COADAPT

- Dune Erosion and safety along the Lodbjerg-Nymindegab Coast Denmark

Lodbjerg - Nymindegab

November 2013

Miljøministeriet

Højbovej 1 • DK 7620 Lemvig
www.kyst.dk • kdi@kyst.dk

Kystdirektoratet
Danish Coastal Authority

Project information

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Startdato Slutdato	01.03.2013 01..11.2013
Projektansvarlig (PA)	Per Sørensen
Projektleder (PL)	Holger Toxvig Madsen
Projektmedarbejder (PM)	Matthew Edward Earnshaw Irene Andersen
Timeregistrering	35210205
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Forfattere	Matthew Edward Earnshaw Holger Toxvig Madsen
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Contents table

Appendix A and B can be found in a separate document

Chapter 1

Introduction

Coastal defences along the stretch of coastline from Lodbjerg to Nymindegab have been financed and implemented in relation to a common 5 yearly agreement between the government and the concerned coastal municipalities along this stretch of coast. The agreement has been based around target setting for the development and changes to the coastline and the consequent economic ramifications.

With regards to coastal erosion target setting has been largely defined by the need to protect infrastructure and property. Erosion is calculated based on comprehensive profile measurements taken from the dune face at a height of 4m to a depth of 6m below sea level. Targets are met for each defined agreement period however due to the difficulty in accurately predicting the morphological changes along the coastline from year to year erosion is usually defined after the developments in the coastline have been analysed over an 8-10 year period.

Protection against storm surges has been achieved through the construction of sand dikes or the management of naturally existing sand dunes. These defences are generally to offer protection against a high water situation with a 100 year return period, with the exception of the Thyborøn stretch of coastline which is required to hold out against a 1000 year storm event. This safety level has been applied and maintained through establishing a minimum dune width. The minimum dune width was established in 1990 based on the analysis of dune erosion resulting from storms in January and February 1990. The results from 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 extra dune buffer of 10m a minimum dune width of 40m was established and has been used since.

Based on many years experience in handling coastal erosion targets it has been deemed appropriate to look back over the available records and establish if we can re-evaluate how appropriate the current dune strength is in relation to the treatment of:

- Target setting: for example where a target of zero erosion is set on a section of coastline for a five year agreement period. Can it be taken into consideration that the coast has advanced during the previous agreement period. This would mean that during the new agreement period a target set of zero erosion can be above and beyond the required safety level for this section of coast. In cases such as this could it be more appropriate to allow an amount of erosion to occur and concentrate defence measures in other locations. The opposite can be said for a section of coast that had previously eroded too much. Should in this case a target be set so that the coastline is advanced during the new agreement period?

- High water safety: The most recent threat to the high water defences occurred at Harboøre Tange and at Krogen north of Søndervig, where the dune width suddenly became much less than the desired 30m and 40m. A better understanding of the frequency of such large erosion events is desired in relation to how much erosion can suddenly occur on a section of coastline as a result of storms with moderate and high sea levels. In addition to this further knowledge is desired into the contrasting lack of erosion at some locations after a significant storm. From a better understanding of large erosion events and their frequency a re-assessment of the current minimum dune width is desired.

An investigation into these abovementioned problems is contained within this report.

Chapter 2

Report Summary

This report has been carried out primarily to investigate the cause of large and apparently unexplained dune erosion events. These erosion events are where large sections of dune are rapidly removed resulting in a significant threat of dune breach and consequent flooding along the west coast of Denmark. The ultimate aim of this investigation is to use new knowledge to develop a new dune safety parameter that is able to withstand a 100 or 1000 year storm based on the safety requirements along a specific section of coast.

The investigation into the large dune erosion events has been carried out using measurements from the Danish Coastal Authority's west coast measuring transects. These measured profiles of the coast have been investigated from 1977-2012 for any large dune erosion events. The identified large erosion events have been extensively quality controlled so they are discounted where hard engineered sea defences are present. Results have also been cross referenced with available aerial photographs and laser scanning. Corrections have also been made to take into account the increasing use of sand nourishment. Coastline and offshore profile developments have been assessed to establish how well these extreme erosion examples fit with a theory of latent erosion. The extreme erosion events found have also been compared to nearby locations where little or no erosion has occurred under the same conditions and timeframe. Further site specific analysis has also been carried out into profile steepening, beach width and sand bar prevalence.

The results of the analysis carried out in this project were such that the largest erosion events that have occurred along the west coast have been found, documented and checked with all available sources to ensure their validity. These results can be seen below.

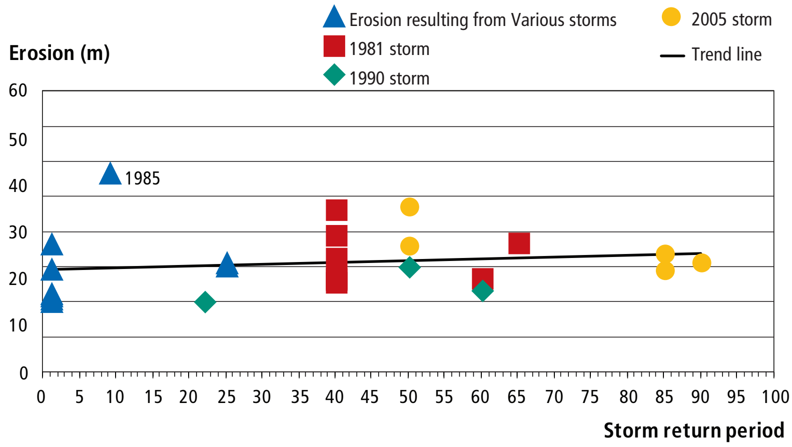


Fig. 2.0.1 Large Dune erosion events 1977-2012

It can be concluded that sand nourishment has had an increasing effect over the most recent years and reduced the frequency and intensity of the actual erosion experienced on the sand dunes. Evidence to support the theory of latent erosion as an explanation for the extreme dune erosion events has only been found in a small number of cases, not enough to discount it as a factor but from this investigation it is clear that it offers no clear or usable explanation for these extreme dune erosion events. It has also been noted that beach width has been reducing and the offshore coastal profile steepening which would suggest an increase in dune erosion. This has however not been realised and surprisingly no real correlation was foundbetween storm return period and dune erosion. This is particularly apparent when the erosion following a 100 year sea level in 2011 was investigated and found not to have resulted in any large dune erosion events. A part explanation for this may be found in the increasing prevalence of sand bars and the increasing use of sand nourishment however no dependable correlation has been found between any of the factors investigated and the large and apparently random dune erosion events.

In relation to a new dune safety parameter more advanced profile by profile analysis is required that simultaneously takes into account the large number of factors that can have an effect on dune erosion. A summary of the Dutch Dune assessment method and developments in dune erosion modelling have also been covered in the later sections of this report. Recommendations have also been made into a basis coast line system that can be used as a future framework to allow stricter control over the dunes. These recommendations fit in with the existing available measuring systems along the west coast of Denmark.

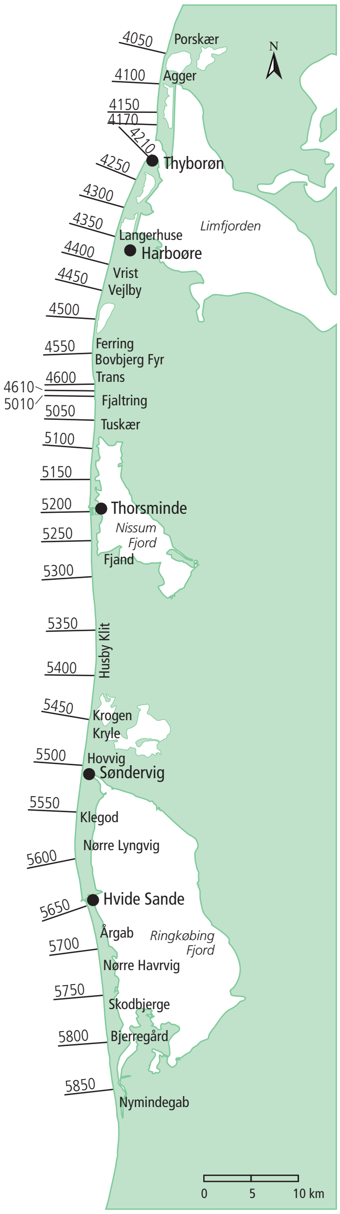
Chapter 3

Dune erosion along the west coast of Denmark

3.1 Explanation of the Danish west coast measuring systems

In 1874 coastal profile measurements were begun around the Thyborøn Channel between Vorupør and Fjaltring. In transects with an interval of 600-1000 m the profiles were measured from a depth of 20 m to the coastline. In the beginning there were several years between the measurement campaigns, but they gradually became more regular and extended to the whole west coast between Skagen and the German border.

In this investigation dune erosion analysis is based on profiles measured since 1977 between Lodbjerg and Nymindegab, see figure 3.1.1. In this period the measurements started at the dune top which is a precondition of this analysis. Since 1998 the profiles have been measured every year. In the period before measurements are generally only available every second year.



