

# Tools for medium- and long-term prediction of nourishments effects





## **Tools for medium- and long-term prediction of nourishments effects**

Alessio Giardino  
Kees den Heijer  
Giorgio Santinelli  
Jebbe van der Werf

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**Title**

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**Summary**

In this study the effect of different nourishment designs at the medium- (years, kilometres) and large- (decades to centuries, tens to hundreds of kilometres) scale was investigated by means of numerical tools and data analysis. The effects were evaluated by looking at a number of morphological indicators of simple use for coastal managers: the MKL position, the dune foot position and the beach width.

Two types of models were used as a basis: the standard cross-shore UNIBEST-TC model, with the addition of the beach-dune module to simulate changes in the dry part of the profile, and the Nourishment Impact tool (alongshore coastline model). The UNIBEST-TC model was used to simulate the effects of a large set of different nourishments scenarios (~300) and the results were then analysed by means of a Bayesian approach. Observations on the efficiency of different nourishment designs were derived for the different indicators at different time scales. The comparison with data showed similar trends than the ones derived using the models. Although still qualitative, the results in terms of bar migration prediction in combination with nourishments have also appeared to be promising.

The coastline model Nourishment Impact Tool was used to predict the coastline development of the Dutch coast for 30 years, using as input the data of the nourishments which were carried out during this period. The model was able to predict reasonably well the large scale MKL development. Nevertheless, the prediction of the dune foot position at the large scale could not be represented. Also the prediction of the morphological changes at the local scale could not be represented by the tool, which contains a large number of simplifications and was originally developed only to simulate the effects of the long-term and large-scale nourishment programmes.

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		dr.ir. C. den Heijer					
		G. Santinelli					
		dr.ir. J.J. van der Werf					

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## Contents

<b>1 Introduction</b>	<b>1</b>
<b>2 Objectives</b>	<b>3</b>
<b>3 Methodology</b>	<b>5</b>
<b>4 Prediction of nourishments efficiency based on UNIBEST-TC simulations</b>	<b>7</b>
4.1 Introduction	7
4.2 Study area	7
4.3 Model set-up	8
4.3.1 General description of the model	8
4.3.2 Boundary conditions	8
4.4 Beach-dune module	9
4.4.1 Review on beach-dune modules	9
4.4.2 Implementation of the beach-dune module in UNIBEST-TC and other changes to the code	11
4.5 Results	14
4.5.1 List of model runs	14
4.5.2 Sensitivity of morphological indicators to different model settings	15
4.5.3 Effect beach-dune module	20
4.5.4 Effect fixed-layer position	25
4.5.5 Morphological response to nourishments	28
4.6 Discussions and conclusions	34
<b>5 Prediction of nourishments efficiency based on Bayesian approach</b>	<b>35</b>
5.1 Introduction	35
5.2 Set-up of the network	36
5.3 Applications	37
5.3.1 Response of the morphological indicators to beach nourishments at different time scales	38
5.3.2 Response of the morphological indicators to shoreface nourishments at different time scales	40
5.3.3 Effects of increasing nourishment volumes on MKL and dune foot position	42
5.3.4 Plan of a nourishment strategy	46
5.4 Discussions and conclusions	47
<b>6 Validation of the “Nourishment Impact Tool” based on 30 years data from the Holland coast</b>	<b>51</b>
6.1 Introduction	51
6.2 Parameter settings	51
6.3 Validation of the Nourishment Impact Tool versus measured data	52
6.4 Relations between nourishment volumes and computed indicators	58
6.5 Discussions and conclusions	60
<b>7 Summary and conclusions</b>	<b>63</b>
<b>8 Applicability of the prediction tools in support to WVL work</b>	<b>65</b>

<b>9 Recommendations for further work</b>	<b>67</b>
<b>10 References</b>	<b>69</b>

## 1 Introduction

The approach to coastal erosion management and control at different spatial and temporal scales requires the use of different concept and tools. Erosion issue at small- scale (from days to months; meters) are generally addressed by means of more complex process-based models, which allow the simulation of the different physical processes taking place at those scales. Nevertheless, those models are too complex and computational expensive to investigate erosion problems at the medium- (years; kilometers) and large- scale (decades to centuries; tens to hundreds of kilometers). Therefore, schematization of the more complex process-based models or development of new approaches and tools is required (Giardino et al., 2013c). The main requirements of these tools should be, besides the computational efficiency, the possibility of providing useful and easy-to-interpret output for coastal managers.

This report describes the development of a number of approaches and tools to be used for medium- and long-term prediction of nourishment effects. To do that, available data have been used to calibrate and support the calculations of simplified models. In particular, nourishment effects have been assessed by means of the cross-shore UNIBEST-TC model (see for example Walstra et al., 2012) combined with a Bayesian approach for the interpretation of the model output. Moreover, the coastline model Nourishment Impact Tool (Huisman, 2012) has also been used to assess the effects of the past nourishment history on the Dutch coastline development. The model output is provided in the form of easy-to-use morphological indicators. In particular, the following indicators are used:

- The MomentaneKustLijn (MKL) position.
- The dune foot position.
- The beach width.

The layout of the report is the following. In Chapter 0, the objectives of the study are described. The methodology of the work is summarized in Chapter 0. Chapter 0 describes the set-up of a cross-shore UNIBEST-TC model to be used for assessing the effects of different types of nourishments at a time scale of 10 years. To be able to investigate the impact of the nourishments on morphological indicators also representative of the dry part of the profile (i.e. dune foot position), the beach-dune module has been added to the model. This model was used to generate a large number of runs (about 300 in total) where different shoreface and beach nourishment designs, with different volumes, were tested. The output of these runs has been analysed in Chapter 0 following a Bayesian modelling approach. In Chapter 0, a different approach to describe the effects of nourishments on the entire Dutch coast has been set up using the Nourishment Impact Tool. In particular, nourishment volumes implemented along the coastline between 1980 and 2010, combined with predicted and measured development of the morphological indicators have been used in the analysis. Chapter 7 summarizes the main conclusions from this study. In Chapter 8 a number of practical suggestions for the use of the tools described in this report during the daily WVL work are given. Finally Chapter 0 provides a number of recommendations for further work.

The present study is part of the project (KPP – Beheer en Onderhoud van de kust; Coastal Management and Maintenance). We would like to acknowledge comments and remarks from Gemma Ramaekers (WVL) and Dirk-Jan Walstra (Deltares), which have resulted into an improved manuscript.



## 2 Objectives

The main objectives of this study consist in:

- Assessing the effects of different nourishment designs and nourishment types on MKL and dune foot position, at different time scale with focus on the medium- and long-term.
- Validating the accuracy of the model predictions using available measurements.

Those objectives fit within the broader objectives of the project Toestand van de Kust, part of the KPP B&O project<sup>1</sup>, which are:

- Supporting WVL in determining where to nourish.
- Advice WVL on the most efficient nourishment strategy.

By analysing a large number of simulated nourishment scenarios and assessing the impacts on a number of computed and measured indicators, it is possible to predict the effects of different nourishment strategies and to put forward suggestions on the most efficient nourishment design schemes. Moreover, the combined use of measured and modelled data along the entire Dutch coast can be used to determine if and where future nourishments will be required.

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<sup>1</sup> Background of the hypothesis and the link with the present management choices are described in an integral report of the project KPP-B&OKust.



### **3 Methodology**

To be able to assess the effects of nourishments at medium- and large- time scale, it is 1) first of all essential to make use of tools with acceptable computational times. Moreover, to be able to support coastal managers in their choices towards an efficient nourishment scheme, it is important 2) that those tools will predict the effects of the designed nourishments on a number of easy-to use indicators, representative of specific coastal functions. Therefore, the tools described within this report do not aim at representing the detailed morphological development of the entire profile.

The methodology of this study was developed keeping those two main goals in mind.

The computational efficiency was achieved using as a basis two simple models: the cross-shore UNIBEST-TC model representative of one specific transect, and the Nourishment Impact Tool based on a simple coastline model of the entire Dutch coast. In this way, also the two main spatial dimensions of the problem (cross-shore and alongshore) were covered in the analysis.

To translate the information from the numerical models to useful information for coastal managers, the output of the model runs was presented in terms of changes to pre-defined morphological indicators: the MKL position, the dune foot position, and the beach width. The MKL position can be considered representative for the coastal functions “medium-term safety”, while the dune foot position and the beach width are indicators of the “available space for nature and recreation”. Moreover, the dune foot position is also closely linked to the additional function “short-term safety” (Giardino et al., 2013a). A Bayesian approach was also used to interpret the model results, as this is an intuitive way of showing cause-effect relations (i.e. between different nourishment schemes and changes to the morphological indicators) and therefore could also be used by coastal managers in their decision and design making process (Chapter 8).



## 4 Prediction of nourishments efficiency based on UNIBEST-TC simulations

### 4.1 Introduction

A 2DV morphological UNIBEST-TC model representative of a cross-shore transect at Noordwijk has been used to predict the impact of different nourishment schemes on a number of morphological indicators. The UNIBEST-TC software comprises coupled, wave-averaged, equations of hydrodynamics (waves and mean currents), sediment transport, and bed evolution. It assumes straight and parallel depth contours.

The model was set up and calibrated by Walstra et al. (2012), which used the model to study cross-shore bar migration, growth and decays of breaker bars. The dune module was added to UNIBEST-TC, to be able to also assess the impact of nourishments on indicators representative of the dry area (i.e. dune foot position and beach width). The simulations were run for a period of 10 years to be able to discriminate between nourishment effects at different time scales.

The advantage of using a profile model with respect to a fully 3D model is that runs are very computationally efficient. This allows the simulation of several hundreds of scenarios within reasonable times. The output from these runs was then used as input data for the analysis based on a Bayesian approach as described in Chapter0.

### 4.2 Study area

The study area is located at Noordwijk aan Zee, in the central part of the Dutch coast (Figure 4.1). The cross-shore profile is characterized by a single quasi-persistent intertidal bar system and two persistent subtidal bar systems (Quartel et al., 2008). The tide is semi-diurnal with a tidal range between 1 m and 1.8 m respectively at neap tide and spring tide.

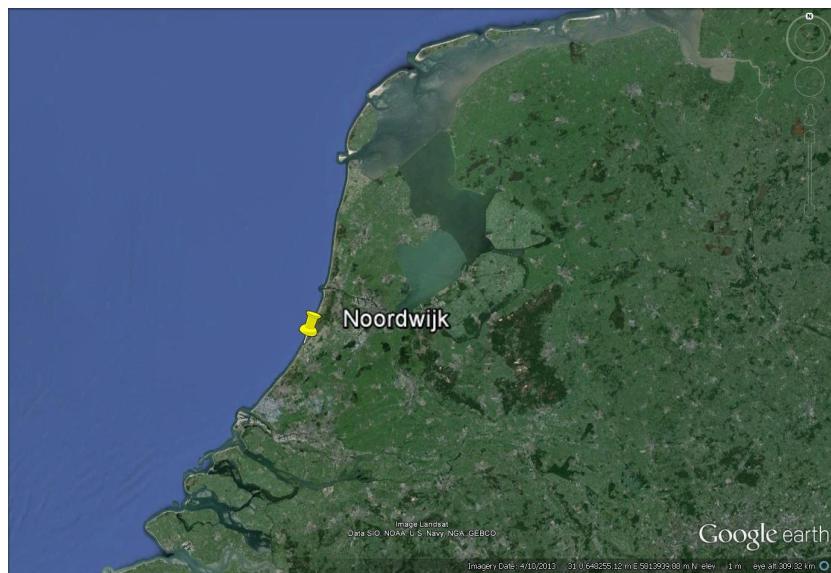


Figure 4.1 Map of The Netherlands and location of Egmondaan Zee.

