ANALYSIS AND MODELLING OF EXTREME LOCALISED DUNE EROSION EVENTS ALONG DENMARK'S NORTH SEA HIGH WATER DUNE BARRIER.

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This paper presents the results of an investigation into cases of extreme localised dune erosion along Denmark's west coast. Cases of extreme dune erosion of over 20m are identified between 1977 and 2012. These are compared to the closest storm events. However, no correlation is found between the occurrence of these extreme erosion events and storm intensity or return period. A general increasing prevalence of sand bars is identified as well as an absence of extreme dune erosion in several of the more recent intense storms. Results of XBeach numerical modelling on a local example of extreme dune erosion showed that the offshore bathymetry and sand bar size has a significant effect on the amount of erosion that occurs at the dune face during a storm.

Keywords: dune erosion; sand nourishment; XBeach modelling

INTRODUCTION

This project focuses on identifying and investigating cases of extreme dune erosion on the high water sand dune barrier along the Danish North Sea coast. This dune barrier is maintained by the Danish Coastal Authority in order to provide protection against flooding of the hinterland during storm surges in the North Sea. The strength criteria for this high water barrier has been defined and maintained through establishing a minimum dune width. This minimum dune width was established in 1990 based on the analysis of dune erosion resulting from storms in 1990. This analysis established that 30m of dune erosion was the most that could be expected to result from a 100 years storm event. With an additional 10m added as a safety buffer a minimum dune width of 40m was subsequently adopted and maintained. Since the establishment of this minimum width criteria examples of dune erosion in excess of 30m have been found. These erosion events resulted from relatively moderate storm surges and have raised doubts as to the validity of the current minimum dune width. These erosion events occur on a very local scale often confined to a stretch of dune a just few hundred meters long, while no significant erosion is seen along neighbouring stretches. Investigation into this unexplained phenomenon was aimed at validating the minimum dune width and exploring different approaches to defining this minimum strength criteria as well as finding explanations to these cases of apparently unexplained erosion. This paper is in two parts, the first addresses the identification of these extreme dune erosion events and investigates the measurable factors that can have caused these examples of extreme local dune erosion. The second part of this report focuses on one case of extreme dune erosion where XBeach dune erosion modelling has been used to try and reproduce this local erosion based on survey data from the area.

ANALYSIS OF HISTORICAL DUNE EROSION DATA

Survey data and background conditions

The dune barrier along Denmark's west coast has been surveyed every year since 1977 in the profiles shown in Fig. 1. These surveys are carried out from the dune face out to a depth of 20m and with a spacing of 600-1000 m. From these profiles dune erosion can be easily calculated from year to year by measuring the changes in the position of the dune face between surveys. In addition to the surveyed profiles a record of all the storm surges that have occurred in this area is available from the sea level gauges located at the ports of Thyborøn, Thorsminde and Hvide Sande. Along this stretch of coast there is a very small tidal range of below 1m and sediment transport that is predominantly towards the south. The average annual coastal retreat along this stretch of coastline is up to 8m however this is managed in several locations by the use of both offshore and beach nourishment. During storm surges a strong western wind with speeds of up to 34m/s travelling across the 600km of North Sea can produce a storm surge with a 100 year return period that raises sea levels along this stretch of coast by up to 3.19 m and produces wave heights that can exceed 7.5m.

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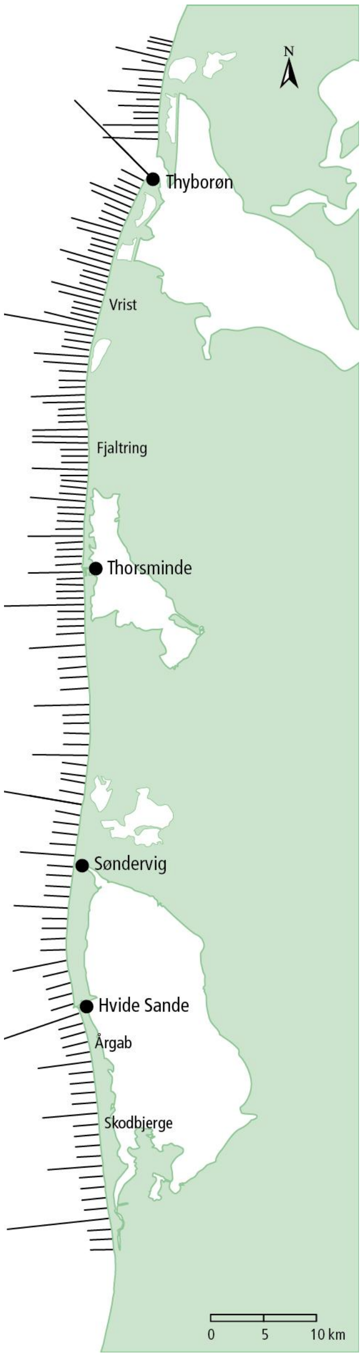


Figure 1. Danish west coast survey transects.

Indentifying and Verifying the Erosion Events

To establish how many extreme dune erosion events have been recorded since 1977 the survey data was extensively checked to remove errors or false overestimations of dune erosion. Not every measured transect was suitable for use in this analysis. Some of the measured transects coincide with groynes and other hard sea defences making them unsuitable for dune erosion analysis. Each transect was cross referenced with coastal defence charts where the location of wave breakers, groynes etc could be identified and the conflicting measuring locations disregarded. Some of the sites in this study have had revetments built as a response to erosion in their location. Measurements from these sites have only been used before such coastal protection was installed.

