

LINKING COASTAL EVOLUTION AND SUPER STORM DUNE EROSION FORECASTS

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Abstract: To assess the long-term safety of a dune-protected coastal area, models are needed for forecasting both long-term coastal evolution and dune erosion due to the occurrence of a super storm. In long-term model forecasts, however, information on dune shape is lost. Explorative calculations show that the output of the event-scale dune erosion model is quite sensitive to the dune height. For a given super storm, a higher dune leads to a larger forecasted erosion volume, but to a less land inward position of the erosion line (the line that indicates how far erosion is expected to reach land inward). Clearly, a solution should be found for adding information on realistic dune shapes to the long-term coastal evolution forecast. EOF decomposition of observed dune profiles provides simple but realistic dune shape functions that could be used to redistribute forecasted dune volumes into realistic dune shapes.

INTRODUCTION

Dunes are part of the coastal system which need to be considered in the scope of coastal management and engineering practices (Saye et al. 2005), since they form an important link in the coastal sediment budget (Arens & Wiersma 1994). Arens & Wiersma (1994) show that, for the Dutch coast, on a yearly basis, an average of 3 – 3.5 m^3/m to a maximum of $25m^3/m$ sediment is transported into the dunes. In addition, in the Netherlands, dunes protect large parts of the coast during storms (see figure 1, 'soft defenses'). However, dunes are often neglected in (long-term) coastal modeling exercises.

Figure 1. Flood defenses along the Dutch coast *(From: CPD, 2000)*

The Dutch government imposes safety standards which should be met by all sea defenses. Along the Holland coast, flood defenses should be able to withstand a 1:10.000 storm, i.e. conditions corresponding to a storm with a probability of occurrence of once per 10.000 years. In the future however, rising sea-level and more frequent and severe storm conditions might jeopardize the safety provided by the flood defenses.

In 1984, the Technical Advisory Committee for Flood Defenses (TAW 1995) published a guideline on how to test safety of the Dutch dune areas. To assess the current 'strength' provided by the dunes, a method was designed to calculate dune erosion as a result of a storm event. This method is based on the DUROS (DUne eROSion) model. From the dune erosion calculations, the position of erosion lines are determined (figure 2). Erosion lines indicate how far erosion might reach land inward as a result of occurrence of an extreme storm event. Figure 2 illustrates that if a 1:10.000 super storm were to occur today, the land seaward of the solid line would be eroded.

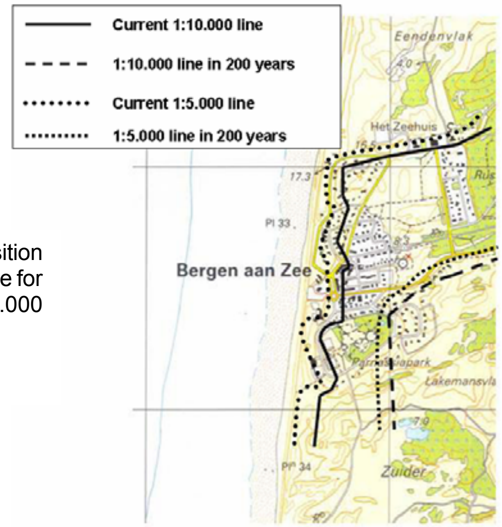

Figure 2. Present and expected future position of erosion lines for a Dutch sea-side village for super storms with a 1:10.000 and 1:5.000 probability of occurrence
(From: RIKZ, 2005)

However, sustainable coastal zone management not only asks for the current dune strength to be known, but also how this dune strength evolves through time, in order to anticipate to future developments. Until recently, long-term safety forecasts involved running the DUROS model with an unchanged beach and dune configuration, but with a higher mean sea level. The dashed line in figure 2 illustrates how the erosion line might shift landward according to this approach. However, evolving morphology might affect the position of erosion lines in the future as well. Therefore, it is of importance to include morphological behavior in long-term safety assessment.

In Dutch coastal management practice, a behavior oriented model called PONTOS is currently used to forecast long-term evolution of the Holland coast (figure 7). In this model, dune morphology is highly schematized, and therefore does not provide the spatially detailed information required for a DUROS calculation.

