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# Beach Restoration and Erosion Protection on the Inner Danish Coasts – A Case Study

Elisabeth Baden[1] and Jesper Aarosiin Hansen[2]

**Abstract**

Introducing hard structures to a sandy coast will inevitably disturb the equilibrium condition and cause erosion. Any initiative involving hard coastal protection should therefore, if it cannot be avoided altogether, come with a sand nourishment scheme. Typical challenges arise when there is a clash of interests, such as economic and recreational. The beach along the community of Faxe Ladeplads is an excellent example for such a conflict. Ramboll has presented different solutions to combat the erosion, with and without hard coastal protection structures. Ramboll chose to recommend the beach nourishment scheme as the preferred solution, with the possibility of combining it with a new harbour breakwater that would improve the flow patterns in the area significantly. It could furthermore be shown that by establishing a beach and hence decreasing the water depth, wave overtopping reduced significantly under a storm situation as wave breaking prevents the larger waves to arrive at the revetment and adjacent road.

**Key words:** sediment transport, beach restoration, erosion protection, coastal management

## 1. Introduction

The moderately exposed coastline framing the community of Faxe Ladeplads is subject to chronic erosion. The once popular tourist destination has lost its beach leaving the coastal road, which is the community's only connection to the city centre, at the mercy of the waves. Figure 1 shows the location of the harbour, beach and upstream groin. The municipality hired Ramboll to find an affordable solution to reclaim the beach and reduce wave overtopping onto the road.

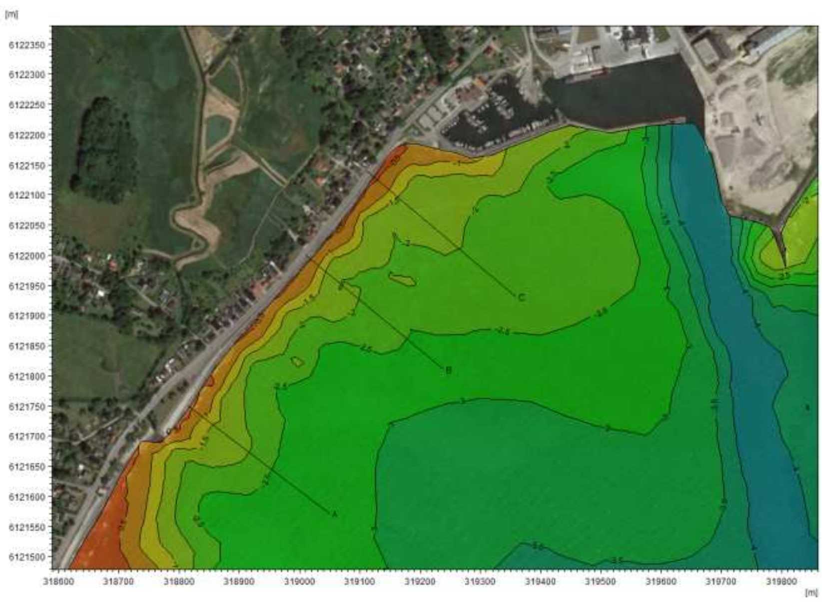

Figure 1. Satellite picture of study area with existing bathymetry map showing location of three beach profiles used to plan the nourishment scheme.

[1]Ramboll Denmark, Copenhagen, Denmark. eab@ramboll.com
[2]Ramboll Denmark, Copenhagen, Denmark. jan@ramboll.com

## 2. Hydrodynamic modelling

The initial steps in quantifying the erosion problem involved assessing the wave and current conditions to which the beach is exposed and estimating the yearly sediment budget. The proposed solutions were then modelled in the Mike 21 program for an average year (2005), consisting of a hydrodynamic (HD) and a spectral wave (SW) model. The HD model was run with an additional sand transport module (ST) in order to capture the sediment transport patterns. Details of the scientific documentation can be found in the documentation on (MikePoweredByDHI.com).

### 2.1. *Wave and wind data*

In the Baltic Sea, and especially in the sheltered areas around the inner Danish coasts, waves are mostly wind-driven. The highest wind speeds are associated to the westerly directions, as the wind rose shows; see Figure 2. The bay is sheltered from the large waves associated to these wind speeds from the west, but yet the beach has suffered severe erosion.