With the data set defined cross section profiles of each beach section were plotted for every year that a survey took place. In most cases this is from 1977 onwards. From these cross sectional profiles an appropriate height interval was selected that can be used to appropriately define the face of the sand dune. This height varies from site to site as of course no two sites have exactly the same topography. The appropriate measuring height can also vary over time and as such the height intervals for each site are defined separately for before and after 1990. Once the vertical position of the dune face has been defined its advance or retreat can be calculated from one year to the next by use of the measured distance between the dune face and a fixed inland reference point. Dune erosion was calculated for each suitable profile between each year's measurements.

Surveys that showed erosion of the dune face that exceeded 20m were selected for further investigation. In contrast to these cases of extreme dune erosion cases were also selected for further investigation where there was limited or no erosion after a major storm. In the case of the most recent major storms from 2005 onwards all locations that showed a dune erosion of over 5m were investigated and correlated for sand nourishment. This prevented the increasing use of sand nourishment from hiding any potentially large erosion events that could have otherwise been overlooked. For comparison examples of minimal dune erosion have been chosen that are close to those that have experienced extremely high levels of erosion. After these locations and corresponding erosion events were selected each site was checked to ensure the erosion value recorded was correct and not anomalous. Anomalous values were removed from this analysis where for example there was a high recorded dune retreat resulting from the erosion of a small for dune or sand bank.

An independent control of all of the large dune erosion values has been carried out through the use of (where available) aerial photographs from the Danish Coastal Authority's archives and various internet sources. Topographic maps made from aerial photography at a scale of 1:2000 have also been used. These maps are generally available from 1983 onwards with approximately 5 year intervals.

Adjustment to Allow for Sand Nourishment

The west coast of Denmark has with increasing intensity been protected through the use of sand nourishment. This will of course have an influence on amount of dune erosion that is experienced, particularly in the case of more recent erosion events where beach nourishment is likely to have played an increasingly significant role. The Danish Coastal Authority has kept a record of beach and near shore nourishment. This record contains the date and volume of sand deposition in a catchment area spanning either side of the measuring transect in question. The volume that has been deposited in this area can then be divided by the distance to the neighbouring transects to give a deposition volume per meter of coastline. For the purposes of this study the effect of any nourishment sand deposited in this area is assumed to lie uniformly distributed between a height of 4m above sea level and a depth of 6m below sea level, see Fig. 2.

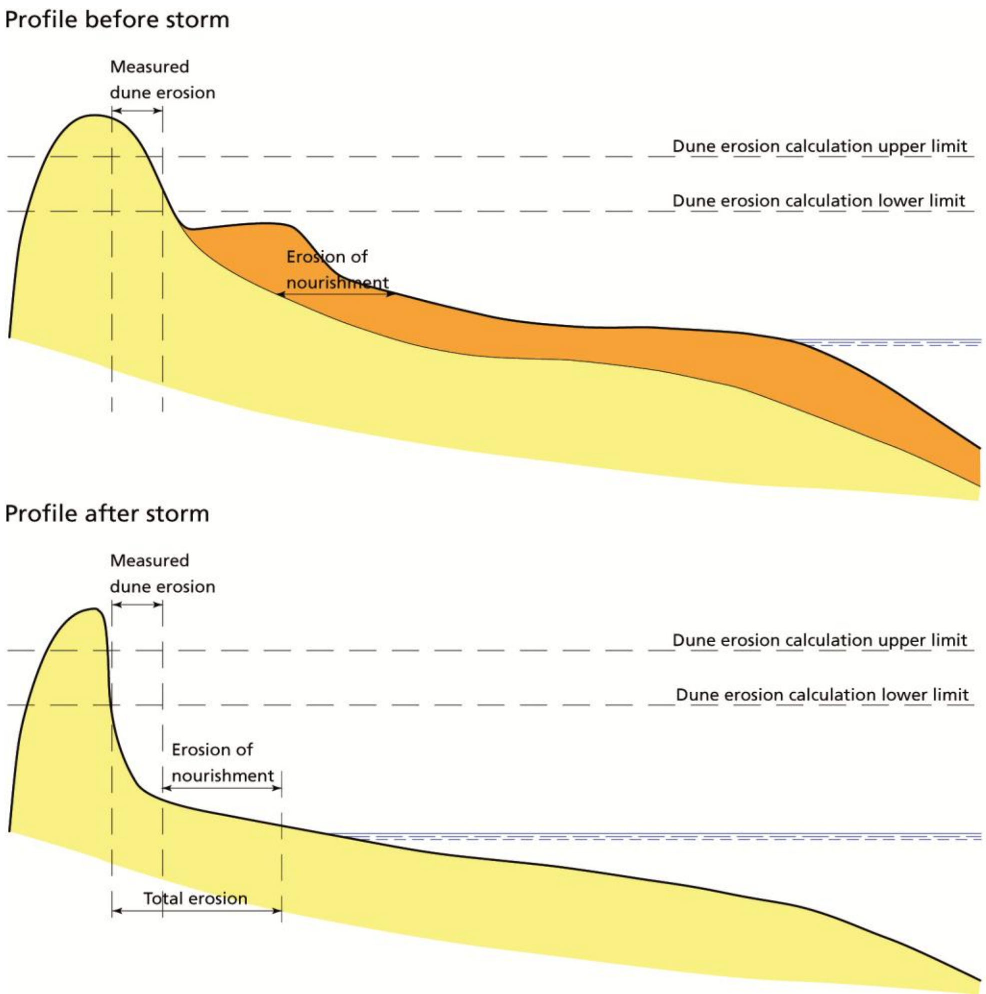


Figure 2. Nourishment adjustment cross section.

To simplify this calculation the effect of sand nourishment is only calculated for 3 years before the storm that is presumed to cause the large erosion event or back until the previous storm with a return period of 5 years or more (see Fig. 3) whichever provides the shortest time span. A few of the large erosion events were measured over a time span where there was no significant storm event, in these cases new years day is used as the assumed storm/erosion event date. This allows beach nourishment over the summer and autumn to be accounted for and presumes the erosion took place during the first winter period between our two dune measurements.