Apparently, there is a ‘gap’ between the model that calculates the effects of low-frequency, high-magnitude events (DUROS) and the model that is designed to forecast long-term coastal evolution due to high-frequency, low magnitude processes (PONTOS).

In this paper, we will explore how the ‘lost morphological information’ can be reintroduced into the PONTOS forecast, in order to make the long-term model forecast suitable for DUROS calculations to obtain erosion line positions (see figure 3).

In order to determine the effect of extreme events 50 to 200 years from now, we need to take into account the temporal and spatial evolution of morphological characteristics of the coastal cross-shore profile. More specifically, we need to consider that part of the profile which is needed for DUROS, i.e. from ca. -2m Dutch Ordnance Level to the dune area.

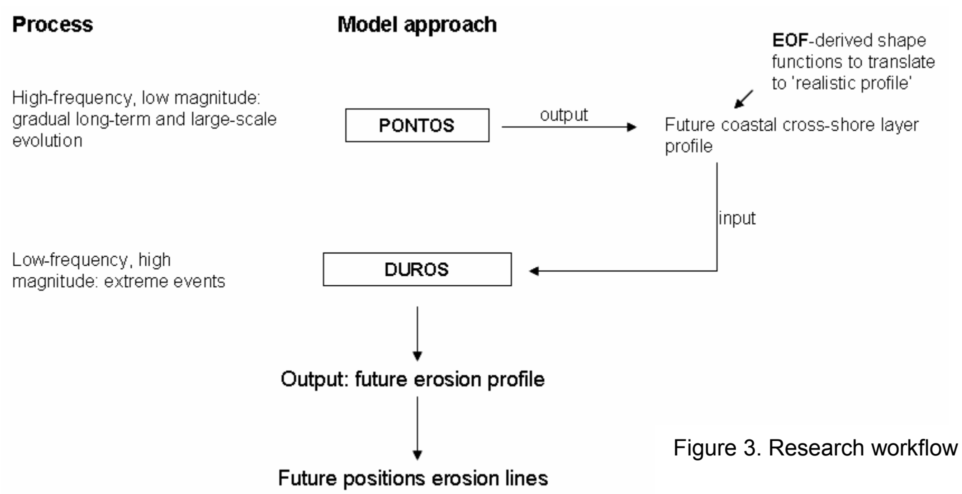

Figure 3. Research workflow

This paper is organized as follows: The next two sections explain the concepts of the DUROS model and the PONTOS model, followed by a section which describes the study area. In the following section, we examine the sensitivity of dune erosion volumes and erosion line positions to the shape of the dune area. Thereafter, we focus on Empirical Orthogonal Function (EOF) decomposition of dune topography measurements. EOF provides realistic shape characterizations for the dunes. The shape functions obtained from EOF may be used to translate the PONTOS dune schematizations to a realistic set of dune profiles.
The gained knowledge might aid in determining the 'optimal' dune configuration to reduce the effects of super storms.

PRESENT SAFETY ASSESSMENT OF DUTCH DUNES: THE DUROS MODEL

DUROS is a cross-shore model that, for pre-defined conditions, calculates the amount of dune erosion as a result of the occurrence of an extreme storm (Van de Graaff 1984; TAW 1995). The DUROS model is used in safety assessment of the Dutch dune area (figure 1 and 7). To determine the amount of erosion, it is required to know the position of the cross-shore profile right *before* a storm, since this will determine the extent of erosion of the dune as a result of the storm, and, hence, the safety provided by the dune as a natural defense against flooding of the hinterland, which in the case of the Netherlands is located largely below MSL.

In DUROS, the amount (volume) of dune erosion is a function of (1) the location (position) of the initial cross-shore profile, (2) the maximum wave height and sediment characteristics and (3) the maximum storm surge level. With these parameters, a sediment balance is calculated, which results in the position of the erosion profile. The shape of the erosion profile is assumed to be known, and is a function of the significant wave height and the fall velocity of the dune sand in standing water (see figure 4).

