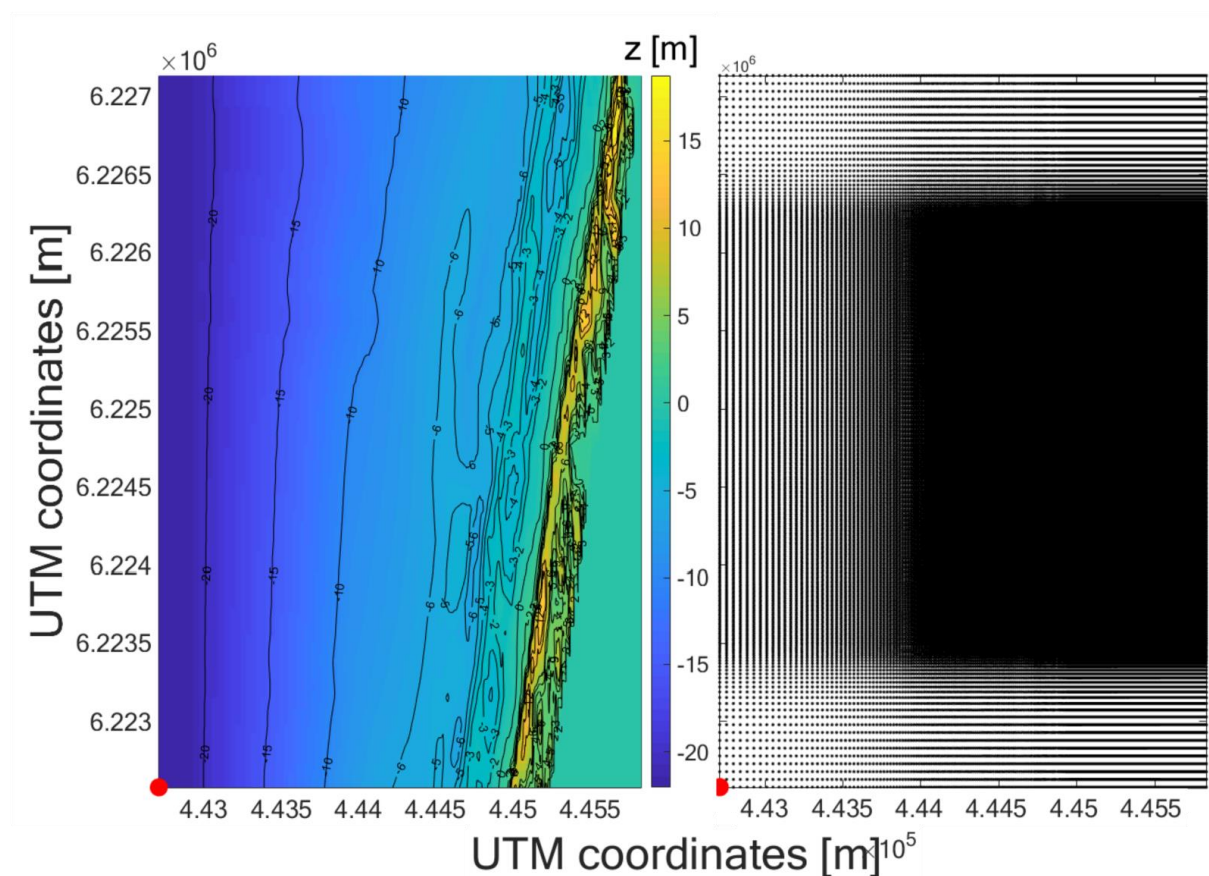cted and created based on different nourishment placement or design, morphological configuration and conceptual climate change profile developments. Subsequently, these scenarios are applied and analysed for all three study sites. The results of the three study sites are combined in a synthesis, in order to derive overall trends and observations, and thus increase our understanding of the effects of nourishments on coastal behaviour during storm conditions.

5.1 Methodology

5.1.1 Scenario selection

Using the previously described models, we want to test different morphological and hydrodynamic settings to learn about coastal behaviour during storm conditions and improve our system understanding. Therefore, scenarios for different placement of nourishments and morphological configurations with and without Sea Level Rise will be run (the Table 5-1 below).

In these scenarios we have certain questions/aim to focus on:

1. How do nourishment designs differ in their performance during storm conditions?
2. What is the effect of different natural shoreface configurations?
3. Insight in conceptual climate change adaption strategies.

Table 5-1 Joint approach SPR's scenarios

Scenario group	Conceptual design	Aim
Current situation – effect of different nourishment designs	→ "do nothing" → Beach nourishment variations → Shoreface nourishment variations	1
Morphological configuration	→ Variation of different two-dimensional bathymetric formations	2
Sea Level Rise (adaption of hydrodynamic forcing)	→ Current profile → Landward shift and heightening beach and shoreface according to the Bruun rule ("do nothing") → No landward shift, heightening beach and/or shoreface ("hold the line")	3

With the aim to gain insight in conceptual climate change adaption strategies, some assumptions were made in the scenario modelling:

- For the sea level rise (SLR) scenarios, a SLR of 1 m was added to the tidal water level input and represents the expected SLR in 2100 (IPCC, 2013). Although SLR may differ for each lab or considering different climate change scenarios, this single value was chosen as this is a first assessment of the potential impact of SLR during storm conditions. The wave conditions are kept the same for all scenarios and represent the 1/100-year event for each lab.
- Regarding the "Bruun-rule" in SLR scenarios, the profile below the dune face is heightened up 1 m and the profile itself is shifted landwards from the Depth of Closure (DoC) in a specific length regarding the Bruun rule (Bruun 1963/88 and Hands 1983).
- As for the conceptual design of beach and shore face nourishments analysed at Sylt and Krogen, it is assumed, that the storm arrives just after the placement of the nourishments. No morphological changed has occurred between placement is done and the storm arrives.

5.1.2 Scenario creation Langeoog

The nourishment scenarios for Langeoog are designed based on previous nourishments on the island. The area where nourishments are needed to secure coastal safety varied in the last decades. The latest nourishments took place on the northern beach of the island, north of the fresh water extraction area called "Pirolatal" (Figure 5-1).
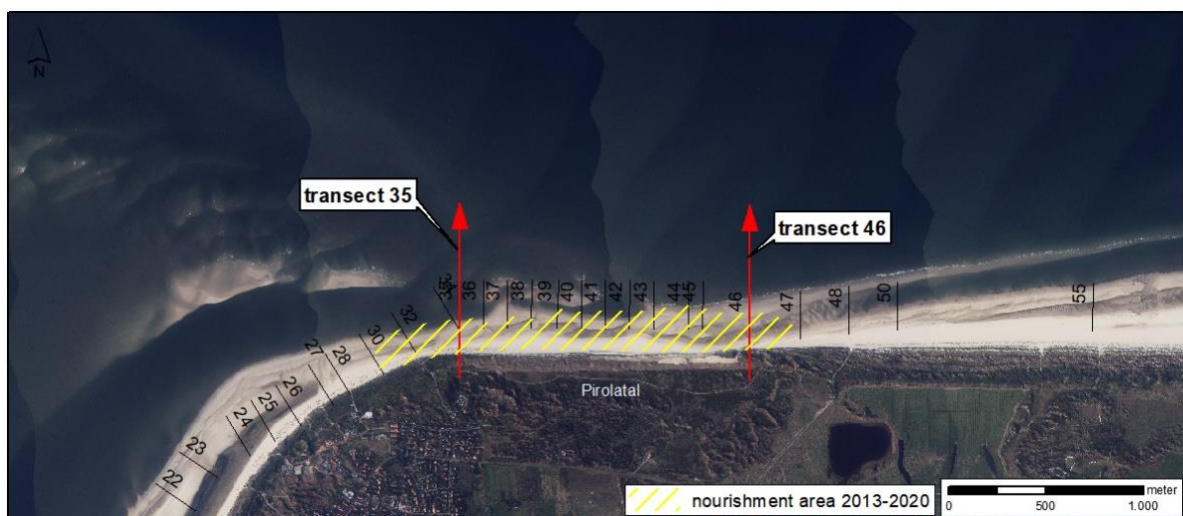
Figure 5-1 Location of scenario transects 35/46 in the Langeoog nourishment area

For Langeoog, 2 transects were selected for the scenario modelling. Transect 35 and 46 are regular monitored transects on Langeoog (see Figure 5-1). Transect 35 is located at the north-western end of the island, where the ebb delta shoals are merging onto the beach. Transect 46 is located in the north of the island, at the eastern end of the current nourishment area. For both transects, changes were made in the profile regarding the scenario selection, whereas the rest of the profile (dune and foreshore area) remains the same in each scenario. The design scenarios are shown in Figure 5-2.
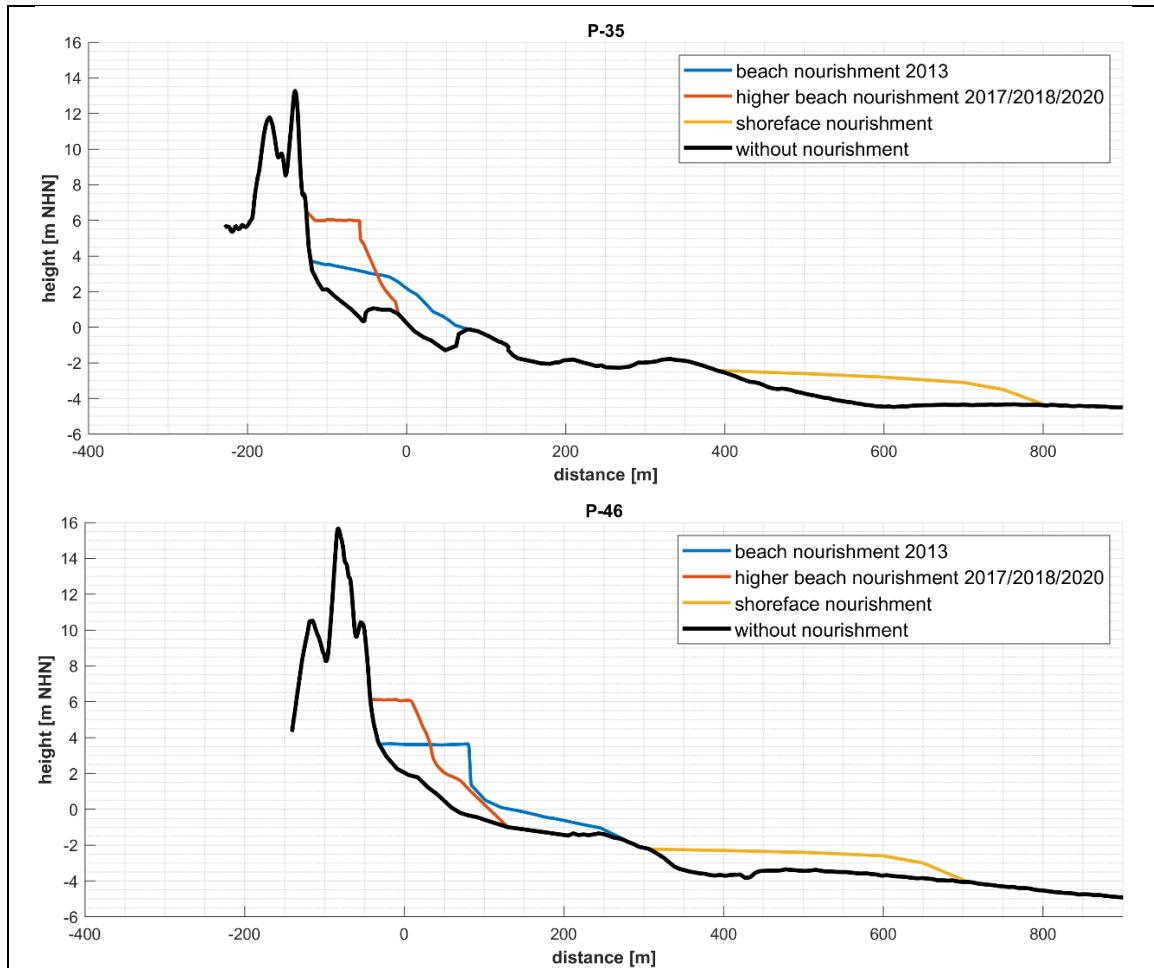
Figure 5-2 designs for nourishments scenarios in transect 35 and 46

