Building with Nature: Numerical simulations of acute dune erosion under storm conditions with MIKE 21 IG, Skodbjerge, Denmark.

Technical note, February 2019

Storm event at Skodbjerge where acute dune erosion was observed on 12-01-2007

Project information

Project	**Building with Nature (InterReg)**
Start date	01.11.2016
End date	01.07.2020
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Time registering	402412
Approved date	20-02-2019

Report	Numerical simulations of acute dune erosion under storm conditions with MIKE 21 IG, Skodbjerge, Denmark.
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Keyword	Building with Nature, numerical modeling, MIKE 21 IG, acute erosion, cross-shore sand transport
Distribution	www.kyst.dk, www.buildingwithnature.com
Referred to as	Kystdirektoratet, BWN Acute erosion Skodbjerge, 2019

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1 Introduction

The objective of the Building with Nature InterReg project is to make coasts more adapted and resilient to the effects of climate change. As a part of this project the Danish Coastal Authority (DCA) are doing research on different subjects in coastal laboratories on Danish coasts.

Coastal dunes are natural barriers protecting the hinterland for erosion and flooding under extreme events like storms. These natural barriers are often exposed to storm conditions where a combination of high wave energy and elevated water levels are capable of producing acute erosion of the dune system. Significant acute erosion occurred to the coastal dunes at Skodbjerge in January 2007. This erosion event is investigated through a morphological analysis of good profile data before and after the storm period and by numerical modeling of acute erosion with the MIKE 21 IG model. The aim of this project is to test and use the new MIKE 21 IG model to quantify the dune-strength against acute erosion and see how this correlates with coastal state indicators (CSI).

DCA investigated acute dune erosion along the Danish North Sea coast for the period 1977 to 2011 where an applicable explanation was not found. However, the study showed a correlation between the nearshore bar morphology and dune erosion (DCA, 2014a). This correlation was further investigated by numerical modeling of acute dune erosion at Skodbjerge in a 1D model – X-Beach. Simulation results showed overestimated dune erosion, which was explained by the lack of longshore sediment transport in the simulations (DCA, 2014b).

2 Summary

The objective of this research project is to investigate local acute erosion and see how this correlates with CSI by using the numerical model MIKE 21 IG. A period with three storm events in January 2007 caused morphologic changes to eight pre- and post-storm profiles surveyed in a coastal laboratory on the Danish North Sea coast. Offshore wave data from Nymindegab wave buoy and water levels from Hvide Sande sea-level gauge were analyzed and used as input to the numerical model.

The morphologic analysis showed that the median and northern parts of the system eroded and the nearby profiles accreted. The dry part of the system generally eroded while accretion occurred at the upper shoreface near the shoreline. Offshore bar migration and erosion of bar crests were typical morphologic changes. The bar heights were generally higher at the northern and southern parts of the coastline than at the median part. After the storm period, the bar heights were reduced at the northern and southern parts of the coastline while they remained constant or increased in height at the median stretch of the coastal laboratory.

Numerical modelling of acute erosion was completed with the MIKE 21 IG model. Real-time waves and infragravity waves were generated from measured offshore wave climate and used as input to the boundary conditions in the numerical model. The modelling was computed on domains generated from pre-storm profiles and the results were directly compared with measured post-storm profiles. The modelling results showed that MIKE 21 IG can reproduce acute erosion that matches measured dune erosion. The model eroded the dune front and accumulated the sand in sediment deposits at the upper foreshore, which was in line with the measured morphologic changes at some of the coastal profiles. Field measurements showed that the eroded sand was not deposited in all profiles like the model predicted. At these profiles the eroded sand was possibly transported alongshore to the nearby profiles.

This study gives an improved understanding of the cross-shore sand transport component at Skodbjerge and emphasizes the need for studying the longshore component as well. The longshore sand transport could be further investigated in a 2D area model in order to get the full picture of the sediment dynamics in the system.

3 Study area and field campaigns

Skodbjerge is situated at the Danish North Sea coast at southern Holmsland Tange – a sandy coastal barrier with well-developed dunes. The tidal range is ca. 1.1 m and the 1 year storm-surge return period is 2.07 m. Eight coastal profiles (figure 3.2) were measured on 06/07/2006 and 25/01/2007 with distances of 200 m out to a depth of app. 6 m. Eight beach profiles were measured 19/12/2006. Offshore wave data are from Nymindegab wave buoy situated 14 km offshore from the study area at a depth of 17.5 m (figure 3.1). Sea-level data were measured at Hvide Sande (sea gauge) situated 11 km north of the study area.

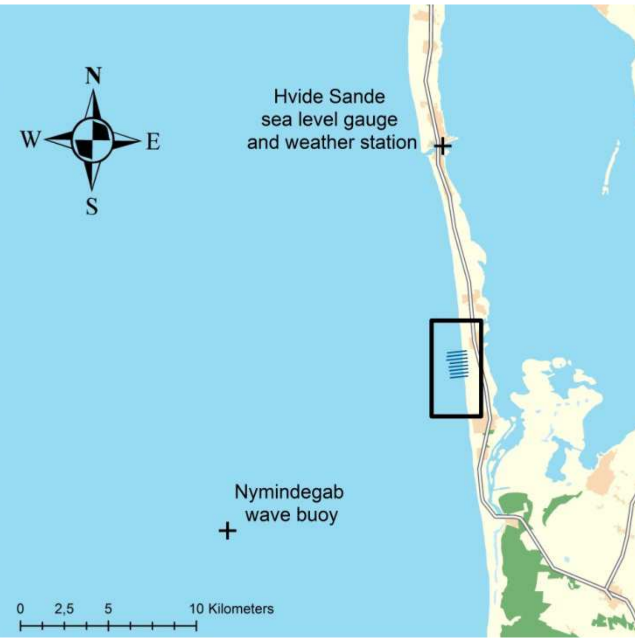


Figure 3.1: Location of Hvide Sande sea-level gauge and weather station, Nymindegab wave buoy and study area at southern Holmslands Tange

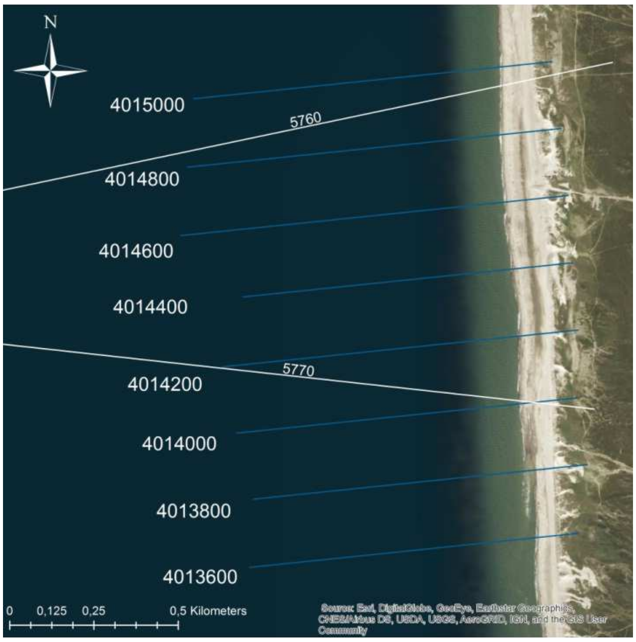


Figure 3.2: Local survey lines (4013600 to 4015000) and west coast lines (5760 and 5770) on orthophoto

4 Profile analysis

A period with storm events caused changes to the coastal morphology both at the subaqueous and subaerial part of the system. The pre- and post-storm profiles are plotted in figure 4.1 to 4.8.

Line 4013600 (figure 4.1): Dune/beach erosion occurred and the upper shoreface eroded. Nearshore bars flattened and troughs accreted.

Line 4013800 (figure 4.2): Accretion dominated the dune/beach, upper shoreface and inner bar. The outer bar was flattened.

Line 4014000 (figure 4.3): The morphologic changes at the dry part of the system were minimal. Erosion of the upper shoreface occurred and the inner bar migrated offshore and the crest was lowered.

Line 4014200 (figure 4.4): The dune and beach eroded significantly and the beach step accreted. Nearshore bars eroded and migrated seawards.

Line 4014400 (figure 4.5): The dry part of the system experienced significant erosion. The inner bar accreted while the middle bar eroded.

Line 4014600 (figure 4.6): A substantial amount of sand was deposited at the beach and upper shoreface. The outer bar crest was lowered and the bar moved offshore.

Line 4014800 (figure 4.7): The dune/beach eroded and the eroded sand was deposited at the lower foreshore and upper shoreface. The bar crests were lowered. A newly formed bar occurred and the outer bar migrated seawards.

Line 4015000 (figure 4.8): The dune/beach eroded and the sand accumulated at the lower foreshore and upper shoreface. The inner and outer bars both migrated offshore.