### 4.3 Model set-up

#### 4.3.1 General description of the model

Grain size was assumed to be described by a  $D_{50}$  and a  $D_{90}$  respectively equal to 0.18 and 0.28 mm. The model was calibrated by Walstra et al. (2012) against cross-shore profile development available between the years 1984 and 1987, in particularly focussing on the following parameters: breaker-delay  $\lambda$ , angle of repose  $\tan\varphi$ , and the current-related roughness  $k_c$ . The resulting optimum set was  $\lambda = 2.76$ ,  $\tan\varphi = 0.157$ , and  $k_c = 0.0056$  m. According to their hindcast simulations, the offshore bar migration was well predicted by the model, nevertheless with an underestimation of the bar amplitude.

#### 4.3.2 Boundary conditions

As the effect of different types of nourishments on the nearshore and beach morphological development differs according to the time scale under consideration, (i.e. beach nourishments have an immediate effect, shoreface nourishments a more delayed effect), it was decided to run the UNIBEST model, originally set-up by Walstra et al. (2012) for a period of about 3 years, for a simulation period extended to 10 years. This was done by repeating the time series of boundary conditions (wave conditions and water levels) approximately 3 times. Figure 4.2 shows the wave boundary conditions.

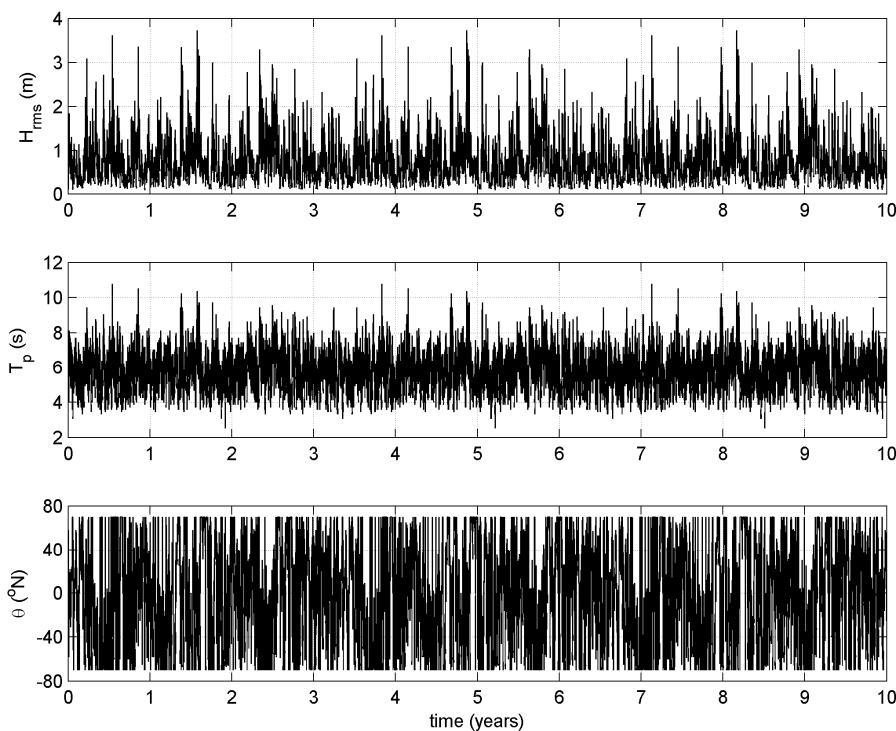


Figure 4.2 Wave forcing used as input to the Unibest-TC model: root-mean-square wave height (upper panel), spectral peak period (middle panel) and angle of wave incidence (lower panel).

## 4.4 Beach-dune module

### 4.4.1 Review on beach-dune modules

Different empirical relations exist in literature which relate changes to the dune foot position to variation in beach width. Based on a 130-years long time series of the Holland coast, De Vriend&Roelvink (1990) found the following relation between the dune foot migration and the beach width:

$$\frac{\partial x_{df}}{\partial t} = \begin{cases} \alpha_{off} (B - B_{eq}) & \text{if } B > B_{eq} \\ \alpha_{on} (B - B_{eq}) & \text{if } B \leq B_{eq} \end{cases} \quad (4.1)$$

with  $x_{df}$  the horizontal dune foot position (positive in the offshore direction),  $\alpha_{off} = 0.024$  1/year an empirical coefficient related to the offshore movement of the dune foot,  $\alpha_{on} = 0.13$  1/year an empirical coefficient related to the onshore movement of the dune foot,  $t$  is time,  $B = (x_{lw} - x_{df})$  the beach width with  $x_{lw}$  the horizontal position of the low water line and  $B_{eq} = 115$  m the equilibrium beach width.

This equation indicates that a cross-shore bed profile strives for an equilibrium beach width. For a wide beach the cross-shore sediment transport between the beach and dune is controlled by aeolian transport which is a relatively slow process and for a narrow beach by the relative fast process of dune erosion. This expression is the one which is implemented in Delft3D (Tonnon et al., 2009; Giardino et al., 2010) and it has been implemented in UNIBEST-TC within this present work.

Huisman (2012) presents a different approach based on research by Arens et al. (2009), De Vries et al. (2012) and others to account for dune growth and erosion. It is based on the same principle, namely that dune migration is the result of the difference between aeolian transport towards the dunes and erosion processes, both mainly controlled by the beach width. The expression for rate of dune volume change or sediment transport from the beach to the dune [ $m^3/year$ ] reads:

$$q_{bd} = \begin{cases} \max\left(\left[C_{max}\left(1 - e^{-\frac{(B-B_{thr})}{B_{half}}}\right)\right], 0\right) & \text{if } B > B_{thr} \\ \frac{H_{active}}{(H_{active,dunes} + H_{active})} H_{active,dunes} \frac{(B_{thr} - B)}{dt} & \text{if } B \leq B_{thr} \end{cases} \quad (4.2)$$

where  $C_{max}$  is the maximum dune growth rate (for infinitely wide beaches),  $B$  is the beach width,  $B_{thr}$  is the threshold beach width between dune growth and dune erosion,  $B_{half}$  is a relaxation parameter defining the dune growth between zero and its maximum value,  $H_{active}$  is the active height of the coastline (between the closure depth and the dune foot),  $H_{active,dunes}$  is the active height of the dune, and  $dt$  the computational time step.

This equation states that if the beach width is smaller than the threshold beach width, a volume of sediment is transported instantaneously (in one time step) from the dunes to the beach to set the beach width to this threshold value. The ratio between the active height of the coastline and the total active height ensures conservation of mass, i.e. the volume change

associated with dune retreat matches the volume change associated with the progression of the coastline.

Huisman(2012) used the following typical values:  $B_{thr} = 80$  m,  $C_{max} = 80$  m<sup>2</sup>/year,  $B_{half} = 150$  m,  $H_{active} = 15$  m and  $H_{active, dunes} = 5$  m.

Figure 4.3 shows the dune foot migration rate as a function of the beach width (defined as the horizontal distance between dune foot and the low water line) based on different relations between the two parameters. The red line shows the dune foot migration computed based on the Huisman (2012) relation with a time step  $dt$  of 1 year, where  $q_{bd}$  is translated to dune foot migration by dividing by the active dune height. The dark blue line shows the dune foot migration computed based on De Vriend&Roelvink (1990) and using their coefficients for offshore ( $\alpha_{off}$ ) and onshore ( $\alpha_{on}$ ) migration. The dashed blue line describes the dune foot migration based on the De Vriend&Roelvink (1990) relation, with coefficients for onshore and offshore migration tuned in order to mimic the Huisman (2012) relation. In particular, the coefficient for onshore migration was set to  $4\alpha_{on}$ , the coefficient for offshore migration to  $2\alpha_{off}$ , and  $B_{eq}$  to 107 m. Finally, the light blue line shows the dune foot migration computed with the De Vriend&Roelvink (1990) relation, with the coefficient as used in Delft3D:  $\alpha_{on} = 0.08$  1/year,  $\alpha_{off} = 0.024$  1/year and  $B_{eq} = 125$  m.

De Vries et al. (2012) defined the beach width as the horizontal distance between the dune foot and the waterline described as the average between mean high water and mean low water. This corresponds to NAP ~0 m, and therefore we compute the beach width that goes into Eq. (4.2) in the following manner:

$$B_{mw} = B_{lw} \frac{(z_{df} - z_{mw})}{(z_{df} - z_{lw})} = 0.75B_{lw} \quad (4.3)$$

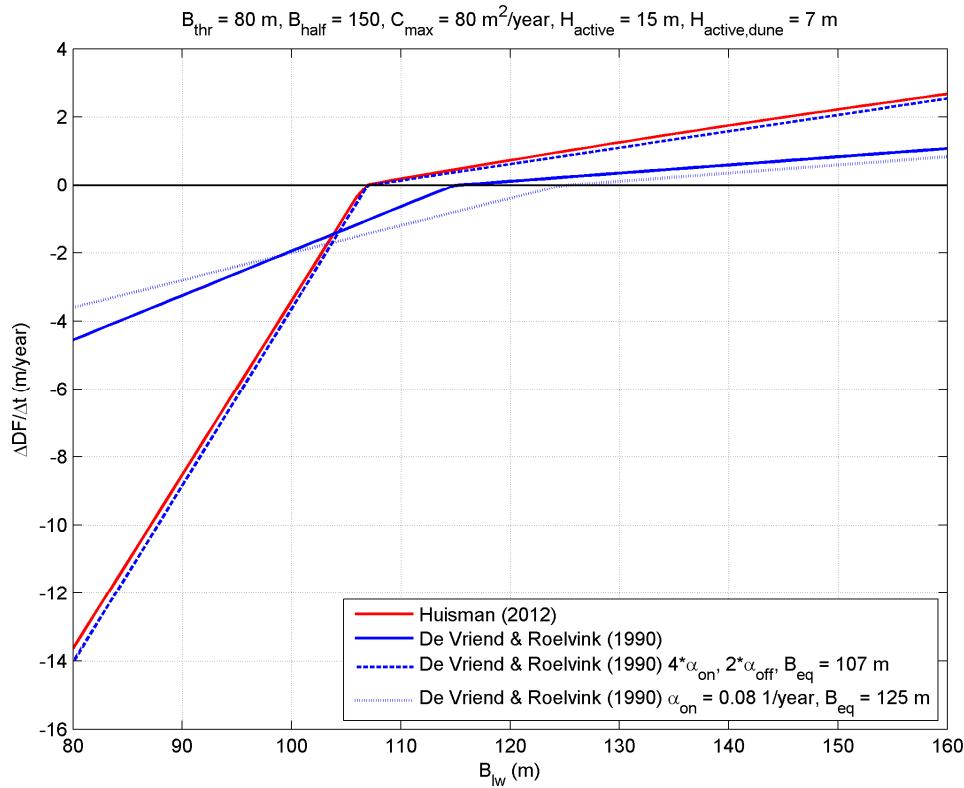


Figure 4.3 Dune foot migration rate as a function of the beach width. Positive values indicate offshore dune migration, i.e. dune growth.