The nourishments from 2013 and 2017/18 and 2020 are realistic designs which were realised in the respective year. However, the chosen shoreface nourishment is fictional as no such nourishment has been implemented on Langeoog so far. This is due to various reasons, for instance a very wide and shallow shoreface area which makes it difficult to place the sand there. Higher beach, beach, and shoreface designs are all created with volumes of same quantity of about 400 m³/m.
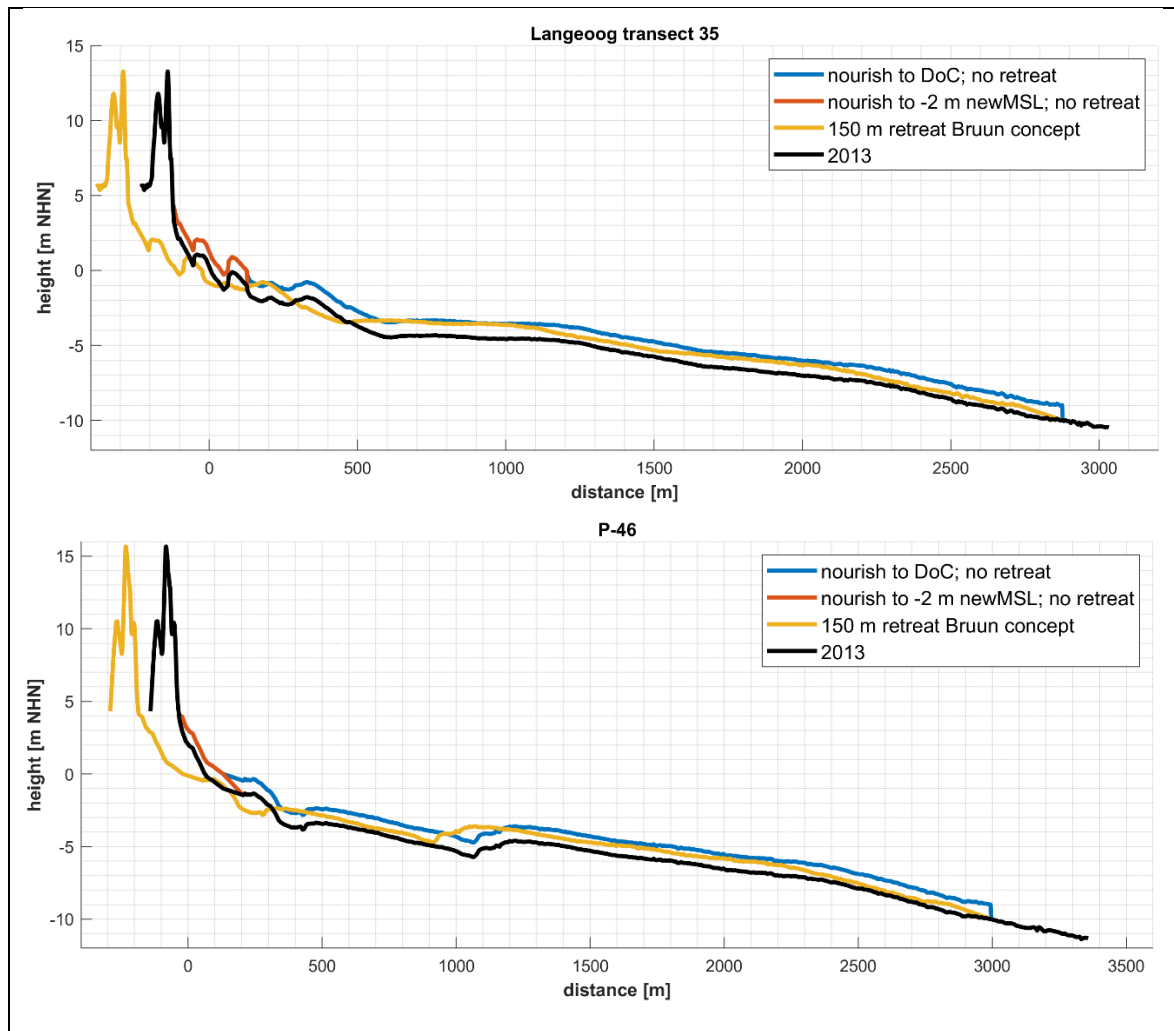
Figure 5-3 Designs for sea level rise scenarios in transect 35 and 46

The sea level scenario designs are, as previously stated, highly conceptual. The scenarios "nourish to DoC (depth of closure)" and "nourish to –2 m" can also be stated as a "hold-the-line" strategy (Figure 5-3). The dune is kept in the same place, but the shoreface area is nourished down from the dune foot to the respective height. The scenario based on the "Bruun rule" is based on the assumption, that with a sea level rise of about 1 m, the coastal profile would retreat in a specific distance. Here, a dune retreat of 150 m and a vertical heightening of the profile by 1 m is assumed, starting from the position of the dune foot down to DoC. The retreat of 150 m is calculated using the Bruun formula (depth of closure = 10 m; upper point of profile adjustment = 10 m; cross-shore distance of depth of closure = 3000 m) (Bruun 1962).

The ebb tidal delta and shoreface area of Langeoog is shaped as a wide shallow area. To test the influence of incoming wide shoals from the ebb tidal delta, two different bathymetries of 2004 and 2013 area compared (Figure 5-4). These different points in time represent different natural morphological configurations. In 2004, high shoals are present in ebb-tidal delta near the beach,

whereas in 2013 there were no large shoals present. To avoid the influence from different beach heights, both model bathymetries have the same 2013 height levels for the beach section higher than the low mean water level.
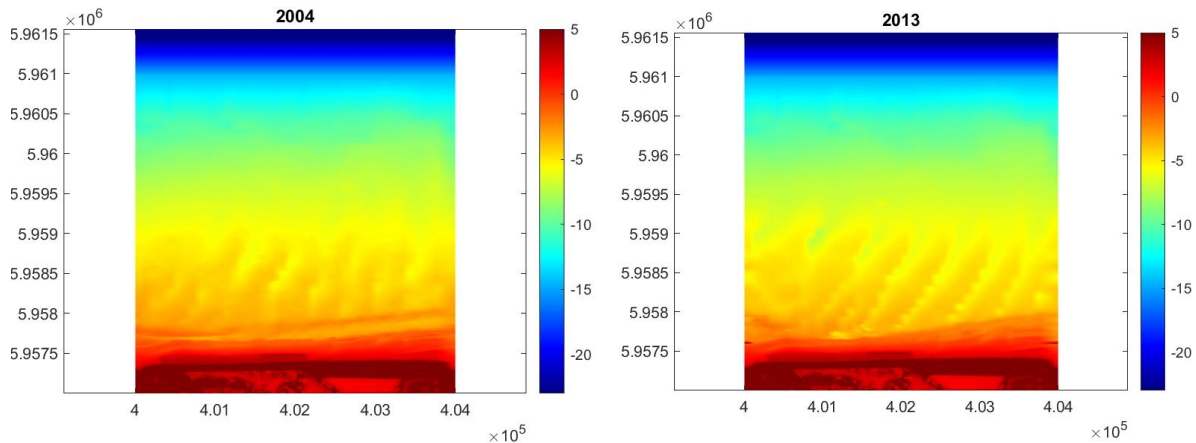
Figure 5-4 Model bathymetry for 2D-model test of the morphological configuration

5.1.3   Scenario creation Krogen/Sylt

To investigate the effect of nourishments on acute erosion from storms research has to be done. Local weather conditions often limit the ability to perform physical measurements immediately before and after a storm, making isolating acute erosion difficult. Implementing theoretical nourishments into XBeach input data and running it, would resolve this issue, and solely give the effect that a nourishment has on acute erosion.

The nourishment strategies used are designed based on an analytic approach, where nourishment volumes are related to the yearly erosion rate in the specific area, and the experienced dune retreat during storms. The shape of the nourishments is however conceptual and is chosen to investigate the effect of a shoreface nourishment carried out using rainbowing or splitting on retreat of the dune face from a storm by different configurations of the pathway determined by XBeach.

It was decided to investigate 3x and 6x the annual erosion of the given area, and to compensate for it with a singular nourishment, which in real life would be a beach-, rainbowing, or split nourishment, over a length of ~1000 m. Volumes used for Sylt and Krogen can be seen in

Table 5-2.

The "3x" and "6x" stem from the annual erosion volume determined from, both Krogen and Sylt. In Denmark, objectives on the amount of erosion within a framework of 5 years is agreed along the west coast of Denmark. To meet the objectives normally 1 and perhaps 2 nourishments are installed during the 5-year period.

Table 5-2 The table holds total nourishment volumes for Syllt and Krogen determined from a 3x yearly erosion and a 6x yearly erosion

Nourishment type	Sylt		Krogen	
	3x yearly erosion [m³]	6x yearly erosion [m³]	3x yearly erosion [m³]	6x yearly erosion [m³]
Beach nourishment	600.000	1.200.000	250.000	500.000
Rainbowing	600.000	1.200.000	250.000	500.000
Split	600.000	1.200.000	250.000	500.000

The nourishments are implemented with design parameters as seen below in Table 5-3 Slope is denoted as "rise over length", I.e. 0.1 = 1 m / 10 m. Wet slope is adopted from the default value in XBeach. The design height of the beach nourishments is determined based on a water level of a 100-year return period with wave set up at Krogen and a design storm chosen by the Agency for Coastal Defence, National Park and Marine Conservation, Schleswig Holstein.

Table 5-3 The table contains relevant design parameters for the different nourishment strategies at Sylt and Krogen

Nourishment type	Sylt			Krogen		
	Height [m]	Wet slope [-]	Dry slope [-]	Height [m]	Wet slope [-]	Dry slope [-]
Beach nourishment	5	0.3	0.1	4.5	0.3	0.1
Rainbowing	-4	0.3	-	-4	0.3	-
Split	-2	0.3	-	-2	0.3	-

All nourishments have been applied along a rigid straight line. Along the line sediment is deposited with the design slope, and volume continuously being calculated and checked against total design volume. Once the nourishment initially reaches design height, it starts expanding westward, still maintaining design slopes and heights. When the design volume is reached this process stops. The method does not have uniform distribution along the defined rigid path, but keeps even width to the user defined starting position.

The shore face nourishment ("split") has been designed approximately along the –6 m contour. This is based on the DCA practice in working with the split hopper dredger vessels. They historically have sailed to the current min. depth (approx. -6 m), unloaded, moving the contour line westward, and repeating these steps. The result hereof is a split nourishment with a high, narrow elevated crest level.

The "rainbowing" nourishment allows the sediment to be boosted 100-150 m east of the -6 m line. DCA experience indicates rainbowing makes for larger spread of sediment, making a wide plateau with low elevated crest level.

The "beach" nourishment pumps a mixture of water and sand through pipes onto the beach and repositioned with machinery. The mixture flows towards the ocean, generating a gentle slope. A crest

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height is for Krogen 4.5 m was used, while it was 5 m at Sylt. The result is a flat plateau extending from the dune foot, followed by a gentle slope, steepening slightly when wet. The different conceptual nourishment designs together with the baseline profile can be seen in Figure 5-5.
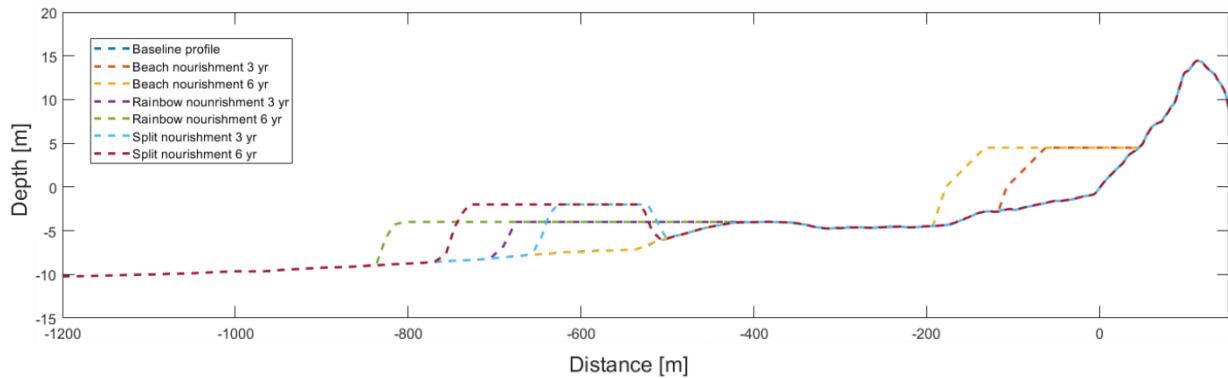
Figure 5-5 Transects showing the different conceptual nourishment designs.