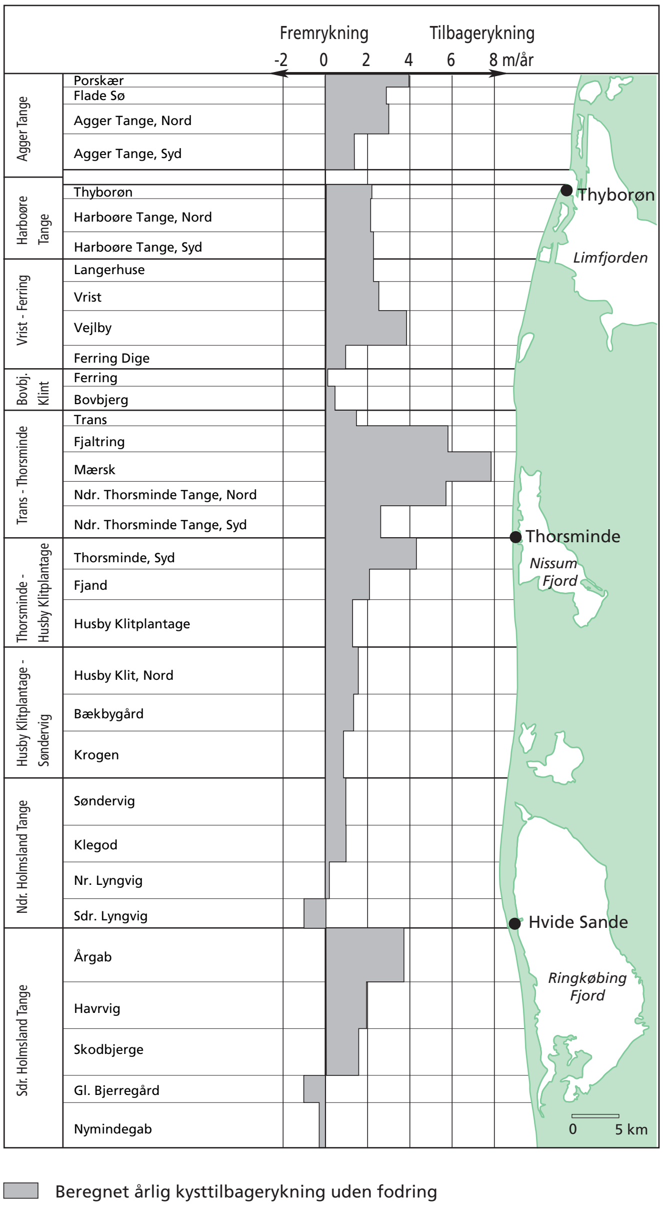


Fig. 3.1.1 (left) Transect numbers used in the analysis. Fig. 3.1.2 (right) The autonomous coastal retreat along the analysed stretch.

3.2 The autonomous coastal retreat

In figure 3.1.2 the average annual coastal retreat is shown for the studied stretch of coast supposing that no nourishment was carried out. The retreat rates are for the coastal profile between dune top and a 6m depth contour. These calculations are based on profile data from the period 1977-96.

3.3 The storms since 1977

Dune erosion is usually seen when the water levels are high during a storm. Below (Fig. 3.3.1, 2&3) the maximum storm water levels since

1977 with a return period above 5 years are plotted from sea level gauges in the ports of Thyborøn, Thorsminde and Hvide Sande.

It appears that there have been some quite extreme water levels over this period. The storm January 8, 2005 gave water levels with return periods up to 90 years. A return period of 65 years was reached during the storm November 24 in 1981. A similar level was reached during the storm January 26, 1990 with a maximum return period of 60 years. It can also be seen that the most recent storm in 2011 reached a 100 year return period but only at Thyborøn.

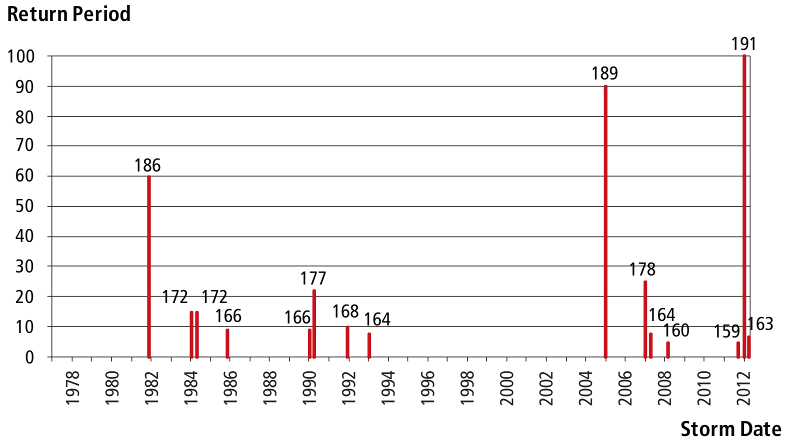


Fig. 3.3.1 High water levels with return period in the port of Thyborøn

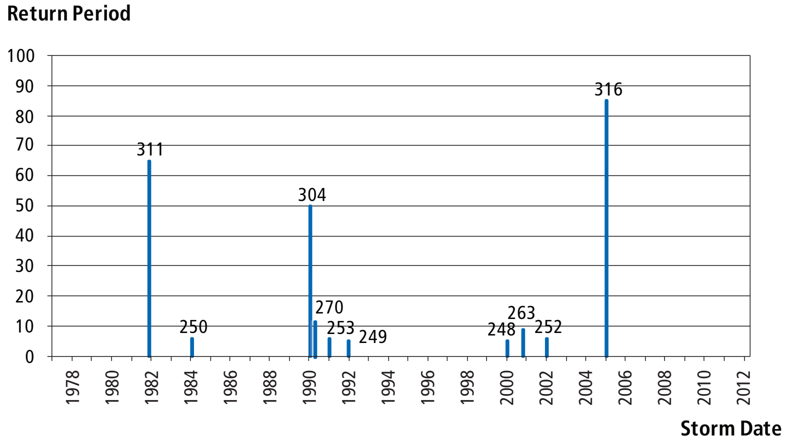


Fig. 3.3.2 High water levels with return period in the port of Thorsminde

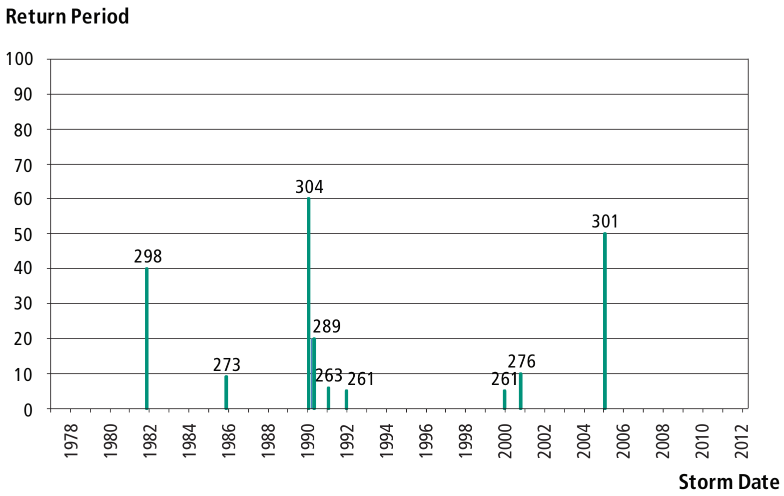


Fig. 3.3.3 High water levels with return period in the port of Hvide Sande

It can be seen from the above graphs that there were 3 storms with a particularly long return period that struck in 1981, 1990 and 2005. Below (Fig. 3.3.4, 5&6) show the water level during these storms and give a good indication of their duration and severity at the three different ports along the west coast.

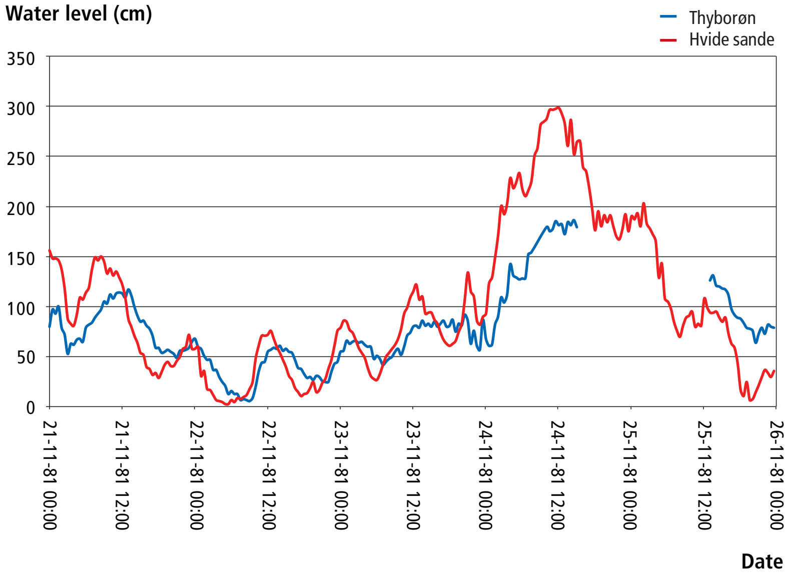


Fig. 3.3.4 1981 Storm water levels

Unfortunately the data for this storm was only completely available for the port of Hvide Sande.

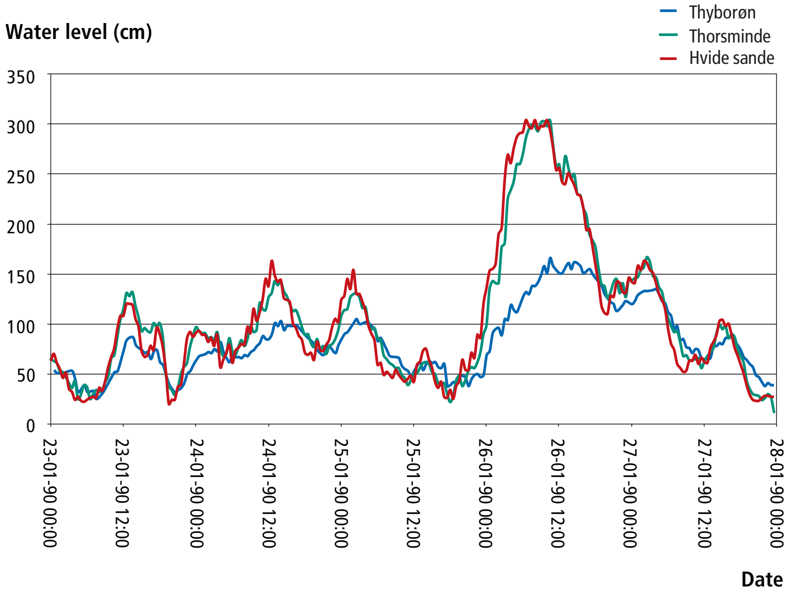


Fig. 3.3.5 January 1990 Storm water levels

It can be seen in figures 3.3.1, 2 and 3 that there were two storms in 1990 a second smaller storm stuck on the 27/02/1990, these two storms both had a high water level and of course they will both have had an impact on dune erosion.