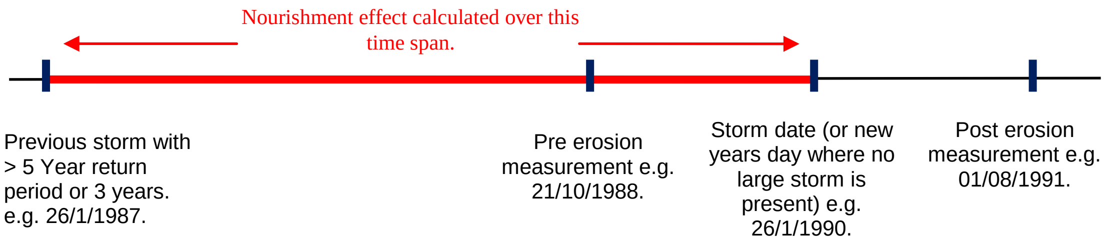


Figure 3. Nourishment adjustment time span.

Latent Erosion

A theory of latent erosion was previously investigated in relation to an extreme dune erosion event that occurred at Søndervig (see Fig. 1) during a storm in 2005 (Knudsen et al. 2006). Latent erosion is based on the theory that coastal profiles have a certain equilibrium state where the form of this profile depends on the wave climate and the grain size of the sand in the profile. On a retreating coast the dune retreat happens during storms where the water level is high and the waves can plunge directly into the dune face. After a long period without storms the part of the profile outside the coastline has retreated as normal, while the dune face has stayed in the same position. An imbalance or latent dune erosion has been introduced in the profile.

When the storm arrives the latent dune erosion could be released. In these cases the dune erosion is larger than what should be expected for the location and with the actual storm water level. The very large dune erosion at Søndervig in January 2005 could partly be explained by a release of latent erosion in the coastal profile.

In this study the possibility of latent erosion has been examined for all the profiles with dune erosion of more than 20 m. The average position of the profile between 0 and -6 m has been compared to the position of the dune face in the years before the large dune erosion occurred. A large profile retreat together with a previously stable position for the dune face would result in the conclusion that latent erosion is an important part of the reason for the large dune erosion. However after investigating all of the instances where over 20m of dune erosion occurred it became apparent that this theory could only apply as an explanation in a handful of cases.

Linking Extreme Dune Erosion to Storm Surge Return Period

Dune erosion is usually seen when the water levels are high during a storm. However this is not always the case. The maximum storm water levels since 1977 were recorded and checked from sea level gauges in the ports of Thyborøn, Thorsminde and Hvide Sande. By using the return period from each of these peak sea levels (Sørensen et al. 2012) the severity of each storm can be compared across all three harbours along the coast. This allows all of the erosion events to be compared to the nearest sea level gauge and thereby a storm return period matched to each individual dune erosion event.

The results of this comparison gave some surprising results as can be seen below in Fig. 4. Here dune erosion is plotted against the return period of the storm during which the erosion occurred. Here it can be seen that there is no apparent correlation between intensive dune erosion and return period. This indicates that the peak sea level during a storm has limited influence on the amount of large erosion incidences that occur and their severity.

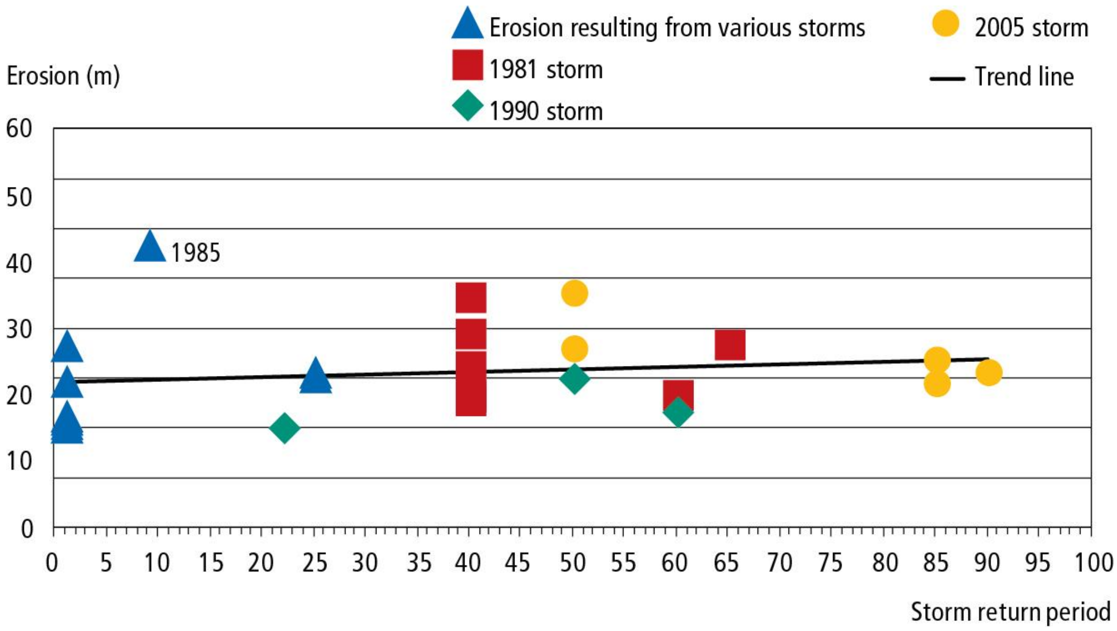


Figure 4. The recorded size of large dune erosion events plotted against storm return period.