The sea level rise (SLR) scenarios are created for a profile where adaptation (nourishment) has been carried out to keep the position of the coastline fixed and for a profile which has due to the yearly erosion rate been shifted landwards (not adapted) regarding the Bruun rule. In both profiles, the pathway from the depth of closure to the maximum storm surge level (MSSL) plus the sea level rise (SLR) of 1 m is elevated by 1m. All SLR scenarios are ran with a modified storm surge curve, where all water levels are vertical adjusted by adding the 1m sea level rise. The different sea level rise scenarios can be seen in Figure 5-6 .
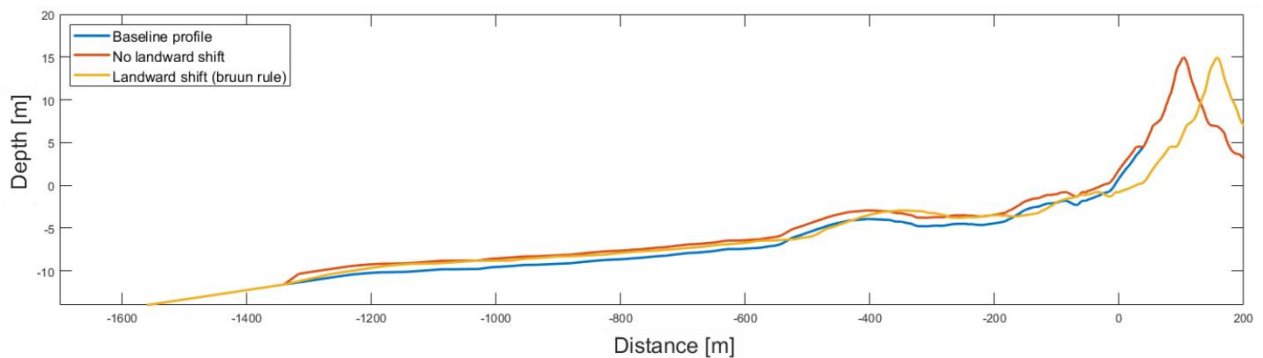
Figure 5-6 Transects showing the different sea level rise scenarios investigated.

5.2 Scenario results Langeoog

In Figure 5-7 the results of the scenario modelling are shown in groups to display the modelled variations regarding the scenario.
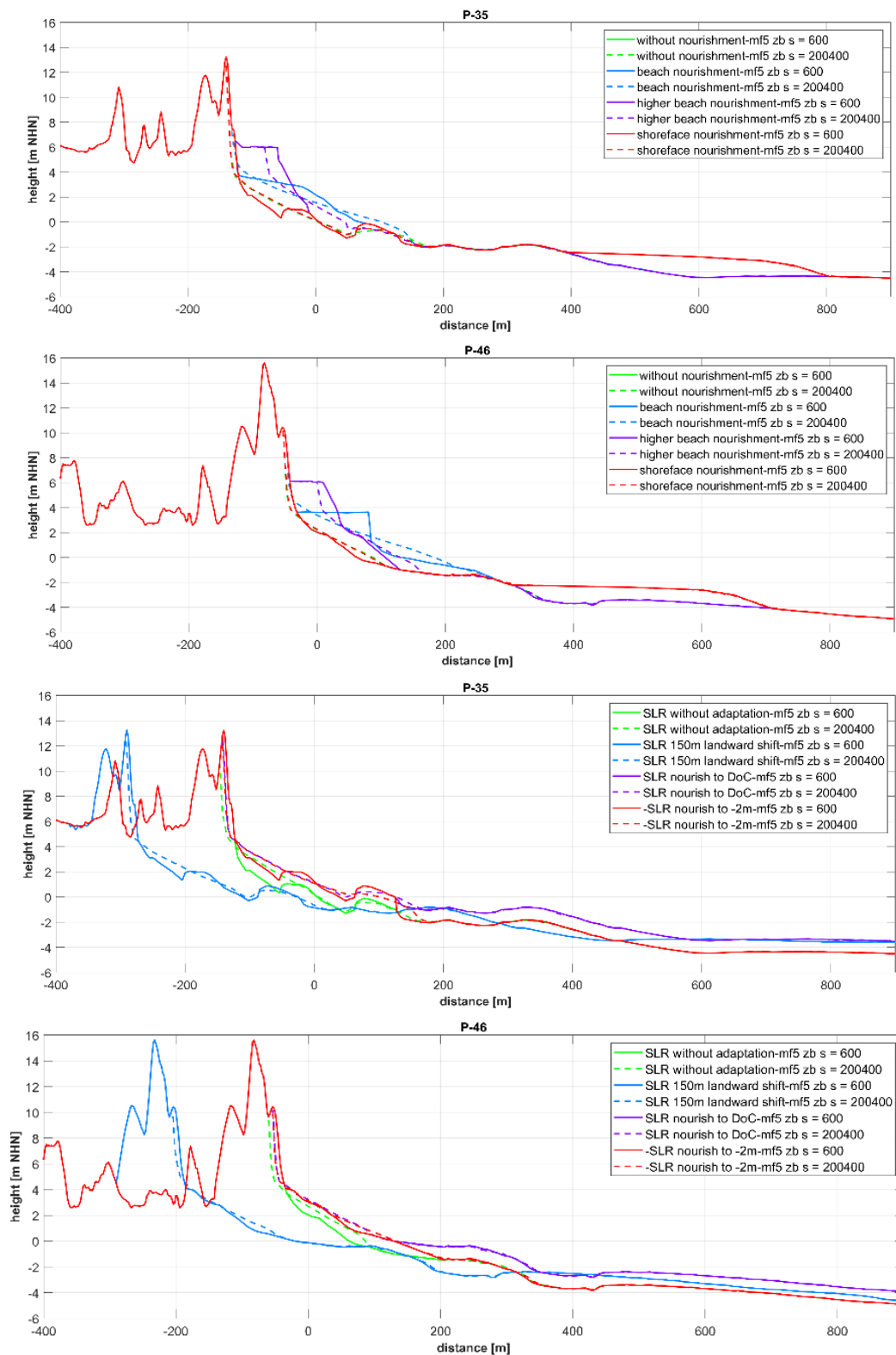
Figure 5-7 1D scenario transects with results (dashed line)

Table 5-4 Results from the scenario models in erosion volume in [m³] and retreat [m]. The beach nourishment ranges to a maximum design level of NHN +4 m, where the higher beach nourishment ranges to a maximum design level of NHN +6 m. Nourished sand volumes per m are equal in all nourishment scenarios. Retreat values are positive for landward directed displacement of the dune face.

| transect	No.	scenario	volume [m³/m]		retreat [m]					
			V_eroded Above MSSL (4 m)	V_deposited above MSSL (4 m)	upper dune face (8 m)	dune face (5 m)	dune foot (3 m)	MHW (+1.3 m)	MSL (0 m)	MLW (-1.3 m)
35	1	without nourishment	43	0	3	7	-7	-25	2	-15
46			34	0	5	7	0	-8	-25	5
35	2	beach nourishment	6	4	0	0	33	9	-34	-17
46			4	4	0	1	65	-22	-49	1
35	3	higher beach nourishment	42	0	0	19	17	-13	-40	-3
46			33	0	0	16	10	-6	-23	7
35	4	Shoreface nourishment	45	0	4	8	-7	-28	-1	-6
46			32	0	5	7	0	-7	-21	4
35	5	SLR without adaptation	94	0	11	11	-24	-42	-2	-5
46			75	0	12	14	-14	-20	-23	6
35	6	SLR 150m landward shift	44	1	4	6	-19	6	3	1
46			34	2	7	4	-4	-18	0	1
35	7	SLR nourish to DoC	46	2	4	7	-20	6	-2	5
46			31	2	5	6	-7	-19	0	1
35	8	SLR nourish to -2m	50	2	5	7	-18	9	23	-25
46			34	1	6	6	-3	-15	-3	-5

In Table 5-4 the model results for nourishment- and SLR-scenarios with modelled volume and retreat values are listed. The eroded sand volume above the maximum storm surge level gives insight in the dune erosion, but may be misleading in the higher beach nourishment scenario (no. 3) because of the high nourishment placement. For this scenario the dune erosion volumes are still large, but this is due to erosion of the beach nourishment and the original dune remains unaffected (Figure 5-8).

In comparison to scenario 1 without nourishment (3/5 m retreat), both scenarios 2 and 3 do not show any retreat on the upper dune face at 8 m. Most retreat in scenario 2 is found at the dune foot (33/65 m), whereas in scenario 3 this retreat is distributed to both the dune face and dune foot area. The modelled end profiles show that scenario 2 yields a wide beach area (between dune foot and mean tidal low water), where in scenario 3 a narrow beach is formed. No major differences can be observed in scenario 4 compared to scenario 3.

Scenario no. 5 shows the maximum dune erosion of all scenarios due to the 1 m SLR added to the tidal input. Scenarios 6, 7 and 8 show similar results, also in comparison to scenario 1.
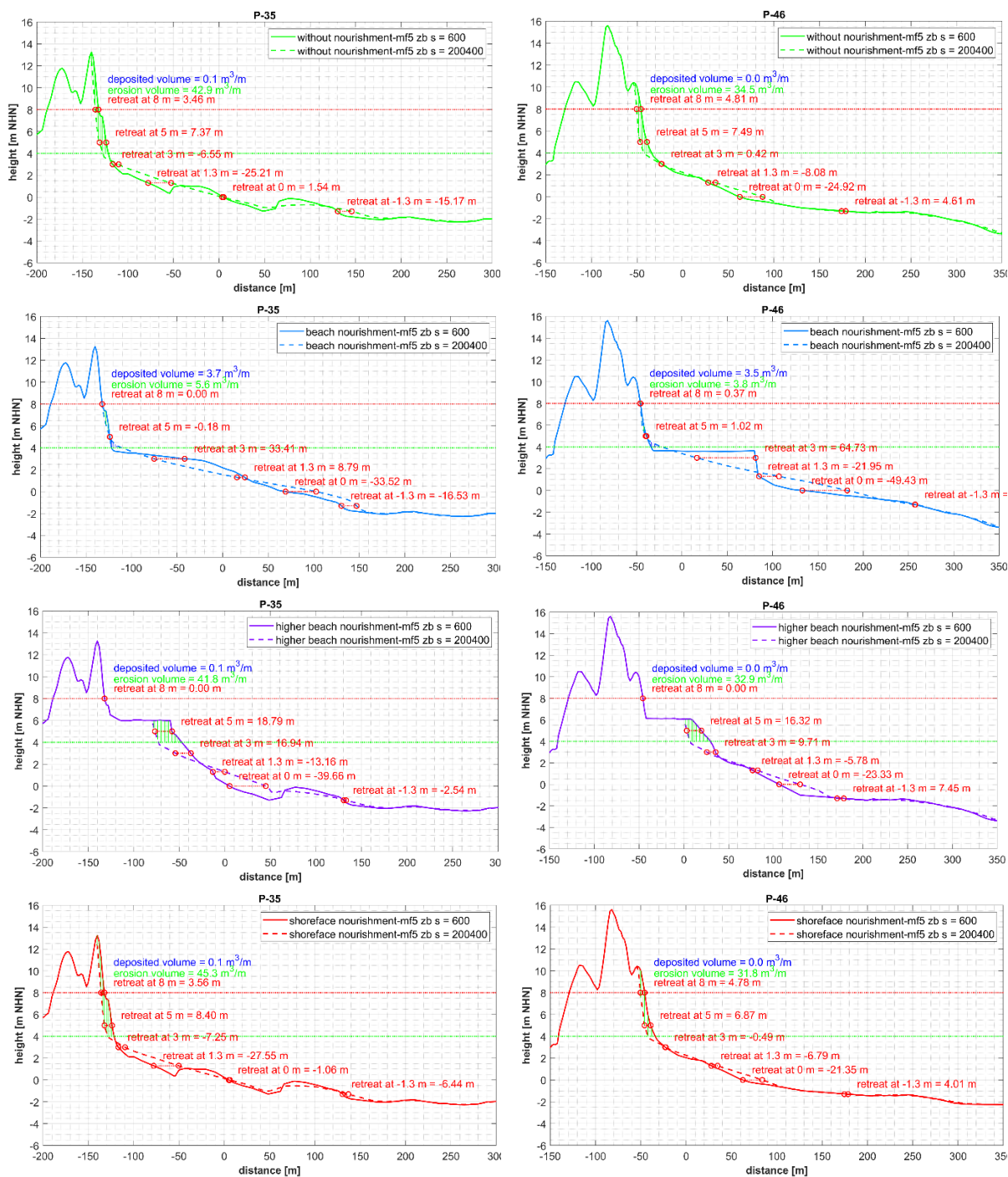
Figure 5-8 1D scenario model results of the nourishment scenarios with volume and retreat values displayed

Figure 5-9 and Figure 5-10 show the result of the morphological configuration scenario. The difference of the two compared bathymetries can be seen in the foreshore area clearly. However, the beach shows some variation in erosion and accumulation patterns, there is not much difference in dune erosion. Smaller differences can be seen in the profile figures, but they do not follow clear patterns. The model did not show significant differences in beach and dune erosion within these two bathymetries. For future research, a new model grid (curvilinear or larger) may be needed to get significant effect from the ebb tidal delta bathymetry.