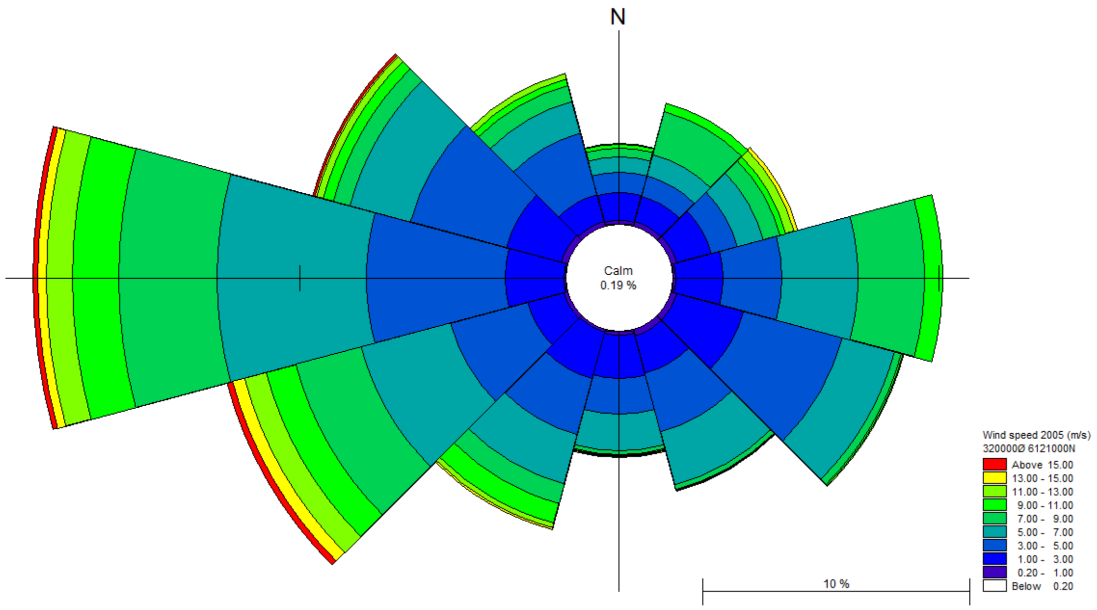


Figure 2. Wind rose at Faxe bay during an average year (2005).

The main driving force for sediment transport along the beach is waves approaching the beach at an angle. Most of the erosion at the beach at Faxe Ladeplads happens during conditions where the wind blows from directions 60, 90 and 150 degrees, which prevail around 22% of the time. The wind time series for the year 2005 has been used as input to both the HD and SW models.

The wave rose is shown in Figure 3. It becomes clear that the majority of the waves approach from directions 90, 120 and 150 degrees north. Waves from directions 90 and 150 approach the beach at an angle and cause longshore sediment transport while the largest waves come from 120 degrees and cause cross-shore transport, moving sediment away from the beach into deeper water.

