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A MODEL BASED STUDY OF SAND NOURISHMENT DECAY

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Abstract

In the present paper a morphological 2DH model combined with a parameterized cross-shore distribution mechanism is applied to the case of sand nourishments on an eroding coast. Schematized representative long straight coasts with representative water level, wave, and profile characteristics are synthesized from data for three typical areas along the Danish coast is considered – a highly exposed, a moderately exposed and a less exposed coast. Sand nourishment formations with different volumes, lengths and locations in the profile are added and the morphological model is run for the different combinations. Examples of morphological responses are presented and discussed in terms of cross-shore and longshore processes. All results are integrated and analyzed for total sand volume loss/decay in the protected area and diagrams for the decay of relative nourishment volume for the three typical coastal areas are given.

Key words: Erosion, sand nourishment, longshore sediment transport, cross-shore sediment transport, morphodynamics, shoreline modelling, wave exposure

1. Introduction

Sand nourishment is a method used for coastal protection where concerns about erosion and a wish for general landscape preservation coexist. As a mean to protect the coast, sand nourishment utilizes the forces of nature in the sense that sand is a natural component of the coastal morphology. In the case of general ("chronic") erosion the coast will be protected to the degree, nourishment can keep up with the erosion taking sand away from the area (typically due to gradients in the longshore transport). At the same time, extra sand in the profile will have a protecting effect on the upper parts of the profile. Sand morphology is dynamic and is constantly being rearranged by waves and currents and the protecting effect will hence evolve along the lines of the morphological development. Sand nourishment constitutes thus both a protecting effect and a perturbation to the coastal system that allows the coastal dynamics to mold and incorporate the disturbance in the natural system by its own means. In the present study we wish to quantify – by adopting newly developed numerical modelling techniques for coastal morphology (Kærgaard & Drønen, 2015; Drønen et al. 2011; Kærgaard et al. 2014) - the main effects of sand nourishments and the dynamic behavior of the nourished morphology. This includes how the sand is moving across the profile and alongshore, and how the protecting effect of the given morphology evolves over time. The overall aim of the study is to obtain order of magnitude central estimates of the decay of nourished sand under the influence of combined cross-shore and longshore processes, and to suggest diagrams for designing sand nourishments on typical beaches in Danish waters.

2. Representative conditions

The decay of a given sand volume introduced to the coast depends on the nourishment's dimension (length in alongshore direction and volume), its original location in the profile (dune foot, beach, shoreface), the wave climate and the (temporal) storm surge patterns. In order to systemize and understand the principal

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components in the nourishment decay process a simplified geometry is set up by introducing a long straight coast with a typical yearly averaged profile to represent the background average morphology. Three levels of wave exposure are chosen that represent three typical Danish areas (see Figure 1). For these three areas 30 years of high quality hindcast data is used to construct a most typical yearly wave climate in the three cases – highly exposed, exposed, less exposed. Storm surge data are constructed by observing the high water level marks in the coastal profile originating from extreme high water levels and waves.