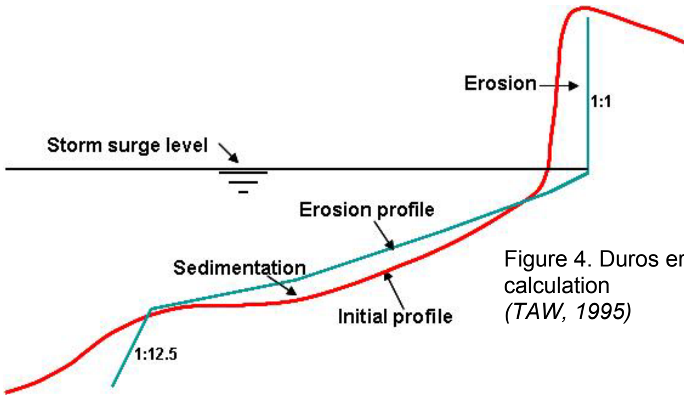

Figure 4. Duros erosion profile calculation *(TAW, 1995)*

The position of the initial profile, rather than the shape of the initial profile, is considered to determine to a large extent the amount of dune erosion (Van de Graaff 1984; TAW 1995). This is because a closed sediment balance in cross-shore direction is assumed. By shifting the erosion profile with respect to the initial profile in such a way that the amount of erosion equals the amount of sedimentation, a closed sediment balance is obtained.

LONG-TERM COASTAL EVOLUTION: THE PONTOS MODEL

The long-term and large-scale evolution of the Holland coast can be simulated by the behavior-oriented PONTOS model (Steetzel & Wang 2003). PONTOS is a physical-mathematical coastline model, in which the coastal cross-section is schematized into five horizontal layers each representing a sediment volume (figure 5). Erosion or sedimentation, modeled per layer, is caused by gradients in the longshore and cross shore sediment transport. PONTOS provides a crude schematization of the cross-shore profile from which a position of erosion lines cannot be obtained. The dune area in PONTOS is represented by one sediment volume layer. This layer is positioned from +3 m with respect to the Dutch Ordnance Level (NAP) to the top of the first dune row.

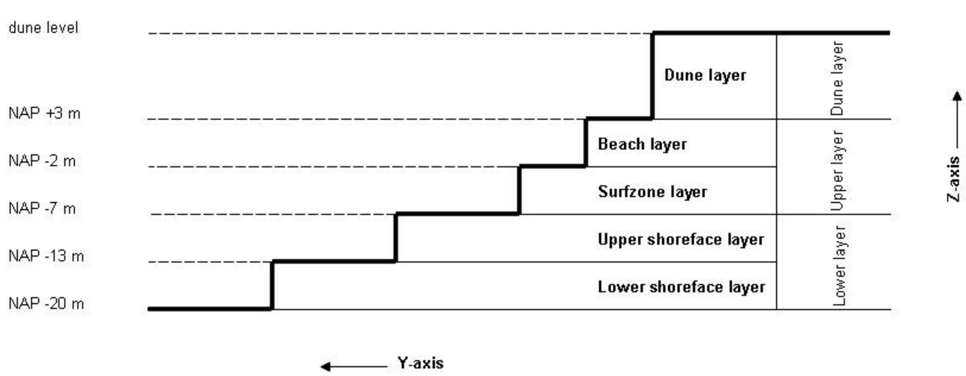

Figure 5. ‘Block’ representation of coastal profile in PONTOS *(Steetzel & Wang, 2003)*

In order to forecast the amount of dune erosion under extreme storm conditions, we need a cross-shore distribution of sediment as input for DUROS, rather than the layer representation of PONTOS. Recent developments to obtain a cross-shore profile from the PONTOS-layers are made by Wang et al. (2006) who transform the layer representation to a smooth profile as follows (see dotted line in figure 6):

1. The cross-shore profile of each layer is replaced by a straight line according to: $y=a_i z+b_i$, for $z_{i+1} \leq z \leq z_i$ (1)
2. In each layer, mass conservation is guaranteed in accordance with the principles of the PONTOS model.

This profile is then used to perform a dune erosion calculation. This profile is however still highly schematized and does not reflect a 'real' profile shape (compare in figure 6 the dotted line with the smooth line based on Jarkus measurements (Yearly Coastal Surveys).