This lack of correlation makes it difficult to define the dune thickness required to protect against a storm with a 100 year return period. This is especially apparent when it is taken into account that this dataset includes a storm in 2011 with a return period of 100 years and that this storm did not result in any significant extreme dune erosion. This indicates that the peak sea level during a storm surge is not the most critical factor in determining the amount of dune erosion that can occur as a storm with high sea levels and a high return period has been shown on numerous occasions to result in little or no erosion at the dune face. Further investigation comparing the duration of these storms was also carried out again resulting in no meaningful correlation.

Causes for the Unexplained Extreme Dune Erosion Events

As attributing the duration and return period of a storm to the amount of erosion that is recorded did not provide a definitive cause for these erosion phenomena further studies were carried out investigating general long term natural trends along sections of coast where targets are set to stop coastal retreat through the use of nourishment. These investigations aimed at identifying an explanation for why there haven't been so many cases of extreme dune erosion in the last few years despite there being several intense storms as well as which factors are changing since the increasing use of sand nourishment. Investigations were subsequently carried out at the locations of Årgab, Vrist, Fjaltring/Mærsk and Thyborøn South see Fig. 1. The parameters investigated are the change in the gradient of the coastal profile (from the coastline to a depth of 6 and 10m), the change in beach width and the number of sand bars that are present, some of which in more recent times can be assumed to result from sand nourishment. The development or trends seen in these parameters can offer an insight into how the coast has changed over the last 35 years and provide some information into factors that could affect the occurrence of extreme dune erosion over time.

From this investigation three trends were identified:

- The prevalence of sand bars has increased significantly at three out of four of the study locations and remained stable at the fourth.
- All of these sites show a slight steepening of the coastal profile from 0-10m depth.
- Beach width has reduced significantly at two locations and shown little change at the other two locations.

Table 1. Changes in number of sand bars, profile gradient and average beach width at four sites where sand nourishment is used to achieve a target of stopping coastal retreat.

Changes from 1977-2012	Årgab	Vrist	Thorsminde S	Fjaltring Mærsk
Average change in number of sand bars (per profile).	+0.5	+0.3	0.0	+0.5
Profile gradient 0-10m	1:154 to 1:151	1:83 to 1:74	1:126 to 1:116	1:113 to 1:98
Average Beach width change	+4m	-24m	-21m	-5m

With the exception of the increase in sand bar prevalence it is apparent that the steepening of the offshore profile and the reducing beach width should act to increase the severity of extreme dune erosion, a pattern that has not been seen. This indicates that the increase in sand bars holds a key role in relation to extreme occurrences of dune erosion.

MODELLING OF DUNE EROSION WITH XBEACH

Investigation and modelling of local extreme dune erosion

Based on the lack of correlation between storm intensity and extreme localised dune erosion further investigation was carried out on a specific example of this type of erosion that took place in January 2007. Here more than 10 m of dune erosion occurred along a 400-500 m long stretch of the coast at the southern Holmsland Tange (south of the harbour Hvide Sande on the Danish west coast), while no erosion was seen along the neighbouring stretches. Good profile survey data before and after is available along this stretch of coast in the period 2005-07.

This local case study focused on a morphological analysis investigating the relationship of the offshore bathymetry to the dune erosion that occurs during a storm. This section of the investigation presents the findings from the use of the open source numerical model XBeach (Unesco-IHE Institute for Water Education 2013) to simulate the resultant erosion or lack of during conditions under which the morphological changes occurred.

Local Study Site Background Data

The 11 km long stretch at the southern Holmsland Tange was surveyed about every 3 months in the period 2005-07, see Fig. 5. Beach surveys were carried out up to 6 times a year with full bathymetric surveys at least twice a year. Full surveys of dune, beach and bathymetry were carried out with a spacing of 200m. Beach profiles were measured at a closer interval of 100m. In this study focus will be on the 1.4km stretch from profile 3600 to 5000 because the severe dune erosion was seen in the middle of this stretch in profiles 4200 and 4400. In addition to the bathymetric surveys data time series are available with wave, sea level and wind conditions from the time of the erosion event recorded at the locations shown in Fig 5.