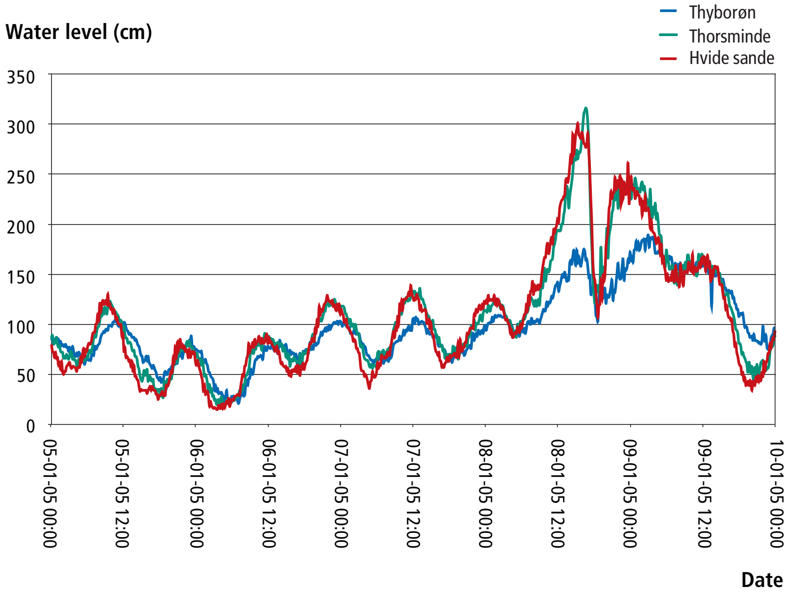


Fig. 3.3.6 2005 Storm water levels

It can be clearly seen that the water level during each storm varies between the three measuring stations. It is also apparent that the duration of the high water level varies from location to location. As erosion should also be a product of storm duration as well as its ultimate high water level a comparison of storm duration can be made to offer a little more insight into the erosive potential of each storm. The amount of time the water level was above that of a 5 year return period was calculated for each storm in each measurement location. This can be graphically viewed below.

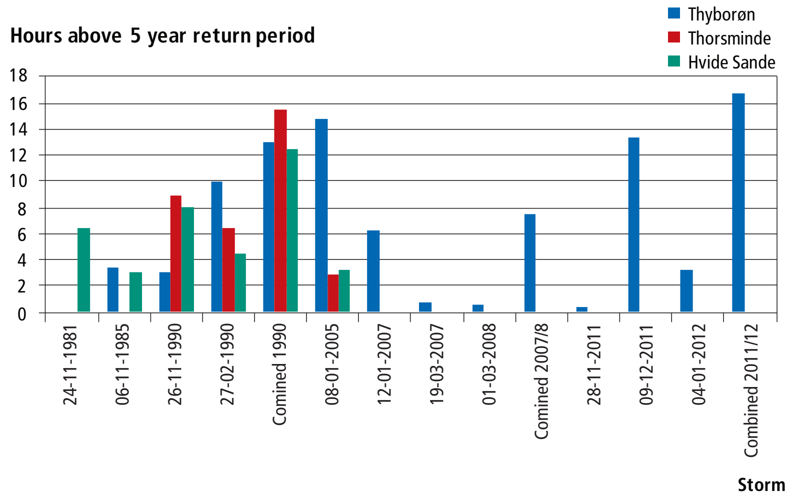


Fig.3.3.7 Storm duration graph

Unfortunately water level data was only available in complete form from Hvide Sande for the 1981 storm, therefore it is difficult to fairly compare the duration of the 1981 storm with that of the storms in 1990 and 2005. Because the two storms in 1990 were so close together they have been combined here into a single storm. It can be seen that in Thorsminde and Hvide Sande the 1990 storm had a much longer duration in comparision to the 2005 storm although in Thyborøn durations were much the same. From Hvide Sande at least it can be seen that the duration of the 2005 storm was around half that of the 1981 storm and around a quarter of the 1990 storm. The large storm in 2007 only significantly affected Thyborøn and here it can be seen that it did not feature a particularly long duration. The winter of 2011/12 was also similar in that water levels with a high return period were only experienced in Thyborøn however when combined these storms exhibit the longest duration.

3.4 Description and selection method for large erosion sites

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. Every 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 slope defences or 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 measurements took place. In most cases this is from 1977 onwards. From these cross section profiles an appropriate height interval was selected that can be used to appropriately define the front slope 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 erosion or advance 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 has now been calculated for each suitable profile between each years measurements. Of course measurements have not always been taken exactly each year at every site and in some cases the difference in dune position has been calculated over a time span of two or more years. To help select the largest erosion events that have taken place the measurements before and after the largest recorded storms have first been used. Measurements before and after a large storm that showed an erosion value of over 20m were selected for extra investigation from the dataset. Erosion calculated at over 20m that resulted after no significant storm or other smaller storms was also selected so that all large erosion events could be analysed. Locations where there has been limited or no erosion after a major storm have also been selected for further investigation. 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 trend of sand nourishment from hiding any potentially large erosion events that could have otherwise been overlooked. Where possible minimal erosion examples have been chosen that are close to those that have experienced 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.

3.4.1 Aerial photo analysis

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.

3.5 Adjustment to allow for sand nourishment

The west coast of Denmark has with increasing intensity been protected through nourishment. This of course will 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 and is simply described in figure 10 below.

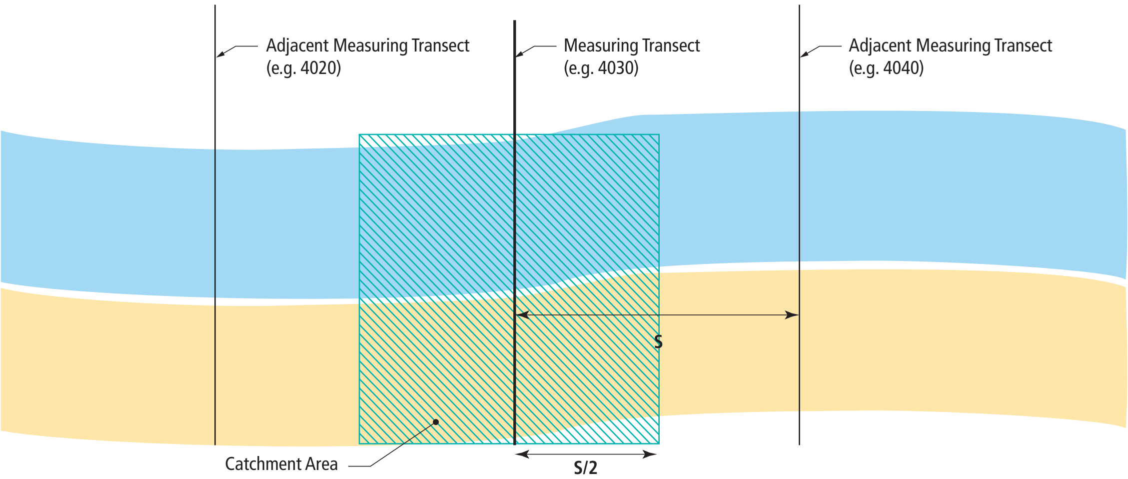


Fig. 3.5.1 Nourishment calculation area

The volume that has been deposited in this area can then be divided by the sections spacing (S) 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 3.5.2).

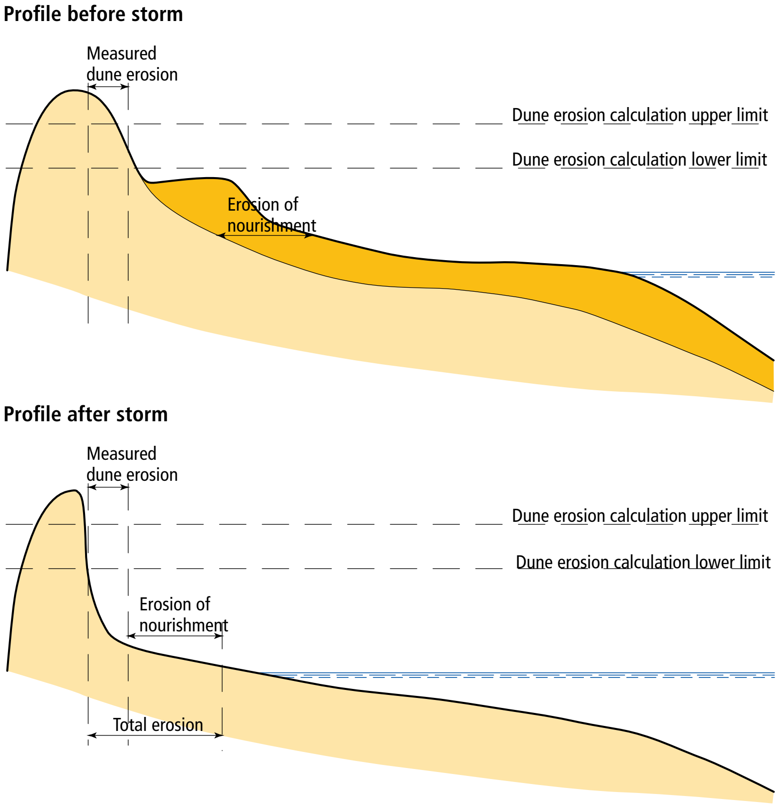


Fig. 3.5.2 Nourishment adjustment cross section.