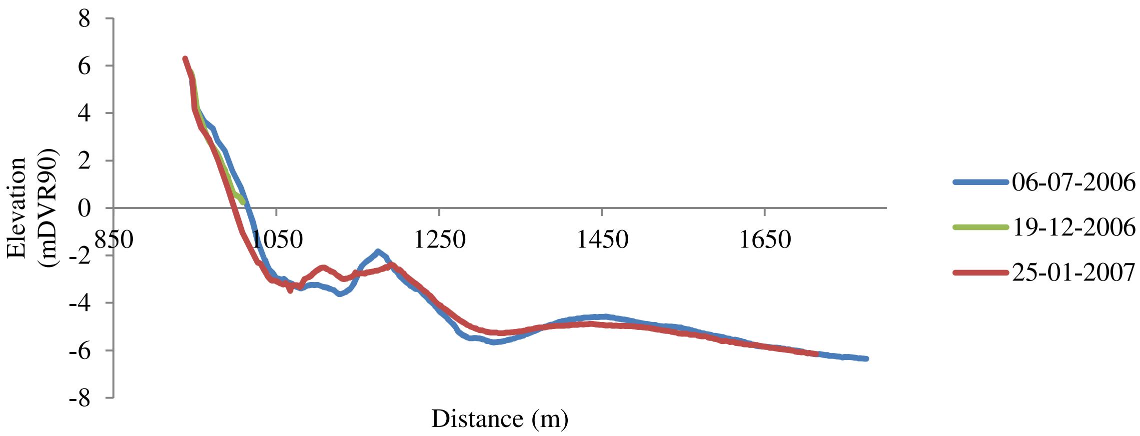


Figure 4.1: Survey line 4013600

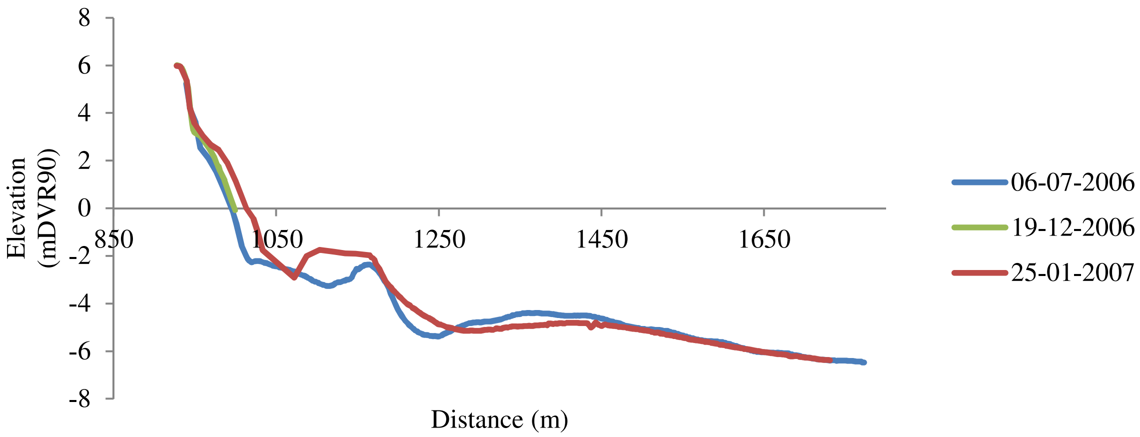


Figure 4.2: Survey line 4013800

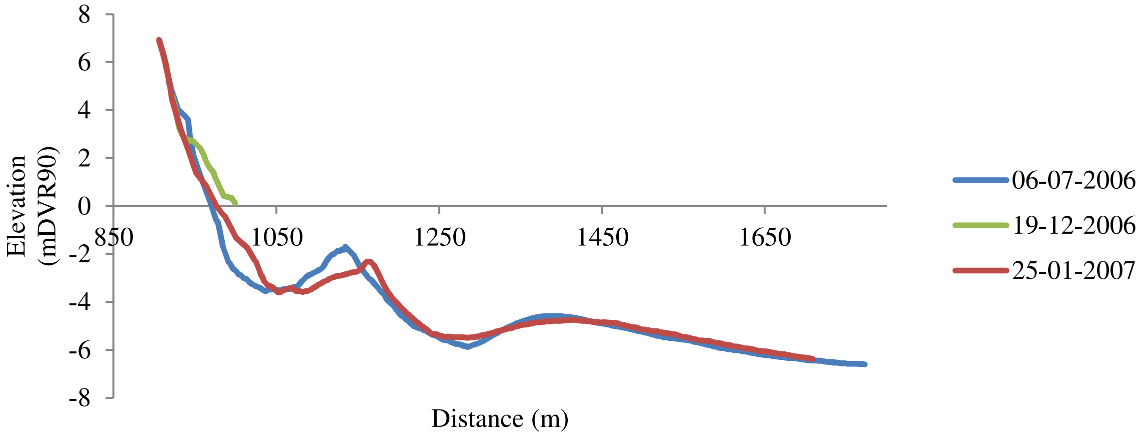


Figure 4.3: Survey line 4014000

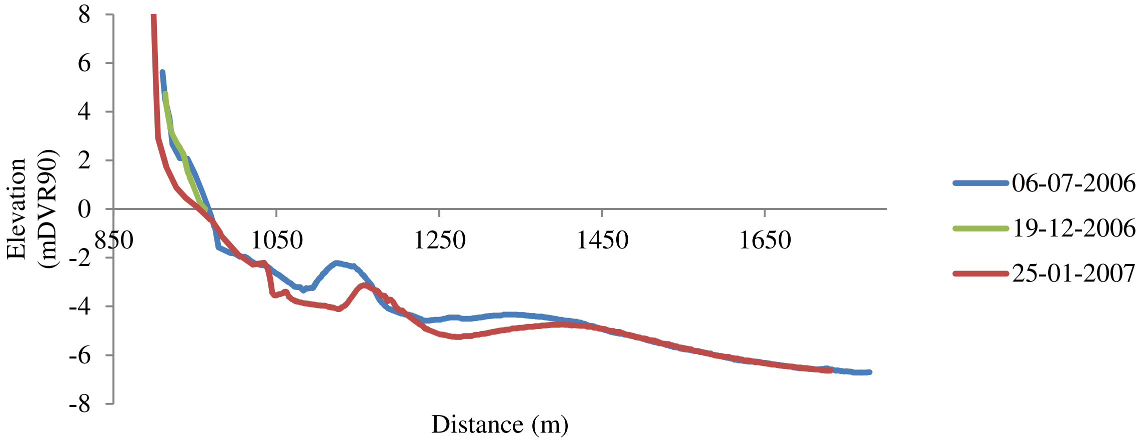


Figure 4.4: Survey line 4014200

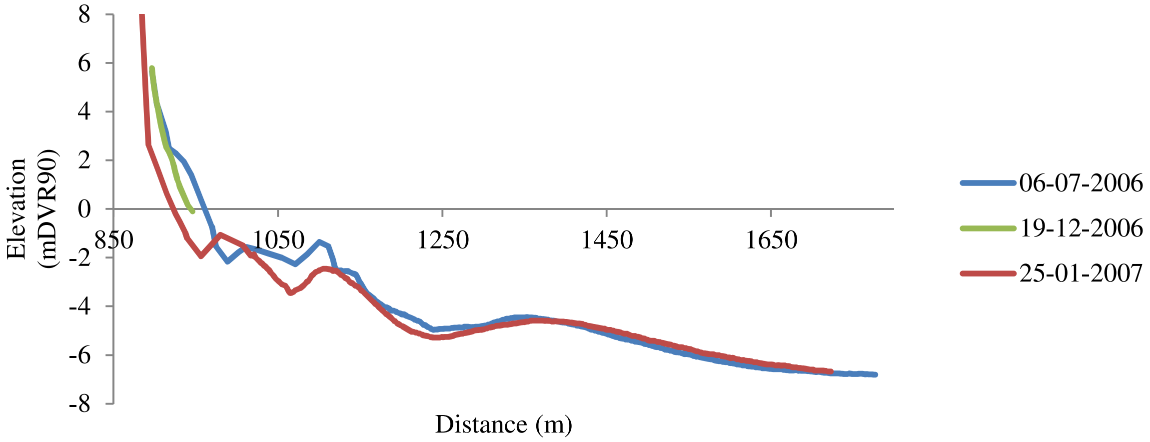


Figure 4.5: Survey line 4014400

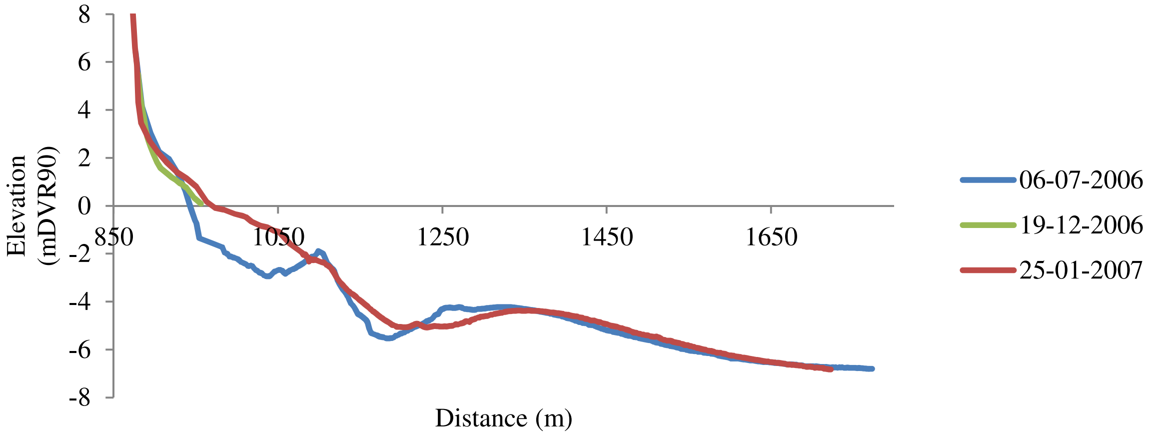


Figure 4.6: Survey line 4014600

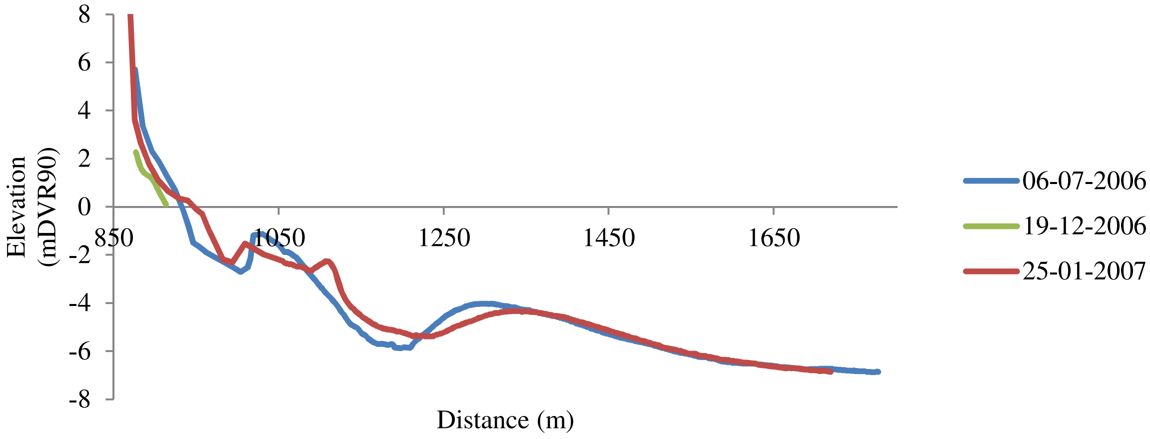


Figure 4.7: Survey line 4014800

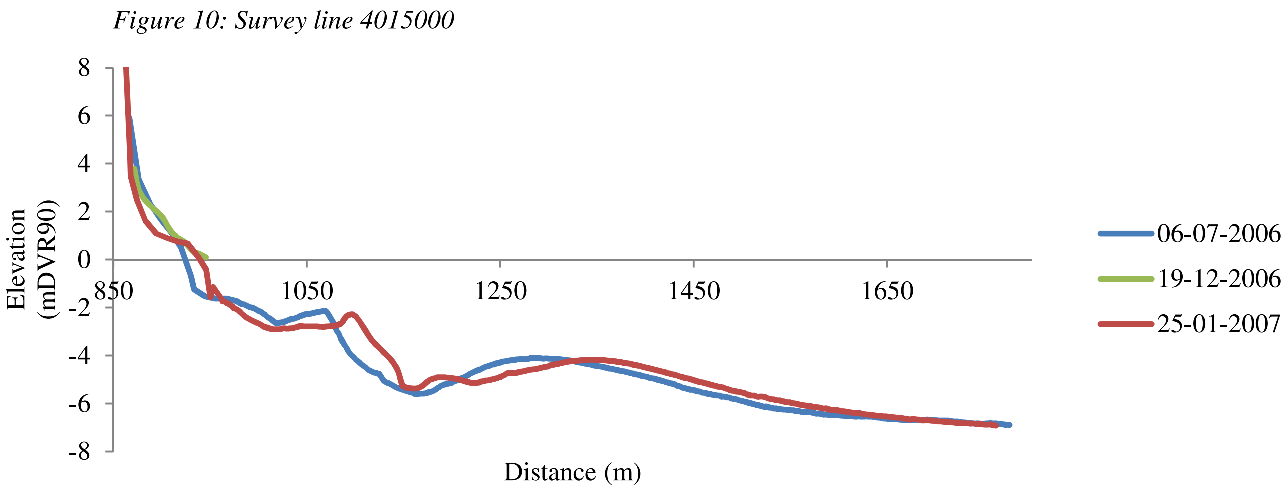


Figure 4.8: Survey line 4015000

The profile analysis of the pre- and post-storm profiles showed a modified coastal morphology and a complicated erosion/accretion pattern. A summary of the morphologic changes is given in table 4.1. A difference map calculated on the eight pre- and post-storm profiles can be found in appendix 1.

Table 4.1: Summary of morphologic changes

	Water		*Land*
Profile	**Lower shoreface**	**Upper shoreface**	**Beach and dunes**
4013600	Bars flattened, accretion in troughs	Erosion	Erosion
4013800	Outer bar flattened, inner bar accreted	Accretion	Accretion
4014000	Offshore bar migration	Erosion	No change
4014200	Bars eroded and migrated seawards	Beach step accretion	Severe erosion
4014400	Inner bar accreted, middle eroded	Erosion	Severe erosion
4014600	Erosion of bar crests, accretion in troughs	Large accretion	Accretion
4014800	Newly formed inner bar, outer bars migrated seawards, crest erosion	Accretion	Erosion
4015000	Offshore migration of bars	Accretion	Erosion

Erosion dominates the median part (4014200 and 4014400) of the system and the nearby upstream and downstream areas are supplied with sand. Offshore bar migration and lowering of bar crests are typical morphologic changes. At the northern part of the system (4014800 and 4015000) the eroded sand from the beach and dunes is deposited at the lower foreshore and upper shoreface. Newly formed bars develop few places along the coastal laboratory.

5 Coastal state indicators

An objective method for determining the dimensions of the coastal morphology in the wave-dominated zone and on the beach/dune has been developed for the Danish North Sea coast.