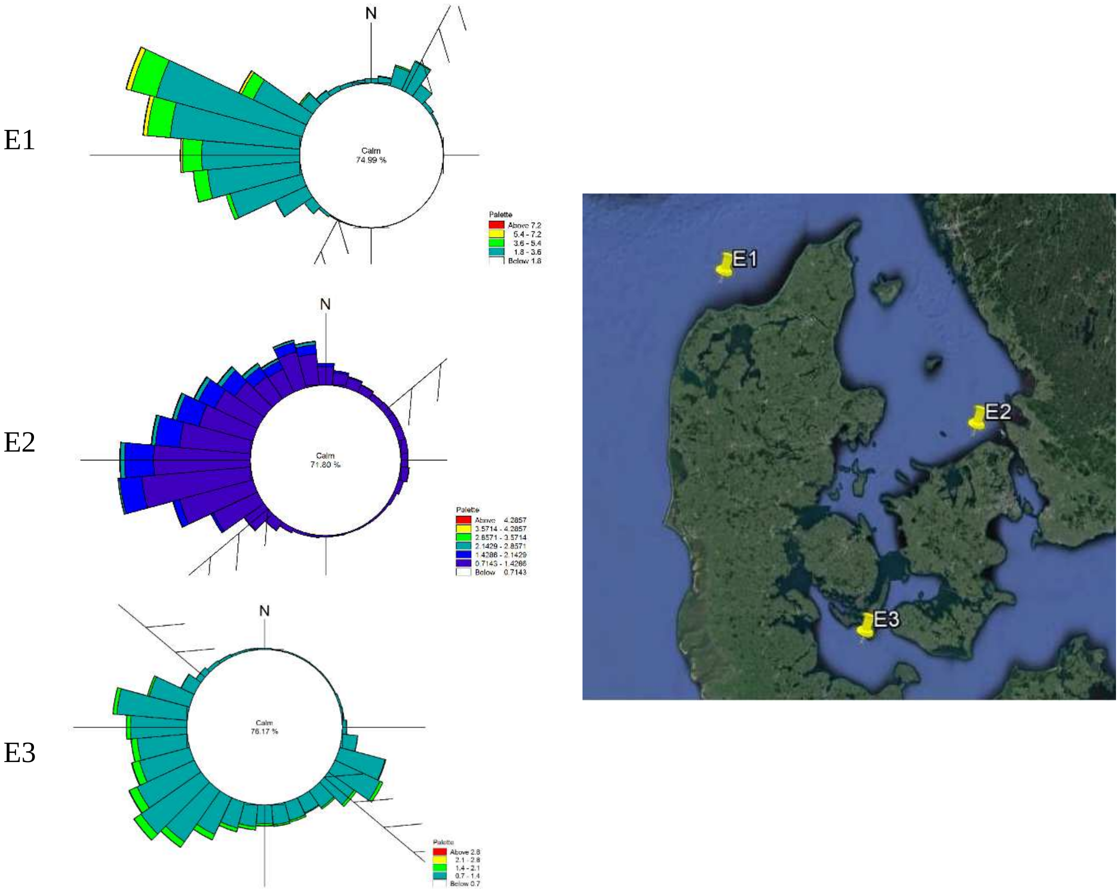

Figure 1 Three representative Danish coastal areas. High (E1), moderate (E2), low (E3) exposure

In the present model approach we will use a 2DH morphodynamic model for a relatively large number of cases. It is not computational efficient to use the 30 years of hindcast data directly as input and simplifications in the wave climate are therefore introduced. Time series that represents the overall mean variability and mean statistics are constructed. In Figure 2 the resulting constructed time series are shown. By adopting these time series it was checked - by using a model for littoral transport LITDRIFT - that the overall longshore transport characteristics are the same as if the complete time series was used. In Table 1 the resulting net littoral drift for the three areas are given.

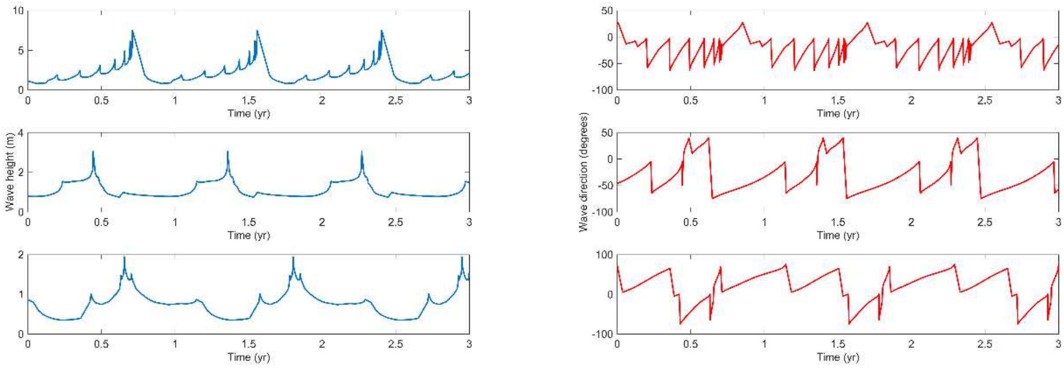

Figure 2 Constructed time series for wave heights (left) and wave angles (right) for the three representative areas. High exposure, top. Moderate exposure, middle. Low exposure (bottom).

Table 1 Typical littoral drift values to represent the three exposure degrees

	High exposure	Moderate exposure	Minor exposure
Net transport	550.000 m^3/yr	60.000 m^3/yr	-15.000 m^3/yr

Tidal variations are very small compared to the storm surge component in these areas and are therefore disregarded in this study. The water level due to storm surge is assumed to correlate with the wave height as

$$\boldsymbol{S = KH}$$

Using a typical value of the dune foot height in the given area as the highest wave correlated storm surge water level over the year, i.e. using the maximum wave height at the given locations, we obtain the correlation factor as

$$\boldsymbol{K = \frac{z_{foot}}{H_{max}}}$$

This method does not take into account the more episodic parts of the water level fluctuations over the year – i.e. the part not directly correlated to the wave height. By only taking the part actually correlated with the wave height into account we focus on representing the events where erosion in the upper parts of the profile and wave driven alongshore currents are simultaneously active. These are important events for sand nourishments (especially when located in the upper part of the profile). The parts that are not correlated directly to the wave height are hence assumed to have a secondary effect on the overall sand budget between the beach, the shoreface and the longshore distribution.