Figure 5-9 difference of modelled end bathymetries from 2013 and 2004

Figure 5-10 Transect 35 and 46 of the 2D morphological configuration scenario

5.3 Results Sylt

In total three different nourishment strategies are investigated for Sylt, a beach nourishment, a shoreface nourishment by rainbowing and a shoreface nourishment by a splitting barge.

These results of Sylt concerns first a comparison between with and without nourishment and the difference between the different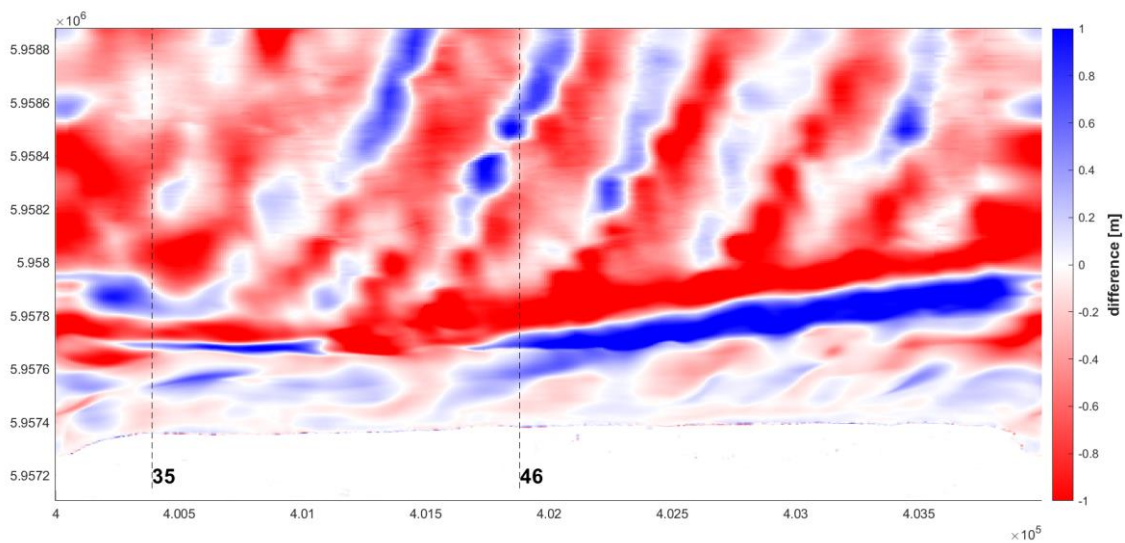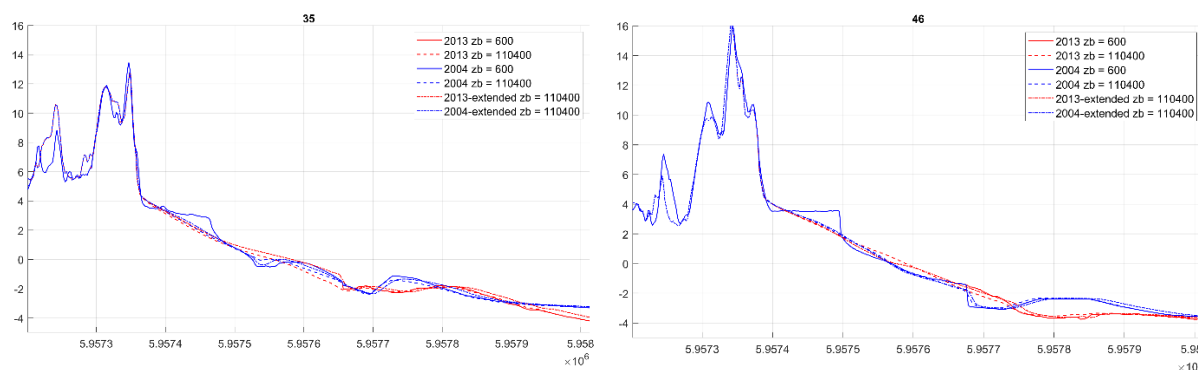 nourishment strategies (aim 1). The alongshore 2D variations in bathymetry are considered as different morphological configurations, due to the difference in configuration of the bar system along the coast. The along shore variations of the coastal state indicators erosion, deposit volumes and retreat distances are presented (aim 2).

Finally, by altering the mean sea level, by a sea level rise (SLR) of 1m, the coastal state indicators are investigated for a single 1D profile.

All analysed transects in the analysis are assumed to have a west-east orientation. The coastline itself differs less the five degrees from the orientation of the analysed transects. This was done due to a strict time plan. Figure 5-11 presents the 2D variations of the coastal state indicators along the coastline of Sylt.
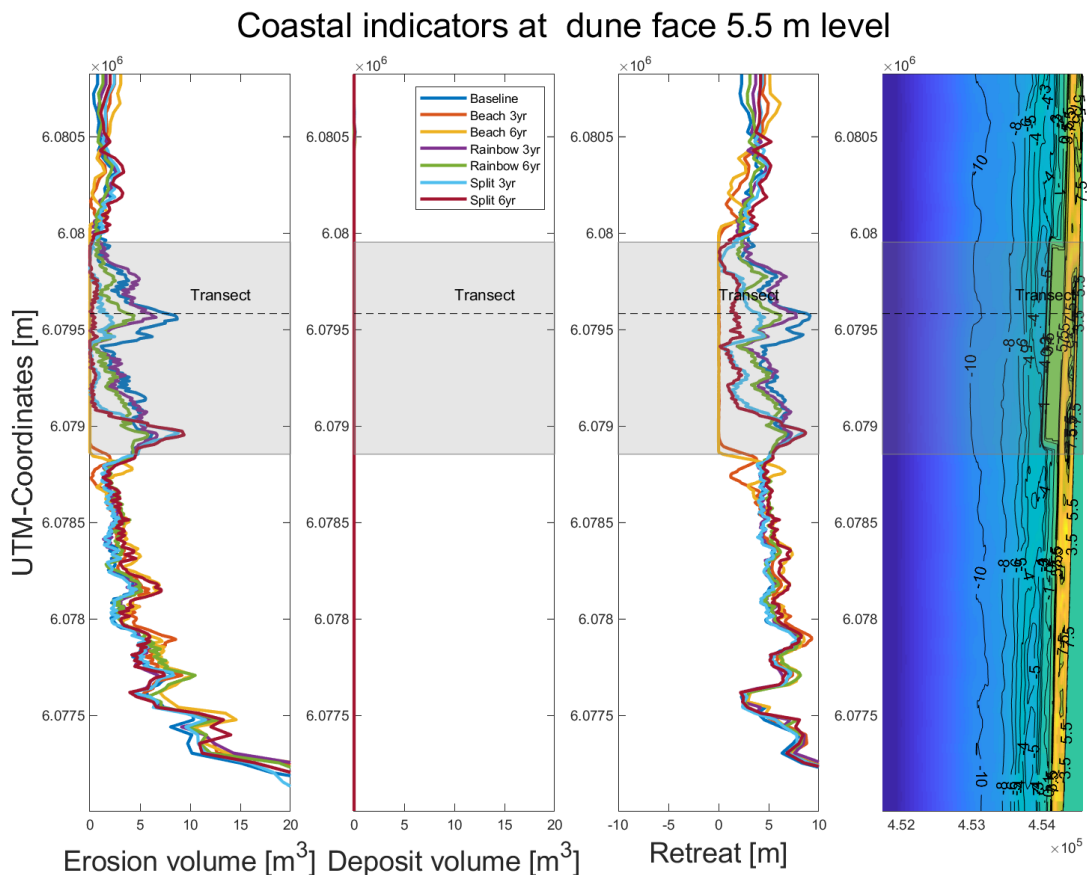
Figure 5-11 A map of coastal state indicators as the erosion volume, the deposited volume and the retreat distance along the coastline of Sylt. Grey filled area indicates nourishment, where a transect (dotted black line) is located where the ambient erosions is large.

Figure 5-11, shows the along shore variations of the coastal state indicators for the morphological reference level of 5.5 m, at the dune face above the beach nourishment.

Only erosion takes place at the dune face level and higher up in the profile, hence the maximum storm surge level (MSSL) is less than 3.5 m and even with the wave setup, sand is not carried up in the dune face level.

It is seen that the beach nourishments prevent erosion at 5.5m and further up in the dune face along the entire nourishment area, since the retreat at 5.5 m and erosion volume for both beach nourishments are close to zero. From the difference plot in Figure 5-12 it can be concluded that the beach nourishment is spread out and provides protection to the adjacent area, with most sand volume deposited to the north of the beach nourishment.

The rainbow nourishment follows the pattern of the baseline model (without a nourishment) for both retreat and erosion volume, it however reduces the erosion in the dune face of 2-3 m, as seen from Figure 5-11 and

Table 5-5.

The split nourishment adds significant protection to the dune face compared to the rainbow nourishment throughout the nourishment zone of up to 4 m regarding

Table 5-5. Though, it does not totally prevent erosion in the dune face as the beach nourishment. It reduces the retreat in the dune face of 5-7m and erosion volume of 4-10 m³ above MSSL (3.5 m) compared to if no nourishment was carried out.

In the southern part of the nourishment area (grey filled area in Figure 5-11), local increase in dune face retreat of 2-3 m is observed when splitting compared to the other nourishment strategies and without a nourishment. From Figure 5-12, a difference plot shows the morphological changes of the baseline model, beach, rainbow and split for the large 6 years nourishment. On the landward side of the split nourishment, boundary effects as channels of deeper water are generated at the lateral boundaries of the nourishment during the storm. These deeper water channels are coinciding with the local increase in erosion from Figure 5-11.
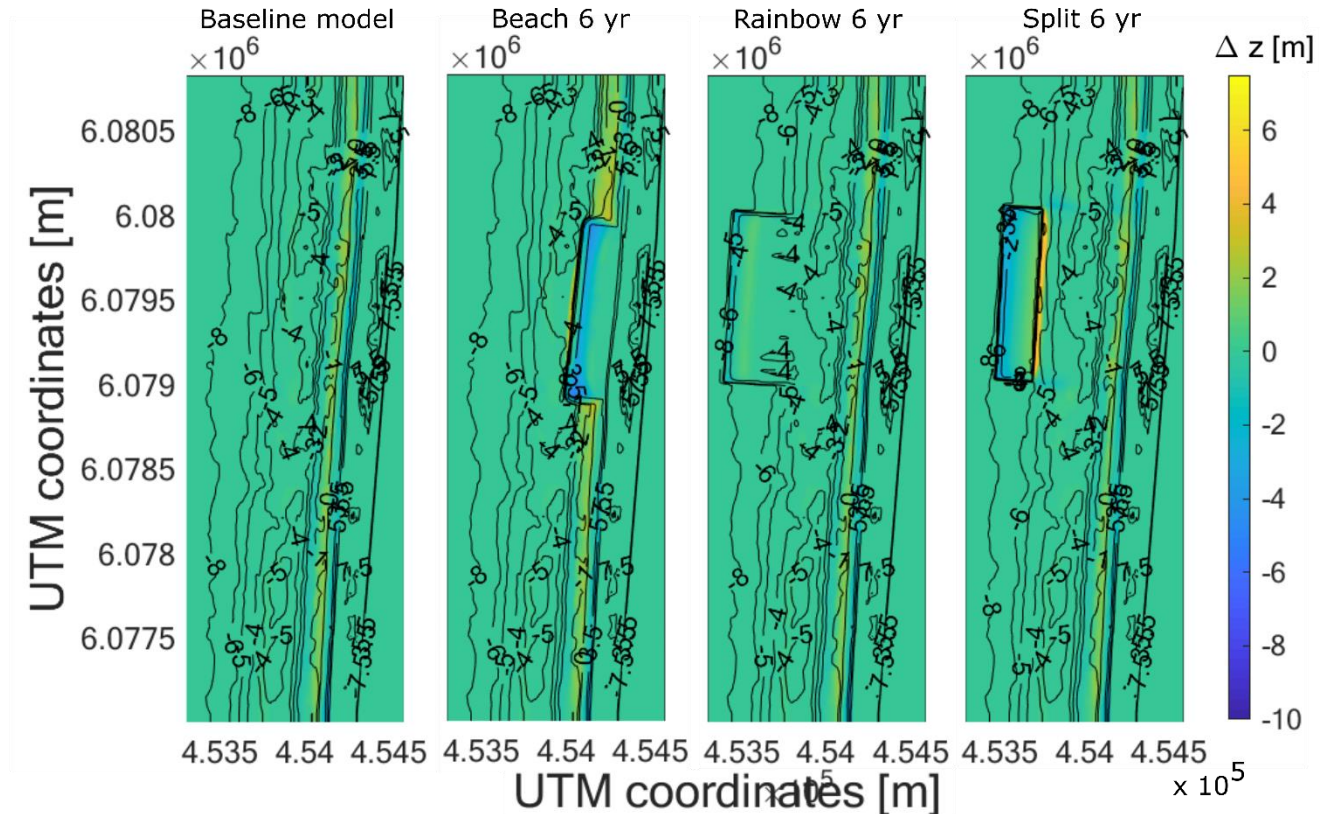
Figure 5-12 Difference plot of the baseline model, beach, rainbow and split nourishment. Yellow colour represents accretion and blue colour represents erosion.