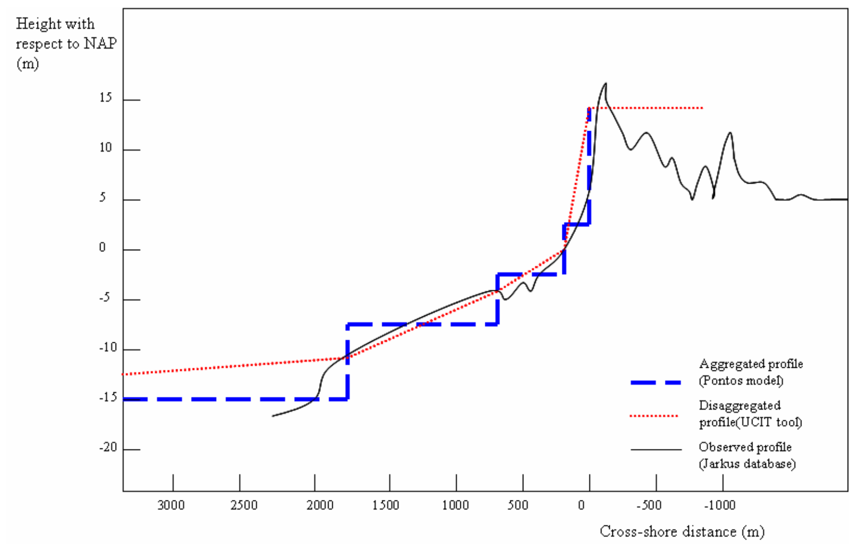

Figure 6. Aggregated profile generated by PONTOS, disaggregated smooth profile and an observed coastal profile by Jarkus data *(Wang et al., 2006)*

DESCRIPTION OF THE STUDY AREA

We use coastal cross-shore data from the coast of Noord-Holland, the Netherlands (figure 7) as input to DUROS to explore the sensitivity of dune erosion to different input profiles. The coastal cross-shore data are obtained from the Jarkus database, which provides year to year measurements of coastal profiles extending from the foredune to app. 1000 m seaward. The distance between the profiles is 200-250 m and there is a total number of about 3000 profiles along the Dutch coast (Guillen et al. 1999). Two Jarkus profiles for the year 2004, viz. transect number 3325 and 4475 (figures 7 and 8) were selected as a first exploration in examining the role of the dune shape on the amount of erosion and position of the erosion line. Transect 3325 is situated close to the coastal town of Bergen aan Zee, whereas transect 4474 is situated near Castricum aan Zee. Hereafter, the transect numbers will be referred to as the Bergen and Castricum transects. For EOF analysis, 87 profiles from Noord-Holland (also for the year 2004) were used.