The figure shows that the standard De Vriend&Roelvink (1990) relation (dark blue line) predicts smaller changes in dune foot position in response to changes in beach width compared to the Huisman (2012) relation. This also holds for the relation with the coefficients as implemented in Delft3D. Nevertheless, by calibrating the coefficient for onshore and offshore migration and the beach width, it is possible to mimic the Huisman (2012) relation by means of the De Vriend&Roelvink (1990) equation. Their calibration coefficients have been derived for the entire Holland coast. Nevertheless, Damsma (2009) has shown that their variability is quite large for different locations along the Dutch coast and therefore a more refined calibration might be necessary when considering a local area of interest.

#### 4.4.2 Implementation of the beach-dune module in UNIBEST-TC and other changes to the code

##### 4.4.2.1 Concept

The above-described beach-dune module of De Vriend&Roelvink (1990) was implemented and used in Delft3D by Tonnon et al. (2009) and Giardino et al. (2010). They assumed that the entire profile (i.e. starting from the LW-line) shifts with the computed dune migration rate while thus retaining its shape. The bed level change ( $z_b$ ) per grid cell then follows from:

$$\frac{\partial z_b}{\partial t} = - \frac{\partial x_{df}}{\partial t} \frac{\partial z_b}{\partial x} \quad (4.4)$$

where the cross-shore coordinate is positive in the onshore direction. This equation states that an offshore (onshore) dune migration, i.e. positive (negative)  $\partial x_{df} / \partial t$ , results in sedimentation (erosion) of the dry part of the profile as the bed slope is mostly negative. The total sediment loss or gain in the dry profile is taken from or put in grid cells offshore from the LW-line, to ensure continuity of mass. This is illustrated in Figure 4.4.

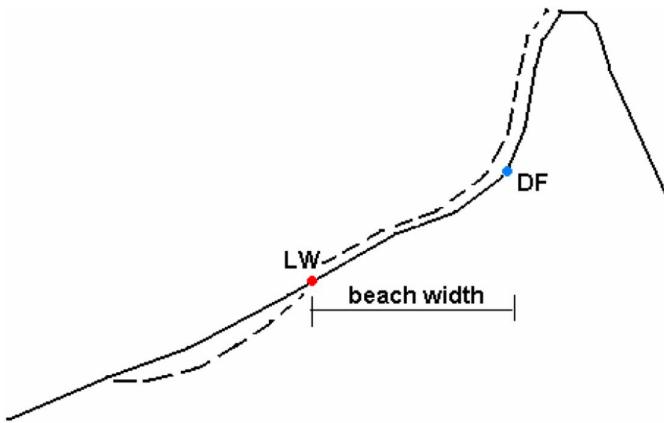


Figure 4.4 Schematization of the beach-dune module as implemented in Delft3D. Changes to the beach width leads to a shift of the entire dune profile from the low water line up to the top of the dunes. The sand for the landward and seaward shift of the dune profile is taken seaward of the low water line (Giardino et al., 2010).

However, the correctness of the LW-line as breakpoint between sedimentation and erosion as implemented in Delft3D is debatable, as the beach-dune module was originally intended to model the interaction between the high active part of the profile (between NAP -3 m and +3m) and the dune front ( $>$  NAP +3 m), which cannot be properly modelled by existing process-based morphological models. Therefore, in line with De Vriend&Roelvink (1990), in this study we choose the dune foot position as the boundary between sedimentation and erosion, i.e. sediment is exchanged between the beach (defined as the part of the profile between the user-defined low water line and the dune foot position) and the dune area (higher than the dune foot position), without a direct change in profile below the low water line due to beach-dune module. This conceptually means that we have de-coupled the bed level change for the parts of the profile lower and higher than the low water line; the first is controlled by the regular bed updating by Unibest-TC and the latter by the newly-implemented beach-dune module. We are aware that this does not fully represent the real situation, as actually there is interaction between the two and the behaviour of the upper part of the profile is now forced towards an equilibrium defined by the pre-defined equilibrium beach width.

#### 4.4.2.2 Code changes

The starting point was the Unibest-TC version used by Walstra et al. (2012), v204-v4\_Gerben\_official\_lin\_04\_output. At each time step, after the “regular” bed updating carried out by the standard UNIBEST-TC model, the STEP.FOR routine calls the new routine BEACHWIDTH.FOR, which takes care of the morphological changes due to the beach-dune module. Table 4.1 shows the new input parameters used by this new routine:

Table 4.1 Input beach-dune module

Parameter	Description	Default setting
Use_DM	Switch for beach-dune module; 0 = off, 1 = on	0
D_LW	Vertical position low water line with respect to still water level	-1 m
D_DF	Vertical position dune foot with respect to still water level	+3 m
D_BEQ	Equilibrium beach width	115 m
D_FACON	Coefficient onshore dune foot migration	0.080 1/year
D_FACOFF	Coefficient offshore dune foot migration	0.024 1/year
D_FAC	Scaling factor dune foot migration	1
D_DVMAXON	Maximum onshore dune migration	1000 m/year
D_DVMAXOFF	Maximum offshore dune migration	1000 m/year

To control unrealistic beach erosion, Walstra et al. (2012) have imposed a fixed layer, see Figure 4.5. As this fixed layer prevents erosion of the beach-dune, we do not adopt it when we update the bed level in the beach-dune module. Furthermore, we adjust the vertical position of the fixed layer with the bed level change according to the changes computed by the beach-dune module. Otherwise the erosion will be undone during the regular bed level updating in the next time step. The same also yields for the sedimentation.

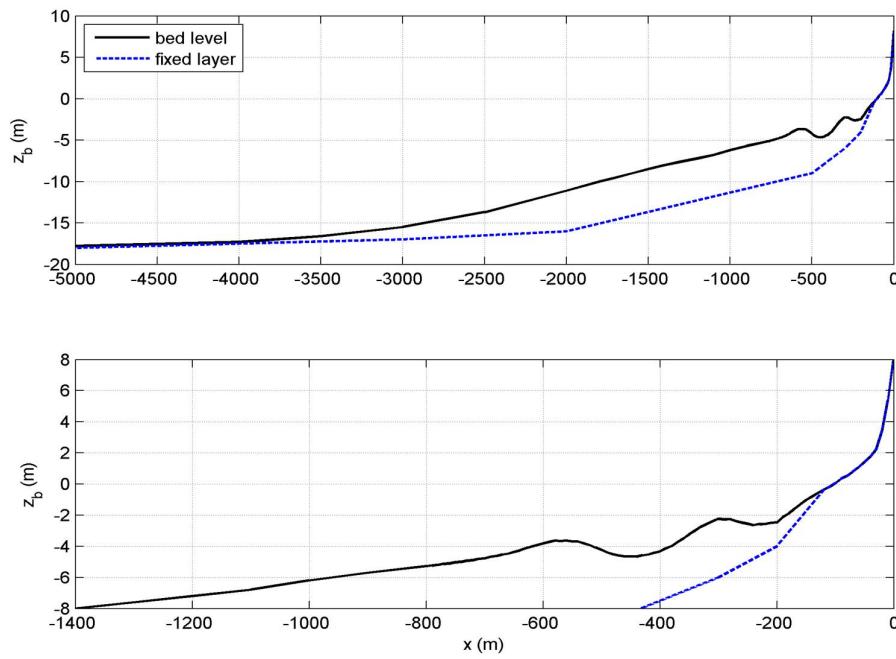


Figure 4.5 Location initial bed level (black line) and fixed layer (blue dotted line) in Walstra et al.'s (2012) Unibest-TC model. The lower panel is a zoom of the top panel which displays the complete model.

The FORTRAN routine BEACH\_PARAMS.FOR called from STEP.FOR has also been added to compute a number of coastal indicators at each time step useful for policy makers and which will be used as input in the Bayesian network (Chapter0). The indicators which are computed are: the beach volume, the dune foot position, the MKL volume and the MKL position. Another adjustment is related to the wave computation in ENDEC.FOR.

The (local) maximum wave height is limited to GAMMAX times the (local) water depth to avoid unrealistic large waves, with GAMMAX a new, user-defined keyword.

## 4.5 Results

### 4.5.1 List of model runs

A number of simulations have been run to test the validity of the implementation of the beach-dune module and to test its sensitivity to different parameter settings. In particular, the following configurations and parameters have been tested:

- Inclusion/exclusion of the beach-dune module
- Change to the equilibrium beach width  $B_{eq}$
- Change to the coefficient for onshore movement of the dune foot  $\alpha_{on}$
- Change to the coefficient for offshore movement of the dune foot  $\alpha_{off}$
- Change to the vertical position of the low water line D\_LW
- Change in position of the fixed layer

An overview of the model runs is given in Table 4.2.

Table 4.2 Overview of the UNIBEST-TC test simulations

Run ids	Beach-dune module	$B_{eq}$ (m)	$\alpha_{on}$ ( $yr^{-1}$ )	$\alpha_{off}$ ( $yr^{-1}$ )	D_LW (m NAP)	Remarks
01-07	No	-	-	-	-	
08-14	Yes	115	0.13	0.024	-1	Default settings beach-dune model
22-28	Yes	125	0.08	0.024	-1	"Tonnon" settings beach-dune model
36-42	No	-	-	-	-1	Fixed layer 0.5 m lower
43-49	Yes	115	0.13	0.024	-1	Fixed layer 0.5 m lower
50-56	No	-	-	-	-1	Fixed layer 1.0 m lower
57-63	Yes	115	0.13	0.024	-1	Fixed layer 1.0 m lower
64-70	Yes	100	0.13	0.024	-1	Smaller equilibrium beach width
78-84	Yes	115	0.13	0.120	-1	Larger offshore migration coefficient
85-91	Yes	115	0.13	0.024	-2	Lower vertical position low water line
92-98	Yes	107	0.13	0.048	-1	"Huisman" settings beach-dune model

The different model set-up have been tested for 7 different bed profiles: 1 without nourishment, 3 shoreface nourishment cases, 1 beach nourishment case, and 2 combined beach and shoreface nourishments (Figure 4.6).

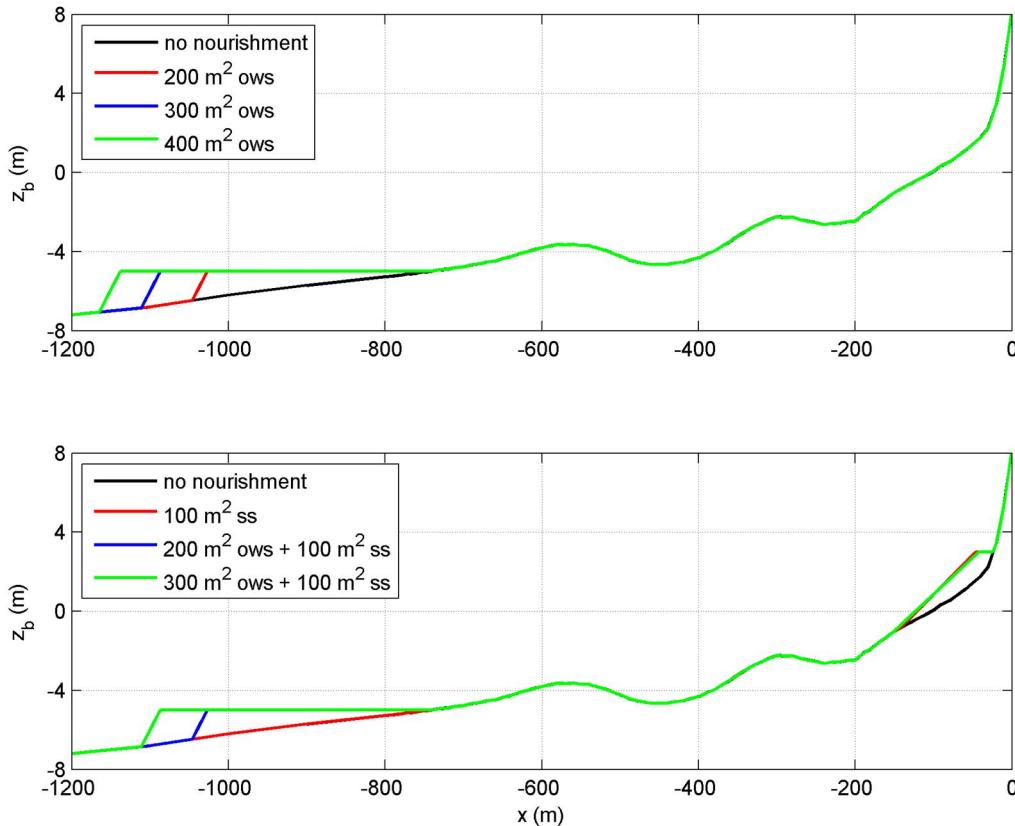


Figure 4.6 Simulated nourishment scenarios. In the figure above, different shoreface nourishment configurations, in the figure below different configuration of beach nourishments and combined shoreface and beach nourishments.