Figure 5-13 shows that both types of shoreface nourishments are migrating towards the coast. The split nourishment is however transported further landward, depth induced wave breaking is enhanced on the high elevated crest of the nourishment and it is therefore more affected by the wave acting forces.

As seen from Figure 5-11, the black dotted line, within the nourishment zone, indicates a coastal transect where the ambient dune face erosion is large as determined from the baseline model. Figure 5-13 highlights the differences between the nourishment strategies of the dry part of the profile.
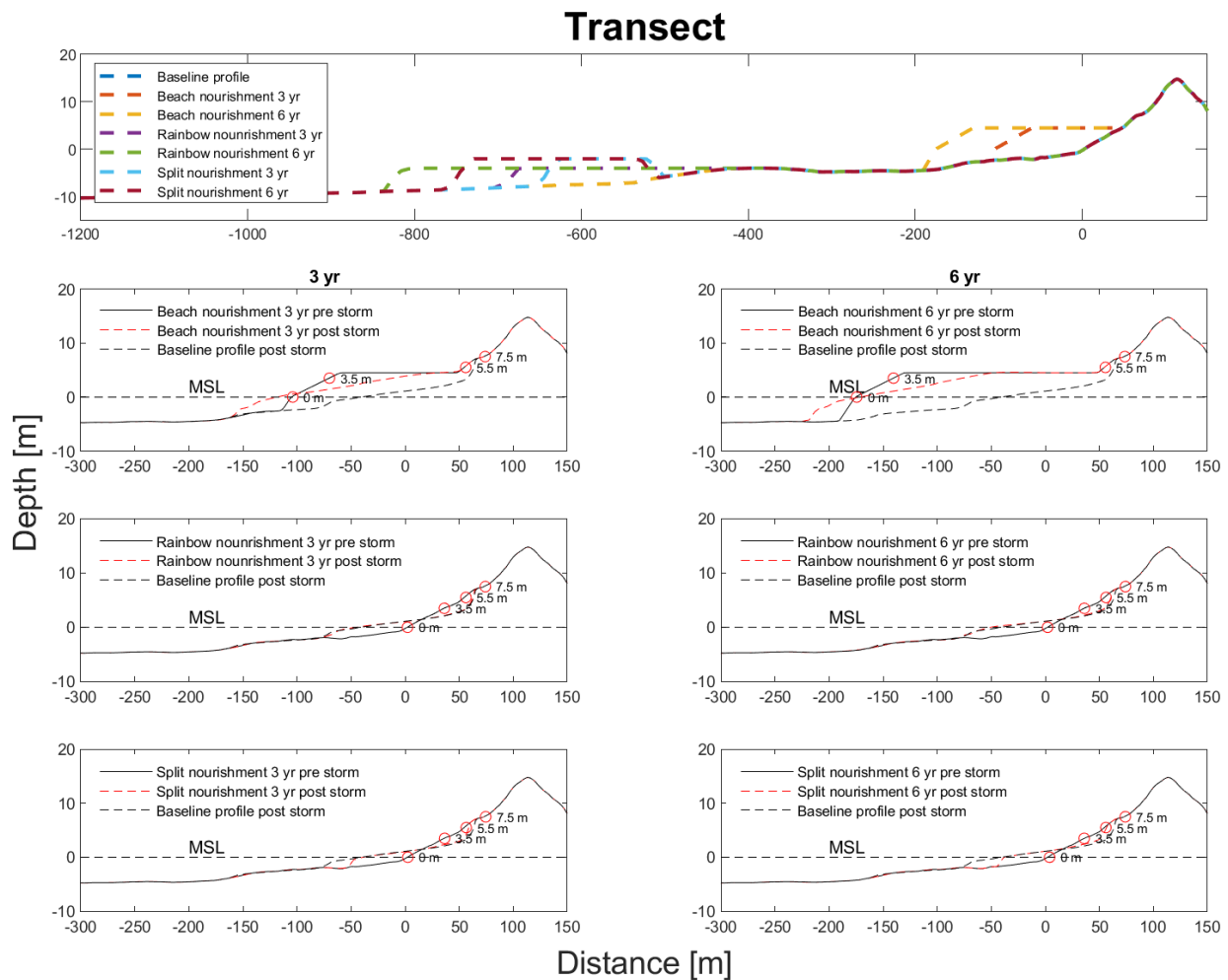
Figure 5-13 Transect plot of the selected profile, dotted black line, from Figure 5.3-1. The transect is shown for all types of nourishments, beach, rainbowing and splitting. Further, the baseline profile without nourishment is included.

Figure 5-13 shows the effect on dune erosion for each of the conceptual nourishment strategies for one transect. Upper most, the different conceptual designs of shoreface and beach nourishment are plotted. Beneath, the figure is divided in nourishments of 3 years erosion rate to the left and 6 years to the right. The rows present the different nourishment strategies as beach, rainbow and split. Solid black lines represent pre storm profiles, dotted red line presents the post storm profile of each nourishment strategy and the dotted black line presents the ambient post storm profile taken from the baseline model, without any nourishment.

Based on the transect plot, Figure 5-13, beach nourishments extent the beach more than 50 m seaward compared to the beaches with shoreface nourishments and without nourishment. The

beach nourishments mitigate the erosion in the dune face above the nourishment, whereas the shoreface nourishments still undergo erosion of 4-8 m in the dune face, see

Table 5-5.

Figure 5-14 presents the model results of the sea level rise scenarios. First, the 1D conceptual profiles are plotted, where the blue line indicates the baseline model, the red-orange curve indicates the scenario where adaptation (nourishment) has been carried and the yellow-orange curve presents the scenario where no adaptation (no nourishment) has been carried out.
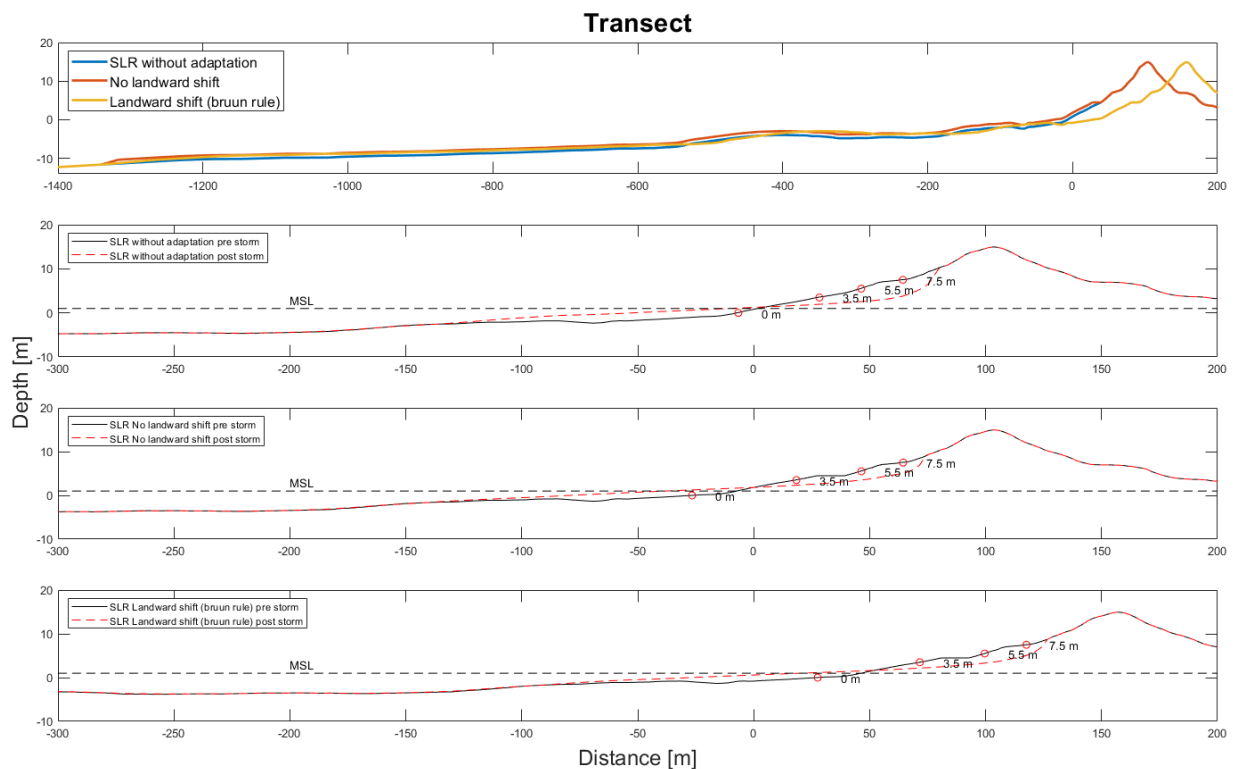
Figure 5-14 Pre and post storm profiles are plotted for all sea level rise scenarios.

In Figure 5-14, pre and post storm profiles are plotted for all sea level rise scenarios. The difference in erosion volume and retreat distances between the adapted (nourished) and the not adapted (not nourished) does not give a clear signal. The adapted scenario observes 1 m larger retreat in the dune face and the upper dune face. Whereas the not adapted profile observes 3 m larger retreat at the dune foot, as found from

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Table 5-5. The baseline scenario undergoes larger erosion than both modified scenarios, ranging from 4-6 m from the upper dune face to the dune foot compared to the adapted and not adapted scenarios.

Table 5-5 The table holds erosion and deposit volume estimates of all model scenarios. Furthermore, retreat distances for four different morphological reference levels (upper dune face, dune face, dune foot and MSL) is presented for all model scenarios.

Transect	No.	Scenario	Volume [m³/m]			Retreat [m]			
			Vol erosion above (MSSL 3.5 m)	Vol deposited above (MSSL 3.5 m)	Upper dune face (7.5 m)	Dune face (5.5 m)	Dune foot (3.5 m)	MSL (0 m)	
1	1	Without nourishment (baseline)	37	0	0	9	22	-43	
1	2	Beach nourishment 3 yr	71	2	0	0	58	-13	
1	3	Beach nourishment 6 yr	72	4	0	0	64	4	
1	4	Rainbow shoreface nourishment 3 yr	33	0	0	8	21	-47	
1	5	Rainbow shoreface nourihsment 6yr	27	0	0	6	19	-53	
1	6	Split shoreface nourishment 3 yr	22	0	0	4	18	-41	
1	7	Split shoreface nourishment 6 yr	15	0	0	2	15	-40	
			Above (MSSL 4.5 m)	Above (MSSL 4.5 m)					
1	8	SLR without adaptation	104	1	13	26	34	-45	
1	9	SLR no landward shift	79	1	9	21	28	-52	
1	10	SLR Landward shift (bruun rule)	75	1	8	20	31	-54	

5.4 Results Krogen

Three different nourishment strategies are investigated for Krogen (DK): beach nourishment, shoreface nourishment by rainbowing and shoreface nourishment by a splitting barge. A representative line for the investigation was chosen along the to-be nourished segment of the beach, based on highest erosion volume and retreat within the un-nourished baseline model run.

This chapter firstly provides the comparison between the nourishments and the un-nourished baseline, as well as the difference between nourishment strategies. Figure 5-15 shows alongshore changes in coastal indicators, while Figure 5-16 shows a difference plot of the pre and post storm bathymetry.

Secondly the comparison between nourishments and the un-nourished baseline along the representative transect, and their effects on the coastal indicators is discussed (Figure 5-17).

Lastly the chapter provides the comparison of different long-term strategies over close to 100 years, and how they individually impact the coastal indicators in a single 1D profile in Figure 5-18.

The coastal indicators extracted from the previously mentioned figures are collectively seen in Table 5-6.

All transects in the analysis are assumed west-east oriented. The coastline itself differs less the five degrees from the orientation of the analysed transects. This was done due to a strict time plan.