3. Morphological model for sand nourishment decay

The numerical model tool used is based on a newly developed coupled wave, current and sediment transport model MIKE 21/3 FM Shoreline (Kærgaard & Drønen (2015), Kærgaard et al. (2014), Drønen et al. (2011)). The model mixes the 2D area concepts for hydrodynamics and sediment transport with the one-line concept for shoreline evolution and a concept for morphological adaptation towards cross-shore equilibrium. The model divides the profile into three zones – outer submerged part of profile (always wet), beach profile (parts only wet during storm surges) and dry parts. The study focuses on the effect of different combinations of sand nourishments scales and configurations (volume, length and location in profile) for the three exposure levels (and three representative degrees of background erosion).

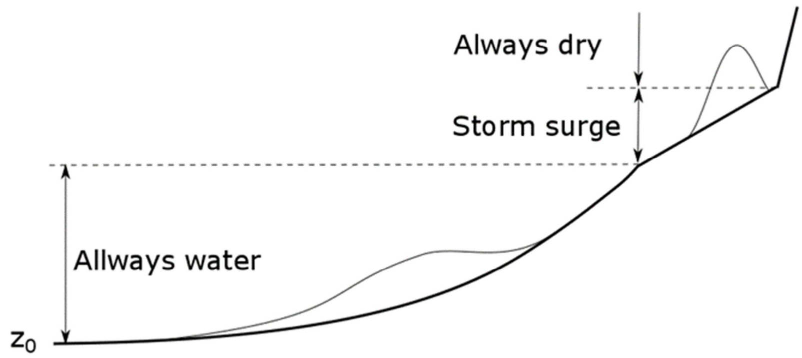

Figure 3 Cross-shore model simplification principles

Depth of closure is taken to proportional to the wave height following Mangor et al. (2017), and will vary over the year accordingly.

3.1. *Cross-shore processes*

We need a mechanism for cross distribution of sand over the morphologically active part of the profile in the cross-shore direction. Instead of attempting to simulate the cross-shore transport in detail, it is - with the present purpose and the accuracy one can expect in mind - plausible to assume a more crudely build mechanism that distributes the sand towards an equilibrium profile with a given time scale. We do that by introducing a gradient based distribution mechanism like

$$q_{cross} = -\alpha(\frac{\partial z}{\partial s} - \frac{\partial z_0}{\partial s})$$

q_{cross} is a cross-shore sediment transport, s a cross-shore axis, z the actual bathymetry, z_0 the equilibrium profile value and α a diffusivity parameter controlling the time scale of the process. By doing this we lump a number of physical/deterministic processes into a parameterized "behavior oriented" model.

In the beach region $z > 0$ we assume a linear equilibrium profile using a typical slope from the given region and a Dean profile in the morphologically active part of the shoreface region $z_{closure} < z < 0$. This cross-shore transport will tend to zero as the profile adjusts morphologically to the equilibrium one, i.e. $q_{cross} \to 0$ for $z \to z_0$. This cross-shore mechanism is now added to the 2DH model as

$$q_s = q_{2DH} + q_{cross}$$

Hereby a morphological model is formulated that combines 2DH longshore gradients and circulation currents over the nourishment with a gradual distribution mechanism in the cross-shore direction, with a time scale depending on the diffusivity input parameter. Notice that for an infinitely high value of the diffusivity coefficient, the profile adjust instantaneously to the equilibrium profile. In that case the profile will thus have a constant shape (=the equilibrium shape) and the resulting morphological response will be an instantaneous "shifting" in the horizontal direction of the profile as a response to longshore gradients in the longshore sediment transport. This resembles the concept used in so-called one-line models, see e.g. Mangor et al (2017).

3.2. ***Background erosion***

Background erosion was included in the model by adding and adjusting alongshore gradients in the wave field to obtain representative erosion rates in the expected order of magnitude for the three areas.