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. 3.5.3) 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.

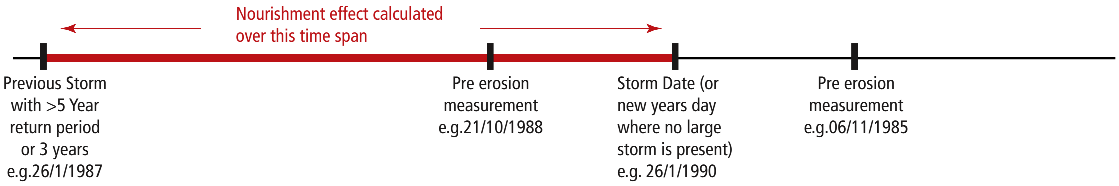


Fig. 3.5.3 Nourishment adjustment time span.

After beach nourishment has been accounted for the movements of the coastline and sand dunes over the years prior to and after the significant erosion event have been analysed. The coastline between a depth of -6 and 0 meters has been plotted along with the advance and recession of the sand dune. These graphics can be found in appendix A along with their respective cross section profile graphs showing the shape of the dune and beach profile before and after the erosion event.

3.6 Hypothesis of latent erosion

The coastal profiles are supposed to 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 in on 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 be partly explained by a release of latent erosion in the coastal profile (DCA, Variationer i kystprofilet (variations in the coastal profile), 2005).

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 rather 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.

3.7 Hypotheses for autonomic related erosion

For each section of the west coast of Denmark an average erosion or autonomic erosion value has been calculated. This value exists as a guide to showing how much each section of coastline is expected to erode from year to year if there is no human intervention. The autonomic erosion level varies greatly from site to site from areas that experience coastal advance to areas that experience high levels of erosion up to 7.82m (Fig. 3.1.2) a year at one location. It is possible that these variations in erosion rates over the coastline influence how drastic large erosion events can be. To investigate this further each site selected for further investigation due to the occurrence of a large erosion event will be cross referenced with its autonomic erosion value allowing a correlation between the autonomic erosion and the severity of erosion under severe storms to be analysed.

3.8 Sand bar, shore steepening and beach width investigation

Dune erosion can is dependent on a large number of factors, due to human influence on the coastline through hard defences and nourishment there are three extra factors that are investigated in this report. These factors 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 newer 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 in relation to how dune erosion amounts have changed over time.

3.9 Sand bar investigation

The investigation into the prevalence of sand bars is carried out at 4 separate locations where a target of zero erosion has been set since 1983. These 4 locations have been nourished regularly so stand as a good example of how the current coastline is developing in reaction to increasing nourishment. Sand bars with a height of over 1m will be counted from the coastline out to a depth of 10m and summarised for each investigative area as an average of three adjacent measuring transects. These sections are:

- Årgab-transects 5670-5690
- Vrist-transects 4390-4410
- Thorsminde South-transects 5220-5240
- Fjalting/Mærsk-transects 5040-5060

3.10 Profile steepening investigation

It has been previously reported that the offshore section of coastline has been steepening over time in some locations as the majority of erosion prevention methods have typically been concentrated on the upper sections of coast. This of course will have some bearing on the amount of wave energy the coastline will experience with a tendency towards seeing later wave breaking and a greater energy transfer to the upper sections of the beach as the coastal profile gradually steepens. In the context of this report the gradient of the offshore profile from 0-10m and 0-6m depth have been calculated for every available west coast measuring transect, for every available year.

3.11 Beach width investigation

The beach width for each available year is also calculated in much the same way that the steepness of the coastal profile is calculated. The horizontal distance between the coastline (0m) and a height of 4m is calculated and the resulting values used to view the trends in beach width from 1977 to 2012.

Chapter 4

Comments and summary of significant erosion events

Note: Supporting graphs for this section can be found in appendix A

4.1 Large erosion events resulting from the 24/11/1981 storm

4230 – Thyborøn

Erosion: 26,6m
Latent erosion can offer a part explanation of the dune erosion at this location.

5210 – 1½ km south from Thorsminde harbour mouth

Erosion: 36,7m
Latent erosion can offer a part explanation for the dune erosion of 32m at this point, this erosion is more serious at this location (36,7m) because before the storm this section of beach had been intensively nourished equating to around an extra 4,7m of erosion.

5380 – Vedersø

Erosion: 46,2m
This 46m of erosion can be explained using the latent erosion theory. At this location the sand dune had also eroded by around 20m up to 1986. Immediately prior to the 1981 storm it can be seen that the offshore coastal profile had retreated by around 60m.

Looking forward to the storm that occurred in 2005 a similar erosion in the offshore coastal profile can be seen however this did not lead to any dune erosion. This location therefore both supports and disregards the latent erosion theory.

5490 – 2 km North of Søndervig

Erosion: 25,5m
Dune erosion at this site occurs after a retreat in the offshore coastal profile, so latent erosion can offer an explanation for the large erosion at this location.

5680 – Årgab

Erosion: 26,2m

There is a dune erosion of 22m at this location as well as 4,5 meters of nourishment sand that has been laid down at this location. However latent erosion cannot provide an explanation in this case.

5760 – Skodbjerge

Erosion: 38,9 m

This site is a good supporting example for the latent erosion theory as the large dune erosion can be traced as a response to a large retreat seen in the offshore coast profile prior to the dune eroding. Since the large erosion event after the 1981 storm the sand dune at this location has not eroded while the offshore coast profile has been retreating since the 80's. If latent erosion is the primary process with which this section of sand dune is eroded then it would be expected that this site is soon due a large erosion event. Looking forward to the most recent 2012 dune position it can be seen that no such erosion has occurred over the last year.

5840 – Nymindegab

Erosion: 26,6m

This section of coast has in general shown a slight advancing tendency of around 0,3m/yr. At this site the offshore coastal profile had been eroding for the three years prior to this erosion event however for the next ten years the offshore profile appear stable. Latent erosion does not occur at this location where coastal advance is the most prevalent coastal behaviour.

5850 – Nymindegab

Erosion: 32,4m

This profile shows the same profile development as that of the site 5840 that is just a few hundred meters to the north.

4.1.1 Small / non erosion events resulting from the 24/11/1981 storm

4360– Langerhuse

Erosion: 1,1m

Only 1m of erosion after the 81 storm, This site does not appear to have reacted to latent erosion.

4470 – Vejlby

Growth: 0,8m

No erosion under the 81 storm this does not support the latent erosion theory.

5080 – Mærsk

Erosion: 0,6m

No erosion in 81. This profile consists partly of clay but only up to 2m below sea level. This site shows a great deal of potential erosion in the offshore profile but this has not resulted in any significant erosion in this case.

5390 – Vedersø

Erosion: 5,0m

There has been dune erosion at this location however in comparison to the 46m of erosion experienced at transect 5380 approximately 1km north from here the erosion here is relatively insignificant. There is no evidence of latent erosion at this site.

5790 – Bjerregård

Erosion: 2,1m

No significant erosion resulting from the 1981 storm and again no evidence of latent erosion.

4.2 Large erosion events resulting from storms on 26/01/1990 and 27/02/1990.

4360 – Langerhuse

Erosion: 20,0m

The large erosion at this location shows that a large amount of dune material was removed, after the storm events it appears that a small for dune has built up. The erosion in this case was confirmed by aerial photographs to be around 20m. None of this erosion can be explained by latent erosion theory.

4470 – Vejlby

Erosion: 32,0m

This site also experienced 22m meters of dune erosion during 1986 where there was no significant storm. This erosion and that in 1990 cannot be explained by latent erosion.

5160 – 3 km north from Thorsminde Harbour

Erosion: 29,2m

Erosion at this site is calculated at 42m at a height of +4-+5m however this calculation also includes the erosion of a small for dune that accounted for approximately 20m of this erosion. After confirmation from aerial photographs an erosion of 30m was measured at this location, there was also a small amount of nourishment sand removed from this location prior to the erosion event accounting for a calculated 0.2m of the erosion. Latent erosion can offer a part explanation for the dune erosion at this site.

5560 – Klegod

Erosion: 23,2m

Erosion here does not appear to be a result of latent erosion.

4.2.1 Small/non erosion events resulting from storms on 26/01/1990 and 27/02/1990

4170 – 2 km North from Thyborøn channel

Erosion: 0,0m

There is no erosion at this site and the offshore coastal profile appears to be stable so this site is not a candidate for latent erosion.

5190 – ½ km North from Thorsminde Harbour

Advance: 10,0m

There is no erosion on this site despite what appears to be a large amount of latent erosion in the period before the 1990 storms. This is made more surprising when the beach nourishment data is included because this shows that a large amount of sand has been removed from this area equivalent to 10m of erosion yet despite this the dune position has remained the same.

5360 – Husby Klit

Erosion: 1,0m

There is no dune erosion here and there doesn’t appear to be any evidence of latent erosion as the offshore coastal profile appears to be in a stable position.

5620 – 2 km North of Hvide Sande Harbour

Erosion: 0,7m

There is minimal erosion here and no latent erosion in the period leading up to the 1990 storm.