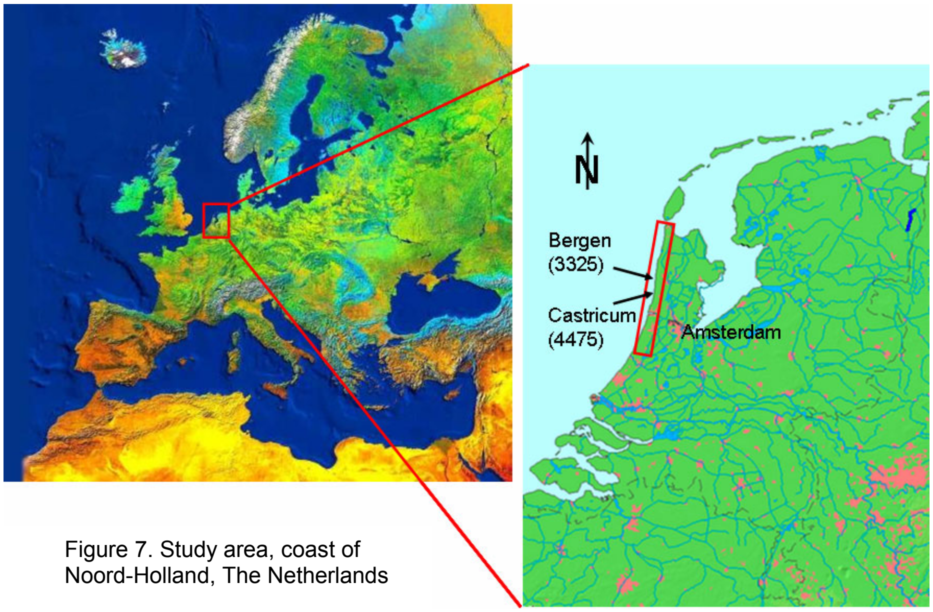

Figure 7. Study area, coast of Noord-Holland, The Netherlands

EFFECT OF DUNE SHAPE ON EROSION VOLUME AND EROSION LINE POSITION

Both the DUROS calculation method and the Jarkus database are embedded in a model environment called UCIT (Universal Coastal Intelligence Toolkit) (Van Koningsveld et al. 2005). For each selected Jarkus transect we can perform a dune erosion calculation, thereby taking into account different forecasting periods, different sea-level rise scenarios as well as user-defined hydraulic conditions, such as storm peak periods and significant wave heights. The selected transects of Bergen and Castricum have different foreshore slopes and the foredunes differ in both transects as well (figure 8). The foredune of the Bergen transect has a height of app. 8 meters, whereas the foredune of the Castricum transect has a height of about 16 meters. This part of the coast of Noord-Holland is intensely used for recreational activities and since most parts of the coast of Noord-Holland are subject to erosion, beach and foreshore nourishments are frequently carried out with positive effects on beach width. The Bergen transect is highly altered by human activity and can be considered an ‘artificial’ dune (Arens 1994).

Castricum is situated 11.5 kilometers south of Bergen. This transect is in a ‘semi-natural’ state; sand fences have been placed and marram grass has been planted in order to stabilize the dunes in this area (Arens 1994).

There are no seawalls or groins situated close to the transects which might influence sedimentation or erosion in this area.

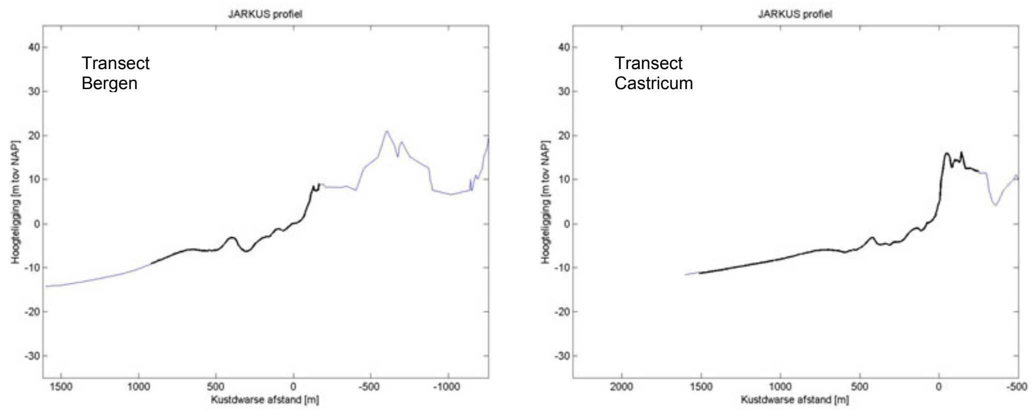

Figure 8. Transects Bergen (3325) and Castricum(4475)

In order to examine the role of dune geometry on the amount and extent of erosion, we performed a model experiment in the UCIT environment for the Bergen and Castricum transects. Each profile was transformed into different hypothetical profiles, varying in height and width, based on a fixed, hypothetical added volume. Figure 9 illustrates two hypothetical profiles for the Bergen transect. We took the +3 m NAP (Dutch Ordnance Level) as the dunefoot position. According to Ruessink & Jeuken (2002), this level roughly corresponds to the break in slope between the beach and the foredune. From this level, we added the artificial dune volume, which we set at 4000 m^3/m, based on expert judgement. We defined the minimum dune width to be 100 m and the maximum dune width to be 500 m. Dune width will be varied in steps of 20 m. According to Volume = width * height, the dune height takes a height belonging to a certain width.

When we plot the different erosion volumes and positions of the erosion lines against the different dune heights (fixed dune volume of 4000 m3/m), we observe in figures 9 and 10 that for the Bergen transect a decreasing dune height leads to a smaller erosion volume, but to a more landward shift of the erosion point position (denoted by R in figure 9). This is because the shape of the erosion profile is fixed, so in order to maintain a closed sediment balance when the shape of the beach and foreshore remain the same, leads to a more landward position of the erosion point if dune height decreases. For the Castricum transect with the same height-width ratios for the dune area as the Bergen transect, similar results are obtained: a decrease in dune height leads to a smaller erosion volume, but to a more landward position of the erosion point. Apparently, the *shape* (height) of the initial dune profile seems to affect to a large extent the dune erosion volume and erosion line position, since a higher dune leads to a higher erosion volume and to a more seaward erosion line position.