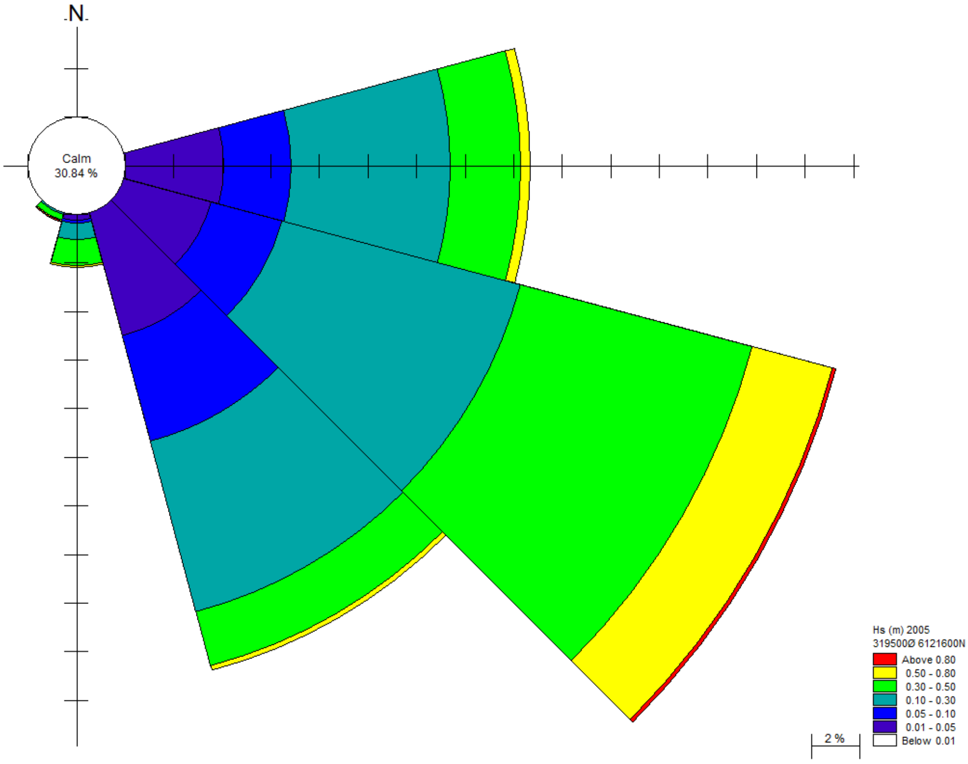


Figure 3. Wave rose from a point to the south-east of the beach during an average year (2005), water depth 3 metres.

### 2.2. *Bathymetry*

In order to get an accurate picture of the existing water depths, Ramboll carried out a single beam survey at the site in August 2016. The survey path is indicated in Figure 4.

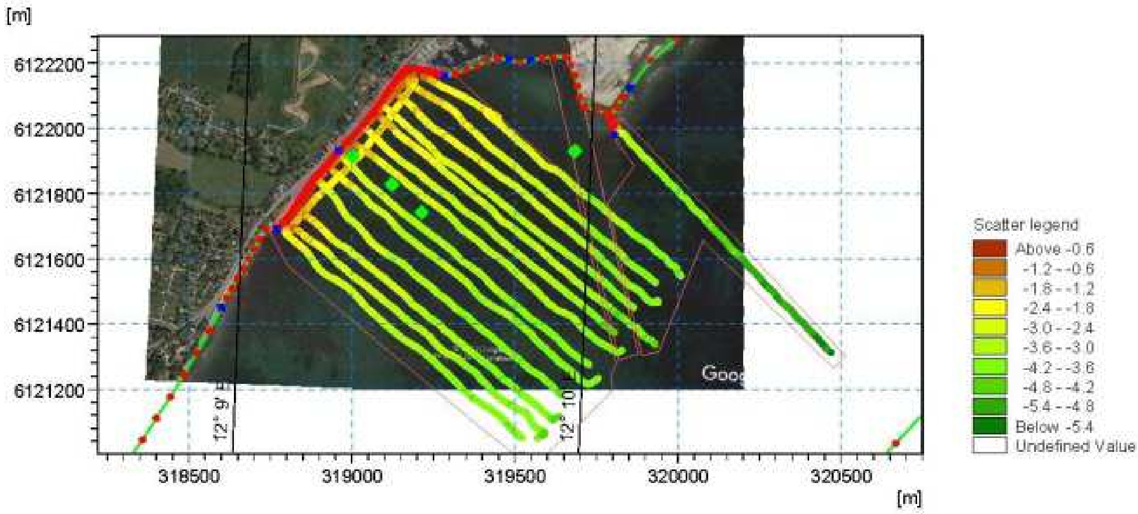


Figure 4. Path of the 2016 bathymetry survey covering the entire area in front of the beach and a cross section upstream.

The water depths were used as input to the numerical models. The existing conditions were simulated to tune the model's performance to the sediment behaviour expected at the site.

### 2.3. *Sediment*

Sediment samples were taken in the entrance channel to the harbour during the dredging operations. Several times a year, the channel is dredged for sand and seaweed that accumulates in the channel. This happens due to the southward current forming a vortex after passing the upstream groin and entering the shallow calm waters south of the harbour. The sediment grain size was analysed and the median grain diameter was found to be in the range of $d_{50}$=0.15mm.

The volumes dredged from the entrance channel during the past years were 24.250 $m^3$ (2013), 20.680 $m^3$ (2014) and 20.580 $m^3$ (2015). The dredged material is a mixture of sand and seaweed, which is abundant in the waters of the Baltic Sea, and which makes the material unsuitable for beach nourishment. The net sediment transport direction is south; however, during weather conditions with southerly winds, considerable transport towards north is seen. It had to be assumed that the entrance channel is filled with sediment settling from both directions. These conditions made it difficult to assess the actual sediment budget along the coastline and didn't allow for actual calibration of the sediment transport model. However, the numbers could be used as a guideline to do sanity checks of the model.