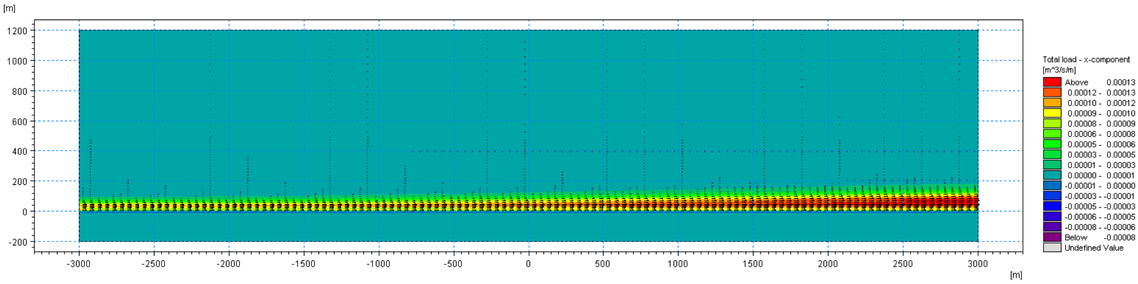

Figure 4 Example of a sediment transport field with a gradient to model background erosion.

4. Sand nourishment dimensions and locations

Different combinations of sand nourishment volumes and lengths as well as 2 different locations in the profile 1) uniformly distribution over the entire profile and 2) beach nourishment. In Table 2 the model program is summarized for the chosen volumes and alongshore lengths – giving a certain volume per alongshore meter. Examples of the two cross-shore locations of the initial nourishment are given in Figure 5.

Table 2. Model program for combinations of nourishment volumes and lengths.

High exposure			
		Length	
Volume	500 m	1000 m	3000 m
20.000 m^3	40 m^3/m	20 m^3/m	
40.000 m^3	80 m^3/m	40 m^3/m	20 m^3/m
80.000 m^3		80 m^3/m	40 m^3/m
Moderate exposure			
		Length	
Volume	100 m	500 m	2000 m
10.000 m^3	100 m^3/m	20 m^3/m	
20.000 m^3	200 m^3/m	40 m^3/m	10 m^3/m
30.000 m^3		60 m^3/m	15 m^3/m
Minor exposure			
		Length	
Volume	50 m	300 m	1000 m
3.000 m^3	60 m^3/m	10 m^3/m	
6.000 m^3	120 m^3/m	20 m^3/m	6 m^3/m
9.000 m^3		30 m^3/m	9 m^3/m

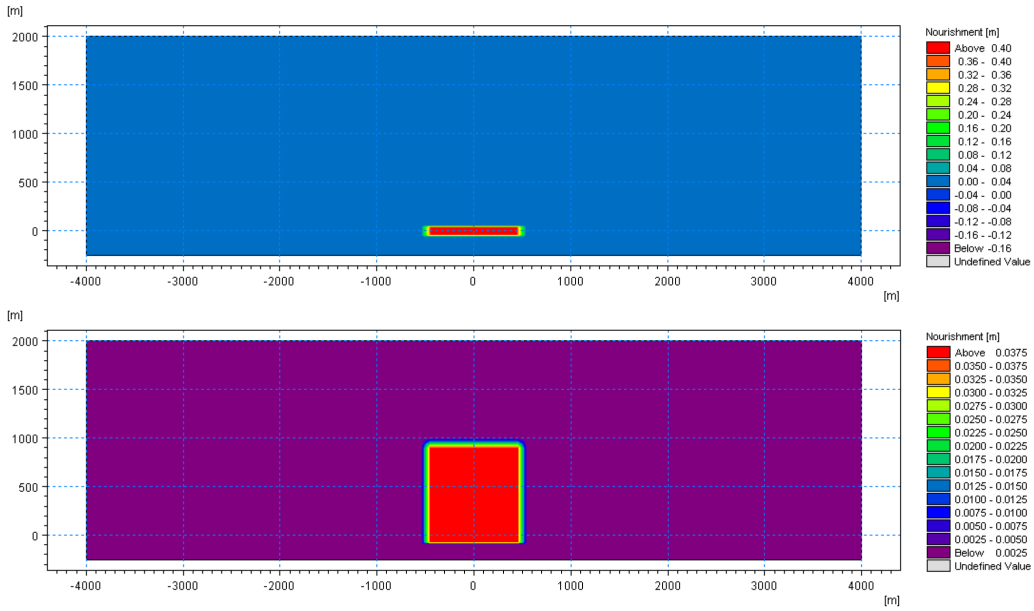

Figure 5. Top panel: Beach nourishment. Bottom panel: Uniform shoreface nourishment.