#### 4.5.2 Sensitivity of morphological indicators to different model settings

Figure 4.7 - Figure 4.13 show the impact of different nourishment schemes on the beach width, MKL volume, MKL position and dune foot position, for different parameter settings. The different settings which were tested are listed in Table 4.2. Changes to the morphological indicators are shown after 10 year simulation, i.e. the final beach width minus the initial beach width (without nourishment) and so on for the other parameters. In particular, Figure 4.7 shows the morphological changes with the beach-dune module switched off, Figure 4.8 using the default settings for the beach-dune module, Figure 4.9 using the “Tonnon” settings, Figure 4.10 changing the equilibrium beach width to 100 m instead of 115 m, Figure 4.11 using a five times larger  $\alpha_{off}$  coefficient for offshore dune foot migration, Figure 4.12 changing the low water line at NAP -2 m instead of NAP -1 m, and Figure 4.13 using the “Huisman” settings.

For each set of parameter, seven different simulations were run corresponding to the following situations (see Figure 4.6):

- No nourishment.
- Shoreface nourishment only of 200 – 300 and 400  $m^3/m$ .
- Beach nourishment only of 100  $m^3/m$ .
- Beach nourishment of 100  $m^3/m$  combined with shoreface nourishment of 200 and 300  $m^3/m$ .

The  $\alpha$ 's shown in the lower two plots of each figure represent the slopes of the blue lines, fitting the model results. Those slopes represent the impact of nourishments on relative changes of the different morphological indicators. We compare these values to the ones computed by Giardino and Santinelli (2013a) based on data analysis for the entire Holland coast; on the basis of data analysis they found that the best fitting line between nourishment volumes and shift in MKL position had a slope of 0.027 m and for the dune foot position a slope of 0.023 m (Figure 5.8).

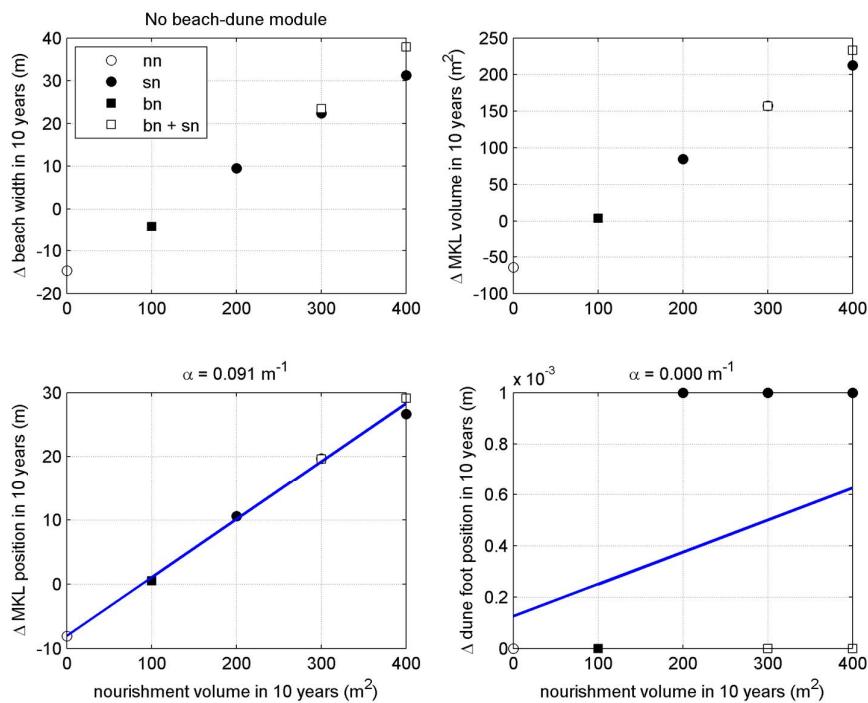


Figure 4.7 Change in beach width, MKL volume, MKL position and dune foot position as function of the total nourishment volume computed with the beach-dune module switched off.

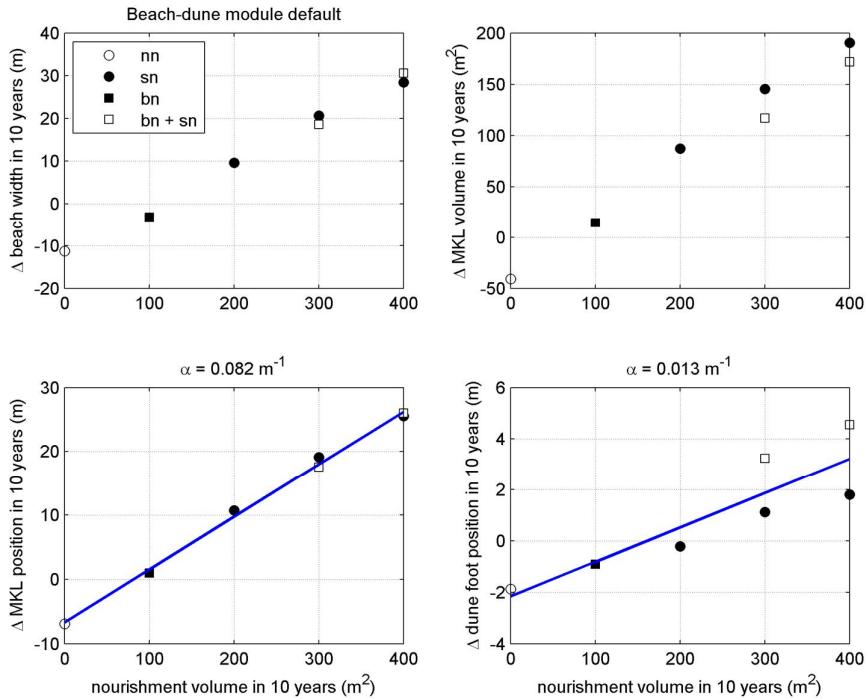


Figure 4.8 Change in beach width, MKL volume, MKL position and dune foot position as function of the total nourishment volume computed with the default settings of the beach-dune module.

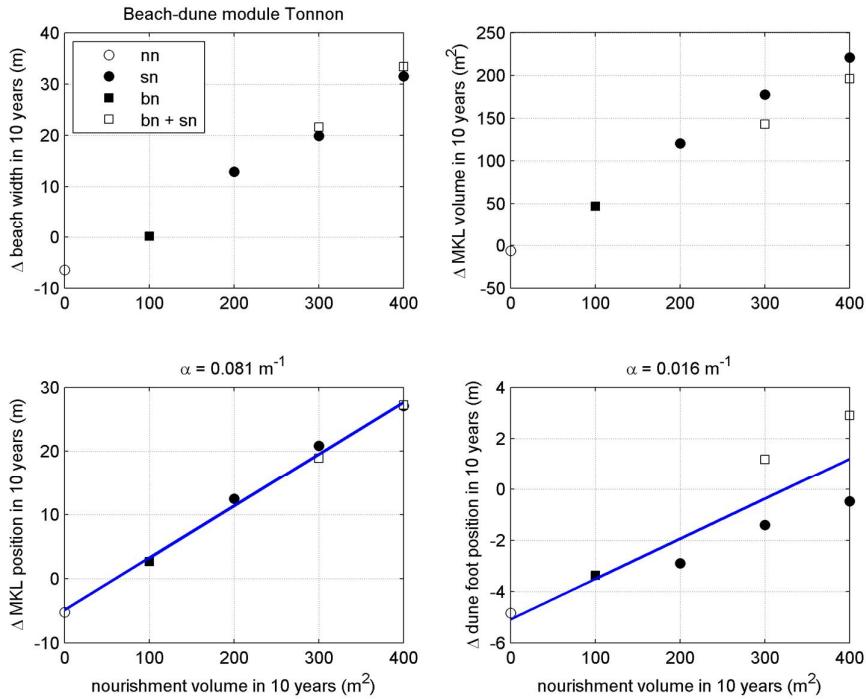


Figure 4.9 Change in beach width, MKL volume, MKL position and dune foot position as function of the total nourishment volume computed with the "Tonnlon" settings of the beach-dune module.

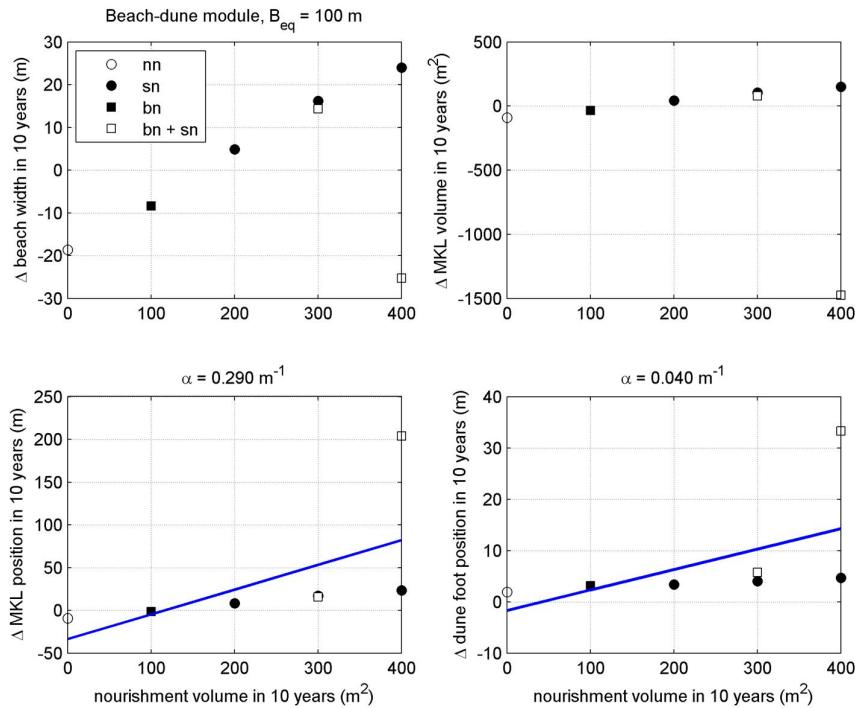


Figure 4.10 Change in beach width, MKL volume, MKL position and dune foot position as function of the total nourishment volume computed with the beach-dune module with an equilibrium beach width of 100 m.