The shoreline is defined to be situated at 0 mDVR90. Bar width is defined as the horizontal distance between the deepest part of the landwards trough and through the bar to the seawards side ending at the same depth. Bar relief is the height difference between the deepest part of the landwards trough to the bar crest. Inner bars are located within 300 m from the shoreline and outer bars are located seawards of this zone. Inner bars are found in water depths between 0 and 4.0 m and have a minimum height of 0.8 m. Outer bars are situated in water depths between 4.0 and 8.0 m and have a minimum height of 0.5 m (table 5.1). These bar dimensions are used as criteria for selection of bars and this seems reasonable since similar criteria were used in DCA (2004). Distance to bar is measured horizontally from the shoreline to the location of the bar crest, i.e. the cross point between vertical bar crest line and the still water level (see figure 5.1).

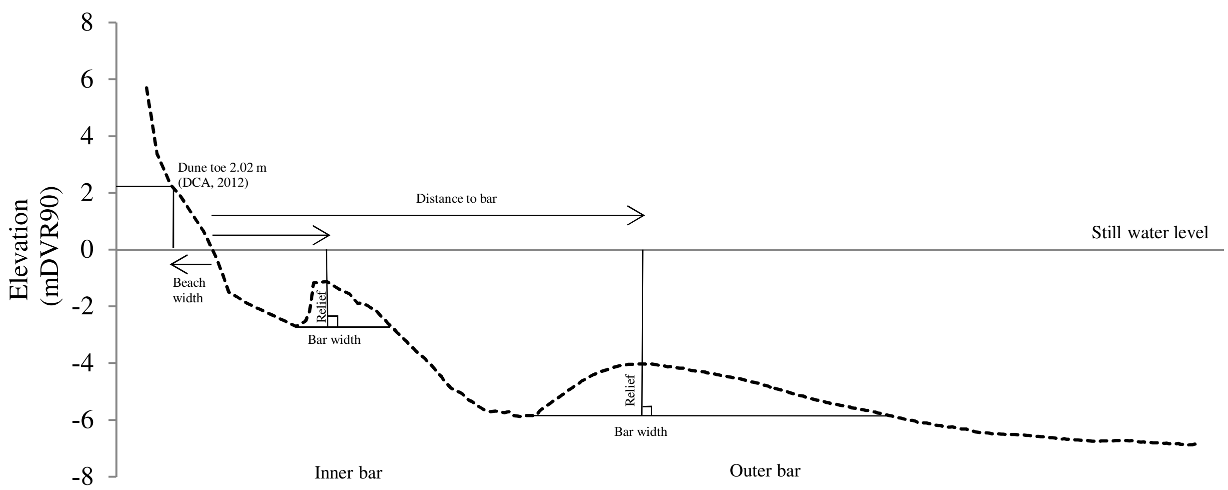


Figure 5.1: Method for analyzing coastal morphology e.g. dimensions of bars, beach and dunes

Elevation of the dune toe is problematic to define objectively on all beach profiles. Therefore it was decided to use extreme water level statistics for determining the dune toe elevation. The extreme water level statistics are from Hvide Sande sea-level gauge that measures sea-levels from the harbor groyne 11.3 km north of the study area. The 1 year storm-surge return period is 2.07 m (DCA, 2012). This value seems to be a reasonable parameter for defining the dune toe elevation since a major part of the observed dune toes are located around this height. Beach width is measured horizontally between the shoreline and the dune toe.

Table 5.1: Criteria for selection of bars

	Inner bars	Outer bars
Min height (m)	0.8	0.5
Depth (m)	0 to 4	4 to 8
Distance from shoreline (m)	< 300	> 300

5.1 Subaerial CSI

CSI from the dry part of the coastal system are presented here. Beach widths and slopes were calculated between the shoreline (0 mDVR90) and dune toe (2.07 mDVR90). Dune front slopes were calculated between the dune toe (2.07 mDVR90) to the same elevation (5.19 mDVR90) at all profiles.

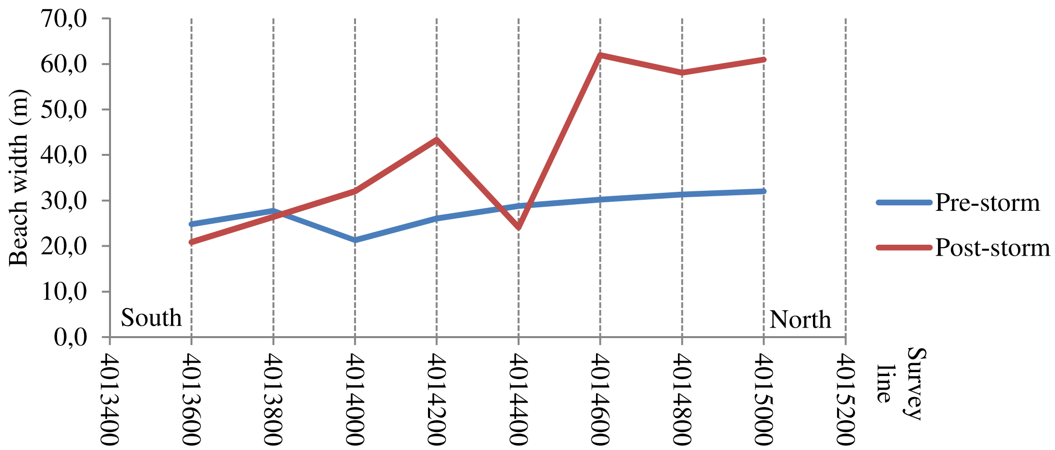


Figure 5.2: Beach width before and after the storm period

The pre-storm beach widths are in average ~ 28 m and are approximately constant along the studied coastline. Post-storm beach widths show a trend of increasing beach width to the north interrupted by a narrow part around the acute erosion profiles. Post-storm beaches are generally wider than before the storm period and the mean post-storm beach width is ~ 41 m.

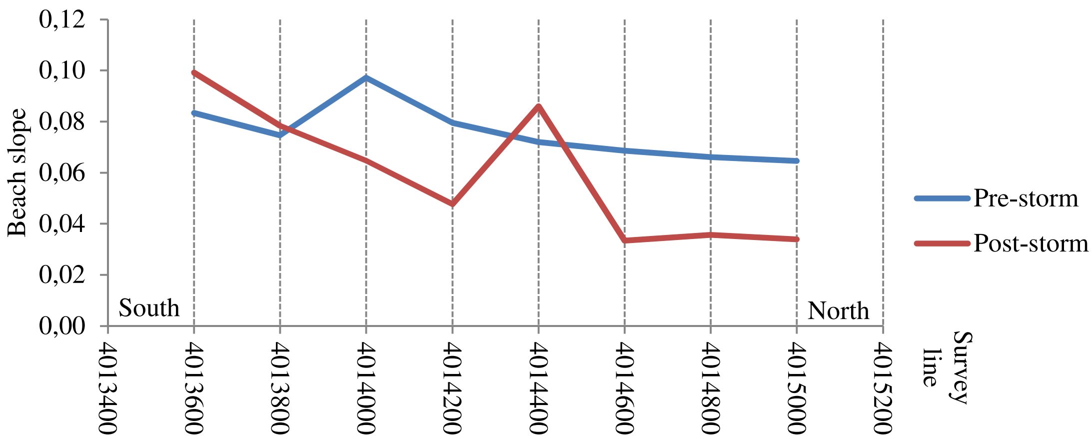


Figure 5.3: Beach slope before and after the storm period

The pre-storm storm beach slopes have an average slope of 0.08 and are almost constant along the coastline. The beach flattens during the storm and this leads to gentler beach slopes with an average of 0.06. Post-storm beach slopes gradually become gentler to the north part interrupted by a steeper part around the area of acute erosion.

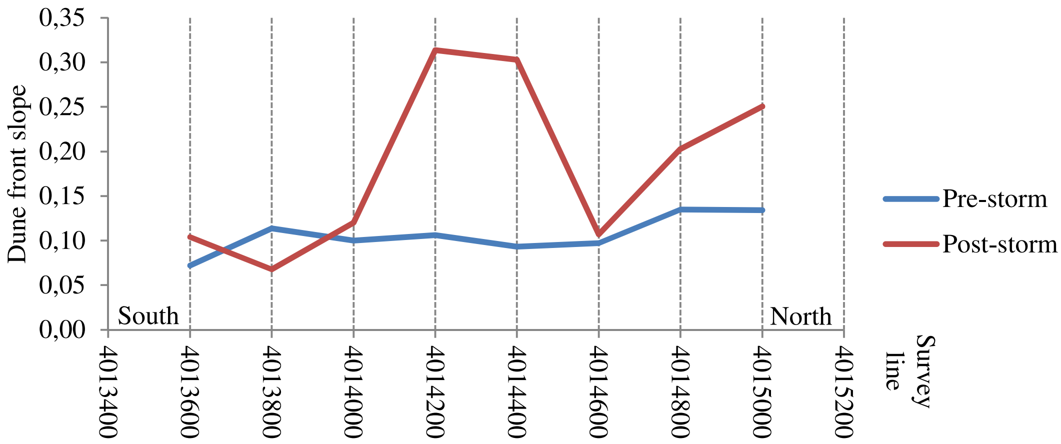


Figure 5.4: Dune front slope before and after the storm period

The pre-storm dune front slopes are in average 0.11 and are approximately constant along the coastline. Post-storm dune front slopes vary along the studied coastline. At the median part, the dune front slopes are steep probably due to erosion scarps of the dune face. The average post-storm dune front slope is 0.27.

5.2 Subaqueous CSI

CSI from the wet part of the profiles are presented in this section. Bar dimensions such as height and width are displayed in two figures. Distance from the shoreline and water depth above bar are also included in this section.

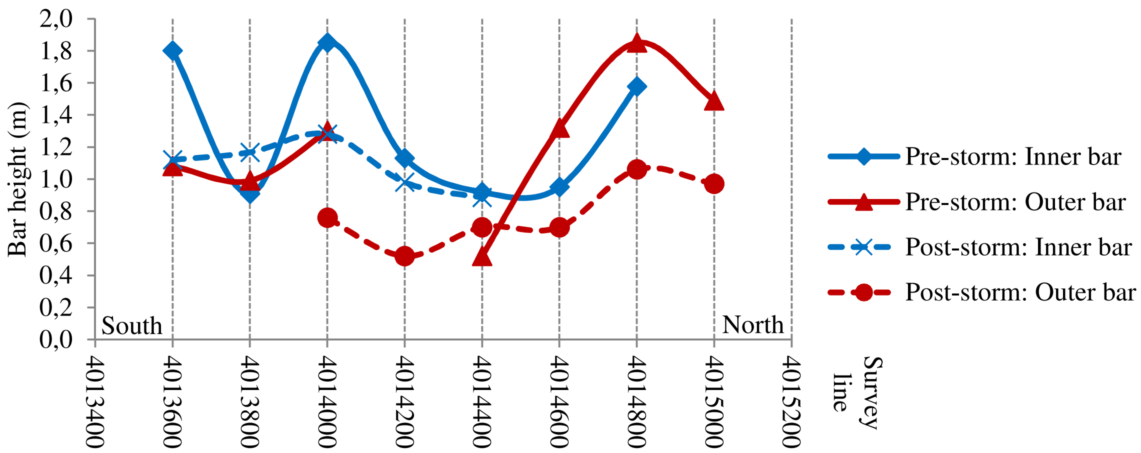


Figure 5.5: Inner and outer bar heights before and after the storm period

Figure 5.5 illustrates inner and outer bar heights before and after the storm. Some of the survey lines have no bars since these bar heights did not fulfill the criteria of selection. A second inner bar was present at survey line 4014400 having a height of 1 m, which is not shown in the chart. Survey line 4014200 have no pre-storm outer bar and the post-storm inner bars at survey lines 4014600 to 4015000 are also absent.

Pre-storm inner bar heights vary between 0.9 and 1.9 m and are in average 1.3 m. Post-storm inner bar heights range between 0.9 and 1.3 m with an average of 1.2 m. Outer bar heights were before the storm period between 0.5 and 1.9 m with a mean of 1.1 m and after the storm period between 0.5 and 1.1 m with a mean of 0.8 m. Pre-storm bar heights are generally higher than post-storm heights. At the northern and southern parts of the coastline the bar heights are generally higher than at the median part of the coastline. After the storm period, the bar heights are reduced at the northern and southern parts of the coastline while they remain constant or increase in height at the median stretch of the coastline.