5. Sand volume evolution – examples

Examples of the resulting morphological changes are presented in the following as *the difference between the evolving bathymetry with nourishment and the corresponding evolving bathymetry without nourishment*. In Figure 6 the evolution of the alongshore distribution of volume over the profile (with the background erosion subtracted) is depicted for the case of uniform distribution over the entire profile. The rows and columns refer to the cases in Table 2. Several features can be observed. First the shortest nourishments with the longest cross-shore protrusion decay the fastest in the beginning. This is expected as it this process is correlated with the gradients in the longshore transport. The longest nourishments tend in the beginning to keep their volume in the center as the development initially is only active at the shoulders of the formation. This continues until the development eventually reached the center. All decay patterns tends toward a classic decaying bell shaped formation (see e.g. Dean (2002)) but there is also a tendency for migration of the formation in the alongshore transport direction – at least in the beginning of the evolution of the formation. The migration is interesting as it is not a feature that would have been captured by a one-line model driven by a simple “local” model for the littoral drift (see e.g. Mangor (2017)). As describe above, in the present case a 2DH model is applied as the driver for the longshore transport meaning that very steep wave incidence and different lag effects in the wave and flow field are handled implicitly. The effect of the initial location of the nourishment is depicted in Figure 8 and Figure 10. Figure 8 shows the case of uniform profile (top) and beach nourishment (bottom) for three different nourishment lengths. The evolution patterns suggests a difference between the two initial distributions in the sense that the beach nourishment decay is somewhat faster. This is possibly because a larger portion of the nourishment in the case of the beach nourishment is “affected” by the longshore transport gradients (from the depth of closure to the highest water level). It is not a general conclusion however that beach nourishments loose the volume faster than uniform shoreface nourishments, but there is an effect that could be studies more carefully when a real case is analyzed in more detail. In Figure 10 the evolution of the beach nourishment is seen to be affected by a combination of sand being taken from the upper parts and put out in the profile - and longshore gradients in the longshore sediment transport acting on the perturbation to form alongshore spreading of the formation. Notice that downdrift migration is more pronounced close to shore because this is where the most sediment transport is happening, which fits with the interpretation of the volume evolution in Figure 8.

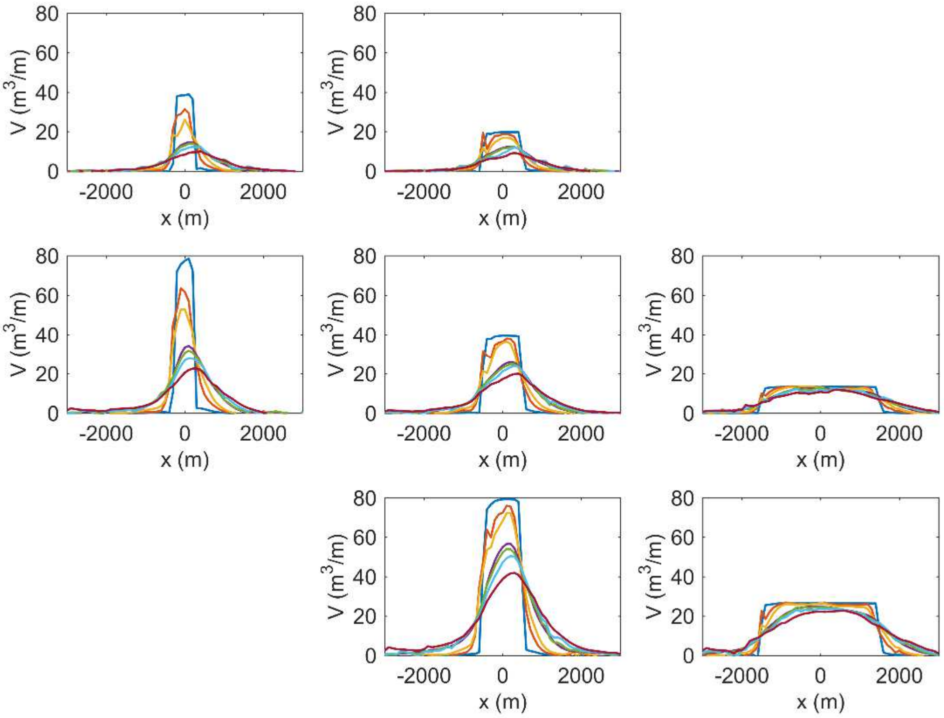

Figure 6 Examples of evolution of alongshore volume distribution. Highly exposed coast. The rows and columns corresponds to the rows and columns in Table 2. The time between each curve is 1 month.