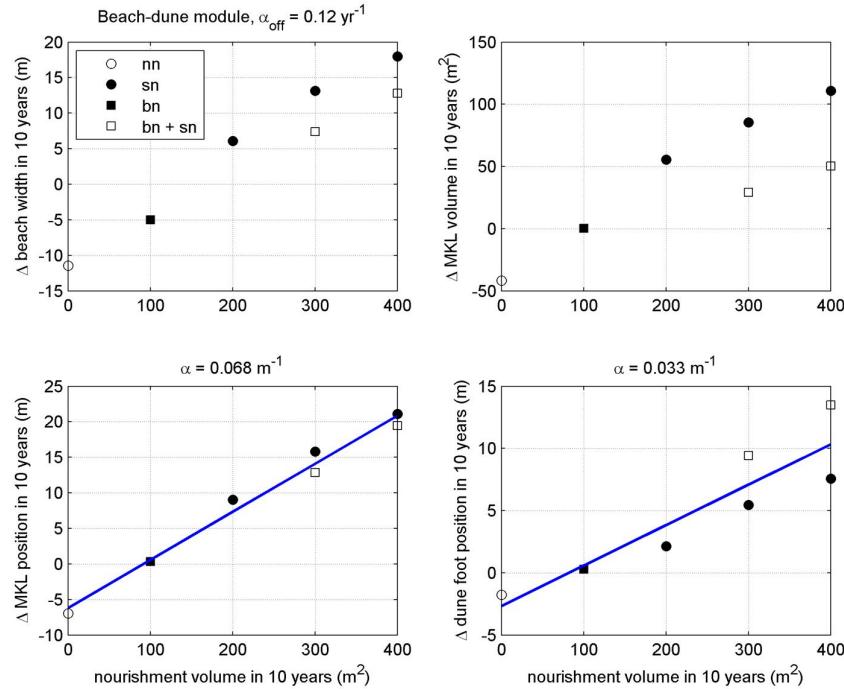


Figure 4.11 Change in beach width, MKL volume, MKL position and dune foot position as function of the total nourishment volume computed with the beach-dune module with an offshore migration coefficient of 0.12 1/year.

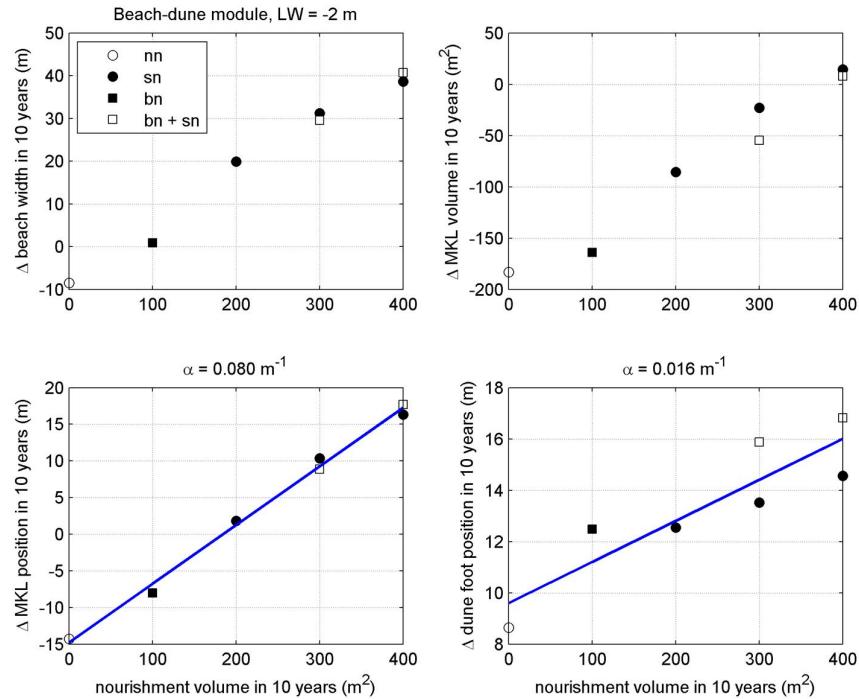


Figure 4.12 Change in beach width, MKL volume, MKL position and dune foot position as function of the total nourishment volume computed with the beach-dune module with the low water line at NAP –2 m.

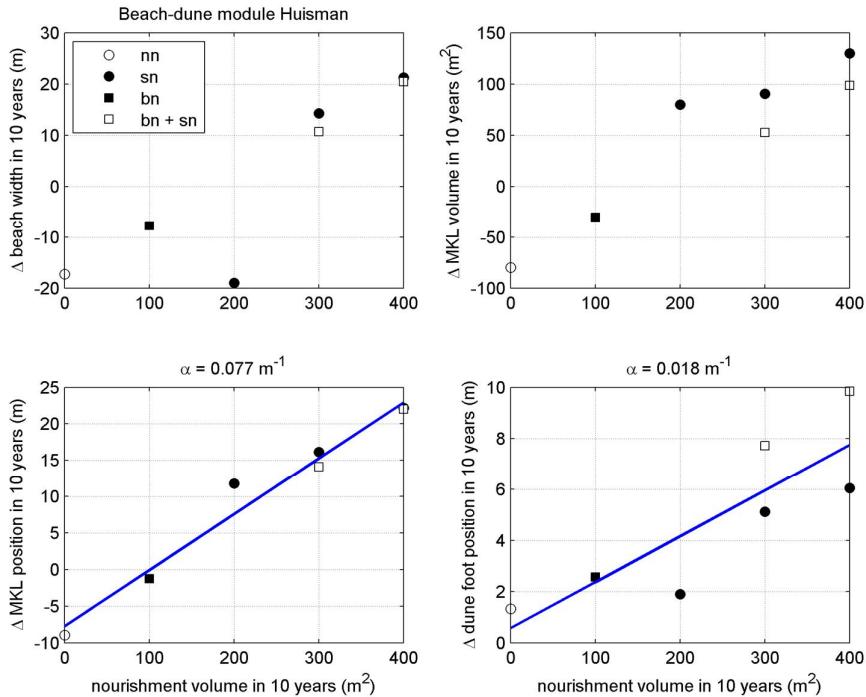


Figure 4.13 Change in beach width, MKL volume, MKL position and dune foot position as function of the total nourishment volume computed with the "Huisman" settings of the beach-dune module.

Best agreement with the trend derived by Giardino&Santinelli (2013) for the dune foot position is obtained with the beach-dune module switched on with a larger coefficient for the offshore movement of the dune foot (see Figure 4.11). It should be noted however, that there is a lot a scatter in the observation data too as data analysis was derived based on data from the entire Holland coast. For the present work, we will stick to these model settings, which showed the best agreement.

In general, the simulations show that nourishments are able to shift from a general erosive trend in case of no nourishment, towards a positive trend. Table 4.3 summarizes the changes in indicators after 10 years for the situation without nourishment and for all simulated types of nourishments. The table suggests that shoreface nourishment after 10 years are more effective than beach nourishment or a combination of beach and shoreface nourishments with the same volume, in increasing the beach width and the MKL volume. Sand put on the beach gets in fact rapidly eroded in the model moving offshore and partly to the dunes. The effects of shoreface and beach nourishments on MKL position after 10 years are very similar. Nevertheless, the values in the table clearly show that using beach nourishments or a combination of beach and shoreface nourishments it is possible to create the boundary conditions for a much larger offshore dune migration. As an example, a shoreface nourishment of 400 m<sup>3</sup> can lead to an offshore dune migration of 8 m, while a combination of 100 m<sup>3</sup> of beach nourishment and 300 m<sup>3</sup> ofshoreface nourishment, can induce an offshore dune migration of 13 m. Offshore dune migration is in general also a very good indicator for an improvement of the safety level (decrease in probability of failure) (Giardino et al., 2013).

*Table 4.3 Relative change in beach width, MKL volume, MKL position and dune foot position after 10 years for the reference case without nourishment and after implementing the different types of nourishments.*

Nourishment	$\Delta BW$ (m)	$\Delta MKL$ vol (m <sup>2</sup> )	$\Delta MKL$ pos (m)	$\Delta DF$ (m)
0	-11	-42	-7	-2
200 sn	+6	+55	+9	+2
300 sn	+13	+85	+16	+5
400 sn	+18	+111	+21	+8
100 bn	-5	+0	+0	+0
100 bn + 200 sn	+7	+29	+13	+9
100 bn + 300 sn	+13	+50	+19	+13

The beach-dune module appears to be very sensitive to the imposed equilibrium beach width (Figure 4.10) and the vertical position of the low water line (Figure 4.12). Given the actual beach width, the equilibrium beach width determines whether the dune area will progress or degrade and how fast this process will take place. The definition of the low water line determines the actual beach width and by this also the regime of volume change in the beach and dune area.

#### 4.5.3 Effect beach-dune module

In this section, the effect of using the beach-dune module is illustrated for the following two cases: i) without nourishment (reference case) and ii) with a 400 m<sup>2</sup>shoreface nourishment. Figure 4.14 - Figure 4.19 show for these two cases the Unibest-TC predictions of the bed level, beach width, MKL volume, MKL position, dune migration rate and dune foot position, distinguishing between runs with the beach-dune module switched on (with the settings that gave closest agreement with observed data, see previous section) and off.

For the case without nourishment, Figure 4.14 shows that the beach-dune module has only a minor effect and limited to the upper part of the profile (above the low water line), while the breaker bars remain unaffected. Beach changes in time are shown in Figure 4.16. In particular, for the case without beach-dune module, as shown by the red line in Figure 4.16, the beach width is in average quite stable with a minimum width of ~110 m because erosion is limited by the imposed fixed layer (Section 4.5.4). Occasionally, the beach becomes wider due to the presence of accreting wave conditions. Switching on the beach-dune module (Figure 4.16, blue line), the same event-driven changes of the beach width can be seen, but now there is also a long term tendency to the imposed equilibrium value of 115 m, which is almost reached after 10 years, for the no nourishment situation. Similarly to an increase in beach width, an increase in MKL volume and MKL position can be expected switching on the beach-dune module. As the starting beach width is smaller than the equilibrium beach width, this will also promote a landward shift of the dune foot position of almost 2 m after 10 years (Figure 4.18).

For the 400 m<sup>2</sup>shoreface nourishment case, we see a stronger effect of the beach-dune module on the higher part of the bed profile (>~ -1 m) compared to the no nourishment case Figure 4.15). In general, the nourishment will promote an increase in beach width, MKL volume, a seaward shift in MKL position (Figure 4.17), and dune foot position (Figure 4.19), with respect to the case without nourishment. The first 3 years of the simulation, the dune foot migrates onshore as the beach width is smaller than the equilibrium value (Figure 4.19). At the same time, sand is transported from the nourishment to the MKL zone by which the beach becomes wider. After about 3 years, the beach is wider than the equilibrium value and the dune starts to migrate in the offshore direction.

As this sediment comes from the area between the lower water line (NAP -1 m) and the dune foot (NAP +3 m) this results into a relative (compared to the simulation with the beach-dune module switched off) decrease in beach width and MKL volume (Figure 4.17). After 10 years the dune has migrated approx. 7 m in the offshore direction as a result of beach-dune interaction (Figure 4.19).