4.3 Large erosion events resulting from the storm on the 9/1/2005

4230 – Thyborøn

Erosion: 31,2m

A dune erosion of 6,1m was recorded here but when taking into account the 25,1m of nourishment in the 3 years prior to this erosion event an erosion of 31,2m is reached. Erosion here does not appear to be a result of latent erosion.

5110 – Mærsk

Erosion: 29,0m

A dune erosion of 7,5m was measured at this location, the 29,0m of erosion is reached when 21,5m of nourishment from the previous 3 years is included. Erosion here does not appear to be a result of latent erosion.

5180 – Thorsminde

Erosion: 33,7m

16,1m of dune erosion has been measured at this location coupled with 17,6m of nourishment produces the 33,7m. Erosion here does not appear to be a result of latent erosion.

5510 – Søndervig (Badevej)

Erosion: 29,1m

22m of dune erosion from spring 2004 to spring 2005. In Autumn 2004 it was established that 3-5m of this erosion resulted after gale force winds. Around 18m of dune retreat actually resulted directly from the January 2005 storm. This is a very large erosion event for a profile that has been advancing for the previous 4-5 years. This is an example where latent erosion can explain a good share of the erosion.

5660 – Årgab

Erosion: 47,1m

10,1m of dune erosion has been measured here despite a large nourishment amount equating to 37,0m.

Erosion here does not appear to be a result of latent erosion.

4.3.1 Small/non erosion events resulting from the storm on 9/1/2005

4510 – Ferring Dige

Erosion: 0,1m

No significant dune erosion has been measured here and there have not been any previous trends in the offshore profile development. No nourishment has been recorded at this location in the previous 3 years.

5570 – Klegod

Erosion: 0,3m

No dune erosion here and no obvious indications of latent erosion however the offshore coastal profile shows many large variations. The dune in this location has been extremely stable since 1988.

4.4 Large erosion events resulting from various storms

4230 – Thyborøn

Erosion: 30,1m (06/11/1985) and 31,0m (12/1/2007)

Large erosion in 1983-85 and again in 2006-08 following the 2007 storm, neither of these erosion events fit with the latent erosion theory. The erosion distance in 2007 also includes a 10,5m correction for nourishment.

4430 – Vrist/Vejlby

Erosion: 56,6m (06/11/1985 storm)

A very large dune retreat after the 1985 storm previous to this in 1984 the dune at this location had also eroded by 18m as a result of storms over the 1984 winter. This erosion has also been recorded in a previous report (DCA, 1991) as an erosion event of particular interest.

4.5 Large erosion events occurring during a time when all storms had a return period of under 2 years

4030 – Porskær North from Agger

Erosion: 29,2m

Large erosion over the winter of 2001-2002, including a correction for 2,9m of nourishment sand. The offshore coastal profile has been advancing in the six years leading up to this erosion event making this example the complete opposite of the latent erosion theory.

4300 – Harboøre Tange

Erosion: 36,4m

This erosion occurred from 1986-88. The offshore coastal profile indicates latent erosion but this is not a completely convincing situation.

4460 – Vejlby

Erosion: 20,7m

21 meters of dune erosion between January 1987 and march 1989, the only storm over this period to enter the top 30 storm record was in February1989 and this had a sea level of just 1.4m above normal. Latent erosion does not offer an explanation for the erosion that occurred here.

4470 – Vejlby

Erosion: 21,6m

Erosion here occoured btween decemeber 1985 and january 1987 over this time there were no significant storms, the offshore coastal profile has been retreating a little before the erosion event so this erosion can be partly explained by latent erosion theory.

5450 – Krogen

Erosion: 22,2m

This erosion occurred from 1996-98 there is a small amount of latent erosion at this location two years previous to this event but this is the only latent erosion that can be seen.

5460 Krogen

Erosion: 20,0m

This erosion occurred over the winter of 2011-12, in the previous 3 years no nourishment had occurred at this location and the beach level previous to this event was reported as being very low. Although there were 3 storms over this winter no especially high sea level was recorded along this stretch of coast. Latent erosion in this case does not offer an explanation.

Chapter 5

Large erosion events summary

In figure 5.0.1 the key information for the most significant storms is presented: water level, return period and duration of the period with water level above the level for a storm with return period 5 years.

	81-storm			90-storm			05-storm			11-storm		
Port	Water level	Return Period	Duration	Water level	Return Period	Duration	Water level	Return Period	Duration	Water level	Return Period	Duration
Thyborøn	1.86	60	-	1.77	22	13	1.89	90	14.8	1.91	100	13.3
Thorsminde	3.11	65	-	3.04	50	15.5	3.16	85	2.8	2.46	5	-
Hvide Sande	2.98	40	6.5	3.04	60	12.5	3.01	50	3.2	-	2	-

Fig. 5.0.1 Storm Sea level, Return period and Duration summary table

5.1 24th of november 1981 – 8 occurrences of dune erosion over 20m.

This storm had return period of 60 years at Thyborøn, 65 at Thorsminde and 40 at Hvide Sande. Due to the lack of water level data for this storm it is difficult to comment on its duration however from the available information it can be seen that in Hvide Sande at least water levels were above a 5 year return period for around 6 hours (Fig. 5.0.1). At this time there was very little in the way of sea defences, wave breakers or beach nourishment. It is noted that 4 of the large erosion events occurred along a section of coast with a natural profile that to this day has had nothing in the way of coastal protection (Vedersø, Skodbjerge, and the 2 sites at Nymindegab).

5.2 26th of January and the 27th of february 1990- 4 occurrences of dune erosion over 20m

These storms had a return period of 22 years at Thyborøn, 50 at Thorsminde and 60 at Hvide Sande. It can be seen in figure 3.3.7 and 5.0.1 that when combined these two storms present a relatively long duration with all 3 measuring locations showing a sea level above a 5 year return period for at least 12 hours. This offers a good explaination for the high number of large erosion events.

5.3 8th of January 2005- 5 occurrences of dune erosion over 20m

In Thorsminde and Hvide Sande this storm has a much shorter duration (Fig. 3.3.7) particularly when contrasted with the high sea level duration in 1990. This is a different story at Thyborøn which had a high sea level duration of over 14 hours. Return periods of 90, 85 and 50 years at Thyborøn, Thorsminde and Hvide sande respectively show that this storm was especially intensive at Thyborøn. It then comes as a surprise that a large erosion event occurred in this year at Søndervig. Søndervig is located between the ports of Hvide Sande and Thorsminde so it was subjected to the least aggressive storm conditing.

5.4 6th of novemeber 1985- 2 occurrences of dune erosion over 20m

Return periods of this storm were 9 years at Thyborøn, 3 at Thorsminde and 9 at Hvide Sande. This storm had a much lower intensity and duration of around 3 hours (Fig. 3.3.7).

5.5 12th of January 2007 -1 occurrence of dune erosion over 20m

A return period of 34 years in Thyborøn but only 2 at Thorsminde and 1 in Hvide Sande. The water level was only raised significantly in Thyborøn and this correlates well with this large erosion event occuring around 1km south from the harbour mouth.

5.6 From a storm with a return period under 2 years – 6 occurrences of dune erosion over 20m

The time when these erosion events occurred is very difficult to define due to the lack of significant storms over this period. It can therefore be concluded that the erosion at these locations is unlikely to have resulted from a single erosion event but rather a long running process over the time span between profile measurements.

Chapter 6

Sand Bar, shore steepening and beach width investigation summary

Note: Supporting graphs for this section can be found in appendix B

6.1 Sand bar prevalence analysis summary

It can be seen that in Årgab, Vrist and Fjalting/Mærsk there has been a significant trend of an increasing prevalence in the number of sand bars. Thyborøn South shows a flat trend with no apparent increase or decrease in the number of sand bars. The trend at Årgab and Fjaltring/Mærsk increase from around an average of 0.5 sand bars per profile in 1977 to around 1.5 now in 2012. Vrist shows a steep increase but from around 0.5 sand bars in 1977 to around 0.8 in 2012. These results give a general indication that sand bar development has been increasing over time and a reduction in erosion experienced on the beach and sand dunes can be consequently deduced. This is however only one of many parameters and its effect on dune erosion could be outweighed or masked by other morphological changes that have occurred over the 35 year time span.

6.2 Profile steepening analysis summary

The steepness of the coastal profile can be seen in appendix B for the previously mentioned 4 sites that have a target set of zero erosion. All of these sites show a slight steepening of the coastal profile from 0-10m depth. For the inner section of the coastal profile from 0-6m depth the trend is very neutral and in two cases shows a slight shallowing tendency. This shows that steepening is occurring further out to sea but is not occurring closer to shore. This offshore steepening although a slow process will have a potential effect on dune erosion as it will encourage later wave breaking resulting in a higher transfer of energy further onto the beach and in high water conditions the dunes.

6.3 Beach width analysis summary

From the 4 investigated stretches it is clear that beach widths have in general been reducing with the exception of Årgab which showed an average increase in beach width of around 8m over the 35 year time span. The most interesting is that Vrist and Thorsminde South show an average reduction over the 35 years of around 25m which is a significant amount considering the zero erosion targets that have been held at these locations. This reduction in beach width is also present as a general trend along the whole coastline. The Reduction in beach width does along with the offshore steepening indicate that there is greater potential for dune erosion at least at these locations.

Chapter 7

Frequency analysis of erosion events

Now that the large erosion events have been checked and validated to be correct a pattern in erosion event size resulting from major storms can be made. Below the frequency distribution of erosion events that resulted from each major storm can be seen. The distributions from 1981 and 1990 (Fig. 7.0.1 & 7.0.2) are very similar with the majority of locations experiencing erosion of under 5 meters and a reducing frequency thereafter with erosion size. When comparing each of the three major storms some variation can be seen with only 1981 and 2005 producing the highest dune erosion values.