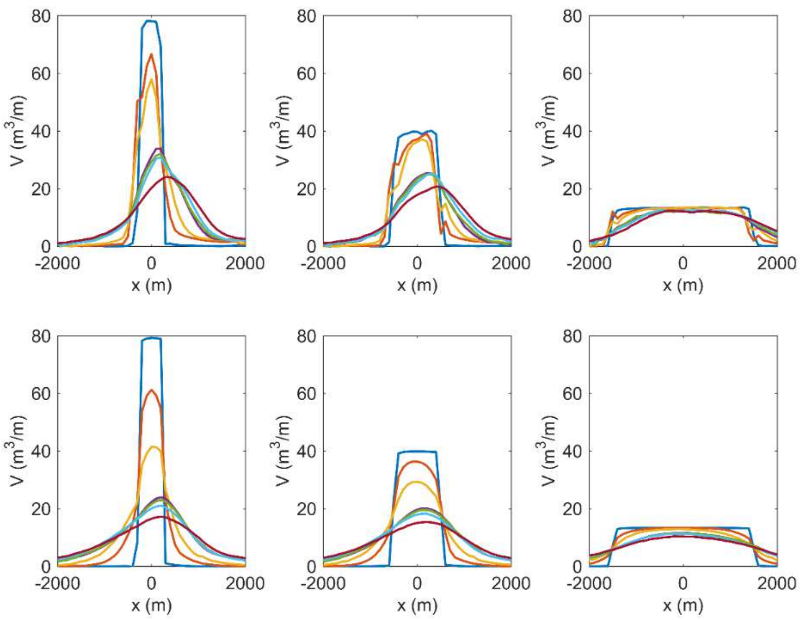

Figure 7. Examples of evolution of alongshore volume distribution. Highly exposed case. Equal distribution over profile. Upper row: Equal distribution. Lower row: Beach nourishment. The columns corresponds to the middle row in Table 2. The time between each curve is 1 month.