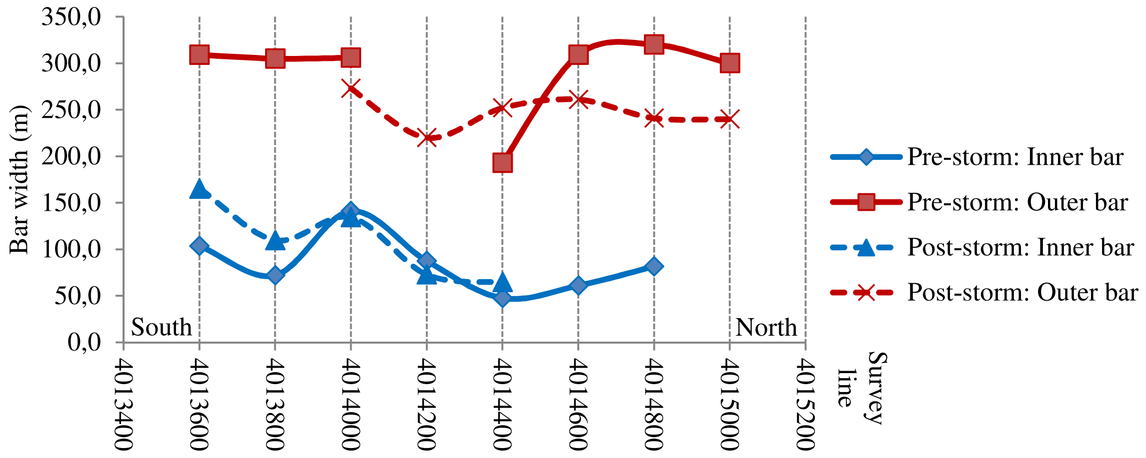


Figure 5.6: Inner and outer bar widths before and after the storm period

Figure 5.6 shows inner and outer bar widths before and after the storm period. In general, the width of the outer bars is a factor three larger than inner bars. The bars at survey line 4014200 and 4014400 have narrow widths compared to the other survey lines. Inner bars become wider at the southern part of the coastal laboratory during the storm period and outer bar widths decrease at the northern end of the coastal stretch under the storm period.

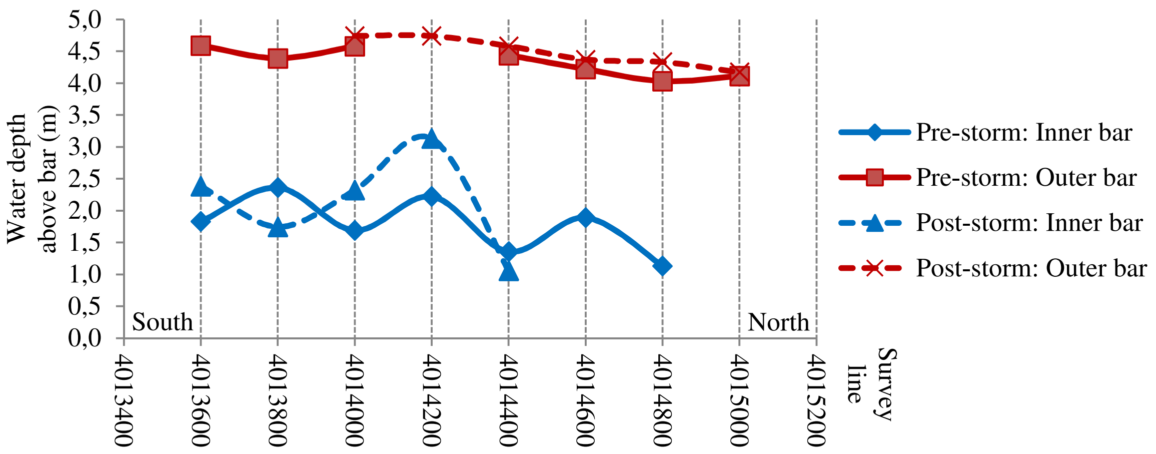


Figure 5.7: Water depths above inner and outer bars before and after the storm period

Figure 5.7 presents the water depth above the bar crests. No significant changes are observed at the outer bars. This is not the case at the inner bars where water depths above bars at survey line 4014000 and 4014200 increase. At line 4013800 the water depth above bar decrease.

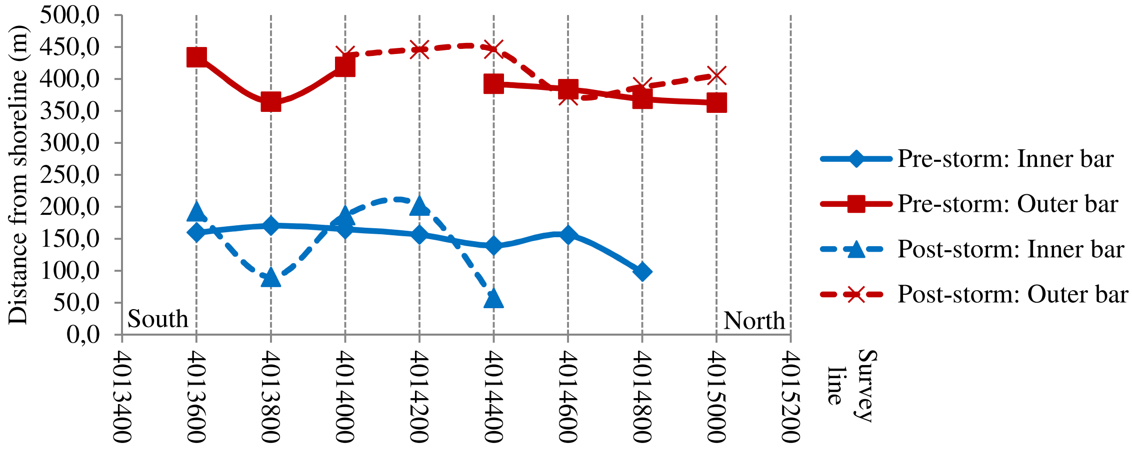
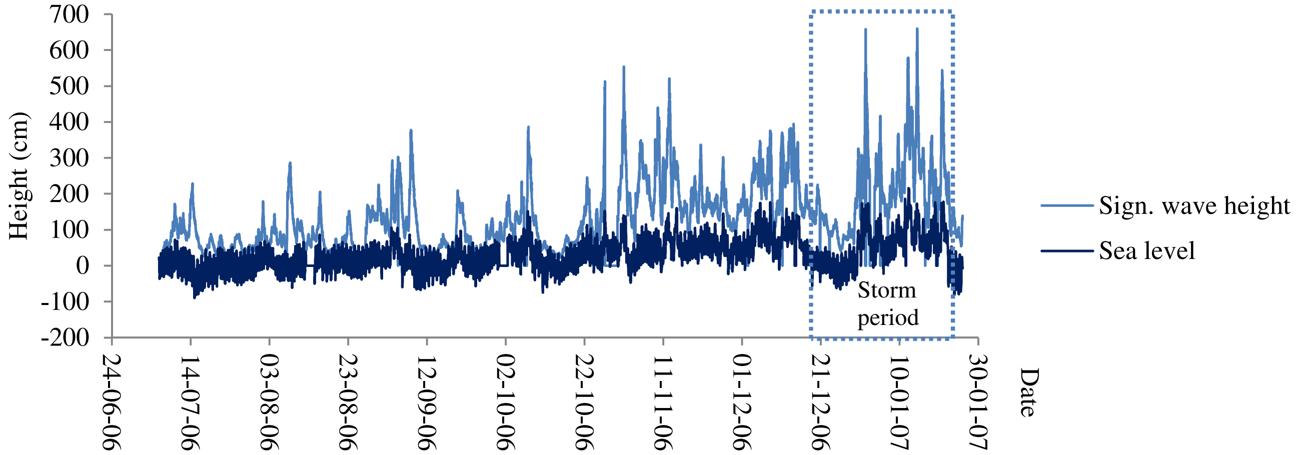


Figure 5.8: Distance from shoreline for inner and outer bars before and after storm period

Figure 5.8 displays the location of the nearshore bars relative to the shoreline. Pre-storm inner bars are located around the same location (app. 150 m) from the shoreline. Bars are modified under the storm period where some bars move closer to the shore while other migrates seawards. Outer bars are in average located 390 m from the shore before the storm period. Outer bars migrated seawards, which is also observed in this figure as the mean post-storm distance from the shoreline is 415 m.

6 Hydrodynamic forcing

Sea-level data come in 10 minute intervals from Hvide Sande (sea gauge) and offshore wave data (figure 6.2) are given in 30 minute intervals from Nymindegab wave gauge. Figure 6.1 illustrates the temporal variations of the hydrodynamic dataset for the period between 06-07-2006 and 25-01-2007 and for the three storm events.



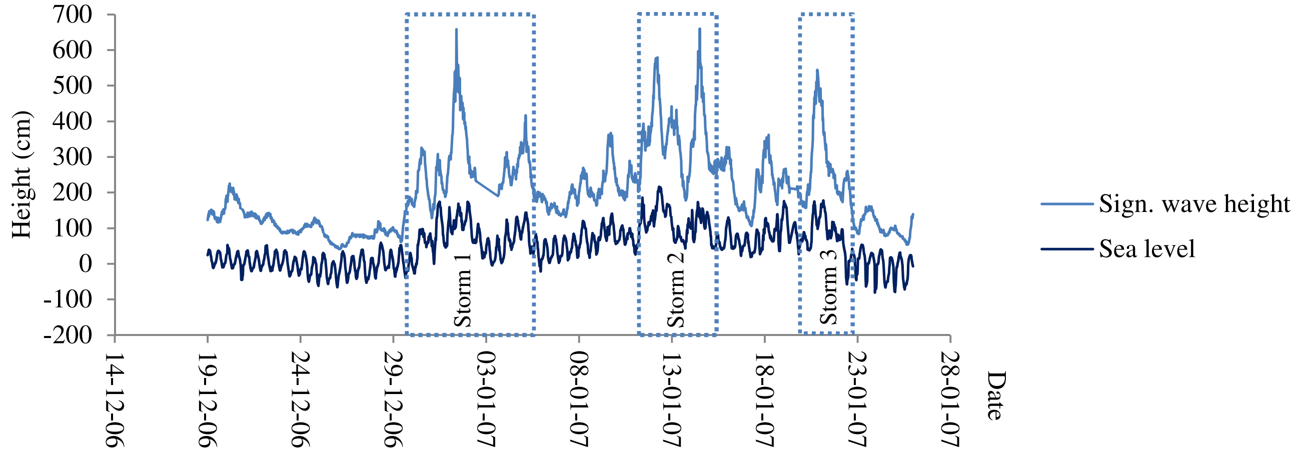


Figure 6.1: Upper figure: Offshore significant wave height and sea-levels between 06-07-2006 and 25-01-2007. Lower figure: The three storm events that will be used as input to the acute erosion simulations.

The temporal variations of sea level and offshore significant wave height are presented in figure 19 where three storm events are identified: (1) 30/12/2006 19:00 to 05/01/2007 20:00, (2) 11/01/2007 09:00 to 15/01/2007 17:00 and (3) 20/01/2007 07:00 to 21/01/2007 22:00. The numerical simulations are run on these three storm events. The offshore wave climate during the storm period is shown in figure 6.2 where the dominant wave directions are W and NW.