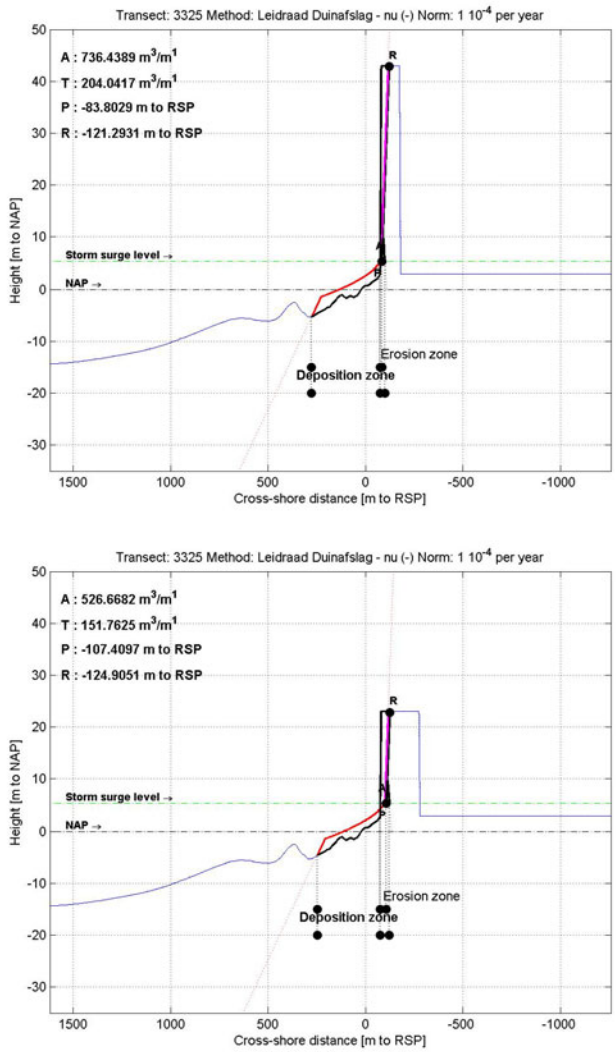

Figure 9. Different erosion volumes and erosion point positions for two hypothetical dune configurations for the Bergen transect
A is the erosion volume
T is an 'extra' erosion volume to account for uncertainties
P is the intersection between the 'new' dunefoot position and the storm surge level
R is the erosion point at the surface

Besides the dune shape, the foreshore configuration also plays a role in the amount of erosion and the position of the erosion point. Figure 10 and table 1 show that although the dune configurations and volumes are identical for both transects, different erosion volumes and erosion line positions arise. A steep foreshore slope 'demands' more sediment from the dunes in order to obtain a closed sediment balance needed for the erosion profile (figure 4).

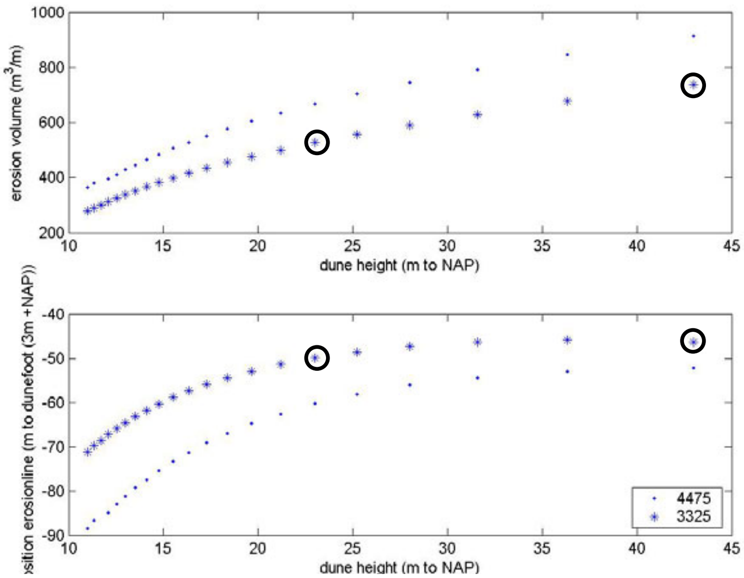

Figure 10. Varying dune heights versus erosion volumes and erosion point positions for Bergen (transect number 3325) and Castricum (transect number 4475). Circles indicate the values of figure 9