### 2.4. *Water levels*

The inner Danish coasts do not experience significant tidal variations. However, water levels can fall and rise more than one meter due to surge effects caused by heavy winds. The statistics of water levels have been assessed by the Danish Coastal Authority for a large variety of coastal towns throughout the country (Danish Coastal Authority 2012). The extreme water levels applied in the calculations for wave overtopping are summarized in Table 1. These water levels include a 0.25m contribution of long-term sea level rise due to climate change according to the latest IPCC report (IPPC 2013).

Table 1. Extreme water levels at the site, including long-term sea level rise due to climate change, see Danish Coastal Authority (2012) and IPPC (2013).

| Return period (y) | Water level (m) |
|---|---|
| 100 | 1.75 |
| 50 | 1.69 |
| 20 | 1.61 |
| 1 | 1.29 |

Water level variations have been included as a boundary condition for both the SW and HD model.

## 3. Model results

The results of the SW model served as input to the HD model, with the waves being the main forcing for the sediment transport module (ST).

### 3.1. *Joint probabilities*

The model results were also applied to understand the statistical correlation between environmental variables. Figure 5 shows a scatter plot of the wind speeds vs the significant wave heights. It can easily be concluded that the majority of the waves are wind generated, and extremes hence can be considered well correlated.

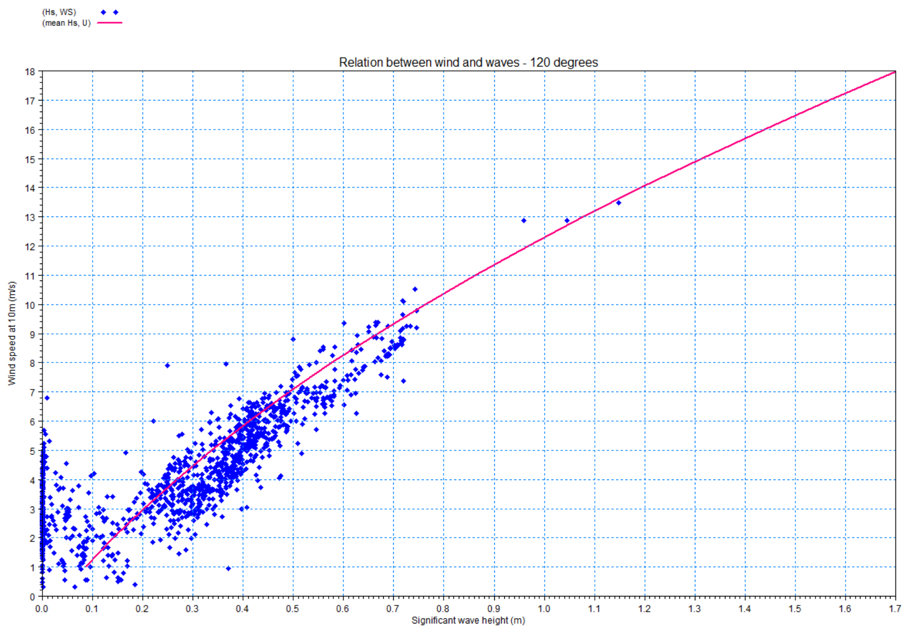


Figure 5. Correlation of wind (y) and wave (x) data during an average year (2005). Extremes are correlated as well as average waves and wind.

Another interesting correlation is the joint occurrence of waves and water levels. Despite both parameters being a function of the wind, the effect of the wind on the water levels is in the Baltic sea often observed with a certain delay. Figure 6 shows the water levels plotted against the significant wave heights, which illustrates that the correlation for average conditions is generally poor. However, large waves seem to depend on a high water level, while high water levels can occur at any time and are not always seen in combination with large waves.