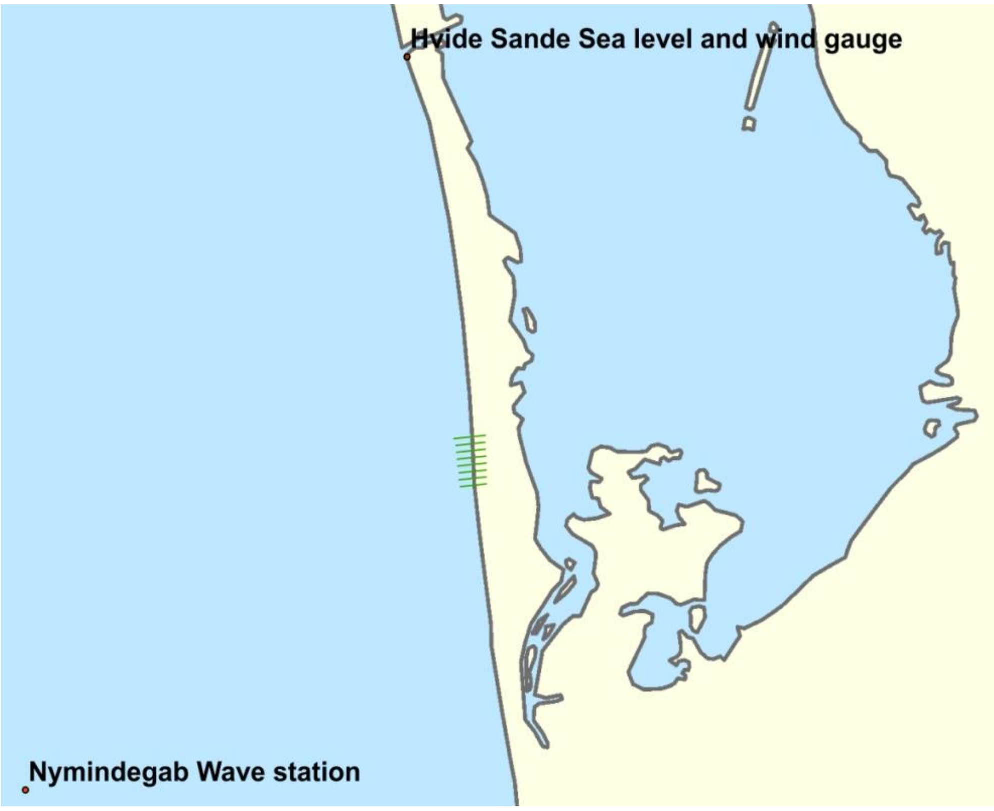


Figure 5. The study area with survey profiles.

For this 1.4km stretch the bathymetries from July 2006 and January 2007 are shown below in Fig. 6 and 7. The profiles where significant dune erosion occurred are shown in red. In these locations dune erosion of just over 10m was recorded at the dune face at a level of +5 to +6m. This erosion was recorded between a beach survey on the 19/12/2006 and full bathymetric survey taken on the 24/01/2007 (Fig.7). All of the other profiles shown in green experienced no erosion at the dune face at the same elevation of +5 to +6m.

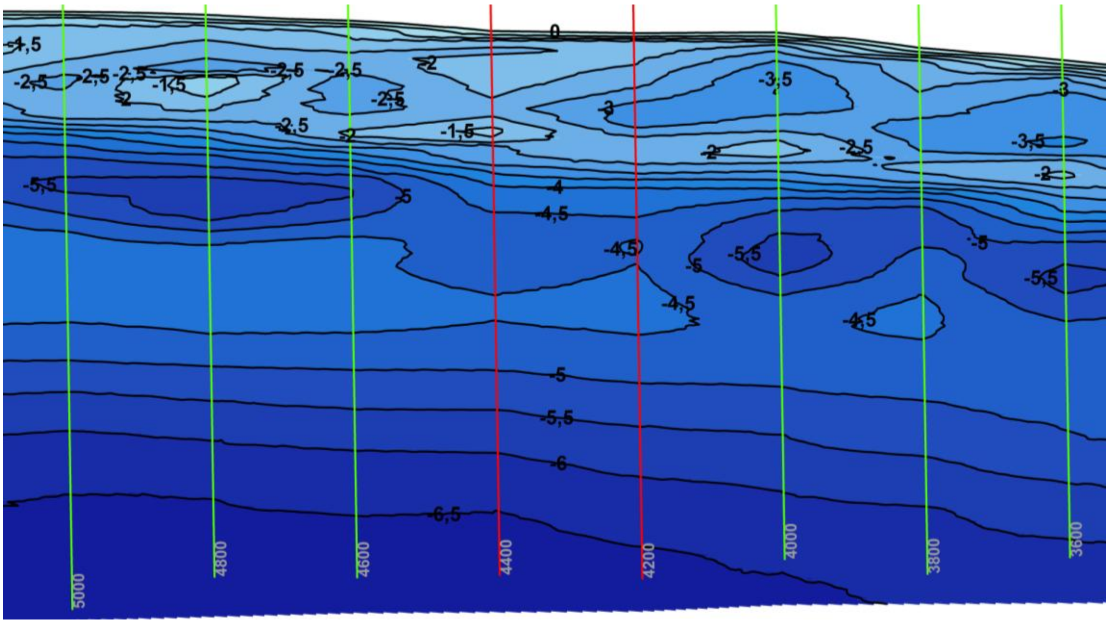


Figure 6. Bathymetry surveyed on the 06/07/2006.

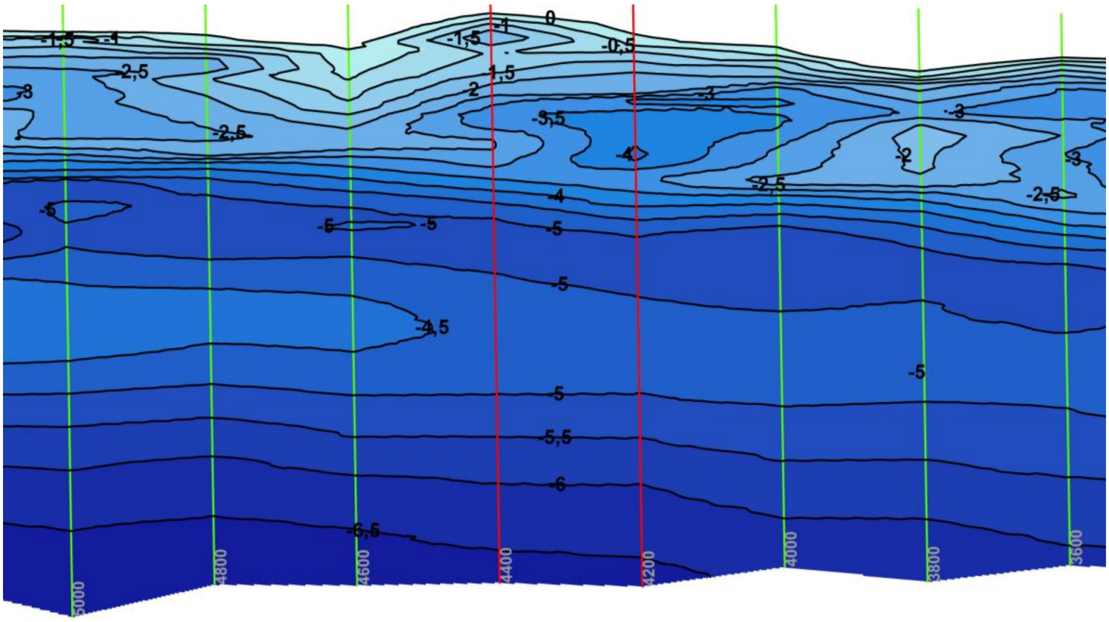


Figure 7. Bathymetry surveyed on the 25/01/2007.