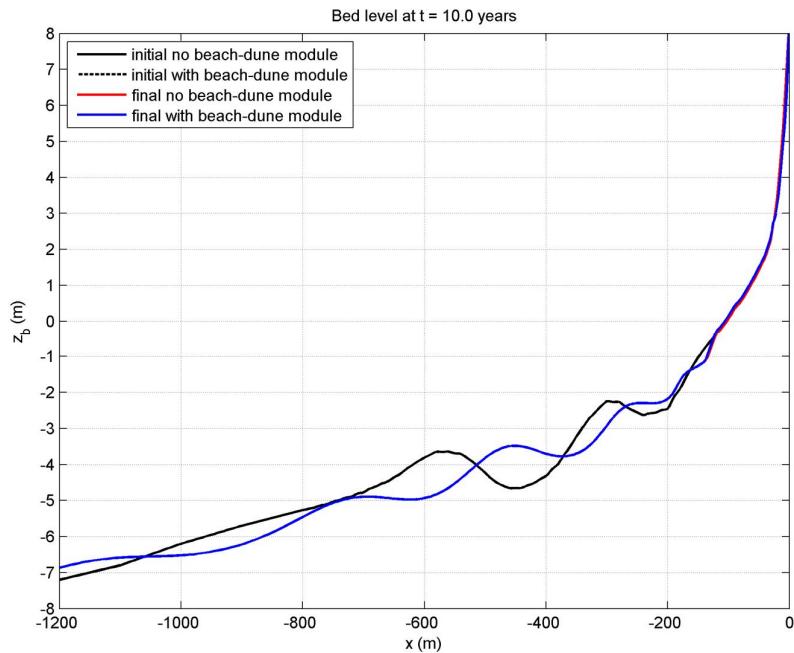


Figure 4.14 Effect of using beach-dune module on bed levels computed by Unibest-TC; no nourishment case.

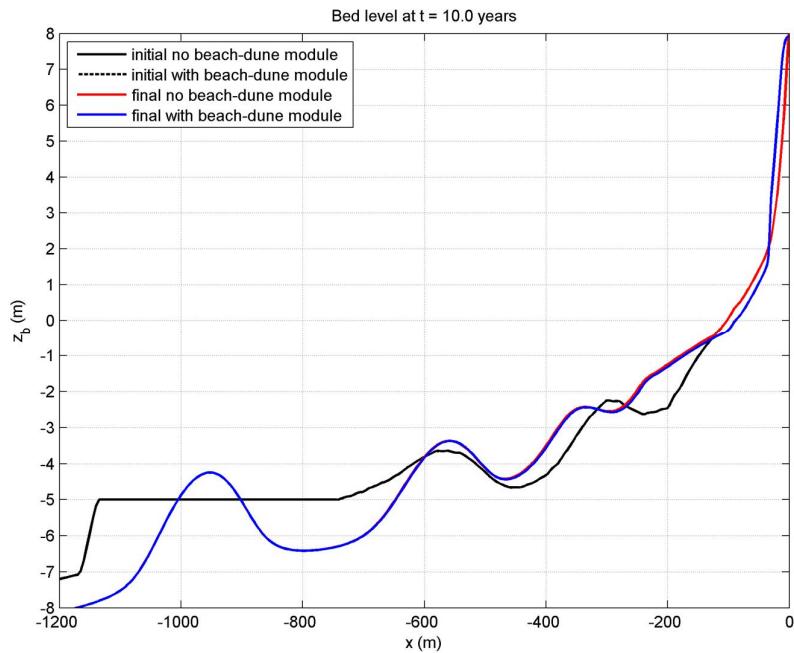


Figure 4.15 Effect of using beach-dune module on bed levels computed by Unibest-TC; 400 m<sup>2</sup> shoreface nourishment case.

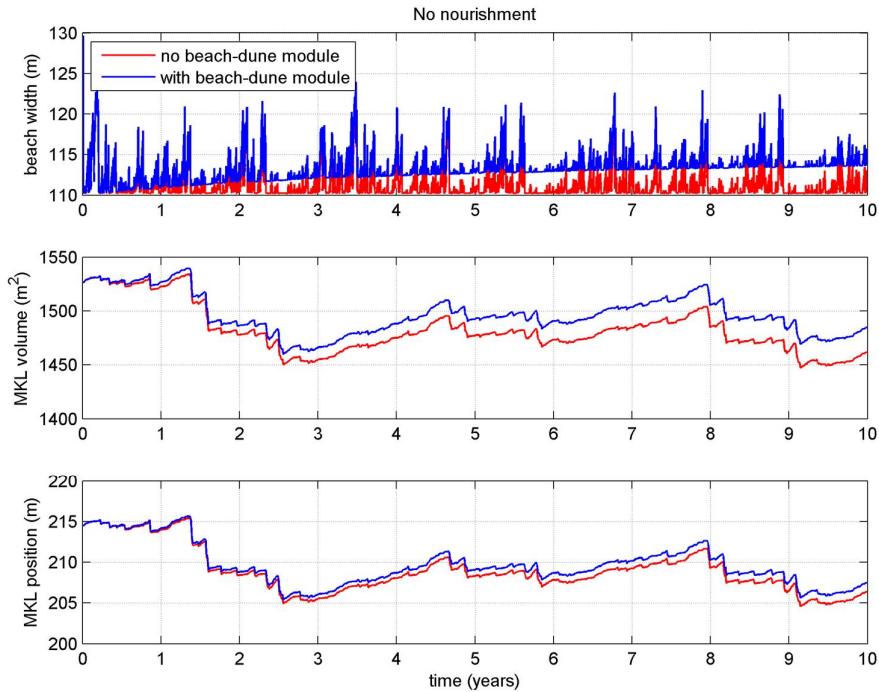


Figure 4.16 Effect of using beach-dune module on beach width, MKL volume and MKL position computed by Unibest-TC; no nourishment case.

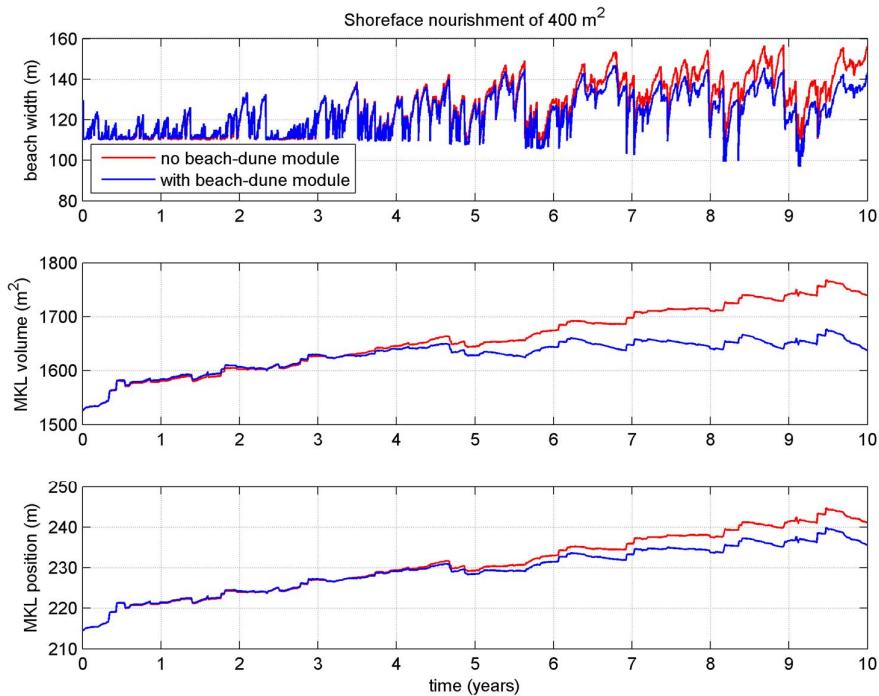


Figure 4.17 Effect of using beach-dune module on beach width, MKL volume and MKL position computed by Unibest-TC; 400  $m^2$  shoreface nourishment case.

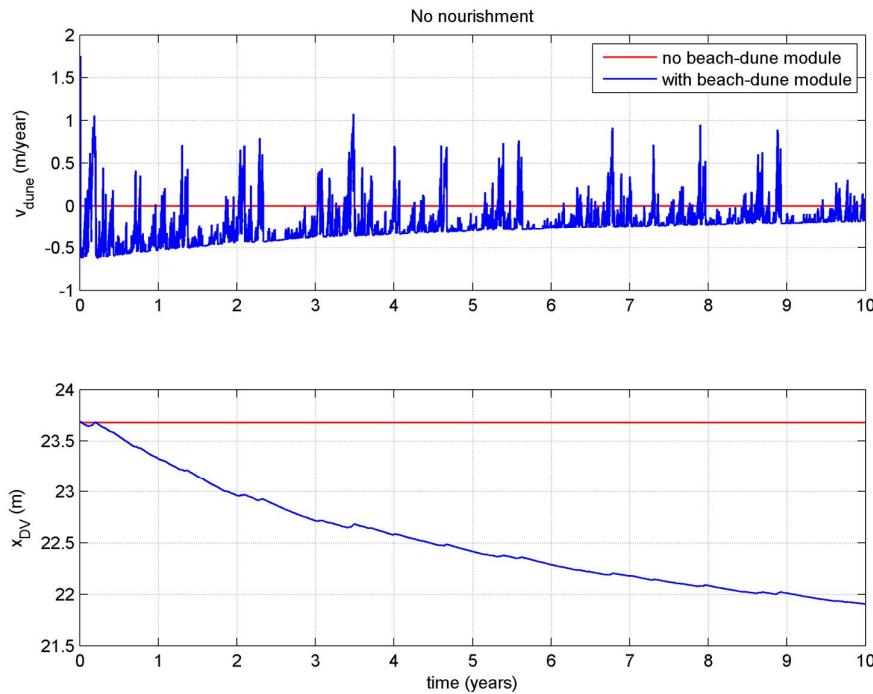


Figure 4.18 Effect of using beach-dune module on dune migration rate and dune foot position computed by Unibest-TC; no nourishment case.

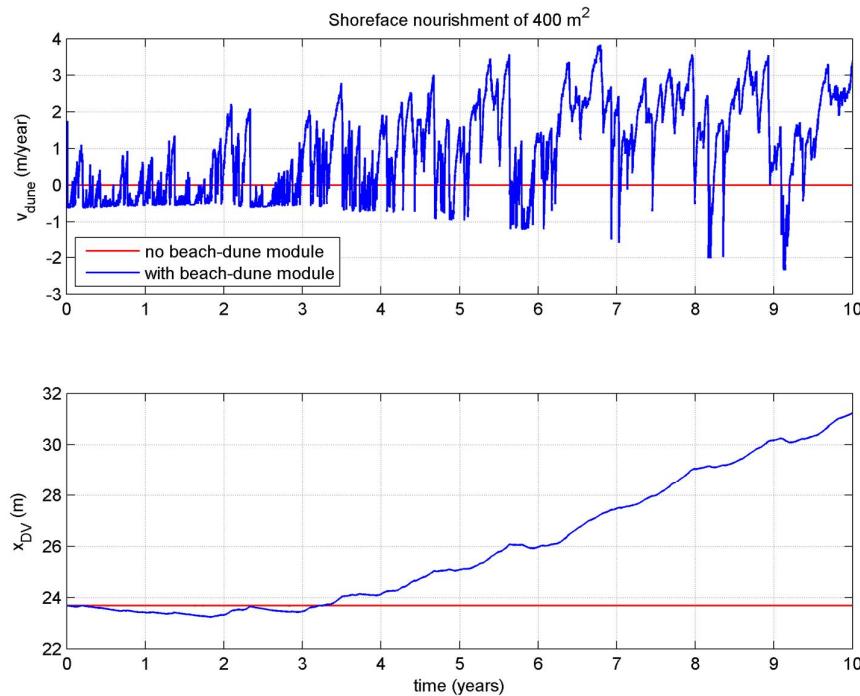


Figure 4.19 Effect of using beach-dune module on dune migration rate and dune foot position computed by Unibest-TC; 400 m<sup>2</sup> shoreface nourishment case.