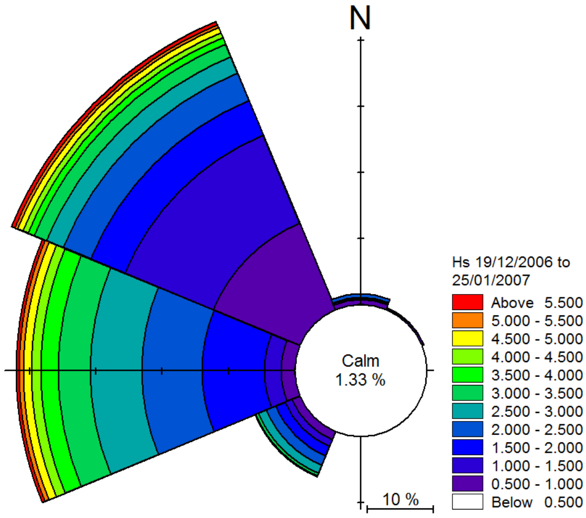


Figure 6.2: Offshore wave climate at Nymindegab wave buoy from 19/12/2006 to 25/01/2007

7 Sediments and nourishments

DCA (1999) investigated the spatial and seasonal variations of the sediment characteristics at the Danish North Sea coast. Sediment samples were collected along the west coast lines and sieved for grain sizes < 2.0 mm. The plot in appendix 2 shows the variation of the median grain size with distance from the shoreline four times during the year 1999. West coast line 5660 is located just north of the coastal laboratory. The plot shows that the median grain size decreases with distance from the shoreline and that the largest seasonal variations are found near the shore. On the outer part of the west coast line the median grain sizes are in the order of 0.1 and 0.2 mm. Nearshore sediment samples showed that median grain sizes are between 0.2 and 0.35 mm.

Building with nature solutions, such as previous shoreface- and beach nourishments, are important to bear in mind when studying the morphodynamics of a coastal laboratory. DCA used different nourishment methods at the coastal laboratory in the years 1986 to 2011 to maintain the minimum dune width of 40 m (see appendix 3).

Large sand nourishments were placed at the coastal laboratory in 1992, 1994 and 1999. In the period between 1999 and 2010 the laboratory was not nourished. In the study period it is assumed that the former sand nourishments would not affect the coastal laboratory and therefore the acute erosion event happened under ‘natural’ conditions.

8 Model preparations

In this section the preparations and setup of the numerical model are explained. Before simulating acute erosion the measured offshore wave parameters have to be transformed to shallower waters. These transformed wave parameters are then used to produce real-time waves, which are put into a MatLAB script generating infragravity wave boundary conditions. The setup of a Q3D sediment table will also be presented.

8.1 Wave transformation

Spectral wave simulations were computed with MIKE 21 to transform the wave parameters from deep-water (Nymindegab wave buoy) to shallower waters (end of coastal profiles). Nearshore scatter data from the 8 coastal profiles were used for the nearshore bathymetry. Scatter data for the rest of the domain were imported from the sea elevation model (Geodatastyrelsen). The model setup can be found in appendix 4.

The wave parameters significant wave height (Hs), wave period (T), mean wave direction (MWD) and directional standard deviation (DSD) from Nymindegab wave buoy were applied to the western boundary as varying in time and constant along boundary while the northern and southern boundaries were set as lateral. The best measured parameter from Nymindegab wave buoy for directional standard deviation is a directional spreading, which replaces the DSD. Wave data were extracted at 8 output points (the most seawards coordinate of each pre-storm coastal profile). The extracted wave climates at the end of each profile can be found in appendix 5.

8.2 Real-time waves

The extracted wave climate from output point 4014200 was found to be representative for the nearshore wave conditions (appendix 5). Wave data from this extraction point have been used as input to generate real-time waves with a time resolution of 0.5 sec for the three storm events with the MIKE tool 'random wave generator', see appendix 4 for model parameters. Hourly real-time wave data have been produced for the three storm events.

8.3 Infragravity

Real-time wave data are used as input to the MatLAB script IGBC_boundary developed by DHI to generate infragravity wave boundary conditions. This creates an input file for the boundary condition in the SW module including radiation stresses, which produces long waves in the HD module. This results in a varying run-up on the profiles.

8.4 Q3D sediment table

A sediment table is needed as input to the sand transport module. This is computed with the MIKE 21 tool 'Generation of Q3D sediment table'. The input data cover the hydrodynamic dataset from minimum to maximum values. Sand transport is calculated for all given values in the table and the numerical model interpolates between these values when simulating acute erosion. The parameters are given in appendix 4.

8.5 Generation of 1D domains

The acute erosion modeling is carried out in 1D rectangular domains. Pre-storm profile scatter data set the elevation values for each 1D domain. The scatter data are taken from the 06-07-2006 coastal profiles. The domains are generated as rectangular meshes with three zones of different resolution; an outer coarse resolution zone, a shoaling zone and a run-up zone (see figure 8.1). A linear interpolation method was used for interpolation of the three resolution zones.

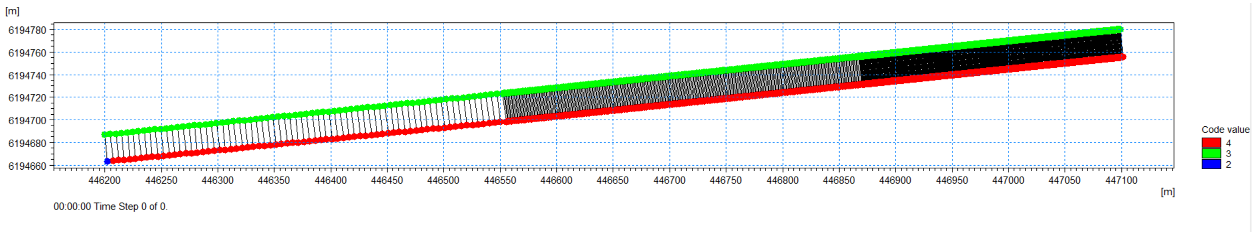


Figure 8.1: 1D domains for the 4014400 profile

The numerical simulations are run on the summer profiles measured on 06-07-2006. The major part of the beach profiles measured on 19-12-2006 follow the beach/dune morphology on the summer profiles. This supports the decision of running the simulations on the summer profiles. Since the morphologic changes occurred in the period between 19-12-2006 and 25-01-2007 the three identified storm events in January 2007 are applied as hydrodynamic boundary conditions to the acute erosion model. The measured post-storm profiles on 25-01-2007 are directly compared with the output profiles from the model.

9 MIKE 21 IG setup

A modified version of the MIKE 21 coupled FM model have been used to simulate acute erosion in this project. The three modules hydrodynamics (HD), spectral waves (SW) and sand transport (ST) are coupled in the model. A new dune erosion engine from DHI has been used to run the simulations.

9.1 HD module setup

The main parameters are presented in table 4. Solution technique is set as higher order in both time and space. No depth correction is chosen. Flood and dry is standard and have been run with the original values. Density is barotropic and eddy viscosity is constant at 0.28.

Initial conditions are set as constant with a surface elevation of 0.56 m corresponding to the start value in the water level timeseries applied to the western boundary condition. The northern and southern boundary conditions are set as land (zero normal velocity). At the western boundary condition the WL from the three storms are applied. To make sure that the infragravity waves will run out of the domain (after being reflected at the shoreface) the code at the western boundary is set to type=10 (a flather condition).

Table 9.1: HD module setup

Parameter	Value
Time formulation	Instationary formulation
Critical CFL number	0.8
Flood and dry	Included
Eddy viscosity	Smagorinsky formulation
Manning number	40
Coriolis force	No
Wind forcing	No
Precipitation-evaporation	No
Tidal potential	No
Infiltration	No
Wave radiation	From SW simulation

9.2 SW module setup

The values for the main parameters are presented in table 5. The geographical space discretization (solution technique) is set as higher order. Wave breaking is set as specified gamma with an alpha value of 1 and gamma (wave steepness) to 2. Under initial conditions the type is set to zero spectra and a JONSWAP spectra is used.

The northern and southern boundary conditions are set as reflective boundaries. The western boundary condition is set to wave parameters (version 2) with the format varying in time, constant along line. A dfs0 file containing the IG waves from the three storms is coupled to this BC.

Table 9.2: SW module setup

Parameter	Value
Spectral formulation	Directionally decoupled..
Time formulation	Instationary formulation
Discretization type	360 degree rose
Number of directions	16
Water level conditions	From HD simulation
Current conditions	No current variation
Diffraction	No diffraction
Wave breaking (gamma)	0.8
Bottom friction	No

9.3 ST module setup

The setup of the sand transport module is given in table 6. The created Q3D sediment table is coupled to the module. The max bed level change and speedup factor are both set as 1 and feedback on hydrodynamic, wave and sand transport calculation is included. Dry- and wet slope failure values are chosen as a new feature in the dune erosion engine. These are given in the next section 9.4. All three boundary conditions are set as zero sediment flux gradient.

Table 9.3: ST module setup

Parameter	Value
Model type	Wave and current
Porosity	0.4
Grain diameter	0.2 mm
Grading coefficient	1.4
Forcings	Wave field from SW simulation
Slope failure	In dune erosion motor

9.4 Model calibration

The model was calibrated at the dry- and wet slope failure parameters, which are incorporated in the new dune erosion engine. It was found that a wet slope failure of 5 degrees and a dry slope failure of 30 degrees gave the best numerical results compared with the measured post-storm profiles.

10 Numerical modeling results

The output profiles from the acute erosion simulations are presented in this section. Three profiles are showed in each plot: pre-storm profile (measured), post-storm profile (measured) and a modeled post-storm profile, which is the line output at the last time step in the model.

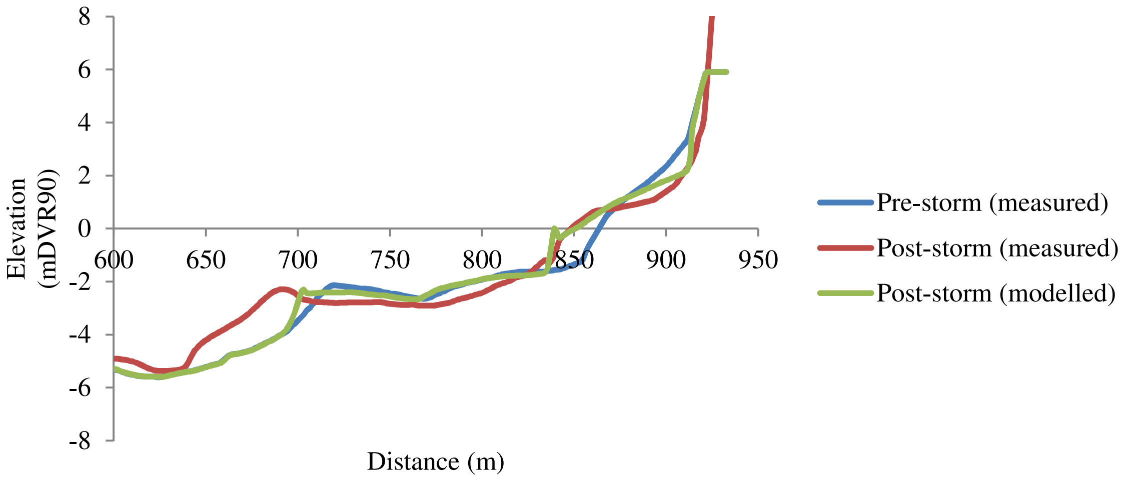


Figure 10.1: Survey line 4015000

Figure 10.1 illustrates the MIKE 21 IG simulations on survey line 4015000. Modeled and measured morphological changes are quite accurate although the measured morphology is more curved than the modeled output profile. The model produces a maximum dune retreat of 12 m, which matches the measured retreat of the dune front. The simulated erosion is although limited to the lower part of the dune and the backshore. The model predicts that the eroded sand is deposited at the foreshore and upper shoreface. This deposited volume of sand is app. equivalent to the eroded amount of sand from the dune front. The simulated bathymetric changes showed offshore bar migration of the inner bar, which was in line with the observed changes although the migration rate was less than the measured.