Table 1. Erosion volumes and erosion line positions at different hypothetical dune heights for Bergen (3325) and Castricum (4475)

DUNE HEIGHT (M TO NAP)	EROSION VOLUME 4475 (IN M^3/M)	EROSION LINE POSITION 4475 (M TO DUNEFOOT)	EROSION VOLUME 3325 (IN M^3/M)	EROSION LINE POSITION 3325 (M TO DUNEFOOT)
43	912.82	-52.20	736.44	-46.29
36.333	845.89	-53.06	677.01	-45.89
31.571	790.95	-54.48	629.61	-46.37
28	744.29	-56.12	590.31	-47.37
25.222	703.69	-58.19	556.445	-48.59
23	667.52	-60.32	526.67	-49.91
21.182	634.84	-62.59	500.26	-51.41
19.667	604.93	-64.81	476.30	-52.93
18.385	577.33	-67.05	454.32	-54.47
17.286	551.67	-69.05	434.07	-55.82
16.333	527.87	-71.39	415.38	-57.30
15.5	505.51	-73.30	397.87	-58.87
14.765	484.46	-75.33	381.52	-60.33
14.111	464.62	-77.47	366.13	-61.92
13.526	445.87	-79.25	351.64	-63.18
13	428.04	-81.16	337.95	-64.60
12.524	411.12	-83.00	324.96	-65.96
12.091	395.00	-84.97	312.63	-67.22
11.696	379.62	-86.65	300.92	-68.67
11.333	364.97	-88.48	289.68	-69.8
11	-	-	279.05	-71.20

Since profile shape affects the amount of erosion and the position of erosion lines, the question arises whether we can find a simple but realistic representation of profile shape to be implemented into long-term morphological model forecasts (PONTOS). To investigate this, we first concentrate on characterization of the dune profile. We propose to use Empirical Orthogonal Function (EOF) to extract shape functions which characterize dune shape.

EMPIRICAL ORTHOGONAL FUNCTION (EOF) ANALYSIS

EOF analysis provides a method to reduce the number of data variables required to represent our data set (Aubrey 1979). With EOF we attempt to reveal a simple spatial structure that is present within the dune profiles.

If we consider the dune profiles – which extend from the dunefoot position (origin) towards a 200 m landward position - along a 22 km long stretch of the coast of Noord-Holland , we obtain a mean profile shape indicated figure 11 (upper panel). This part of the coastal cross-shore profile corresponds to the dune layer in the PONTOS model, viz. from NAP + 3 m to the dune top. The mean dune top is situated at about NAP + 16 meters, but there is a standard deviation of approximately 4 meters (lower panel figure 11).

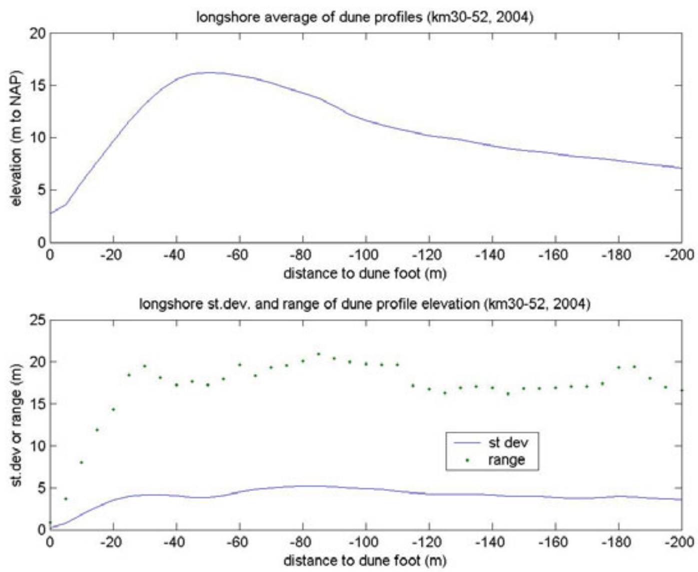

Figure 11. Mean cross-shore dune profile of Noord-Holland and standard deviation and range of the mean profile