#### 4.5.4 Effect fixed-layer position

For the same two initial bed levels, Figure 4.20- Figure 4.25 show the effect of the initial fixed layer position on the Unibest-TC predictions. The fixed layer is used to avoid excessive erosion of the beach during the simulation, by stopping it whenever the fixed layer is reached after erosion of the sand above it. These are runs with the default settings of the beach-dune model (Table 4.2), but changing the position of the fixed layer from the default position, to a position respectively 0.5 m and 1.0 m lower.

These figures show that the (initial) fixed layer position has a strong effect on the bed levels of the beach and dune area. In a few time steps the bed level is in fact eroded until the fixed layer. This can be seen in the sudden initial increase in beach width, MKL volume and position (Figure 4.22 and Figure 4.23) and decrease in dune foot position (Figure 4.24 and Figure 4.25). This eroded sand ends up in the MKL zone, and therefore the MKL volume and position initially increase strongly. For the no nourishment case, we also see some effect on the breaker bars (Figure 4.20), whereas for the 400 m<sup>2</sup>shoreface nourishment case this effect is overruled by the nourishment impact (Figure 4.21). The trends in the morphological parameters are comparable, despite the position of the fixed layer. In the 400 m<sup>2</sup>shoreface nourishment case, the lines tend to convergence in time, i.e. the difference due to the initial fixed layer becomes smaller.

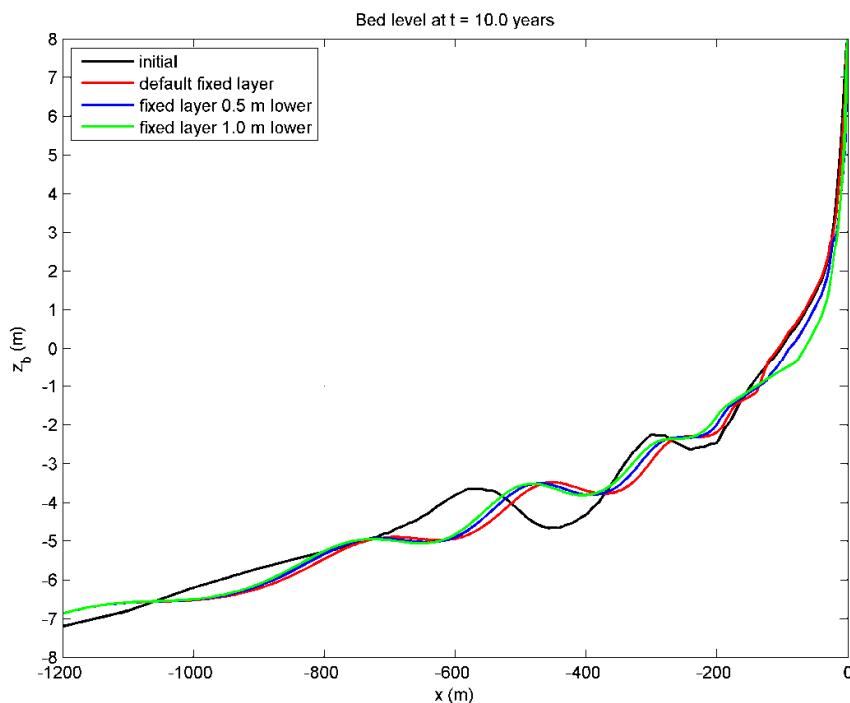


Figure 4.20 Effect of fixed layer position on bed levels computed by Unibest-TC; no nourishment case.

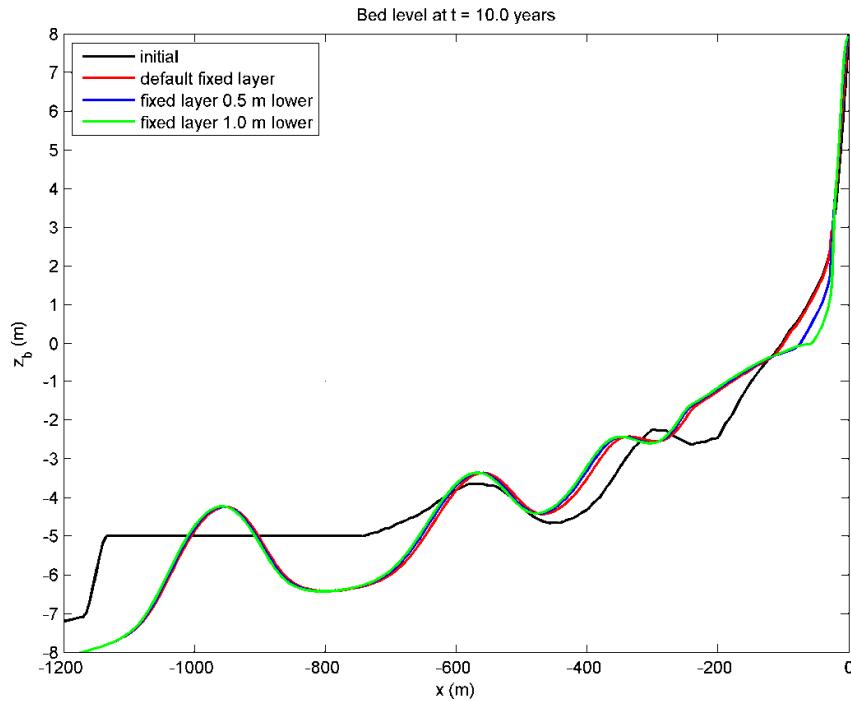


Figure 4.21 Effect of fixed layer position on bed levels computed by Unibest-TC;  $400 \text{ m}^2$  shoreface nourishment case.

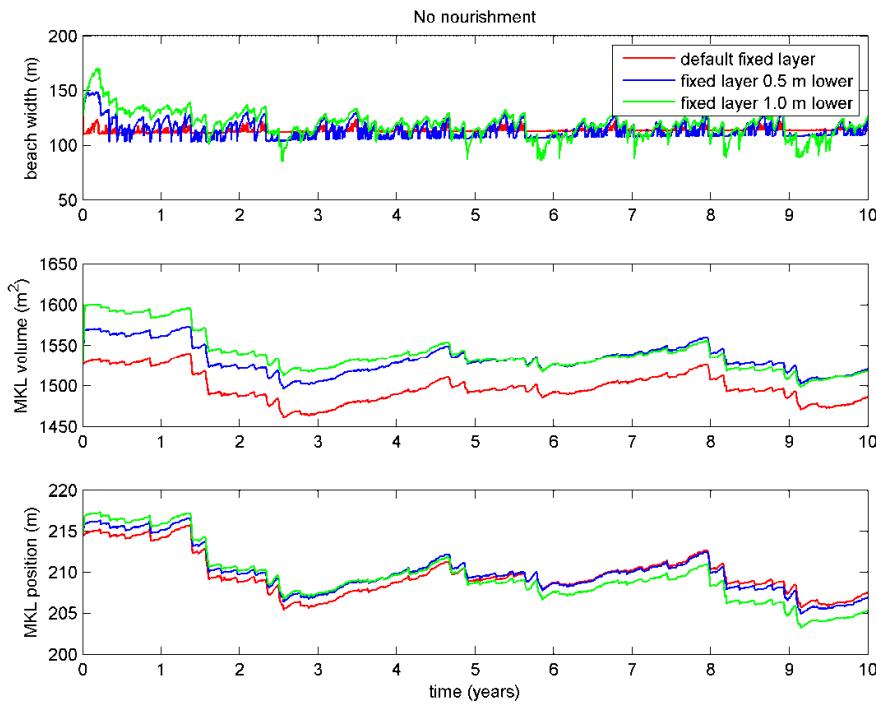


Figure 4.22 Effect of fixed layer position on beach width, MKL volume and MKL position computed by Unibest-TC; no nourishment case.

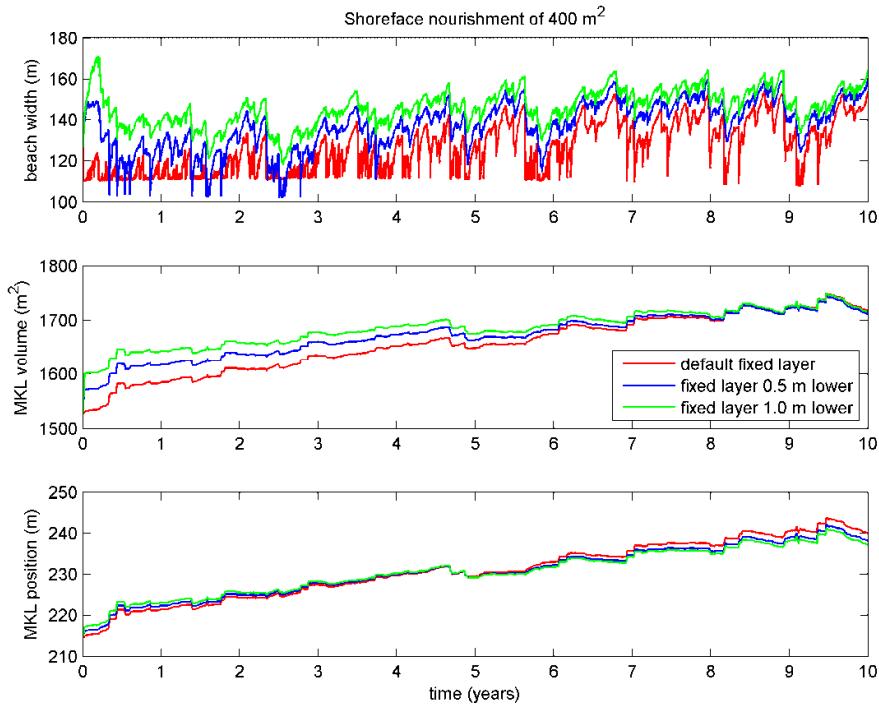


Figure 4.23 Effect of fixed layer position on beach width, MKL volume and MKL position computed by Unibest-TC; 400  $m^2$  shoreface nourishment case.

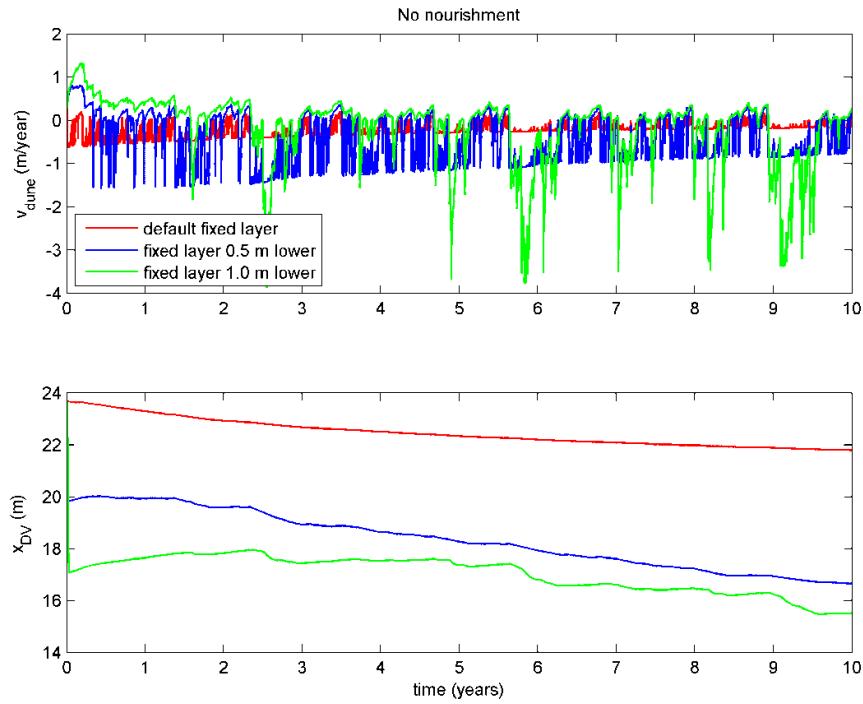


Figure 4.24 Effect of fixed layer position on dune migration rate and dune foot position computed by Unibest-TC; no nourishment case.