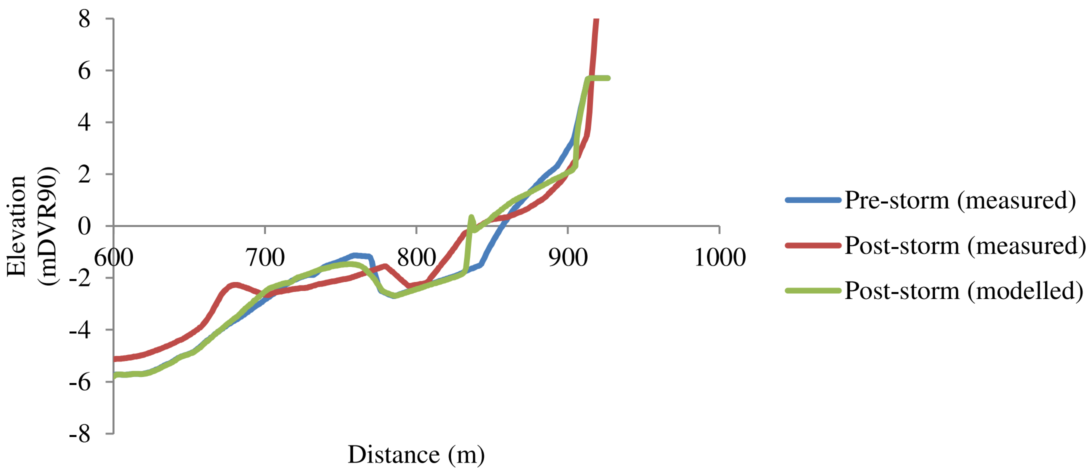


Figure 10.2: Survey line 4014800

Figure 10.2 displays the simulations on survey line 4014800. The simulated and monitored changes at the dune and beach are very similar. Also here, the modeled morphology at the dry part of the system has a less curved morphology compared to the measured. The model simulates a maximum dune retreat of 10 m, which is identical to the measured retreat of the dune front. Similar to the 4015000 simulations, the modeled erosion is restricted to the lower part of the dune and the backshore and the eroded sand is deposited at the foreshore and upper shoreface. The modeled bathymetric morphology shows a beach step and a flattened offshore-migrated inner bar. Monitored morphological changes also showed offshore bar migration and flattening and the development of a new inner bar.

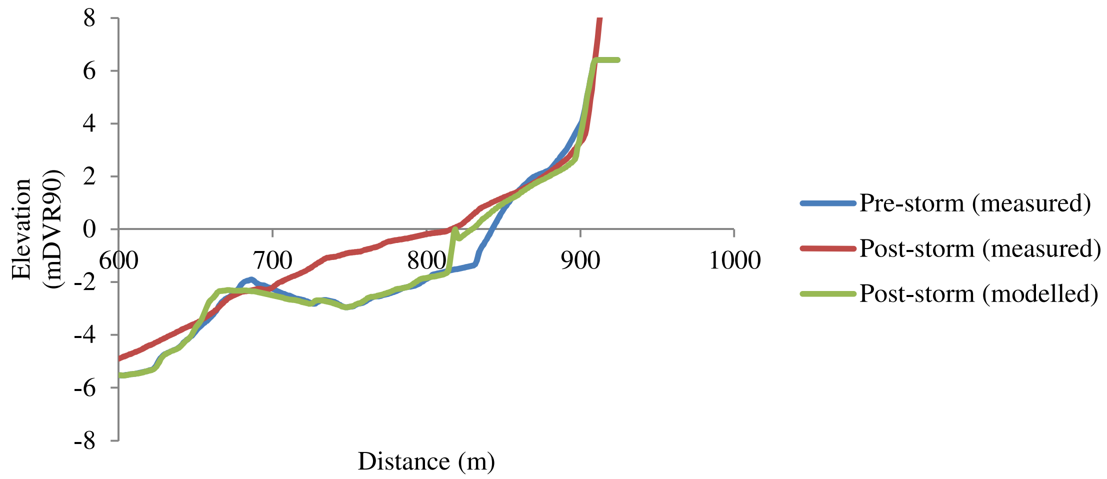


Figure 10.3: Survey line 4014600

Figure 10.3 shows the numerical simulations run on survey line 4014600. After applying the high energetic wave climate and elevated water levels on the input profile the simulated output profile shows a comparable morphological shape to the monitored post-storm profile. The simulated maximum dune retreat is ca. 10 m while the measured maximum dune retreat was ca. 7 m. Numerical modelling shows that accretion occurs at the foreshore and upper shoreface, which is identical to the morphological changes at the beach and upper shoreface. The measured morphological change although showed substantial accretion between the beach step and the inner bar that was filled up with sand.

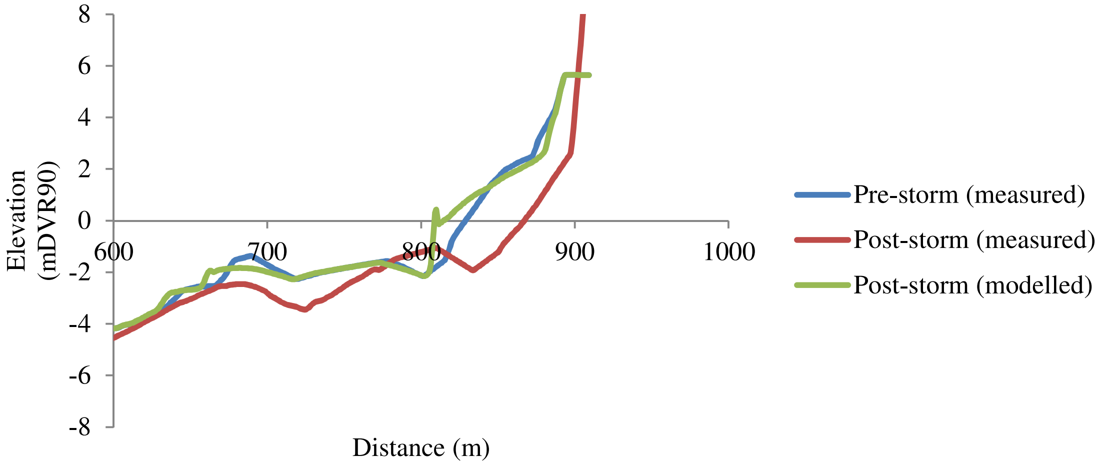


Figure 10.4: Survey line 4014400

The MIKE 21 IG simulations on survey line 4014400 are presented in figure 10.4. The numerical model underestimated the erosion of the dune and beach. The entire profile eroded significantly, which could not be predicted by the model probably due to the fact that this 1D model only simulates sand transport in a cross-shore direction with normal propagating waves. The longshore sand transport is therefore not incorporated in the model. A local hotspot with longshore gradients in sand transport possibly caused erosion of this profile. This longshore transported sand seems to be deposited in the profiles nearby.

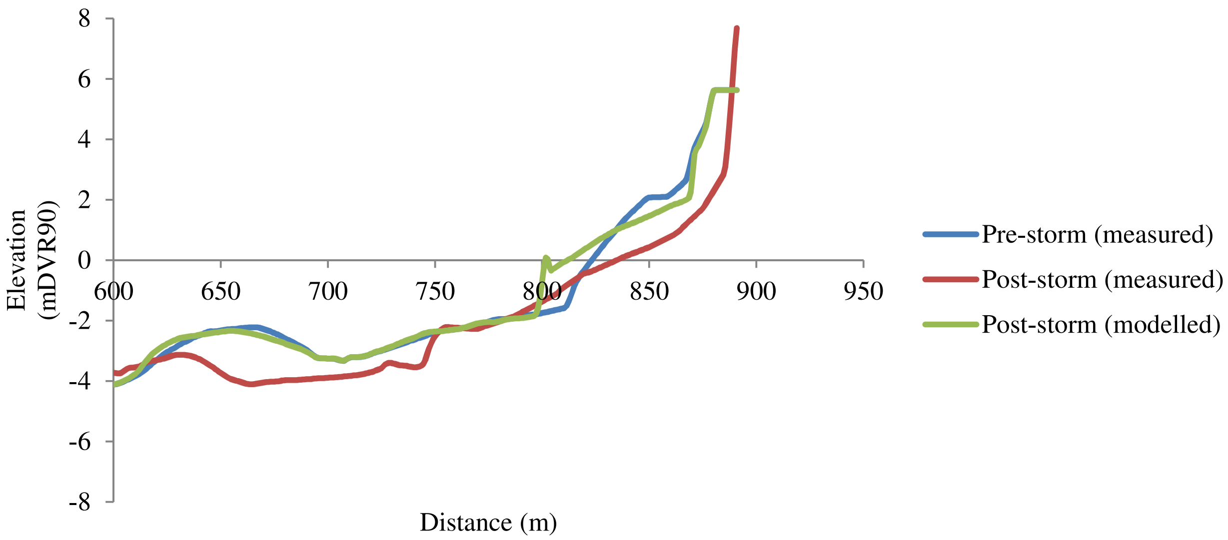


Figure 10.5: Survey line 4014200

Numerical simulations run on survey line 4014200 are illustrated in figure 10.5. The modeled erosion is underestimated at the beach and dune front. The simulated erosion at this coastal profile is although closer to the measured morphological changes than the 4014400 numerical results. Again the post-storm measured profile has a more curved morphology than the simulated output profile. The measured post-storm profile shows that the eroded sand was not deposited in this profile. This also points out that the sand might have been transported to other places probably alongshore. This supports the hypothesis of a local hotspot with longshore transport gradients around profile 4014400 and 4014200.

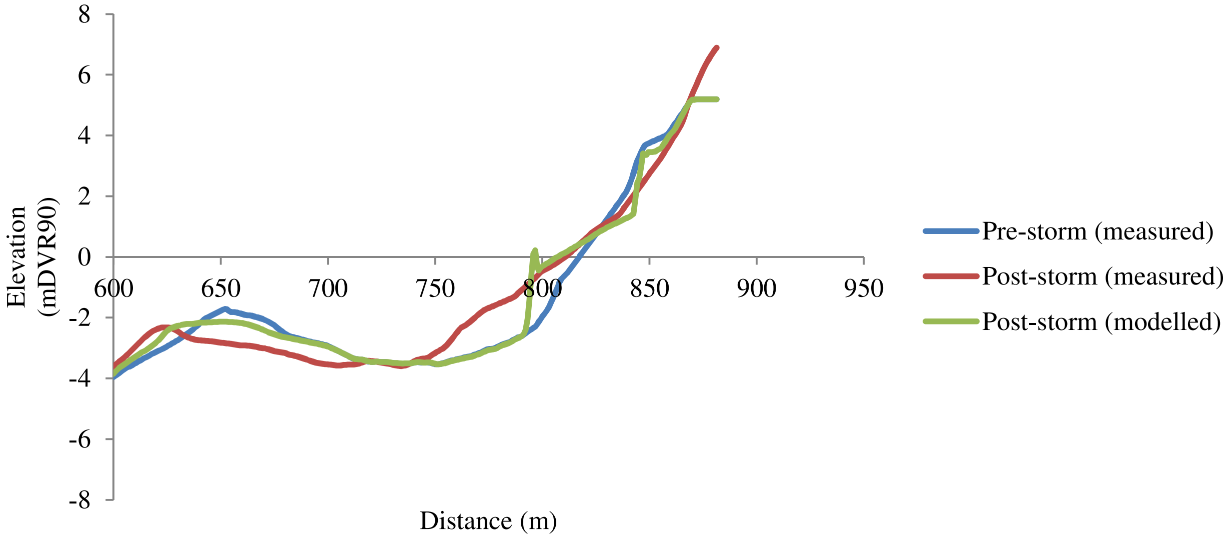


Figure 10.6: Survey line 4014000

In figure 10.6 the numerical results from the simulations on survey line 4014000 are presented. The computed erosion caused retreat of the dune face, which was quite similar to the measured dune retreat. The output profile from the model although kept the shape from the measured input profile. The eroded sand was deposited at the lower foreshore and upper shoreface. The model created a beach step and the inner bar was flattened and migrated offshore, which was in line with the measurements.