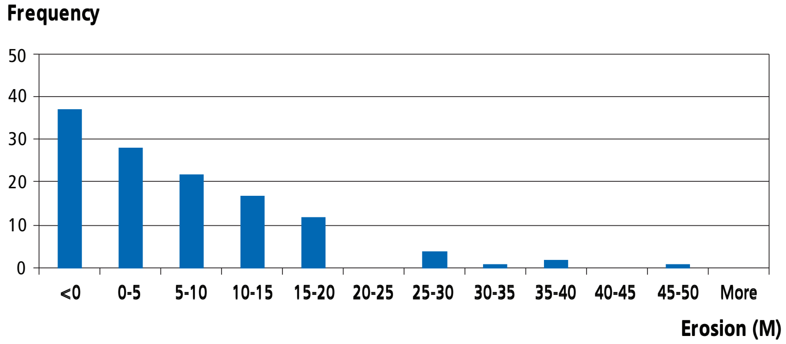


Fig.7.0.1 1981 Storm erosion frequency distribution graph

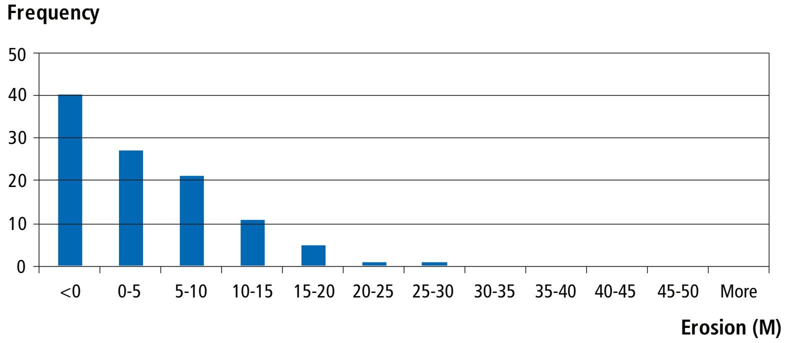


Fig.7.0.2 1990 Storm erosion frequency distribution graph

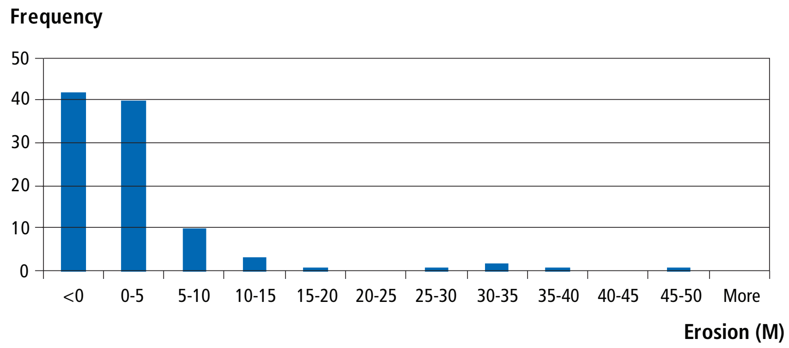


Fig. 7.0.3 2005 Storm erosion frequency distribution graph

Chapter 8

Latent erosion conclusion

All of the above examples have been evaluated to establish if latent erosion can offer a part explanation for such large dune retreats. The selected locations that showed little or no sign of erosion were also assessed to establish if their lack of erosion could be explained by a lack of latent erosion.

From the site by site evaluation it can be seen that latent erosion is rarely regarded to offer the main explanation. However there are a few good examples for instance transect 5510 at Søndervig during the January 2005 storm.

From these results it is clear latent erosion cannot stand alone as an explanation when the risk of large erosion during storm is evaluated for a specific position at the coast. The results show as expected that the reason for large dune erosion is more complex than the hypothesis for latent erosion.

Autonomic erosion conclusion

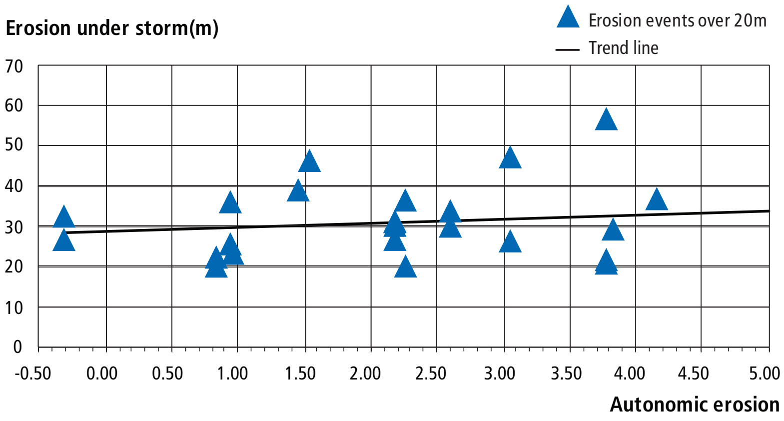


Fig. 9.0 Autonomic erosion against large storm erosion events

The graph above (Fig. 9.0) shows a correlation between the autonomic erosion at each site and the largest erosion occurrences. A slight correlation can be seen however based on the information available here it can be safely concluded that the autonomic erosion rate of a particular location does not offer a convincing solution for the occurrence and size of these large erosion events.

Chapter 10

Denmark’s west coast dune erosion conclusion

From the analysis of all the major erosion events from 1977-2012 it can be established that latent erosion does not offer a satisfactory explanation for these large erosion events. However there appears to be a slight correlation between maximum erosion size and the autonomic erosion at that location. Neither of these theories appear to offer a satisfactory all inclusive explanation for the large erosion events recorded in this report. Erosion has been seen here to vary hugely over a small stretch of coastline for example dune erosion of over 50m has been recorded in certain locations whilst only a few kilometres away little or no erosion has resulted from what would appear to be a greatly similar section of coastline.

The largest recorded dune erosions were 56,7, 47,1 and 46,2m. These were registered respectively after the 1985, 2005 and 1981 storms. The 81 and 05 storms featured significantly raised water levels offering an explanation as to the cause of the large erosion. In contrast to these large storms the largest dune erosion occurred as a result of the storm in 1985 which had a sea level of just a 9 year return period. From this project questions are raised as to the validity of measuring dune erosion and its safety level in relation to a sea level derived return period. This is particularly apparent when viewing the erosion resulting from the storm in the winter of 2011 which featured a sea level with a 100 year return period at Thyborøn. From the west coast profile measurements available no major dune erosions could be attributed to this storm in the Thyborøn area despite its having by far the highest sea level. Of course there are a large number of variables that can influence the erosion experienced along certain sections of coastline. From the results found here sea level and storm duration appear to provide no meaningful correlation in relation to the largest dune erosion events.

Basic investigations into the development of sand bars, beach width and shore steepening under the scope of this project showed that there is a trend of reducing beach widths, and a steepening in the offshore coastal profile, both of which should point to increased erosion which is however not realised at least in the context of the most substantial erosion events. The analysis of sand bars showed that they are increasing in prevalence certainly in the four sites chosen for extra investigation. This could be a potential area for further investigation particularly in relation to sand bar prevalence in the run-up to certain large erosion events identified in this report.

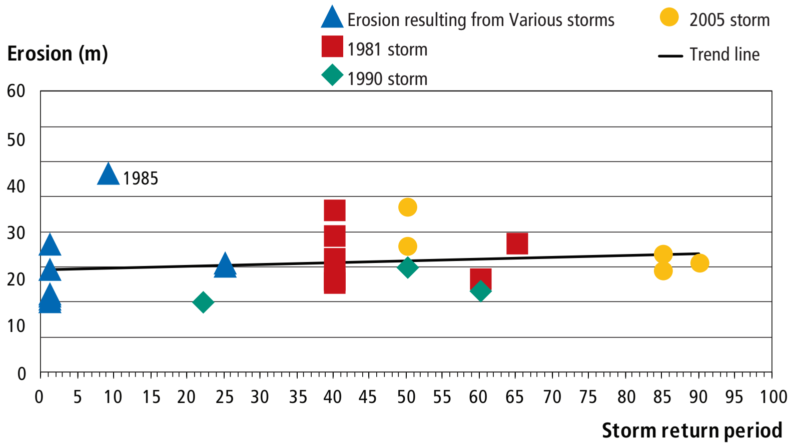


Fig. 10.0 Large dune erosion events 1977-2012

The above graph summarises all of the large dune erosion events that were found and quality controlled within the context of this project. Figure 10.0 above shows the erosion events with a correction for sand nourishment. It can be seen that the large erosion events resulting from each storm are all on a relatively even level with little apparent signs of an increase in erosion in relation to sea level. Sand nourishment can be seen to be the largest significant change that has occurred over the investigated period with a greatly increasing effect in more recent times. In figure 10.01 below the erosion events from figure 10.0 are displayed but this time without a correction for sand nourishment. A large effect can be seen on the more recent erosion events in particular it can be seen that all of the erosion events recorded after the 2005 storm drop down the graph considerably and as a result showing an inverted correlation between storm return period and dune erosion distances. This shows that actual dune erosion that is experienced after significant storms has been reducing despite there being some extremely high sea levels over the last decade.