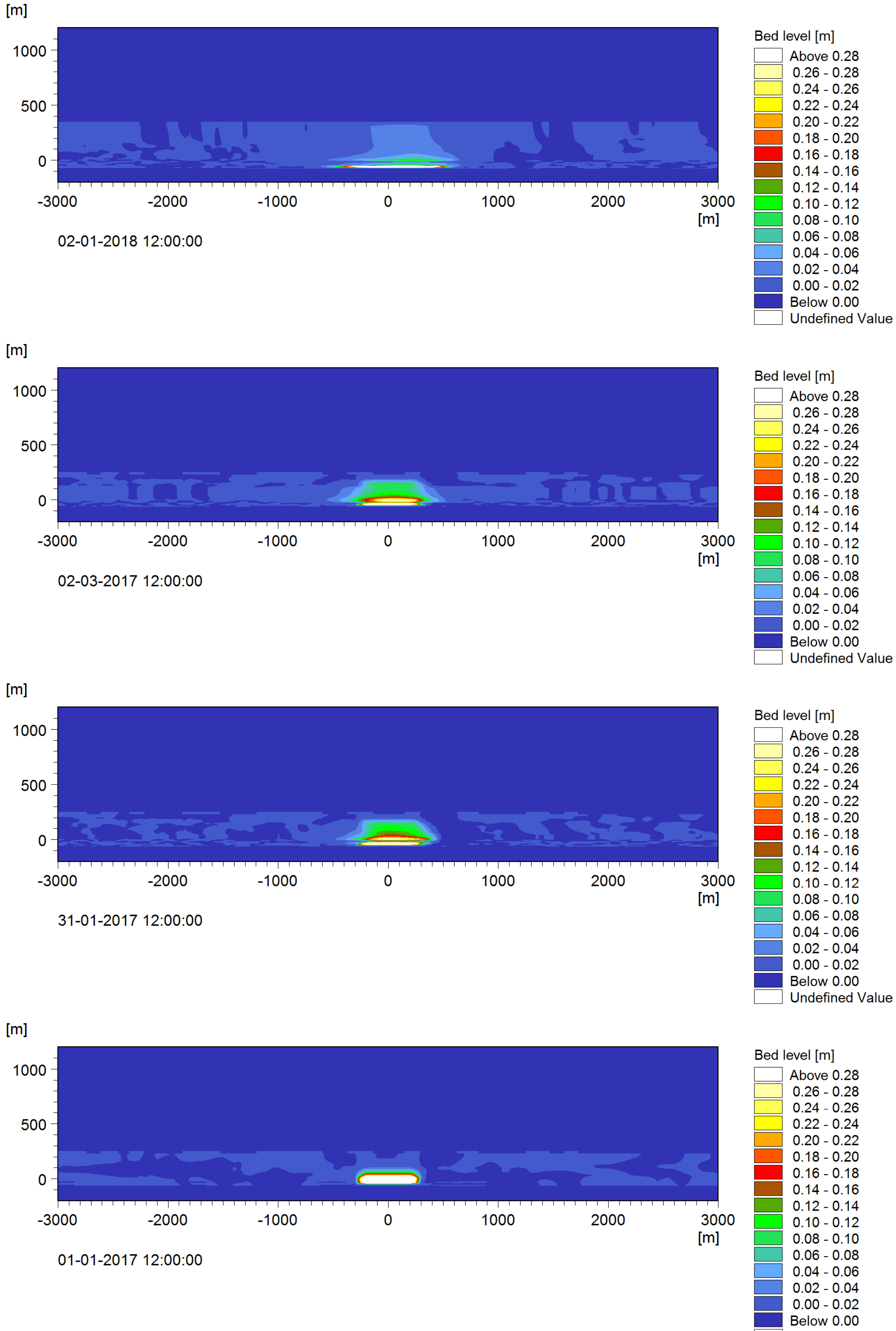

Figure 8. Example of temporal evolution of beach nourishment. Moderate conditions. Total volume 20.000 m^3. Length 500m. Bottom: Initial condition. Lowest middle: 1 month. Highest middle: 3 months. Top: 12 months.

6. Decay diagrams

As a measure of the efficiency of the nourishment the evolution of nourishment volumes were integrated over the initial nourishment stretch to get the temporal decay of the volume in the protected area.
It turns out that volume decay curves with the same nourishment length tends to collapse - for a given exposure degree - when plotting the total nourishment volume (at a given time) relative to the initial nourishment volume against time (see e.g. Figure 9).

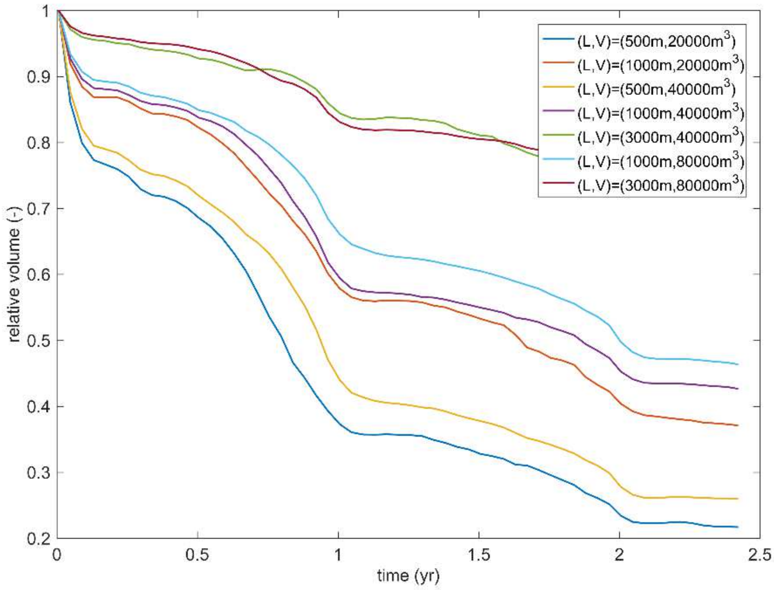

Figure 9 Example of decay of total volume relative to initial volume in nourished area. Highly exposed case. Uniform distribution cases.

By lumping all results and assuming a mean decay for a given length to be exponential, central estimates of relative volume decay for the three representative coasts can be constructed

$$\frac{V}{V_{initial}} = A(L)e^{-K(L)t}$$

where A and K are constants for a given length L and t is the time from the initial nourishment.

Furthermore introducing the undisturbed background erosion by a time scale relating the erosion and the initial nourishment volume per meter

$$T_0 = \frac{initial\ volume\ per\ meter}{rate\ of\ volume\ erosion\ per\ meter}$$

we can combine the decay curves with corresponding background erosion curves (linear), as is seen in Figure 10. From these curves it is now possible to get the approximate life span of a given sand nourishment formation. The time it takes before an infinitely long nourishment has been eroded is equal to the erosion time scale. If the nourishment has a finite length, the longshore processes will make the formation decay faster, and the time where this happens is where the curve for the background erosion and the decay curves cross.

Notice that Dean (2002) gives similar diagrams, however the present analysis is based on detailed wave and water level data from the given locations and takes into account a more advanced model that includes important physical effects not present in a more simple model/analysis.