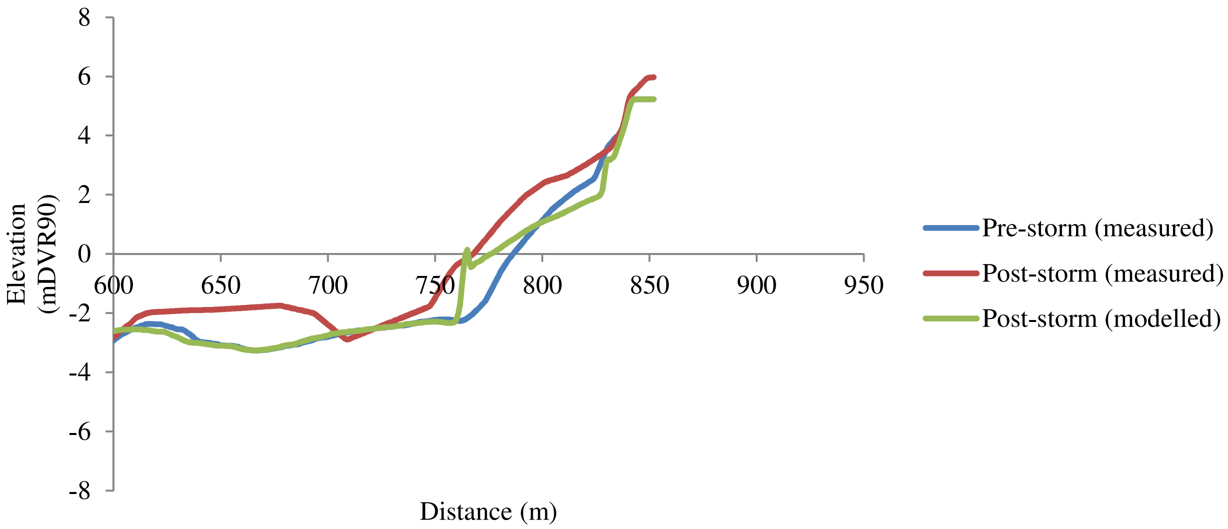


Figure 10.7: Survey line 4013800

Accretion dominates the profile evolution in figure 10.7. Sand is supplied to the profile and deposited both at the beach and at the inner bar thus increasing the inner bar width significantly. The numerical model computed erosion on the input domain and accretion at the upper shoreface. The supply of sand to the profile could not be simulated since the acute erosion model is a cross-shore sand transport model in 1D. This emphasizes the need for a better understanding of the longshore component in this area.

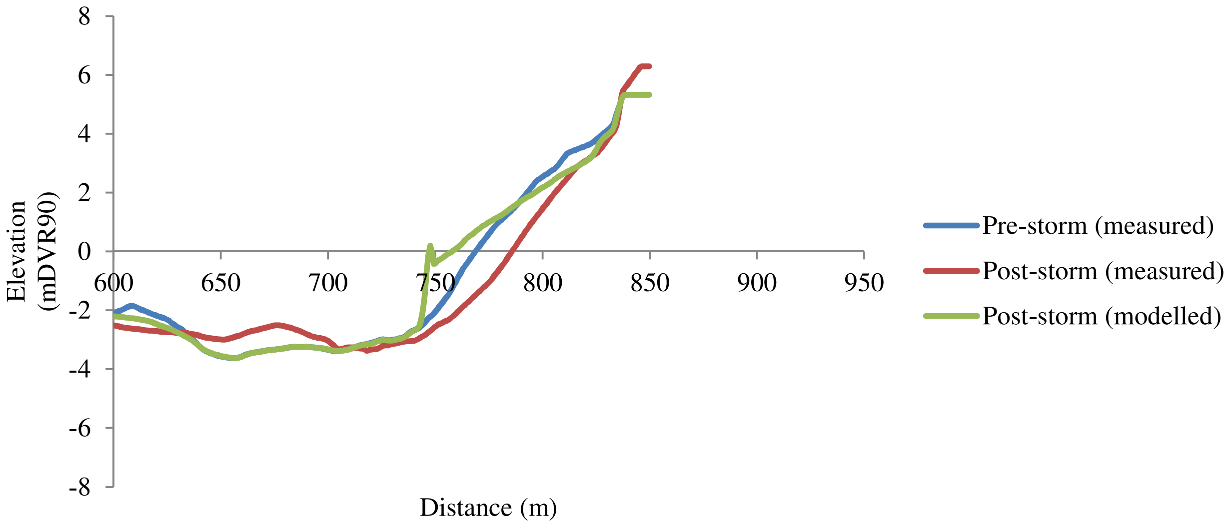


Figure 10.8: Survey line 4013600

The numerical model can reproduce acute erosion of the upper part of the dune. The model predicts that this amount of eroded sand from the dune is deposited at the foreshore and upper shoreface. This is different from what was measured. The dune, beach and upper foreshore eroded and this sand was not deposited in the profile, but has been transported elsewhere probably alongshore.

11 Discussion and perspectives

In this section the CSI and morphologic analysis are discussed with the MIKE 21 IG simulations and perspectives on further development are given.

The subaerial pre-storm CSI did not show a clear correlation with the profiles of where the acute erosion occurred. The morphologic changes that occurred to the subaerial CSI were increasing beach width and flattening of the beach slope. At the acute erosion profiles the beach width and slope did not increase while the dune front slope increased due to erosion scarps of the dune face. More interesting observations were found in the analysis of the subaqueous CSI. Pre-storm subaqueous CSI showed that the northern and southern parts of the coastal laboratory had higher bar heights than the median part of the coastline. Also, the width of the bars was less wide at the median part of the coastal laboratory. The morphologic changes of the subaqueous CSI were reduced bar heights at the northern and southern parts of the coastal laboratory while they remained constant or increased in height at the median stretch. These observations of wet CSI are interesting and should be looked more into in other studies of acute erosion.

Simulations run on survey line 4014800 and 4015000 showed that MIKE 21 IG is able to reproduce acute erosion. The numerical modeling on these survey lines produced a dune erosion and dune retreat that matched the field measurements. The numerical simulations showed that the eroded sand was accumulated in a sediment deposit at the lower foreshore and upper shoreface, which was in line with the measured morphologic changes. Local acute erosion occurred at profile 4014200 and 4014400. Unlike the two northern most profiles (4014800 and 4015000) the eroded sand was not deposited at the upper shoreface like the model predicted. The eroded sand at profile 4014200 and 4014400 was probably caused by a local hotspot of longshore gradients, which could not be simulated in a 1D cross-shore sand transport model. The nearby survey lines 4014600 (north) and 4014000 (south) of these areas experienced severe accretion, which probably originated from a supply of sand from the survey lines where the severe erosion took place.

Numerical modeling results showed erosion of the dune front, which were quite similar to the measurements. Although the measured morphological changes had a more curved morphology compared to the modeled results. The model predicted that the eroded sand from the dune was deposited on the foreshore and upper shoreface. Modeled profiles showed that the eroded volume of sand from the dune was app. equivalent to the deposited sand volume at the foreshore and upper shoreface. The model creates a berm around still water level, which may be a result of the two converging sand transport components in the model. The morphologic analysis showed offshore bar migration and flattening of bears, which were also simulated by the model although the modeled migration rate was slower than the measured.

This research project improves the understanding of the cross-shore sand transport component at Skodbjerge. An analysis of the morphology and numerical results showed that the model was able to reproduce acute erosion that matched with measured data. At some of the profiles the eroded sand from the dune was not deposited like the model predicted. It was most likely transported alongshore to the nearby profiles. In DCA (2014b) overestimated dune erosion was also explained by interacting processes between the profiles such as longshore transport. This project and DCA (2014b) both underline the need for investigating the longshore component in the system. This could be done by setting up a 2D area model to obtain a complete picture of the sand transport in the coastal laboratory.

12 Conclusions

This research project focused on acute dune erosion at Skodbjerge and investigated how this correlated with CSI by the use of the numerical model MIKE 21 IG.

CSI and morphological changes were analyzed from 8 pre- and post-storm coastal profiles. In January 2007 a period of high-energetic wave climates and elevated water levels caused local acute erosion to some of the profiles while others experienced no erosion. The eroded sand was typically accumulated at the upper shoreface or transported alongshore to the nearby profiles. Offshore bar migration and flattening of the bars were also typical morphological changes. The CSI analysis showed that the bar heights were generally higher at the northern and southern parts of the coastline than at the median part before the storm period. After the storm period, the bar heights were reduced at the northern and southern parts of the coastline while they remained constant or increased in height at the median stretch of the coastal laboratory.

The MIKE 21 IG model was used to simulate acute erosion under storm conditions. The model was run with wave parameters and sea-levels recorded from three storm events in January 2007. Real-time waves and infragravity waves were generated from the recorded dataset and applied to the model. The simulations were completed on 8 pre-storm profiles and directly compared with measured post-storm profiles.

This study showed that MIKE 21 IG can reproduce the magnitude of acute erosion under a storm impact close to measured morphological changes at Skodbjerge. The model predicts that the eroded sand from the dune accumulates in a sand deposit at the lower foreshore and upper shoreface, which is identical to what was observed at some of the profiles. At the other profiles this amount of sand this was not the case. The model shows some odd gradients in the modeled nearshore bathymetry. Further development of the model is encouraged.

13 References

Danish coastal authority (2014a): *Dune Erosion and safety along the Lodbjerg-Nymindegab Coast Denmark.* COADAPT, Danish coastal authority, Lemvig.

Danish coastal authority (2014b): *Analysis of local high water dune erosion by use of the dune erosion model X-Beach.* COADAPT, Danish coastal authority, Lemvig.

Danish coastal authority (2012): *Højvandsstatistikker 2012*. Danish coastal authority, Lemvig.

Danish coastal authority (2004): NOURTEC 2. Danish coastal authority, Lemvig.

Danish coastal authority (1999): Sedimentanalyse Vestkysten. Kystinspektoratet, Transportministeriet.

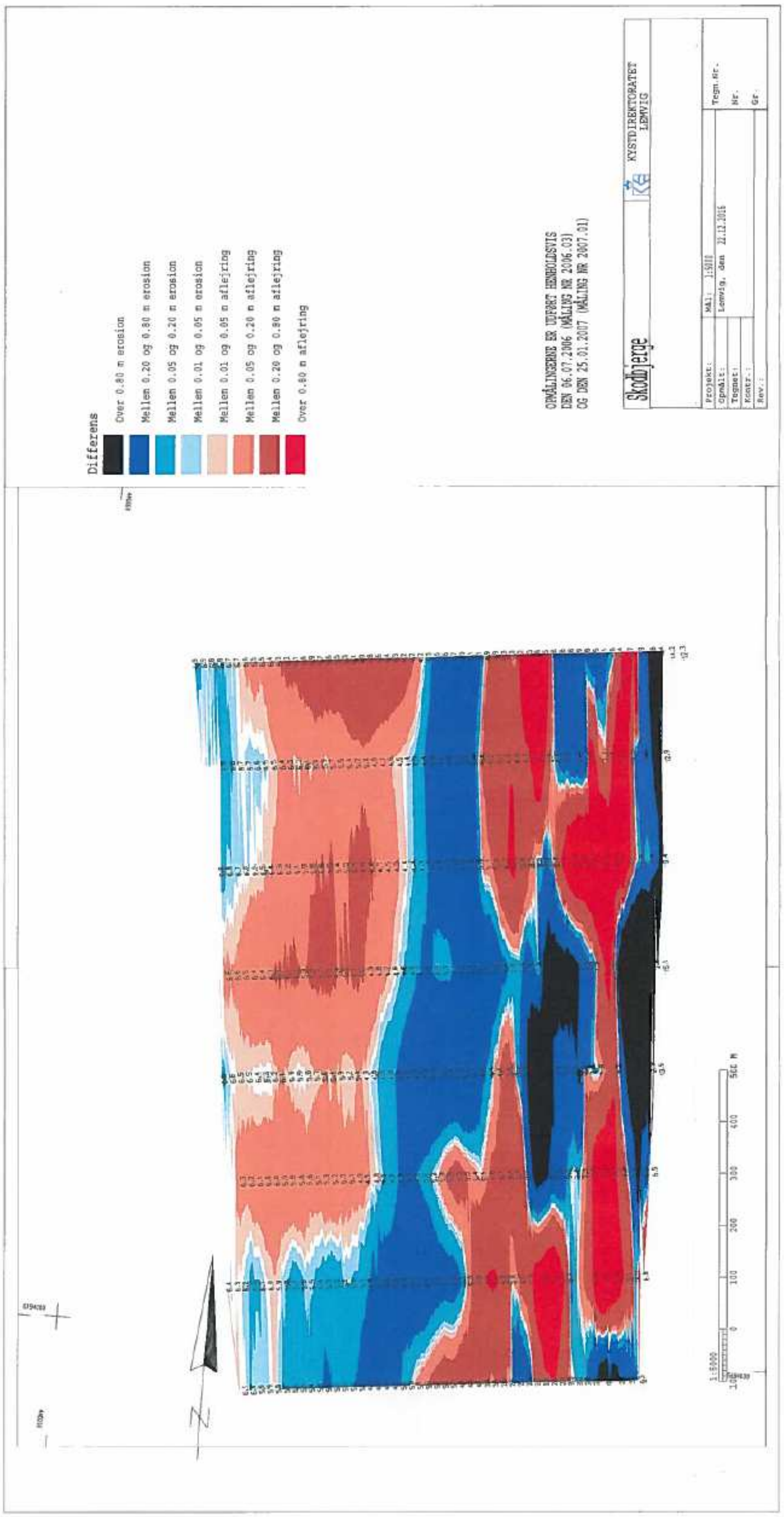
14 Maps:

Farvandsdybdemodel, Geodatastyrelsen

Kort10

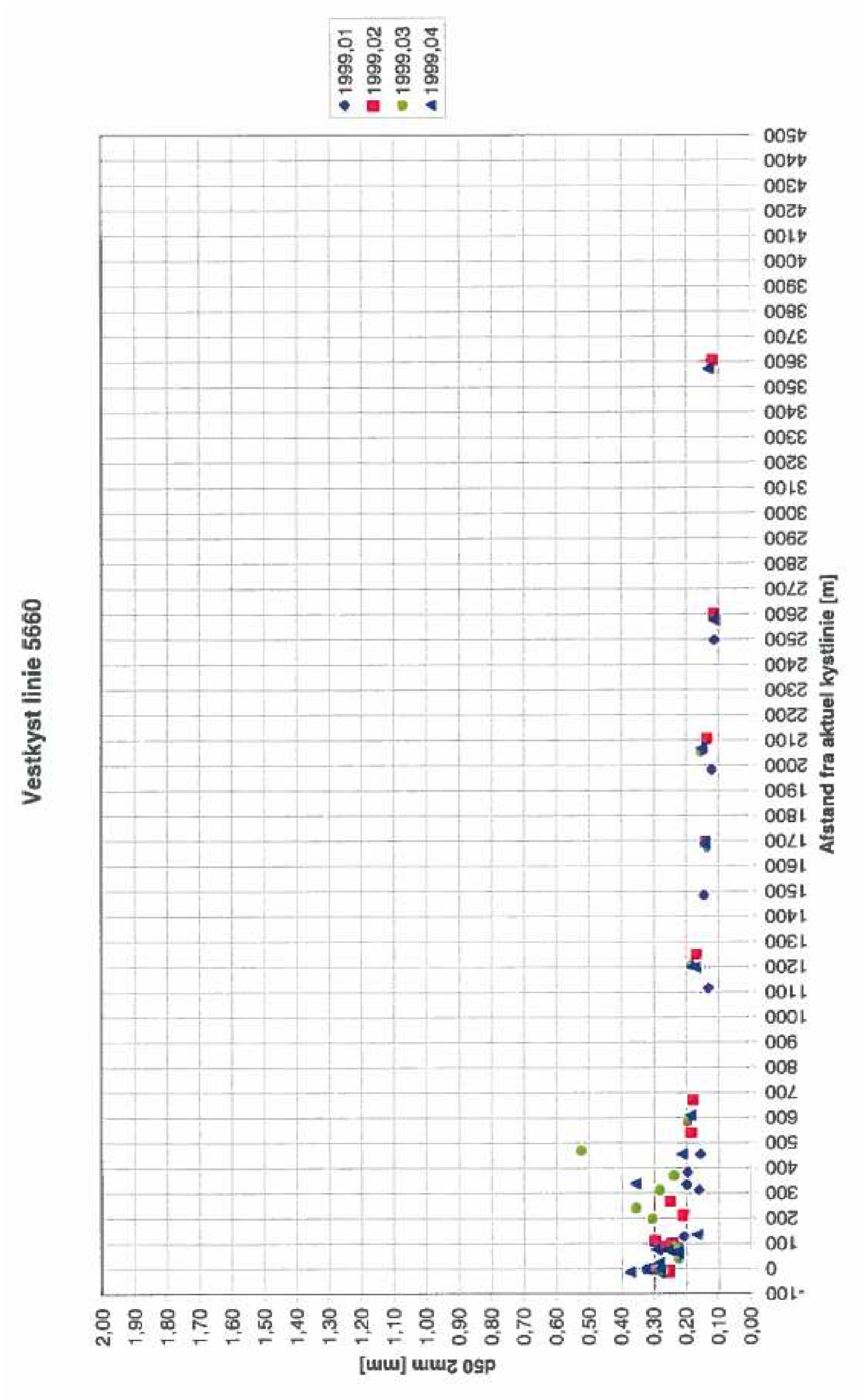
Basemap world image

Appendix 1



Elevation differences showing areas of erosion and accretion (aflejring)

Appendix 2



Seasonal variation of median grain sizes < 2.0 mm with distance from shoreline for west coast line 5660

Appendix 3

Nourishments at west coast line 5760, 5770 and 5780 in the years 1986 to 2011

LINE_NR	YEAR	DATE	NOURISHMENT m^3	METHOD
5760	1986	86-12-31	15680.0	To dune/dike
5760	1986	86-12-31	4730.5	To dune/dike
5760	1986	86-12-31	-15680.0	Removed
5760	1986	86-12-31	-4730.5	Removed
5770	1986	86-12-31	-7080.0	Removed
5770	1986	86-12-31	-13570.0	Removed
5770	1986	86-12-31	2360.0	To dune/dike
5770	1986	86-12-31	7899.5	To dune/dike
5770	1986	86-12-31	3240.0	To dune/dike
5770	1986	86-12-31	7080.0	To dune/dike
5770	1986	86-12-31	-2360.0	Removed
5770	1986	86-12-31	13570.0	To dune/dike
5770	1986	86-12-31	-7899.5	Removed
5770	1986	86-12-31	-3240.0	Removed
5760	1987	87-12-31	-10260.0	Removed
5760	1987	87-12-31	32960.0	To dune/dike
5760	1987	87-12-31	-32960.0	Removed
5760	1987	87-12-31	10260.0	To dune/dike
5760	1992	92-06-15	51514.6	Beach nourishment
5770	1992	92-06-15	38135.8	Beach nourishment
5760	1994	94-08-01	40316.1	Beach nourishment
5760	1994	94-08-01	42840.2	To dune/dike
5770	1994	94-08-01	21648.1	Beach nourishment
5770	1994	94-08-01	23003.5	To dune/dike
5760	1999	99-07-28	75513.0	Beach nourishment
5770	1999	99-07-28	40547.5	Beach nourishment
5760	2010	10-07-2011	54231.3	Shoreface nourishment
5770	2010	10-07-2011	53378.9	Shoreface nourishment
5780	2010	10-07-2011	54167.0	Shoreface nourishment
5760	2011	11-09-2027	245830.2	Shoreface nourishment
5770	2011	11-09-2027	64286.2	Shoreface nourishment

Appendix 4

Wave transformation: Model setup of the SW and HD modules in MIKE 21

SW module		*HD module*	
Parameter	**Value**	**Parameter**	**Value**
Spectral formulation	Directionally decoupled..	Time formulation	Instationary formulation
Time formulation	Instationary formulation	Critical CFL number	0.8
Discretization type	360 degree rose	Flood and dry	Included
Number of directions	32	Eddy viscosity	Smagorinsky formulation
Solution technique	Higher order	Manning number	32 m^(1/3)/s
Water level conditions	No water level variation	Coriolis force	No
Current conditions	No current variation	Wind forcing	No
Diffraction	No current variation	Precipation-evaporation	No
Wave breaking (gamma)	0.8	Tidal potential	No
Bottom friction	No	Infiltration	No
		Wave radiation	From SW simulation

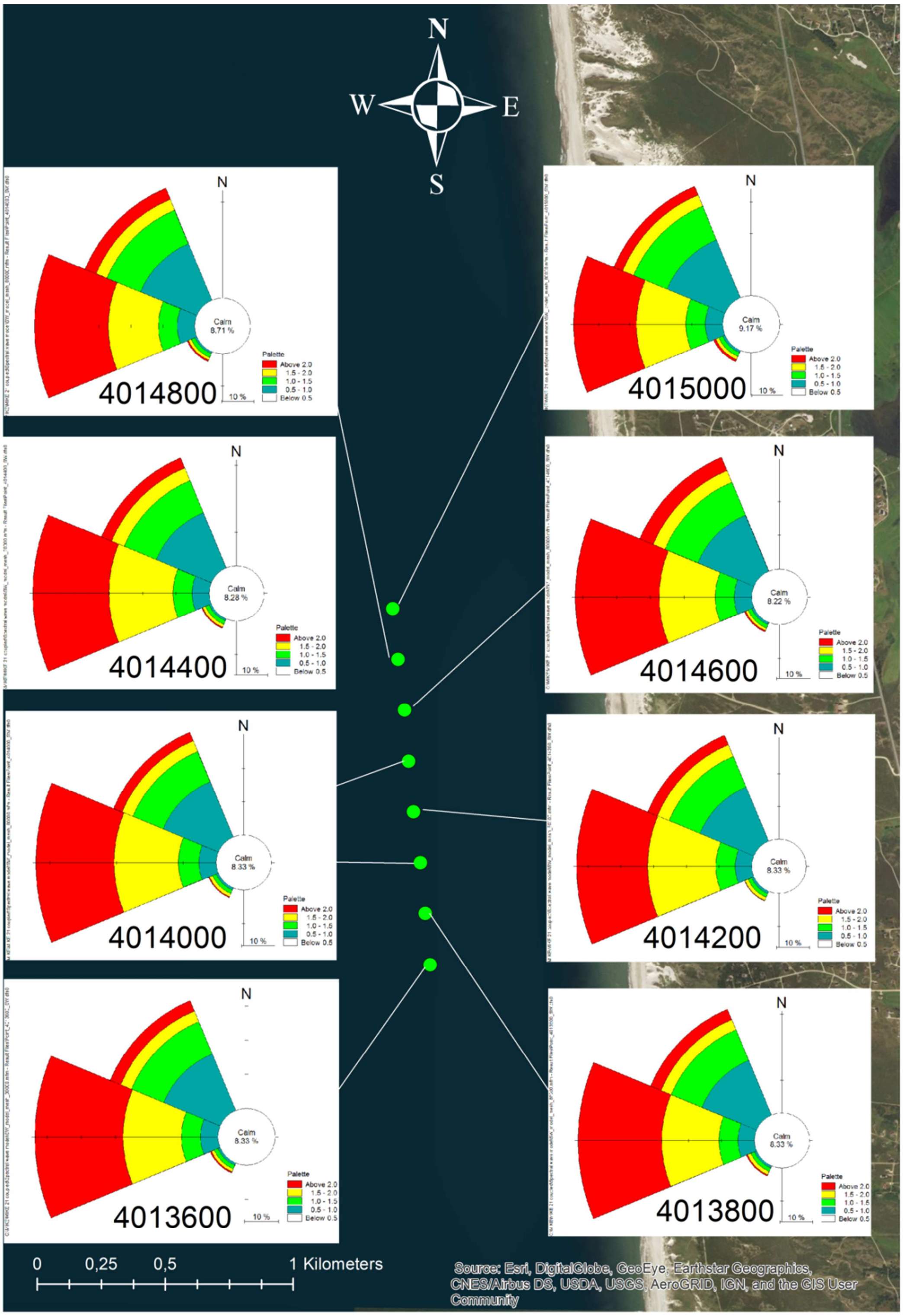
Random wave generator setup

Parameter	Value
Frequency spectrum	JONSWAP
Gamma	3.3
Sigma_a	0.07
Sigma_b	0.09
Type of waves	One-dimensional
Initial random number (seed)	100
Water depth	6.7

Q3D sediment table setup

Parameter	Value
Relative density of sediment	2.65 g cm-3
Critical value of Shields parameter	0.045
Water temperature	10 C
Ripples	Excluded
Bed slope effects	Excluded
Bed concentration	Deterministic
Streaming effects	Included
Cross current transport	Excluded
Centrifugal acceleration	Excluded
Undertow	Included
Wave theory	Stokes 5th order

Appendix 5



Extraction points of transformed wave data