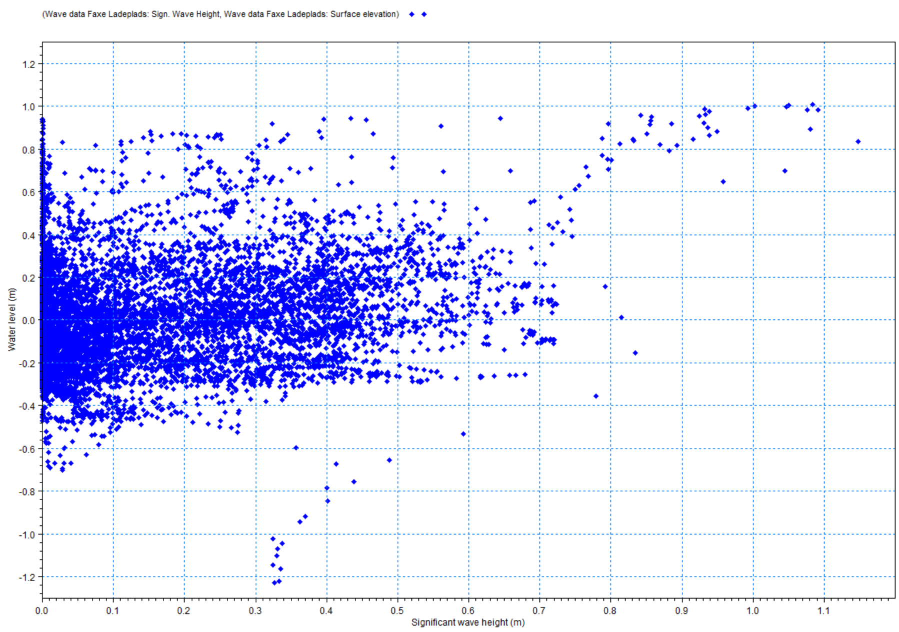


Figure 6. Scatter plot of waves (x) and water levels (y) during an average year (2005). Extreme water levels can occur without extreme waves, but wave extremes only occur at high water levels.

### 3.2. *Flow patterns*

The flow pattern proved to be very unfortunate for the harbour entrance channel (indicated in Figure 1) as the leeside effects of the upstream groin cause the sediment to settle in the calm area south of the harbour, directly into the entrance channel. The vortex caused by the groin is clearly visible from the simulated flow pattern shown in Figure 7. Besides the velocity vectors, the figure also shows the cumulated change in bed level with red colours indicating erosion and blue colours indicating deposition.

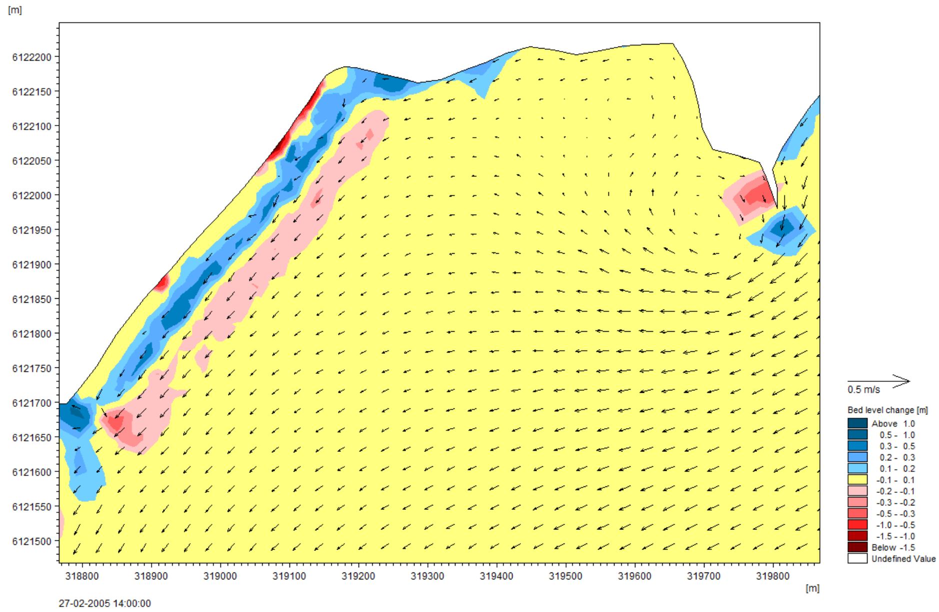


Figure 7. Simulated flow pattern in area south of harbour during strong easterly winds. Cumulated bed level change is also depicted.