There is a marked difference between the pre storm bathymetry measured in July and that measured just after the erosion events in January. The July 2006 bathymetry shows more regular sand bars across all of the profiles and no substantial undulations. The survey taken in January 2007 just after the erosion events tells a different story. This bathymetry shows an irregular dip in the inner bar system just in front of the two profiles where dune erosion is observed. Another observation is that the zone between the coastline and the 3m depth contour also has an inward undulation of 60m at the stretch in front of the same two profiles.

Both phenomena cause more wave energy at the dune foot. The XBeach model is used to explore the effect of the changed bathymetry and analyse the reason for the dune erosion quantitatively.

XBeach Simulations

The XBeach model was run for all of the profiles using a summer bathymetry (Fig. 6) and a winter bathymetry (Fig. 7). All tests used the beach and dune profile that was surveyed in December just 36 days before the post erosion survey. The model was run using individual profiles and not with the complete 3D bathymetry. Below in Fig. 8 the results of simulations using both summer and winter profiles are shown for the profile 4200 where dune erosion was surveyed in reality. In the two profiles where the dune erosion occurred the XBeach results with both the winter and summer bathymetries showed significant erosion close to that of the surveyed erosion.

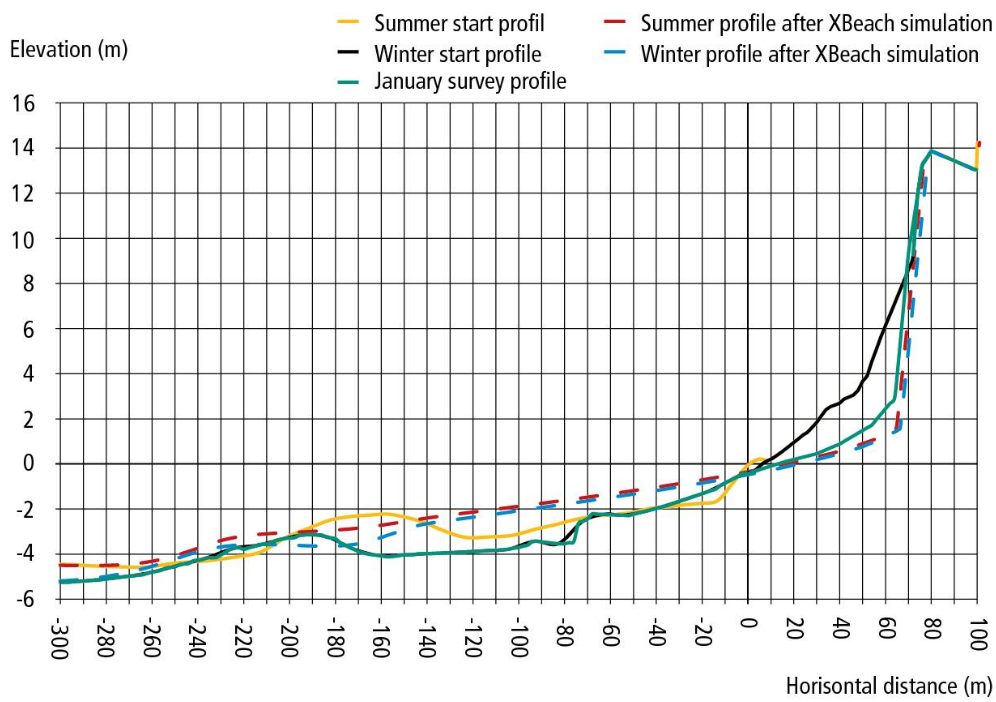


Figure 8. XBeach input profiles and results using the summer and winter bathymetry profile 4200.

In other neighbouring profiles the erosion calculated by XBeach produced a greater variation between the summer and winter bathymetries. As with the profile below in Fig. 9 similar results were achived in the profiles 3800 and 4000 with no erosion being produced at an elevation of 6m when the winter bathymetry was used.