The standard deviation does not provide information on how actual deviations from the mean profile are related in space. EOF's describe how the dune profiles differ from the mean profile in terms of orthogonal shape functions (for instance the sine and cosine functions). Since we consider 87 profiles along the coast, each cross-shore position (with respect to distance in meters to the dunefoot) has different heights in longshore direction. Therefore, each cross-shore position has a variation around the mean profile, which can be expressed in terms of variance (or standard deviation, lower panel in figure 11). The first EOF (upper panel, figure 12) explains 43% of this observed variance. The second eigenfunction explains 24% of the observed variance.

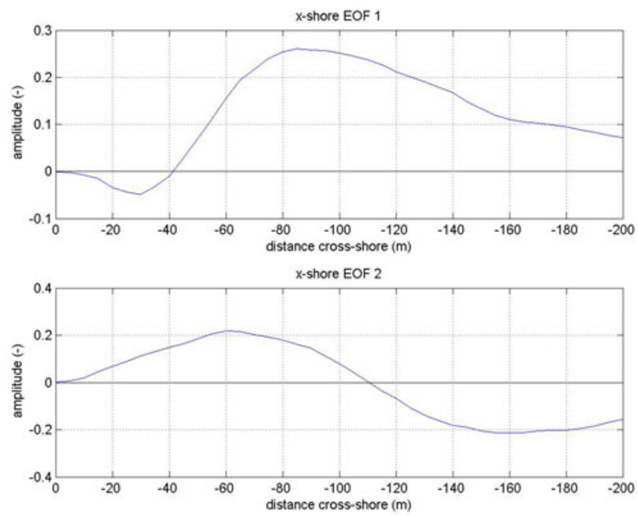

Figure 12. First and second shape functions of the selected profiles from transect 3000 to 5200

Thus, the first two shape functions explain two-third of the observed variance, which means that the shape functions describe to a large extent the variation we observe in the mean profile.

Potentially, the shape functions can be used to remodel the PONTOS dune layer into a (more) natural shape, on which a dune erosion calculation can be performed in DUROS.

It is still premature to assign a physical explanation for these observed variations, but variations are possibly related to the absence or presence of vegetation, sediment supply and management practices (Saye et al. 2005).

DISCUSSION

This research shows the first steps towards examining the importance of the dune/beach configuration in calculating erosion volumes and position of erosion lines. We want to stress the fact that the dune volumes we considered are highly schematized, without accounting for a width-height-slope relationship (Hesp & Hastings 1998). In reality, dune height cannot continue to grow without a corresponding increase in width, although it appears that especially dune height is important in the DUROS calculations. Different dune slopes will also affect the amount of erosion and position of erosion lines, since it will affect the closed sediment balance needed for DUROS. Also, dune slope affects dune stability, which implies that certain dunes might be more prone to erosion than other dunes.

Since the foreshore configuration also plays a role in the erosion calculations, examining a beach-dune morphological relationship might provide additional insight with regard to the state of the dune and a possible trend in dune evolution, i.e. eroding or accreting (Saye et al. 2005).

For the EOF analysis, we have considered all transects within a 22 km long coastal stretch irrespective of differences in dune type such as (1) the developmental stage of the dune, (2) aeolian processes at work (erosion or deposition) and (3) effects of dune management (human-altered vs. natural dunes) (Arens & Wiersma 1994). Whether more refinement in dune shape functions is actually needed is not clear yet. Applying EOF analysis to subsets of dune profiles grouped by dune type, will reveal whether these differences are reflected in differently shaped dune shape-functions or not.

CONCLUSIONS

This research illustrates the importance of dune configuration in dune erosion calculations. For a given storm, dune configuration determines to a large extent the erosion volume and position of erosion lines. Higher dunes result in a more seaward position of erosion lines, but result in higher erosion volumes compared to a lower dune. In addition, it also appeared that foreshore configuration matters in the erosion calculations.

We have proposed EOF analysis as a tool to characterize the dune shape in order to reintroduce the 'small scale information' to long-term forecasts such that a dune erosion calculation in DUROS is possible. It is thus a method to bridge the cap between a small scale, event-based model and a long-term, large scale model.

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