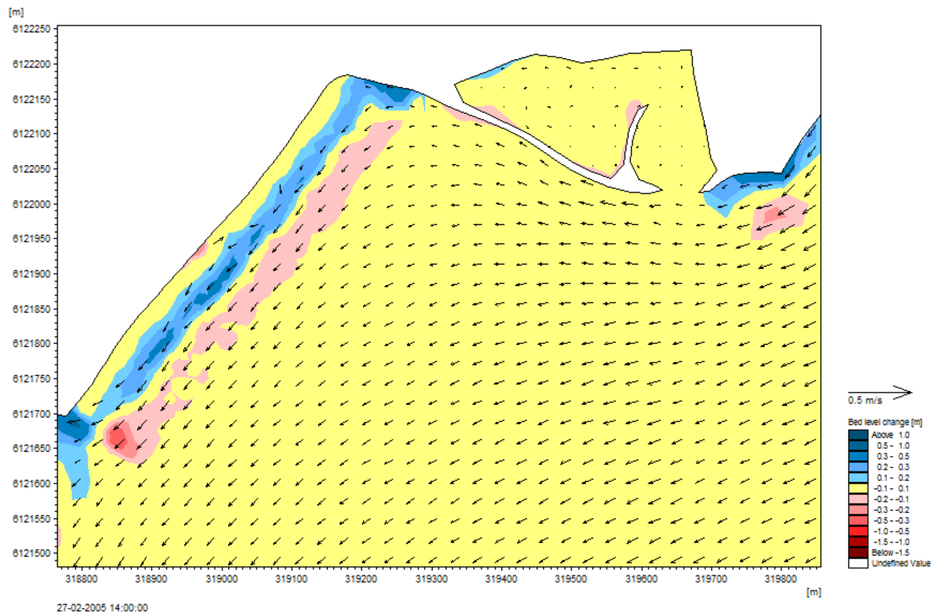


Figure 8. Simulated flow pattern in area south of harbour during strong easterly winds. Cumulated bed level change is also depicted.

A new harbour breakwater that can help bypass sediment was modelled as an option for a future harbour extension and to assess the effect on the nourished beach. The result is shown in Figure 8.

The beach nourishment has been implemented in the bathymetry for both scenarios shown in Figure 7 and Figure 8. The results show that the beach remains largely unchanged after one year of simulation, both for the situation with and without the new breakwater. The new breakwater can hence be regarded as a hard structure that does not have any adverse effects on the nourished beach.

### 3.3. *Beach solution*

Figure 9 shows the beach nourishment solution at the beginning of the simulation period while Figure 10 shows the bathymetry after exactly one year of simulation time.

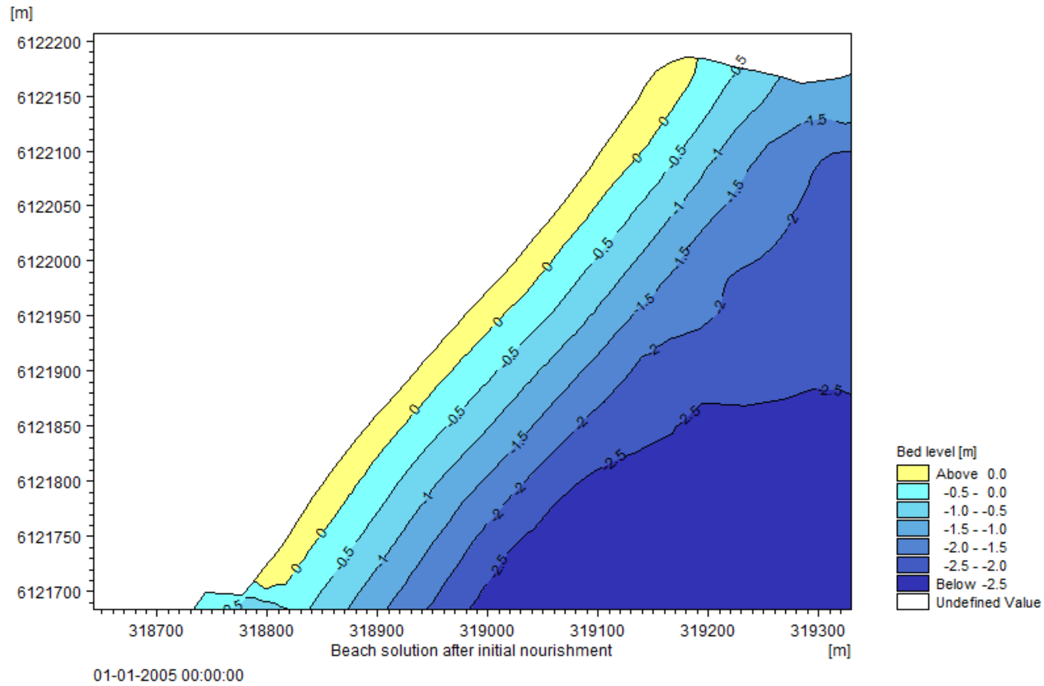


Figure 9. Beach nourishment in the beginning of the simulation period. Beach slope approximately 1:50.

The beach was designed to be nourished with a sand resource of median grain diameter $d_{50}$=0.3mm. The grain size is chosen larger than the existing sand for stability reasons but not too large, with the intention to keep the beach attractive for recreational purposes. The beach is designed with a top elevation of 0.5m above sea level and a gentle slope of 1:50 according to the recommendations for beach stability given in Mangor (2004). This geometry led to a total volume of around 60.000$m^3$ of sand to be sourced offshore and transported to the beach for initial nourishment.