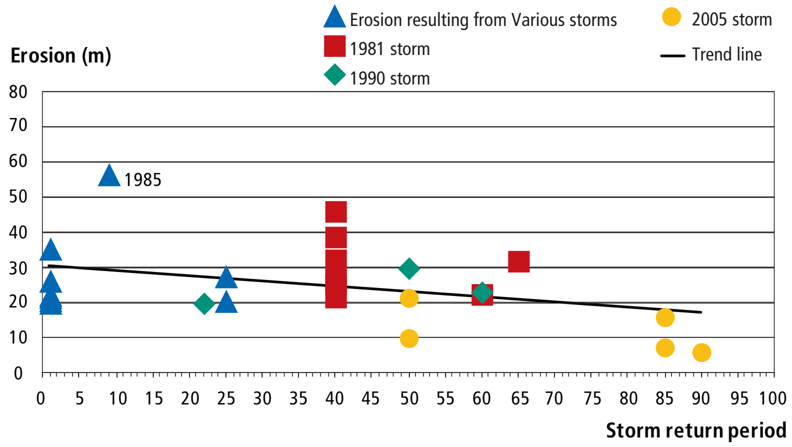


Fig. 10.0.1 Large dune erosion events without nourishment adjustment 1977-2012

As the storm event that produced a sea level with a 100 year return period produced no significant erosion event defining the maximum level of dune erosion that can occur as a result of a 100 year storm event is difficult. From the data available and the analysis used here it is not possible to produce a dune erosion model that is better than the currently used experienced based minimum dune width. It is now apparent that in order to achieve a dune strength value profile by profile analysis is required. To produce a meaningful strength value modelling that allows the inclusion of the numerous micro and macro scale variables that have an effect on the coastal system should be carried out. Inclusion of more local transect measurements may also be required due to the large spacing between west coast measuring transects and the inherent chance of missing specific details or other large erosion occurrences. For this purpose these quality controlled high erosion values found in this report could be used as calibration points in combination with a much larger group of variables in an advanced dune erosion model such as the XBeach model. This provides potential to establish a site specific minimum dune thickness for many of the most critical sections of dune.

10.1 Dune Strength recommendations

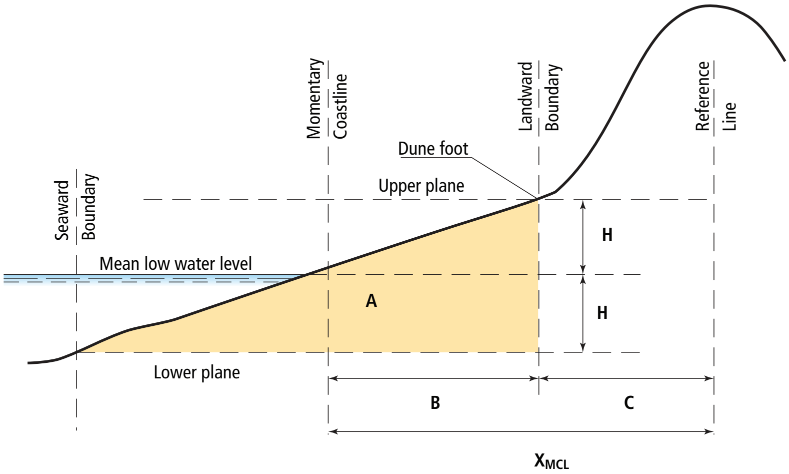
As previously presented the increasing intensity of sand nourishment can be seen to have had a significant impact on the maximum sustained dune erosion. Therefore if a new dune width is to be chosen an adjustment for the amount of nourishment material that is on the beach below the dune should also be included. It can be seen from the analysis carried out here that there has been only one instance of dune erosion in excess of 50m. Without a correction for nourishment the maximum dune erosion that has been experienced over the last ten years has been less than 25m therefore the previously used 40m of dune width remains appropriate if an extra sand nourishment buffer is present.

Chapter 11

Summary of Dutch dune erosion monitoring program

The Netherlands are of great interest in relation to the monitoring and modelling of dune erosion. Due to their coastal structure and low lying geography a high price is placed on dune strength. As is now the case along the west coast of Denmark the Dutch coast is measured in cross-shore profiles. After this measuring is carried out the coastal position is calculated yearly so action can be taken for any coastal retreat that has occurred. Over the longer term the whole dune system is measured and modelling carried out to establish the dunes strength.

In further detail the yearly monitoring uses a Momentary Coastline – MCL. This coastline position is based on a calculation of the volume of sand in the near shore zone (see Fig. 11.0). If H is the vertical distance between the dune foot and the mean low water level the MCL is calculated as the mean position of the profile between an upper plane H above the mean low water level and a plane H below the mean low water level. The mean position is based on calculation of the sand volume between the two planes (Mulder, 2004)



H = Height between dune foot and mean low water [m]
A = Momentary Coastline Zone [m^3]
B = A / 2H = Momentary Coastline position [m]
C = Distance dune foot to reference [m]
X_{MCL} = B + C = Momentary Coastline position + Distance dune foot to reference [m]

Fig. 11.0 Momentary coastline diagram (Mulder, 2004)

This calculation is based on data from the yearly monitoring program JARKUS. In which coastal profiles are measured from the foremost dune to about 1 km in the seaward direction. These profiles are measured in transects with a long shore interval of 250 m. The inshore dune system behind the seaward dune is only measured every 5 years.

It is the objective for the Dutch coastal planning to maintain the coastline at its 1990 position. The 1990 coastline is regarded as the reference or Basal Coastline – BCL. The BCL is defined as the estimated position of the coastline on January 1 of 1990. The BCL position is derived from a linear trend of the MCL positions during the years 1980 to 1989. The position of the BCL is updated approximately every five years to allow for the coastal advance that results from beach nourishment (Rijkswaterstaat, 2011). By periodically updating the position of the BCL the strength of the coastline can be increased or changed so as to meet a future desired strength.

Every year it is examined if the actual coastline - the so-called Testing Coastline TCL - is in the right position compared to the BCL. As for the BCL the TCL is calculated by an extrapolation from the previous 10 years MCL positions. The TCL is compared to the BCL and if the trend of the TCL for the future goes landward of the BCL an intervention has to be considered. The principal intervention procedure in the Netherlands is sand nourishment. When the necessary nourishment volume should be calculated a certain lifespan has to be decided upon. If the lifespan is 5 years the theoretical nourishment volume is calculated as five times the annual autonomous erosion. The Dutch use an active depth of 20 m in the calculations where the Danish Coastal Authority uses 6 m for the North Sea coast. They also use a loss factor which accounts for the uncertainties in the design method. For beach nourishment the factor is 1.1-1.5 and it is 2 for shore face nourishment.

The Dutch coastal condition is published in a yearly report (Rijkswaterstaat, 2011) that is released in december each year and shows the condition of the coastline in relation to the BCL. Measurements from approximately 1450 transects that have a spacing of 250m can be seen in this report where the BCL and current TCL can be seen. Where minus figures appear in this report it can be seen that the TCL has retreated behind the 1990 BCL and at these locations actions will be taken to reinforce the coastline.

11.1 Summary of Dutch dune erosion modelling

Due to the importance of the Dutch dune systems the Netherlands has been a key player in developing methods to assess the strength of sand dunes. As mentioned previously in 1990 the Dutch government decided that the coastline in 1990 should be held and any further erosion should be stopped (Marcel Taal, 2006). The result of this decision is necessary regular assessments of dune strength to ensure that the countries sea defences all conform to an agreed level.

The Dutch approach to measuring dune safety is not based on a pre defined width but on periodic dune modelling every six years (Jaap van Thiel de Vries, 2011). This model named DUROS was developed from flume experiments and allows the coastline to be assessed in as a 1D section (Jaap van Thiel de Vries, 2011). The Duros model uses the shape of the dune profile before a storm, sediment characteristics, wave characteristics, water level and cross shore profile (L.M. van der Burgh, 2007) to calculate the resultant erosion. This model being 1D does not however take into account the long shore aspect of dune erosion such as wave direction and sediment transport so is most appropriate for a completely straight uniform coastline. The restrictions of the DUROS model have been reported (Heijer, 2011) to lead to an underestimation of dune strength on curved coastlines as well as in relation to sediment transport, dune height, bathymetry variations etc. The inherent under estimation in the DUROS model results in the application of safety factors to help account for variations in various long shore coastal properties. The DUROS model has been enhanced for use with curved coastlines by the incorporation of an extra formulation, under this guise it is named the DUROS+ model (Heijer, 2011). Wave incident angles and long shore sediment transport cannot be incorporated into the DUROS+ model (Heijer, 2011) so this offers only part potential to explain the variations in erosion along a coastline. A further development of this called the DurosTA model (Heijer, 2011) offers potential to predict long shore transport and velocities by using a secondary ray with an incident angle to the coastline.

From the Duros model a new 2D model has been developed by (C.(kees) den Heijer, 2008) this model called XBeach (Dano Roelvink, 2008) is a true 2D model and therefore allows the use of many more inputs to provide a better estimation of erosion that can result from varying long shore conditions. The XBeach model has been developed for complicated coastlines where there is much long shore variability both off and on shore. XBeach takes into account offshore bathymetry, wind direction, wave direction, wave period and the varying properties of the coastline in question, if it is curved for example or if there are variations in dune height or structure (Annelies Bolle, 2010). XBeach has been developed as a collaboration from many different sources (Deltares, 2012) and is still being developed and tested further. The XBeach model allows complicated coastal sections to be incorporated into a model and thus offering an alternative to the strength underestimation that occurs through the use of a 1D model where many of the varying long shore differences cannot be included.

There have been studies carried out comparing the performance of the new XBeach model to that of previously tested Duros models (Heijer, 2011). Real storm events have also been modelled using XBeach allowing for a comparison between actual results and the modelled results (Annelies Bolle, 2010). Annelies Bolle et.al's report concluded that the XBeach model performed equally as well as the Duros model however it had the distinct advantage that it allowed the extra erosion occurring on a curved coastline to be modelled.