Figure 5-15 below shows the 2D variations of the coastal state indicators for the reference level of 5.5 m along the coastline following the storm event. A general note about the nourishment area: there is limited retreat and erosion volume in the un-nourished baseline model, except for slight increase in the most southern part of the area. This might be the result of the ongoing nourishments campaigns done intermittently on the stretch, possibly rendering it more resilient to storms than expected. In the most southern part of the model domain, approximately 2 km south of the nourishment zone, large variations in erosion volume and retreat distance are present. The XBeach model is run with a random generation on the wave input at the offshore boundary, however this will only explain some of the variations. Furthermore, the mesh generated for the nourishment models are not exactly the same as for the baseline model. A new refinement procedure is conducted for every nourishment model set-up, to ensure small cells at large bathymetric gradients induced by the nourishment and thereby secure high resolution at positions where the waves are affected by the sea bed. The different model mesh consists of the same number of cells. The difference in model mesh set-up might explain the variation in erosion volumes and retreat distances.
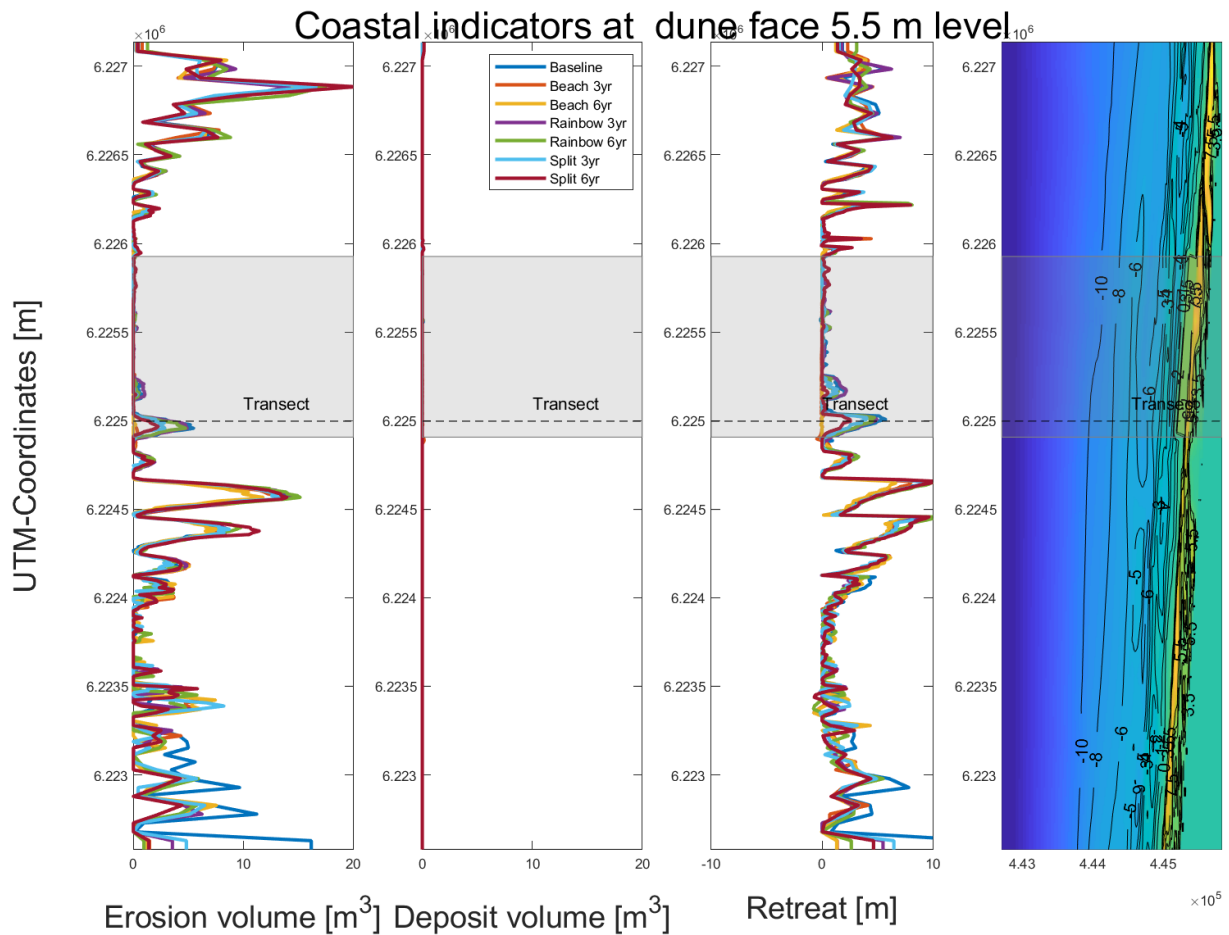
Figure 5-15 A map of coastal state indicators as the erosion volume, the deposited volume and the retreat distance along the coastline of Krogen. Grey filled area indicates nourishment, where a transect (dotted black line) is located where the ambient erosions is large.

Figure 5-15 in combination with Table 5-6 tells us that the beach nourishment completely halts the retreat of the 5.5 m contour line around the nourished area and selected cross section. At 3-5 m level a large erosion volume and large retreat at the 3.5 m line as seen from Table 5-6, but without the compromising the dunes safety level. It should be noted that the cross sections shown in Figure 5-17 show that the mass is not conserved in the profile, which indicates a high longshore transport of sediment. Furthermore, it must be noted, that the 3.5 m contour is shifted shoreward by the beach nourishments, and not by the shoreface nourishments. The net effect on the pre beach nourishment position of the 3.5 m level is not calculated. Outside the nourished area there generally seems to be an improvement on the retreat and erosion volume along the coastal indicator as result of the beach nourishments.

The rainbowing nourishment shows no beneficial or adverse change in retreat or erosion volume and seems to not affect any part of the beach in the 5.5 m line. From Table 5-6 a reduction of erosion at the 3.5 m contour (dune foot) is observed, indicating that the rainbowing nourishment might have a, albeit small, beneficial impact on the dune safety.

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The split nourishment reduces the retreat by around 50% at the 5.5 m line. The erosion volume decreases by a similar order. This could possibly be attributed to the split nourishments height and slope making it act like a sandy, underwater breakwater, diminishing the effects of the breaking waves on the coast.

Figure 5-16 shows the height difference of the bathymetry pre- and post-storm event at Krogen. The large beach nourishment sees substantial erosion around the front and its northern and southern boundaries, seemingly causing accretion in the un-nourished adjacent parts of the coast. The rainbowing nourishment sees slight erosion at the front and simultaneously some accretion at its crest. The split nourishment sees the largest apparent changes, as seemingly the entire nourishment sees large erosion, while the bathymetry east of the nourishment sees large accretion, indicating that the split nourishment during the storm event generally moved towards the shore.
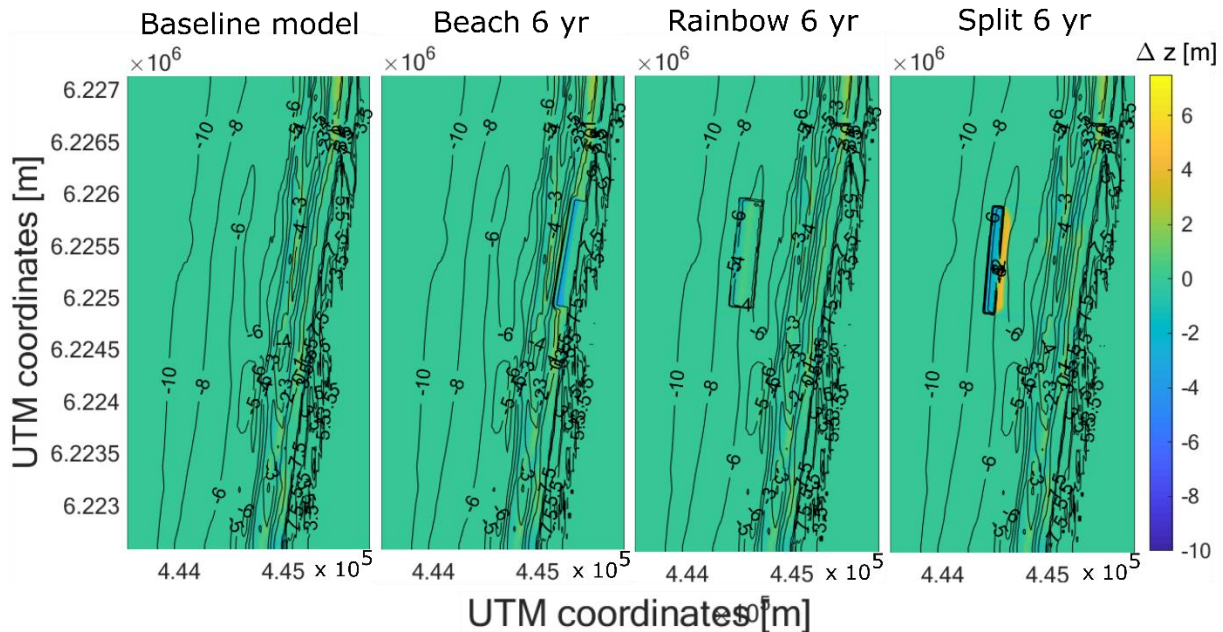
Figure 5-16   Difference plot of the baseline model, beach, rainbow and split nourishment. Yellow colour represents accretion and blue colour represents erosion.

Figure 5-17 shows pre- and post-storm profiles for the transect chosen and shown in Figure 5-15 for the various nourishment types and sizes. Additionally, the topmost figure shows all the pre-storm transects together, including the un-nourished baseline model, for a conceptual comparison between nourishment strategies. The post-storm baseline model is included in the figures comparing pre- and post-storm transects of the individual nourishment type and sizes. This helps highlight benefits and drawbacks from each scenario and makes for an easier comparison. While investigating Figure 5-17 values in Table 5-6 will simultaneously be referenced.

Figure 5-17 Transect plot of the selected profile, dotted black line, from Figure 5.3-1. The transect is shown for all types of nourishments, beach, rainbowing and splitting. Further, the baseline profile without nourishment is included.
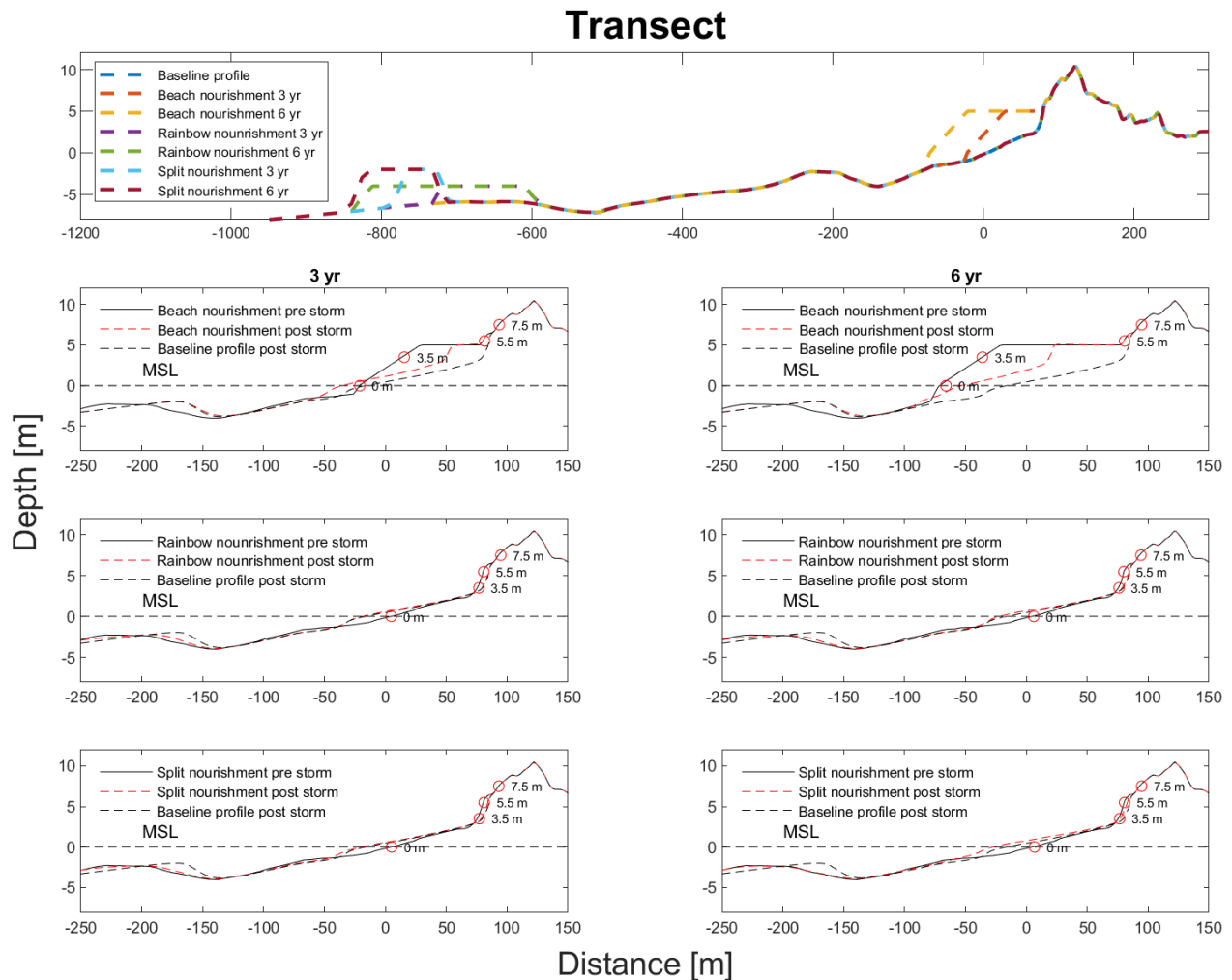
Figure 5-17 and Table 5-6 indicate a large retreat for the beach nourishment at the 3.5 m line post nourishment, 36 m and 55 m for the 3y and 6y respectively, while completely stops all retreat at the 5.5 m line. The un-nourished model comparatively saw 5 m retreat at 5.5 m contour, for which both beach profiles have increased the post-storm dune safety level. The large retreats at the 3.5 m line for the beach nourishments is a product of the 3.5 m line having been moved significantly westward by each of the beach nourishments.