The new beach proved to be reasonably stable during the average simulation year, with minor erosion in the southern part of the beach.

The beach has been shown to be rather sensitive to the weather conditions and especially wind directions, which needs to be kept in mind when interpreting the modelling results. Had a different year with different weather conditions been simulated, the picture might look slightly different as well. Similarly, it needs to be kept in mind that the picture shown in Figure 10 is only a snapshot of a situation, and should be interpreted with care.

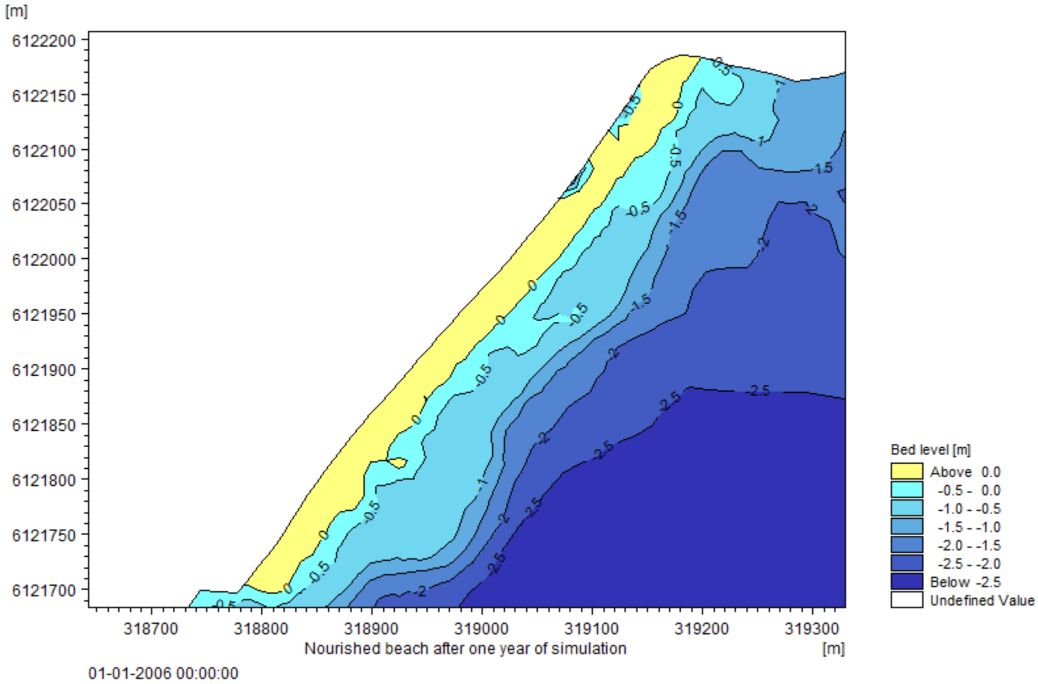


Figure 10. Nourished beach after one year of simulation.

In order to formulate the appropriate maintenance recommendations, the sediment discharge has been extracted from the model. Figure 11 shows the cumulated discharge at two cross sections A and B (locations indicated in Figure 1), revealing that around 5000m$^3$ sand has left those cross sections during the year 2005 (negative discharge is to be understood as going to the south).

Regular sand nourishment will be required and possible sources could be identified in reasonable distance from the coast. The distance will determine the cost of the sand resource.

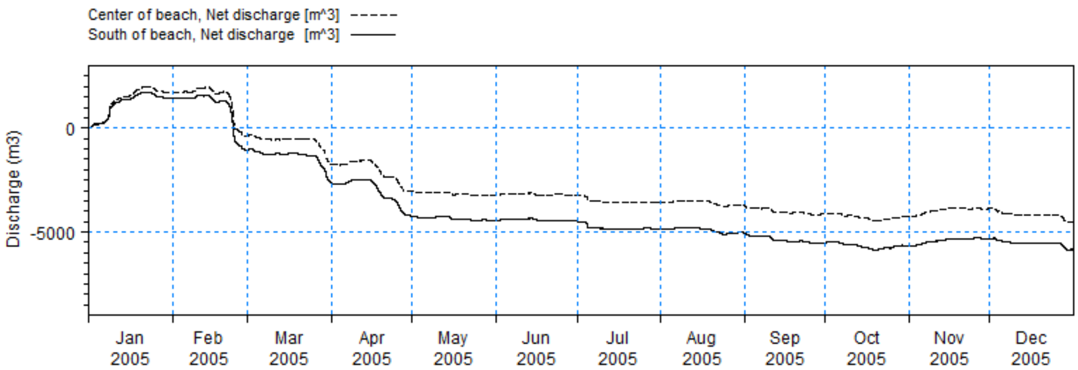


Figure 11. Net sediment discharge at two cross sections A (South of Beach) and B (Center of beach). Negative discharge = going towards south.