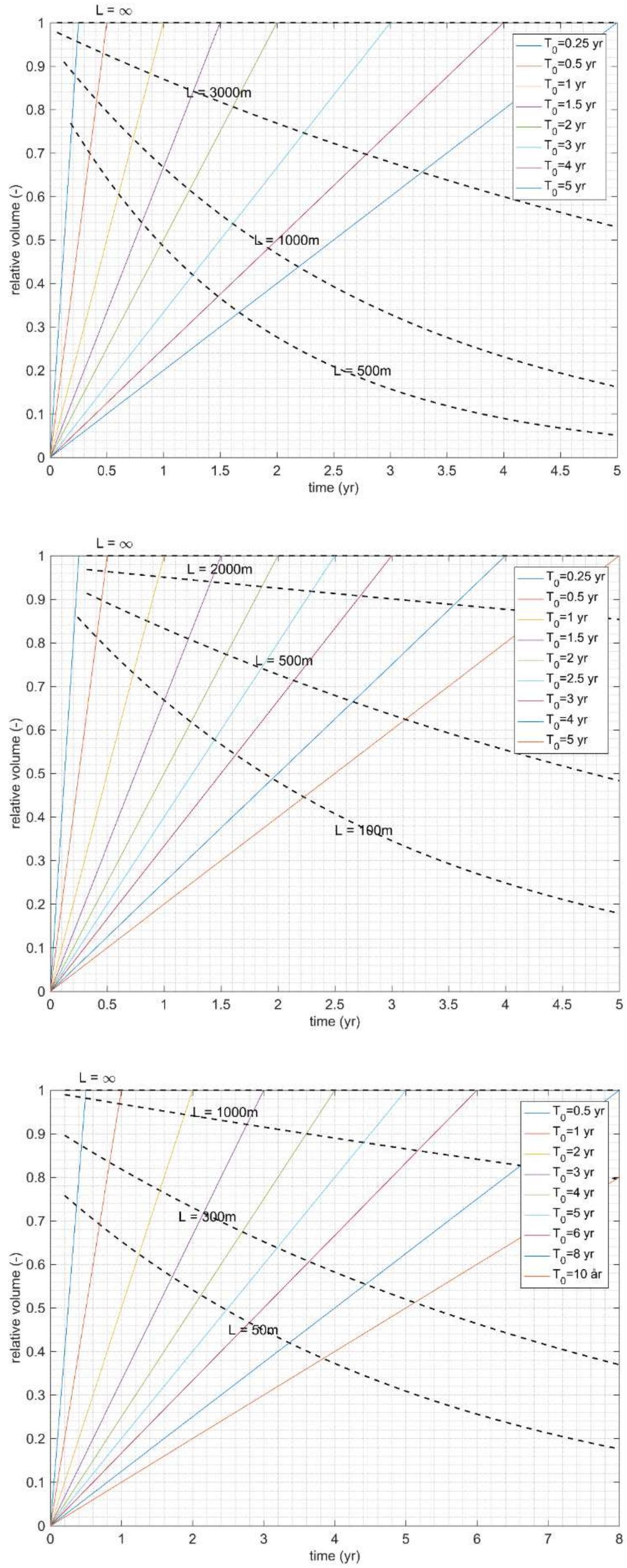

Figure 10 Decay diagram based on numerical model for sand nourishment. Top: High exposure. Middle: Moderate exposure. Bottom: Minor exposure

7. Conclusions and discussions

The present paper has presented a model based analysis of nourishment decays used for different model set-ups approximating and representing three Danish coastal areas with three different degrees of wave exposure. The model includes not only local longshore processes, but also a cross-shore sand distribution mechanism and all physical lag mechanisms that is offered by the 2DH model used to drive the longshore current and sediment transport over the sandy nourishment formations. It has been demonstrated how this constitutes a model that in principle takes the important processes of sand nourishment into account to model not only uniformly distributions of nourishment sand, but also beach nourishments. Given the uncertainties and the focus on aiming at central estimates for a wider range of coasts - and not accurate results for a very specific stretch - this procedure is believed to give valuable information about the time scale involved in the decay of sand added to the coast as a mean to protect eroding coasts. In future applications many other aspects will be interesting to try to cover. It will e.g. be interesting to model the cross-shore process in a more deterministic way and also study the effect of more sporadic extreme events and alongshore variability not expressed by a long straight coastline and a the direct correlation between water level and wave height used in the present analysis.

Acknowledgements

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