The rainbowing nourishment, as previously stated, shows no identifiable changes in the post-storm profiles, indicating very little positive effect of the rainbowing nourishment on the dune safety levels, based on the established XBeach simulations at Krogen.

Finally Figure 5-17 and Table 5-6 shows that the split nourishment has reduced the retreat at 5.5 m from 5 m to 4 m and 3 m for the 3y and 6y nourishment respectively, while simultaneously widening

the post-storm beach, as the advance has increased from –21 m to –23 m and –31 m for the 3y and 6y nourishments respectively. Post-storm dune safety is higher for both split nourishments.

Figure 5-18 shows the previously chosen transect and the effects of climate change, and which strategy is chosen to manage it. The climate change is asserted by increasing the water level in the models by +1 m. In the upper most panel the conceptual transects can be seen. The three approaches are: 1) sea-level rise without adaptation ("SLR without adaptation"), 2) No landward shift and 3) Landward shift (Bruun rule). 1) is the baseline model, where nothing is changed except the water level. 2) assumes that nourishment program continues into the future, and therefore the beach is lifted from depth-of-closure up till the dune foot. 3) assumes no nourishment has been performed, and that the coast naturally moves landwards. This is known as Bruun's rule.
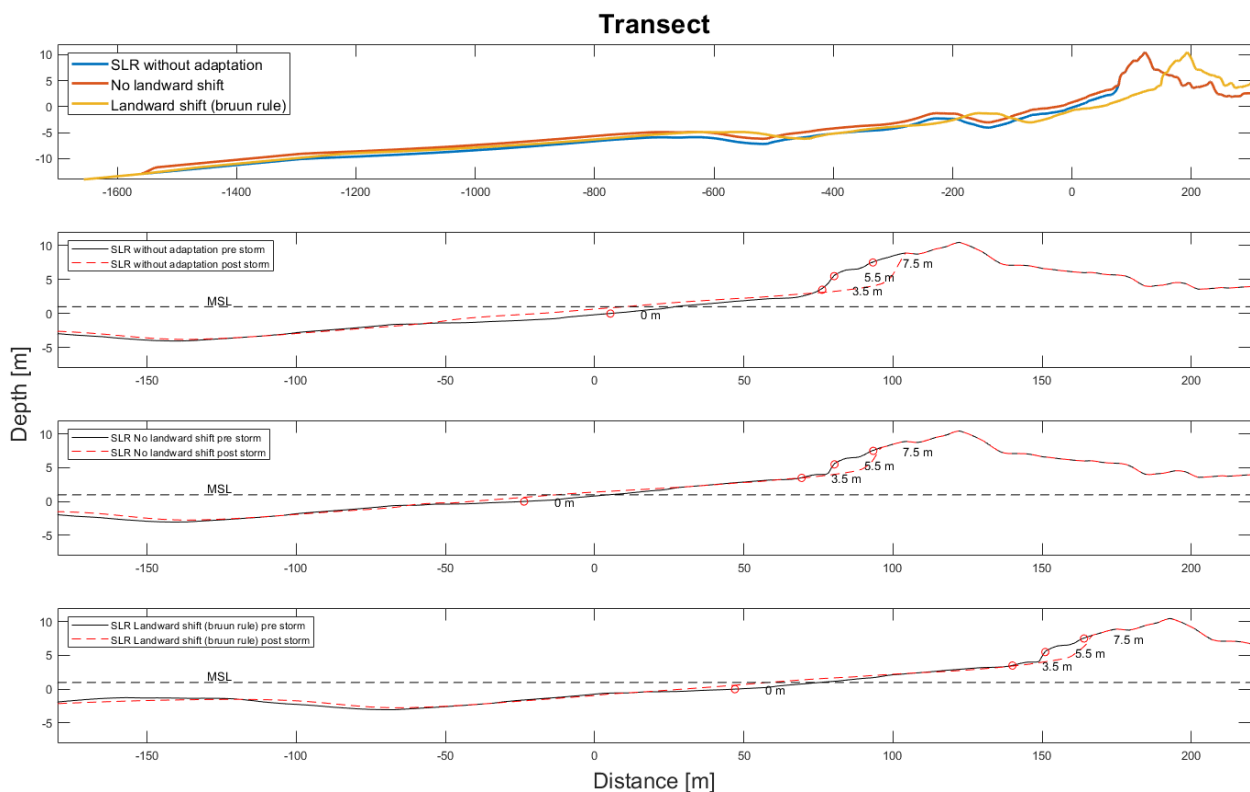
Figure 5-18 Pre and post storm profiles are plotted for all sea level rise scenarios.

Figure 5-18 and Table 5-6 indicate an increased dune face retreat at the 5.5 m line for a sea level rise (SLR) without adaptation, compared to the un-nourished baseline in Figure 5-17, as the dune retreat was 19 m and 5 m respectively. This is the effect of increasing water level of the storm, as higher water level allows for greater exposure of the dune.

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The sea level rise with continuous nourishment ("SLR No landwards shift") sees lower dune face retreat and erosion volume when compared to the SLR without adaptation, at approximately a factor of 2 for both. A higher dune safety is achieved with regards to sea level rise, when a strategy of continuous nourishment is utilized. However, the sea level rise scenario without adaptation (nr. 8) is unlikely to occur. Therefore, it is unfair to compare to, since the structural erosion is left out and assumed that the profile remains in equilibrium when the sea level rises.

Alternatively

Figure 5-18 and Table 5-6 also shows, that if the dune can be allowed to freely move landwards ("SLR landwardshift (bruun rule)") it achieves a similar safety level as the non-moving dune for which continuous nourishment were performed ("SLR No landwards shift"). The retreats and erosion volumes are the approximately the same for both in the post-storm scenario.

Table 5-6 The table holds erosion and deposit volume estimates of all model scenarios. Furthermore, retreat distances for four different morphological reference levels (upper dune face, dune face, dune foot and MSL) is presented for all model scenarios

Transect	No.	Scenario	Volume [m³/m]		Retreat [m]			
			Vol erosion above (MSSL 3 m)	Vol deposited above (MSSL 3 m)	Upper dune face (7.5 m)	Dune face (5.5 m)	Dune foot (3.5 m)	MSL (0 m)
1	1	Without nourishment (baseline)	15	0	0	5	4	-21
1	2	Beach nourishment 3 yr	66	1	0	0	36	-11
1	3	Beach nourishment 6 yr	103	2	0	0	55	16
1	4	Rainbow shoreface nourishment 3 yr	14	0	0	5	4	-23
1	5	Rainbow shoreface nourishment 6yr	12	0	0	5	3	-26
1	6	Split shoreface nourishment 3 yr	11	0	0	4	3	-23
1	7	Split shoreface nourishment 6 yr	6	0	0	3	2	-31
			Above (MSSL 4 m)	Above (MSSL 4 m)				
1	8	SLR without adaptation	64	0	9	19	10	-24
1	9	SLR no landward shift	29	0	2	12	1	-18
1	10	SLR Landward shift (bruun rule)	27	0	2	11	2	-17

5.5 Synthesis of the results

In all labs Langeoog, Krogen and Sylt, the model shows large differences in dune erosion, depending whether a nourishment has been placed prior the storm or without any nourishment (baseline scenario). Without a beach or shoreface nourishment placed, dune erosion is present in the dune face (all labs) and in the upper dune face (only Langeoog). In contrast, an upper beach/beach/2y&3y-beach nourishment protects the upper dune face (all labs) and particularly for Krogen and Sylt the dune face. On Langeoog the upper beach nourishment shows retreat on its high shaped profile, however the original dune is also still protected from erosion. There is also no erosion in the upper dune face in all nourishment scenarios from Krogen and Sylt, possibly due to a lower storm surge intensity than on Langeoog. A beach nourishment, which is (partly) eroded during a storm event, forms a new beach profile depending on the performed nourishment design. In general, the eroded sand is deposited further seaward and additionally spread along the coast to adjacent areas, seen in 1D (only cross-shore deposition) and in 2D models (cross- and longshore). The eroded volume above MSSL is generally hard to evaluate in nourishment scenarios, because the nourishment itself is often also reaching above the MSSL and therefore adds sand volume to the original dune.

Shoreface nourishments do not directly protect the dune area by working as a wear and tear body, but they affect the hydrodynamics with processes like wave breaking and are seen as a long-term sediment supply for the coastal profile. Long term effects by shoreface nourishments are addressed in the discussion. On Langeoog, the shoreface nourishment scenario did not show significant differences from the baseline scenario. However, on Krogen and Sylt variations of shoreface nourishments were modelled, based on different nourishment techniques. Here, XBeach predicts larger dune face erosion for rainbow nourishments than for split nourishments. The narrow and high elevated crest of the split nourishments is considered to increase wave breaking and offer higher protection to the dune face, compared to the wide and shallow crest of the rainbow nourishment.

A schematic figure of the model results is presented in Figure 5-19.

The effect from a different natural shoreface situation is analysed in a 2D model for Langeoog, which does not show significant differences in dune erosion. For Krogen and Sylt, shoreface nourishments can partly be seen as morphological variations due to distinct bar-through systems in those areas, so no additional scenarios area made here.

The results for a modelled sea level rise of 1m show similar results for all labs. The scenario without any manual modification in the profile shows the highest erosion volume above MSSL from all SLR-scenarios in the respective lab. Additionally, the retreat for the upper dune face is the highest of all scenarios. The difference in erosion volume and retreat in the upper dune face between the scenarios with and without a landward shift while heightening the profile is rather small, however the profile shifted according to the Bruun rule shows slightly less storm impact.
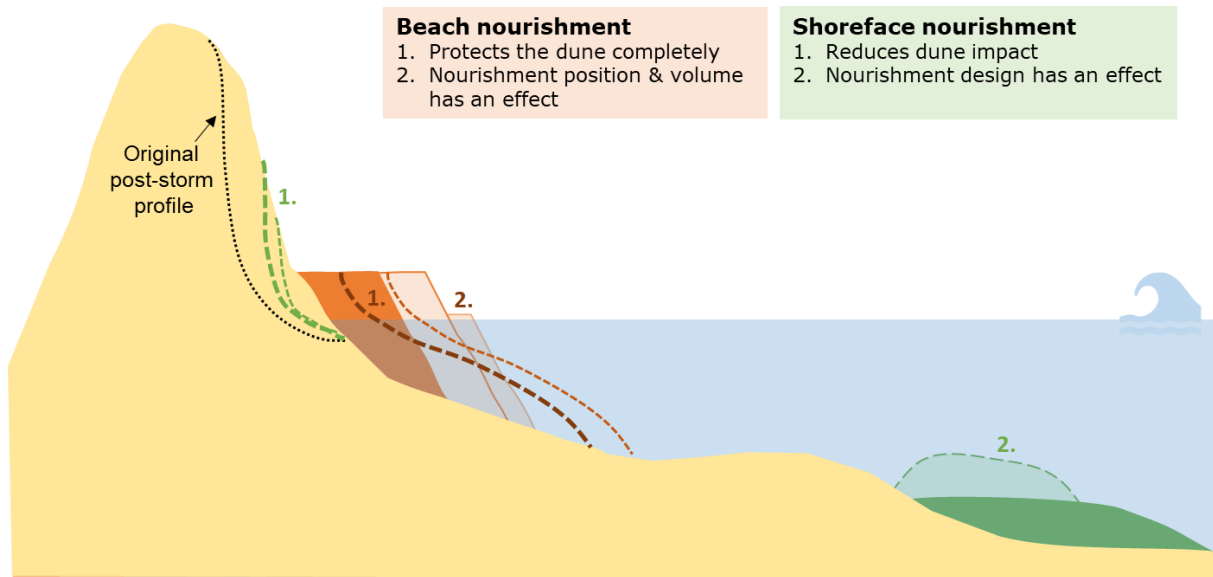
Figure 5-19 conceptual figure of the scenario modelling results

6   Discussion

The scenario modelling results show that beach nourishments are most effective in reducing storm impact immediately compared to shoreface nourishments which is, while depending on the location, significantly cheaper to install. However, nourishments can have multiple functions, such as safety, counteracting structural erosion, recreational or ecosystem related, and are often an important motivation for nourishment placement. Shoreface nourishments are cheaper to execute and can therefore be a more cost-effective solution compared to beach nourishments, and additionally have less impact on the recreational use of a beach. Despite being less effective immediately in reducing dune erosion compared to beach nourishments, shoreface nourishments still result in a reduction of the impact during storms. A shoreface nourishment results in a more filled beach on the longer term (Wilmink et al., 2021). They keep the shoreline/coastal profile in place to gain a combined effect short-term (storms)/long-term (coastal retreat). This effect has not been modelled and therefore it is the expectation that shoreface nourishments in the longer term will have additional benefits not investigated in this study. Therefore, shoreface nourishments can also be a suitable solution if dune safety during storms is considered.