It should be noted that the recommendations for beach stability (Mangor 2004) apply for open coastlines without disturbance from other structures. The equilibrium slopes achieved at Faxe Ladeplads might deviate from these recommendations as the beach section is heavily influenced by the harbour groin in the north and the small historic groin to the south.

## 4. The beach as a coastal protection feature

Beach nourishment or existing conditions, both situations will experience the same extreme water levels in the future. The same freeboard will apply between the still water level and the storm barrier along the road. However, the water depth in front of the revetment (and storm barrier) will be smaller with an elevated beach. As a consequence, the large waves that used to cause overtopping will be filtered and break at a distance to the shore. Ultimately, the beach alone will be able to reduce the volumes of water overtopping the storm barrier.

A relative comparison of the overtopping volumes has been performed using the approach in EurOtop (2007) and looking at four different scenarios; the existing situation under high water level with 1 and 50 year return period and the beach nourishment situation under the same extreme conditions. The parameters and results are summarized in Table 2.

Table 2. Relative comparison of overtopping volumes during two different high water scenarios and for the existing situation and the nourished beach.

| Parameter | Existing situation | Beach solution | |
|---|---|---|---|
| Water level (m) | 1.7 | | **50y high water level** |
| Total water depth (m) | 2.2 | 1.2 | |
| Max wave height $H_b$ (m) | 1.7 | 0.9 | |
| Max $H_{m0}$ (m) | 1.1 | 0.6 | |
| Freeboard (m) | 2.4 - 1.7 = 0.7 | | |
| Overtopping (l/m/s) | 32 | 1 | |
| Water level (m) | 1.0 | | **1y high water level** |
| Total water depth (m) | 1.5 | 0.50 | |
| Max wave height $H_b$ (m) | 1.2 | 0.39 | |
| Max $H_{m0}$ (m) | 0.80 | 0.26 | |
| Freeboard (m) | 2.4 – 1.0 = 1.4 | | |
| Overtopping (l/m/s) | 0.06 | 0 | |

It can be confirmed that the existing situation will experience significant overtopping in case of an extreme event with large return period. The beach solution manages to reduce the volumes by almost 100% in both high water level scenarios.

## 5. Beach nourishment scheme

The nourished beach will have to be inspected each year after the storm season and certain criteria need to be identified that will require a maintenance nourishment to be carried out. A beach will always reveal its submerged profile and steepness as the slope continues on the exposed part of the beach. Hence, the beach width and/or the top elevation could be indicators for the required action to be taken.

In addition to the yearly inspections, the beach should be visited after an unusually severe weather event in order to assess the damage done.

Figure 1 showed the existing bathymetry of the site, which revealed a particularly steep beach profile between the sections A and B. Section C runs through the northern end of the beach, which with its sheltered conditions seems to experience less erosion than the southern end between section A and B. It is hence recommended to place special focus on this area during the regular maintenance nourishment.

## 6. Summary and conclusions

Establishing hard coastal protection structures such as groins or revetments will inevitably increase the erosion problem because the beach will become deprived of its natural sediment buffer. The beach is no longer able to balance its sediment deficit by “eating” from the land and its existence becomes thus dependent on the sediment sources from the sea. Regular sand nourishment should therefore follow any hard coastal protection measure, should the coastal features remain intact. If nourishment remains a necessity to avoid the coast suffering the long-term consequences, the alternative to hard structures may in many cases be an intelligently planned sand nourishment scheme.

## 7. Future work

The beach solution has been simulated under normal weather conditions to assess the average erosion that it experiences. Further modelling should also examine the behavior of the beach under extreme storm conditions.

A detailed beach design should specify the nourishment volumes - both for the initial nourishment but also for the regular maintenance nourishment - more precisely. Furthermore, a detailed monitoring and maintenance scheme should be set up and milestones for inspections scheduled.

## Acknowledgements

I would like to thank the municipality of Faxe, for sharing this case study with the global coastal community.

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