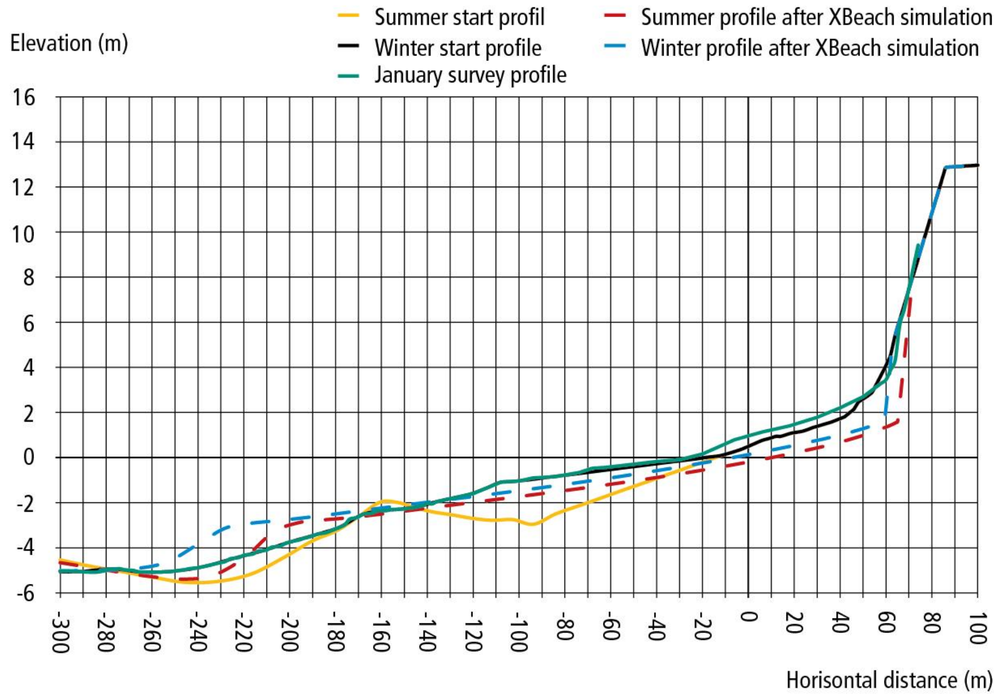


Figure 9. XBeach input profiles and results using the summer and winter bathymetry profile 4600.

Sand Bar Tests

Some of the profiles tested with XBeach produced more erosion at the dune face than was surveyed in reality. An explanation for this could be that the bathymetry that existed immediately prior to the storm and consequent erosion event was different to that surveyed in July and January. In four profiles the inner sand bar was raised by 1m. As expected this height increase of this sand bar resulted in a significant reduction in erosion at the dune face in each test case, see Fig. 10. In three of these cases erosion at the dune face was reduced to zero or extremely close to that of the surveyed erosion.

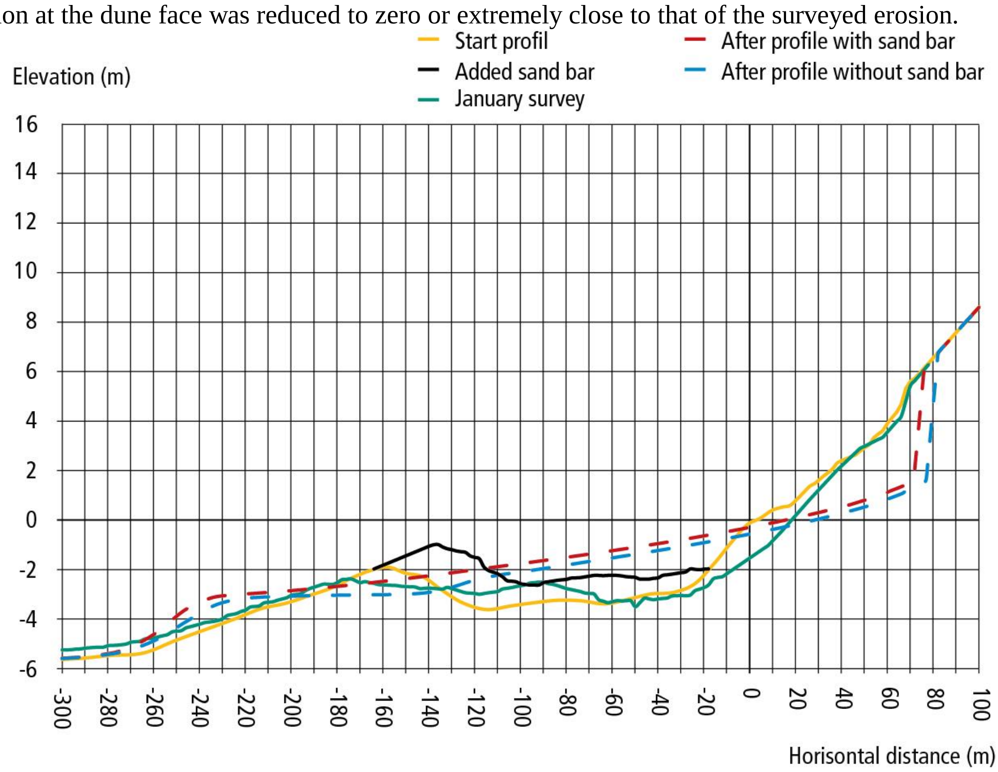
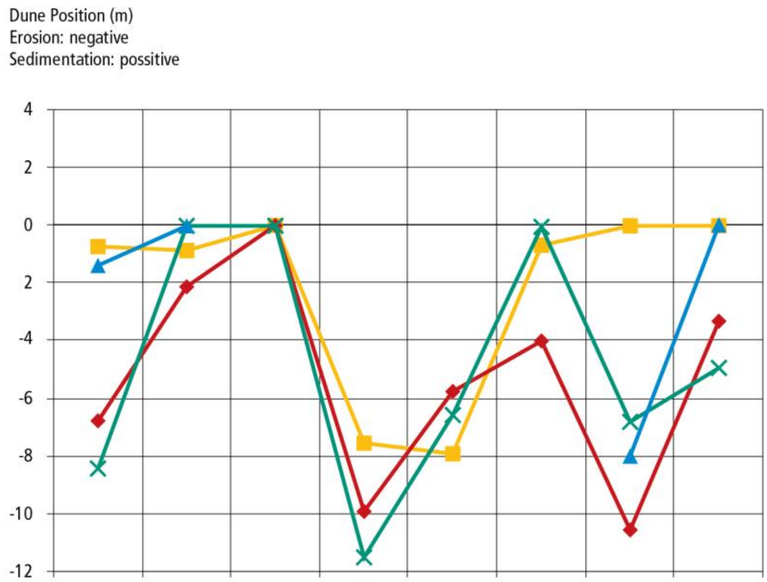


Figure 10. Profile 3600 tested with a raised sand bar.