Currently XBeach appears to offer a good approach to modelling a complex coastline and incorporating variations in a multitude of different factors to offer a route to explaining and ultimately predicting where and why large erosion events occur. However it may not necessarily prove the most helpful tool in explaining why large erosion events can occur over a period where there has not been a large storm. The XBeach modelling necessitates the input of a storm event to model an erosion event however this is extremely difficult to model when the precise sea and weather condition were not known at the time the erosion even occurred.

11.2 Demands and availability of XBeach

XBeach is freely available via www.xbeach.org (Dano Roelvink, 2008) and is a working model that is being regularly updated so its effectiveness should only improve with time. The downside to having a more complicated model is that there is a greater data requirement. A detailed measurement of the offshore bathymetry would be required. For modelling a specific storm a record of wave conditions would also be required along with wind conditions, water level and an accurate model of coastline and dune system.

Chapter 12

A proposal for the future handling of the coastal retreat and high water safety at the Lodbjerg - Nymindegab stretch

12.1 Introduction

The analyses of the dune retreat during storms since 1977 has shown several much larger retreats than the 30 m which has up till now been used as an estimation for the maximum dune erosion. From the analyses it has also been concluded that it is not possible to foresee large dune erosion based on the hypothesis of latent erosion. The hypothesis was - at least in the form it has been used - based on a two-dimensional way of looking at the coast. The connection between impact and coastal development is much more complex and the connections that have to be analysed are in three-dimensions with the parameters on either side of a coastal profile requiring inclusion. There is still potential to be able to foresee and predict large scale dune erosions, just that the methods for making such predictions have not been previously available. This fact should be part of the background for the future handling praxis for the coastal stretch.

The Dutch method with a basal coastline BCL as the ultimate limit for the coastal retreat represents a solution to the Danish problem of starting from scratch for every five year agreement period. The Danish method does not include the possibility to handle the situation where a section of the coast in previous years has advanced or retreated more than had been the objective for the section. Because there is a landward limit for the position of the coastal profile at each section of the coastline it makes obvious sense to start out by finding this position and then from this building up the coastal monitoring program.

12.2 A short presentation of the coast and the present handling system

The 110 km long section of the coast between Lodbjerg and Nymindegab is generally retreating if there are no nourishment carried out. From figure 12.2.1 it can be seen that the so-called autonomous retreat would be 6-8 m/year north of Thorsminde and between 1 and 4 m/year along the largest part of the rest of the stretch.

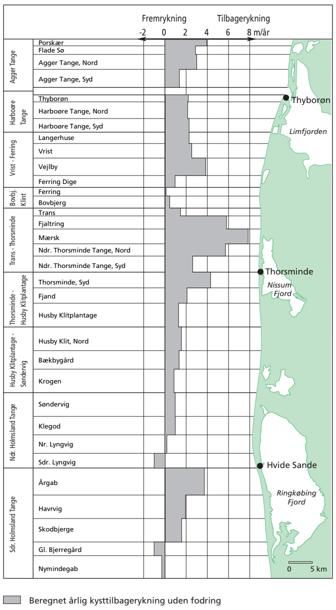


Fig. 12.2.1 The annual coastal retreat rates (the autonomous retreat) without nourishment

In figure 12.2.2 the topography in the hinterland is shown. There are large low-lying areas and the barrier between these areas and the North Sea is narrow. Therefore inundation is a potential risk if the barrier breaks in a storm.

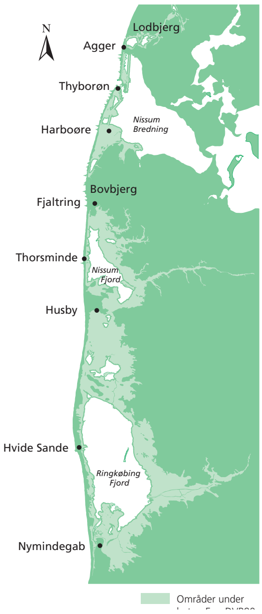


Fig. 12.2.2 Low-lying areas in the hinterland

So the challenges are the coastal retreat and the risk of inundation. Therefore the objective is to stop the retreat where houses and infrastructure are close to the coast. The objective for the retreat is shown in figure 12.2.3 It appears that the retreat should be stopped or reduced along most of this stretch. Besides the objective for the coastal retreat the high water barrier should also be kept at a level where it is able to withstand a storm with a water level of a 100 years return period. Outside Thyborøn the barrier should be able to protect against a 1000 year water level.

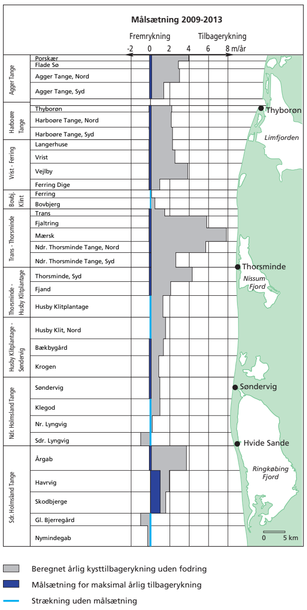


Fig. 12.2.3 Objective for maximal coastal retreat in the period 2009-13 (shown in blue)

The objectives are met with an annual nourishment of about 2 Bn. m³ of sand. Until 2003 the nourishment level was 3 mill. m³. 83 sea groynes between Fjaltring and Agger, 88 low breakwaters at 1 m depth and 25 km of concrete block revetment also make up part of the coastal protection.

12.3 Defining the basal coastline position BCL

Along the North Sea coast annual profile surveys are carried out in transects with an interval of 600-1000 m, see figure 3.1.1. The position of the basal coastline BCL shall be determined in these transects like in the Netherlands. However, because of the narrow dune barrier it is not possible to take the BCL-position on for instance January 1, 2012 and use it in the future. Another difference is the much larger interval between transects in Denmark. Therefore a BCL also has to be defined at the stretches in between the surveyed transects.

The first question is which part of the profile should be used in the definition of the BCL. A suggestion would be to use the part of the profile between +4 and -6m, because it is already used in many of the analyses and reports the Danish Coastal Authority has prepared over the years. It is often denoted “the inner part of the profile” and it is advantageous that it includes the whole bar zone. If the Danish part of the profile should be parallel to the Dutch the profile between +3 and -3m or maybe between +4 and -4m should have been used. With the use of the profile between +4 and -6 it is in fact the position of the -1m depth contour which is determined and not the coastline as in the Netherlands. A new abbreviation could be BCP for Basal Coast Position.

The method to define the BCL is naturally dependent on the specific type of coast. Therefore some typical coast examples will be described below.

12.3.1 A coastal section with revetment

When the revetment was designed a very low and steep beach was used in the calculations. Often a beach level of 0m at the foot of the revetment and a beach slope of 1:33 were used, there are of course deviations from this general rule. However, there is no reason for using these design conditions directly in the calculation of the BCL. A beach level of +1m and an average beach slope could be a good choice.

12.3.2 A coastal section with a narrow dune barrier

To withstand a storm with a 100 year water level the dune barrier should have a certain minimum width W. Because the former topographic maps based on aerial photos only had height contors pr. 2.5m the 5m these contor was used to control the width of the dune. When the safety level is classified as 100 years the corresponding water level should not result in water flow over the lower parts of the dune. The required dune height therefore also takes into account the wave set-up experienced under such a scenario. The dune width W should therefore be measured at or above these heights.

To define the BCL in a cross shore transect the required dune width (W) is measured from the inner height contour at the dune. This gives a point that is either inside or outside the dune. The BCL is then established using the existing coastal profile’s shape by virtually moving the profile forwards or backwards so that it lines up with the required minimum dune width (W). If the profile at the time of establishing the BCL has been significantly altered after a storm for example a previous, more natural profile shape should be used within the same process.

12.3.3 A coastal section with a wide dune barrier or high hinterland

If there are no houses or infrastructure close to the coast the BCL could be placed far inside the dune face. However, if the section of coast is located between sections where it is necessary to stop coastal retreat then the BCL should be placed according to the BCLs in the neighbouring transects. In this way it is possible to maintain an orientation of the coast like the present.

When the BCL is defined in all the surveyed transects there are still spaces between the transects that require definition. To keep all the information organized it is probably necessary to define fixed transects here for instance with intervals of about 200 m.

When these new transects are determined the method to define the BCL is in principle the same as for the surveyed transects. To obtain profiles for the calculations it will be necessary to transfer the beach and bathymetric profiles from the neighbouring surveyed transects and combine them with the dune profile in the specific profile.

12.4 The annual test of the actual coastline position compared to the BCL

Every year each transect should be surveyed. In addition to this more data could be provided by laser scanning's perhaps every second year. Also land surveys at short critical parts of the coast and simple handheld GPS-positions for the dune edge could be carried out.

All the available data should be used to calculate the most correct actual coastline position TCL. In the surveyed transects the measured profile is used. To avoid the effect of short time fluctuations it could be an idea like the Dutch to look at the trend for the previous years. In the new transects between the surveyed transects the best available data should be used in combination with the bathymetric profile from the surveyed profiles. If new information or data is suddenly available a fast up-date should be carried out.

12.4.1 Organizing the work

The basis for the work with the definition of the BCL and the annual control of the TCL compared to the BCL should idealy be carried out within a GIS system where it is possible to organize all the data and the results from the different calculations.

It is probably best if only two or three people are allowed to make corrections in the system. It is clear that these people will have to be meticulous in their work.

The actual status for the coast should be accessible all the time for everybody in the Danish Coastal Authority. Some kind of reporting that is accessible on the home page would also be worth to consideration. The Dutch publish a report with the status for their coast every year in December (Rijkswaterstaat, 2011). The same system could be used here. If the level of the reporting is kept at a realistic level this would also be of good value to the public. The calculations have to be done nevertheless and will simply require presenting in a public friendly way.

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