For the scenario modelling investigation, a couple of assumptions and simplifications have been used, which have some implications for the results presented in this report:

- For all study sites measured bathymetric profiles have been used to simulate the scenarios, and nourishment volumes are based on realistic site-specific values. The shapes of the nourishments are mostly conceptual and based on pragmatic approaches. What the exact effect of a nourishment will be for a certain location, highly depends on site-specific conditions. In this study the effects of nourishments are tested conceptually in order to determine general trends and support our general understanding of nourishments. In addition, the actual shape and position of the nourishment at the start of a storm event may have changed after months (or even years) being subjected to more regular wave and tidal conditions.

- The goal of the SLR scenarios is to gain insight in conceptual climate change adaption strategies. In this study the "Bruun-rule" was applied to represent the effect of SLR on the long-term profile development. However, there are some limitations and uncertainties associated with application of the Bruun Rule (e.g. Ranasinghe et al., 2012), as it for example does not include any significant sediment sinks or sources, or alongshore gradients in net longshore transport. In addition, using the XBeach Surfbeat model to simulate one storm on an estimated future profile may have its limitations. A more complex modelling approach that combines both storm event processes (i.e. dune erosion), long term processes (i.e. beach recovery, aeolian transport, SLR) and human interventions (i.e. nourishments) could provide the knowledge needed to increase our system understanding of the impacts of SLR on future coastal development. The results in this report on the impact of SLR on dune safety are therefore merely a first assessment.

- In the scenarios a couple of variations in the initial morphological configurations are setup to include some of the natural variability in the initial bathymetry, but this is not systematically investigated. Therefore, the potential longer term (in the order of years) effects of a shoreface nourishment on the shape of the beach and dune profile are not included. A shoreface nourishment adds sediment volume to the system and can dissipate wave energy under daily conditions, which can result in an increase in beach or dune volume. This changes the bed profile and may contribute (indirectly) to the dune safety during storm conditions.

- Besides the indirect long-term effects of a shoreface nourishment on the dune safety, the beach nourishment seems to have an indirect effect on the safety as well. In the 2D simulations XBeach predicts that the beach nourishment spreads out in alongshore direction, thus adding sediment volume to the un-nourished adjacent beaches. This effect is not included in the 1D simulations.

7 Conclusions

The results in this study show that XBeach can be used as a tool to assess the impact of Building with Nature techniques as nourishments on dune safety. XBeach models are developed and validated for three labs, and subsequently run for a set of scenarios based on different nourishment placement or design, morphological configuration and conceptional climate change profile developments.

When comparing our results from 3 different labs, we are able to conclude similar patterns: The storm impact without any nourishment is greater in both erosion volume and dune retreat than with a nourishment. It clearly shows the effect from beach nourishments in reducing the impact of a storm on the dune, affecting the dune safety. Less impact reduction is found for shoreface nourishments, but it depends on the nourishment design. However, shoreface nourishments have shown to reduce coastal retreat on the long-term and could change the coastal profile in such a way that it results in additional reduction of storm impact. This effect was not included in the scenarios, and thus shoreface nourishments can also be a suitable solution when considering dune safety during storms. These findings are in line with our project results from the Building with Nature Co-Analysis.

With sea level rise scenarios, we gained insight in the general coastal behaviour during storm conditions with higher sea levels due to sea level rise. Different conceptual adaption strategies show small variations regarding dune safety. However, it can be concluded that nourishments also dampen the dune erosion during storm surges when sea level rise is taken into account. Nourishments have a double effect on the coastline they:

- Reduce dune erosion during storm surges
- Compensate gradual sediment losses at the coast and are preventing gradual coastal retreat.

Both effects combined provide benefits for the management of our coastlines.

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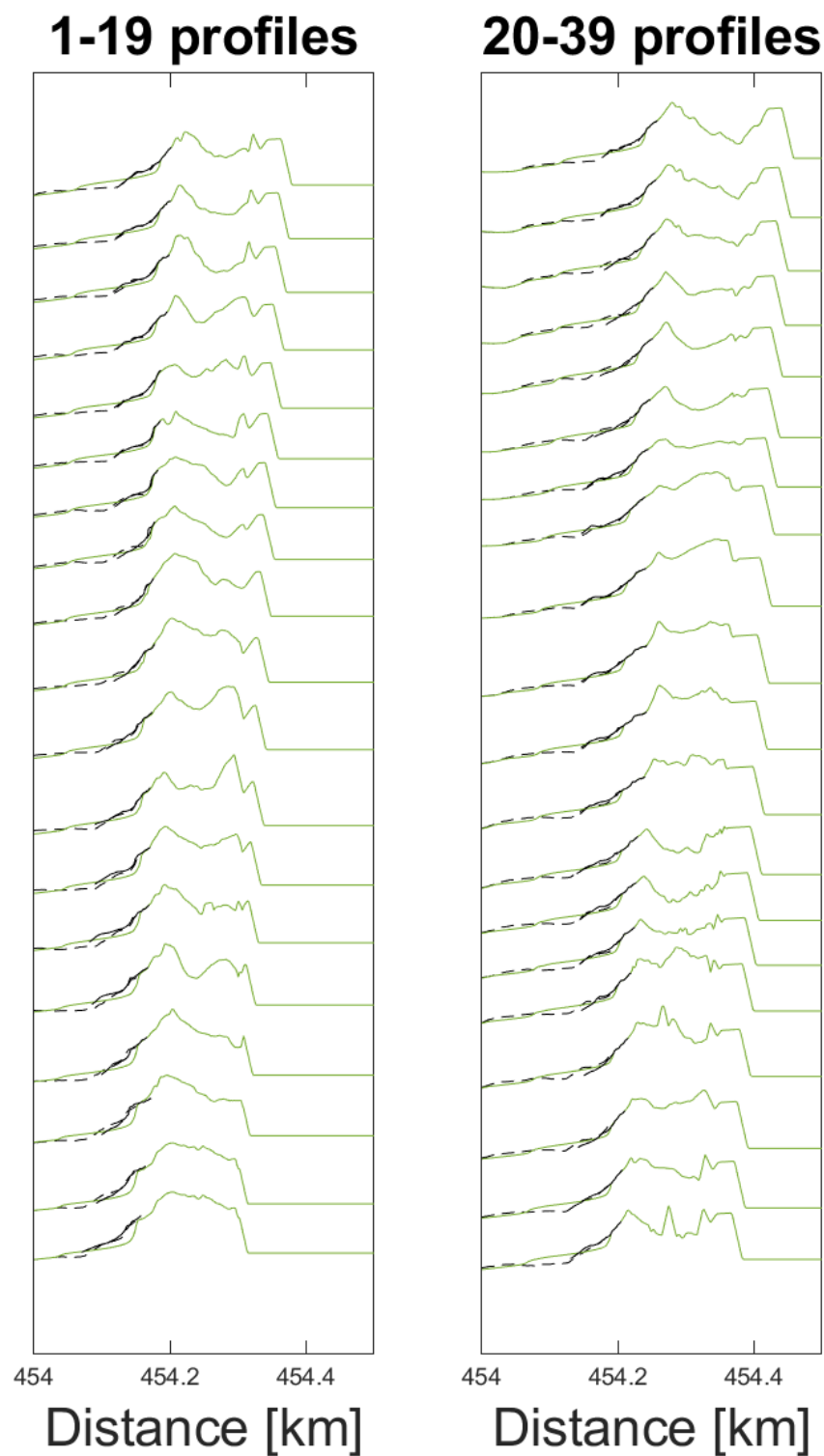
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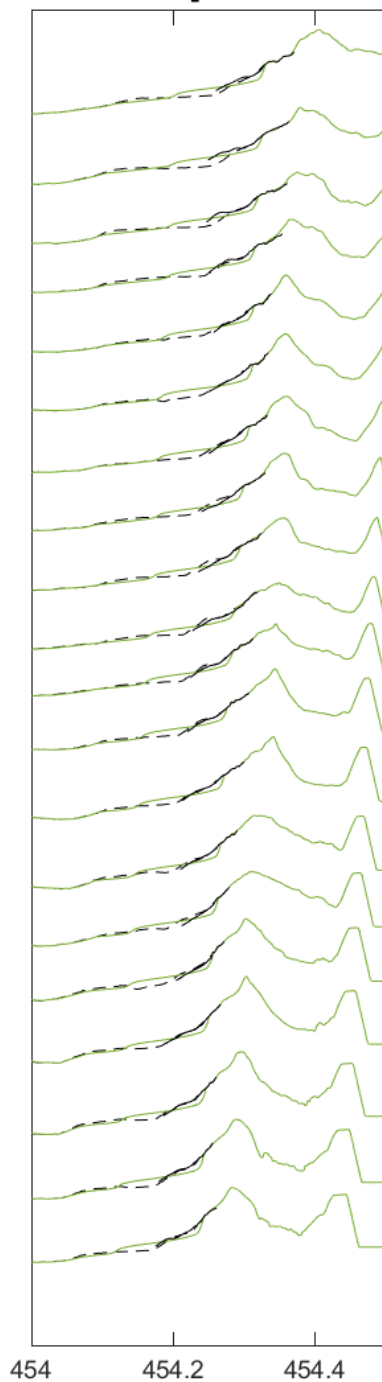
Appendix A – XBeach settings

Table A1 Overview of XBeach model settings applied in the simulations for Langeoog and Krogen/Sylt

Parameter	Value Langeoog	Value Krogen/Sylt
Wavemodel	surfbeat	surfbeat
Bedfriction	manning	chezy
Bedfriccoef	0.02	55
facSk	0.13	0.3
facAs	0.10	0.3
break	Roelvink_daly	roelvink2
Gamma	0.51	0.55
Gamma2	0.31	NA
Alpha	1.37	1.0
Beta	0.11	0.1
Wetslp	0.25	0.3
morstart	1200	100
Tidetype (only with a time varying water level)	hybrid	velocity
nuhfac	0	1
Single_dir (only 2DH simulations)	0	0
morfac	5	2

Appendix B - Sylt validation, all profiles
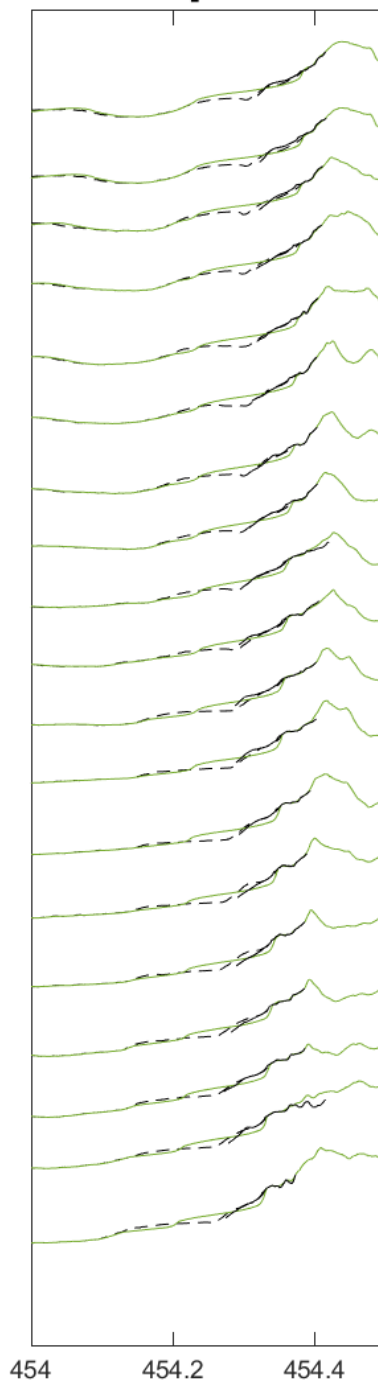

1-19 profiles

20-39 profiles

Distance [km]

Distance [km]

40-59 profiles

60-78 profiles

Distance [km]

Distance [km]