A difference in bathymetry could not however completely explain the absence of dune erosion in all of these four test cases. Profile 4800 featured a particularly low beach (surveyed in December). In this profile the beach is much wider after the storm in January. Due to this extremely low beach from the December survey changes to the bathymetry had limited effect on the amount of erosion experienced at the dune face.



Profile number	3600	3800	4000	4200	4400	4600	4800	5000
Surveyed erosion between December and January	-0.7	-0.9	0	-7.5	-7.9	-0.7	0	0
XBeach results using July bathymetry	-6.8	-2.1	0	-9.9	-5.7	-4.0	-10.5	-3.3
XBeach results using January bathymetry	-8.4	0	0	-11.5	-6.6	0	-6.8	-4.9
XBeach sand bar test results	-1.4	0					-8.0	0

Figure 11. Surveyed dune erosion and XBeach simulation results (6m height).

A marked difference can be seen between the simulation results using the January winter profile and the July bathymetries in Fig. 11. The significant difference in dune erosion between these two bathymetries highlights how big a role the unseen bathymetry plays on the erosion experienced at the dune face. Although the January bathymetry is from after the modelled storms it is time wise much closer to the storm events than the bathymetry measured in July. The difference between the XBeach results given by these two bathymetries highlights the value of an accurate bathymetry that is measured just before a storm. The inability to reproduce the exact pre storm bathymetrical conditions offers an explanation for the simulated results shown in profiles 3600, 4800 and 5000 that are drastically different to what was experienced in reality.

The influence of the bathymetry on the erosion XBeach simulates is further reinforced by the results of the sand bar tests. The enlargement of the inner sand bar in the profiles where XBeach exhibited much larger erosion than that produced in reality acted to bring the simulated dune erosion much closer to the measured reality. This indicates that a pre storm bathymetry existed before the storm event that was different to the measured bathymetries that were available for use in this study. The sand bar tests showed that an enlarged sand bar offers an explanation to the lack of dune erosion at these locations. The contradiction for every test carried out in this investigation is profile 4800 where no erosion was measured in reality but where XBeach consistently produced results with large erosion. Changes in the bathymetry for the 4800 profile through using winter, summer and a sand bar profile did affect the amount of dune erosion produced by XBeach. However the closest result XBeach produced for this profile was still 6.8m more than the surveyed erosion. It appears that the most plausible explanation for XBeach calculating such aggressive erosion is the very low and narrow beach that was measured in December prior to the storm. At this location the beach surveyed after the storm in January was actually much larger than that surveyed before the storm in December. This beach growth indicates that in this profile the pre storm beach survey provides a poor representation of conditions immediately prior to the storm.

Although XBeach produced dune erosion rates that in most cases strongly matched the measured reality it is apparent in many profiles that XBeach produces more extreme beach erosion than shown by the pre and post storm beach surveys. This highlights some shortcomings in its cross shore sediment transport with all eroded material being moved much further offshore than is observed in reality. This could be the cause of the exaggerated dune erosion seen in some of the modelled cases as there is less beach volume in the latter stages of the simulations to absorb wave energy. It can be concluded that the fast changing nature of offshore sand bars has a large influence on the dune erosion, the results of which can be effectively reproduced by XBeach however the accuracy of this reproduction is very reliant on a truly representative pre storm bathymetry that is in practice difficult to obtain.

GENERAL CONCLUSIONS

Investigations into the cases of extreme dune erosion along Denmark's west coast identified multiple examples of extreme dune erosion of over 20m. The extent and prevalence of these erosion incidences does not appear to be related to peak sea level/storm return period. Since 2005 very few extreme erosion events have occurred despite the occurrence of several extreme storms in particular one storm with a 100 year return period. Investigations into background trends for the west coast showed that the amount of offshore sand bars has been increasing over time. This trend corresponds with the increasing use of sand nourishment during recent years. The use of XBeach further reinforced the importance of the offshore bathymetry and in particular size of the offshore sand bar on the amount of erosion that is experienced at the dune face. The influence of changes in the offshore bathymetry as well as the size of sand bar on the erosion simulated at the dune indicates how the increasing prevalence of offshore nourishment has an effect on the erosion that can occur at the dune face during extreme storms. Based on these conclusions it was not deemed necessary to change the minimum dune width criteria as the findings here do not indicate an increasing risk of extreme dune erosion events.

FURTHER DEVELOPMENT

It can be clearly seen through the results of this investigation that the bathymetry plays a large part in determining where dune erosion will occur and its severity. A constantly changing sand bar system offers a good plausible explanation as to the occurrence to extreme dune erosion at certain locations while little or no erosion is experienced at others. To build on the results of this investigation and gain further insights into the effect a sand bar system has on dune erosion would ideally require a bathymetric measurement much closer to the storm event so there can be little doubt over the shape of the offshore seabed just prior to a storm. The availability of a more reliable pre storm bathymetry would also justify the use of XBeach in a 2D format which would allow the interaction between sand bars and the effect on wave energy distribution to be investigated. Based on the ability of XBeach to reproduce the actual measured erosion in this study there is further potential to use XBeach to evaluate the width and height of dune required to resist a storm with a specific return period. XBeach or another numerical model could be run on for example the worst bathymetry and beach conditions with data from a storm the dune is required to resist. This would offer a good estimation for the width and height a dune must be to offer an acceptable level of protection. Investigation in this way would allow a dune strength guideline to be established that can be used as a simple guideline to ensure sand dunes that are relied upon as a sea defence are maintained to an adequate level.

ACKNOWLEDGMENTS

This work has been supported by the Danish Council for Strategic Research (DSF) under the project Danish Coasts and Climate Adaptation – flooding risk and coastal protection (COADAPT), project no. 09-066869.

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