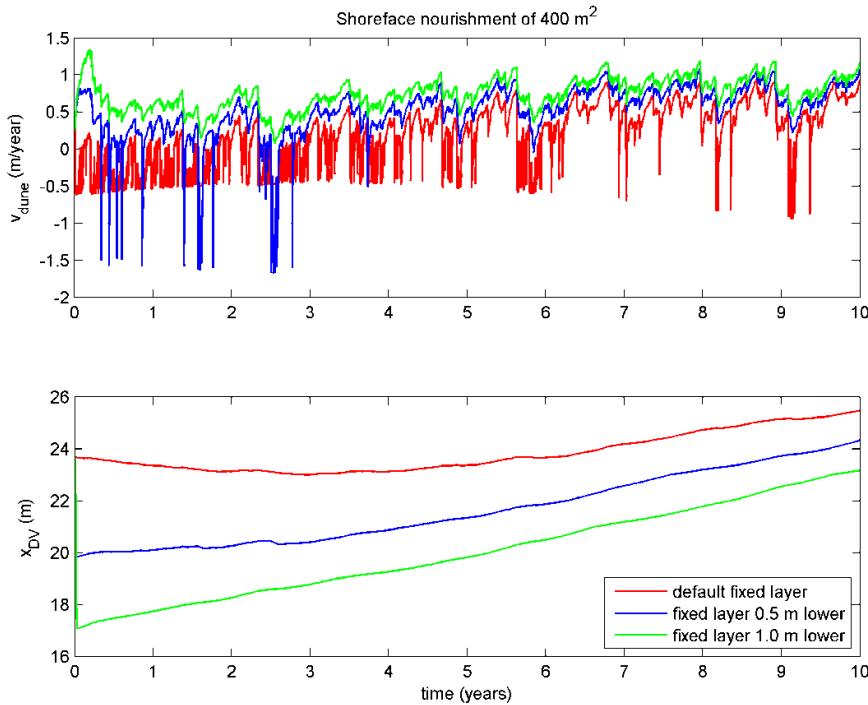


Figure 4.25 Effect of fixed layer position on dune migration rate and dune foot position computed by Unibest-TC;  $400 \text{ m}^2$  shoreface nourishment case.

#### 4.5.5 Morphological response to nourishments

Figure 4.26 - Figure 4.31 show time stacks of bed levels and bed level perturbations (difference between bed level and time-averaged bed level *without* nourishment) for the no nourishment case, the  $400 \text{ m}^2$  shoreface nourishment case and the  $100 \text{ m}^2$  beach nourishment case. The black dots indicate the position of the crest of the breaker bars or other smaller perturbations in the bed.

Figure 4.26 and Figure 4.27 show the typical natural cyclic behaviour of breaker bars. They originate near the coast, migrate in the on- and offshore direction depending on the wave condition, and on the long term they move offshore where they decay.

Figure 4.28 and Figure 4.29 show the morphological development in case of a shoreface nourishment, which was put at year 0 approximately between the cross-shore locations -750 and -1150 m as given in the design in Figure 4.6. The shoreface nourishment disappears partly in offshore direction and partly merges with the original outer bar which migrates in the offshore direction thereafter. This new most offshore located outer bar is still present after 10 years of simulation. The bars also increase consistently in height and volume. Furthermore, the shoreface nourishment slows down the offshore migration of the breaker bars.

Figure 4.30 and Figure 4.31 show the simulation results for the beach nourishment case, which was put approximately between the cross-shore locations -30 and -160 m. The beach nourishment itself disappears quite quickly; after  $\sim 0.5$  year it is hardly recognizable in the time stack plots. The beach nourishment has not a strong effect on the breaker bars, only leading to a minor increase in their offshore migration.

In both cases, the nearshore zone (between  $x = -300$  and  $150$  m) gains sand from the nourishments; this effect is strongest for the shoreface nourishment which has a four times higher sand volume than the beach nourishment.

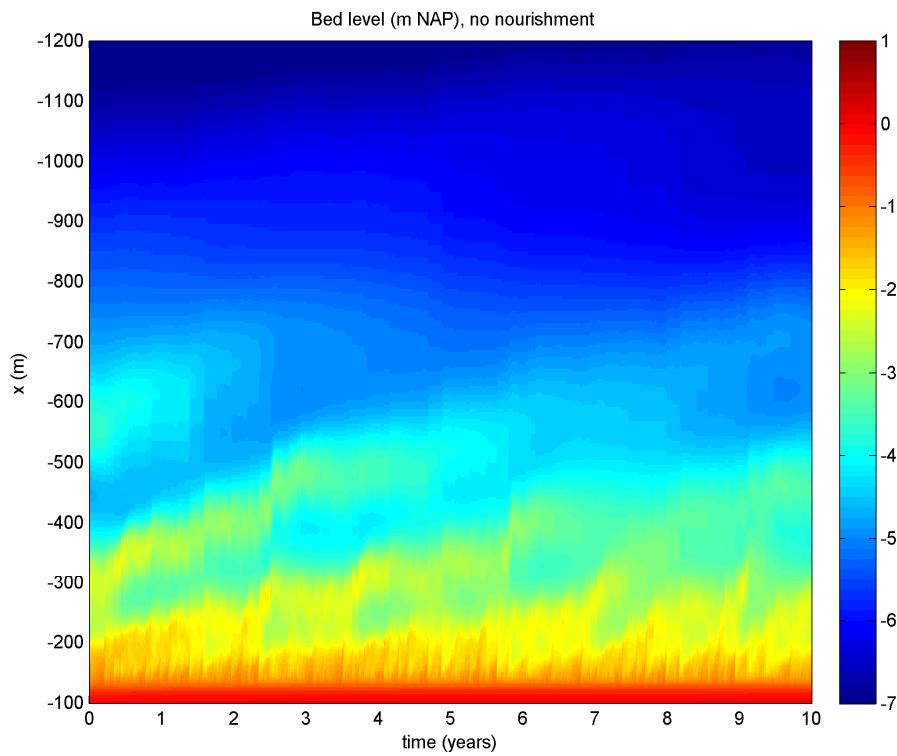


Figure 4.26 Time stack of computed bed profiles; no nourishment case.

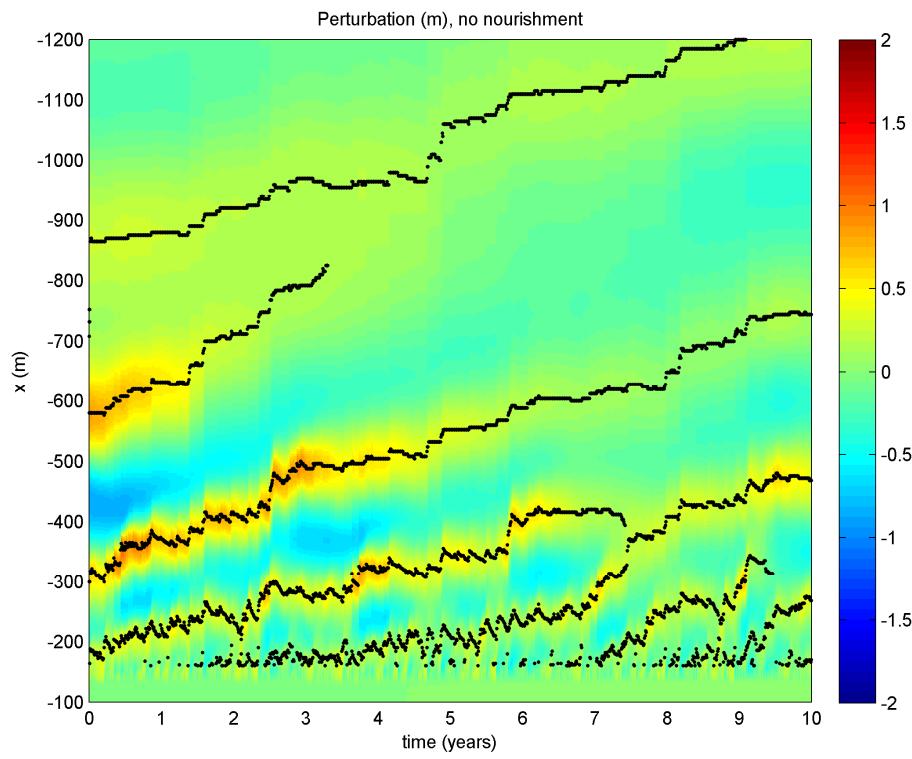


Figure 4.27 Time stack of bed level perturbations; no nourishment case.

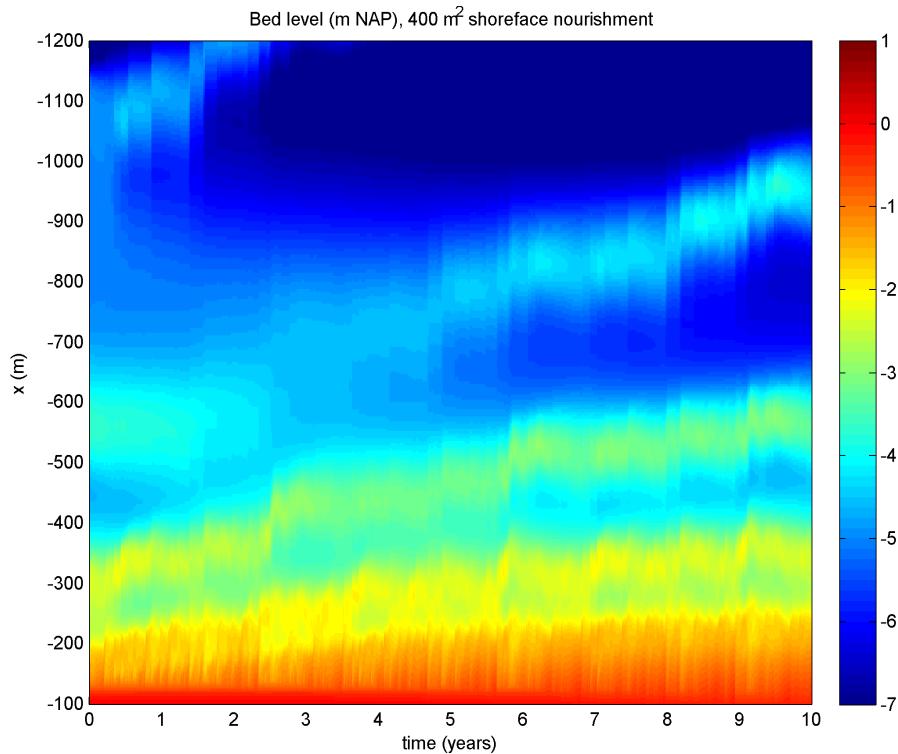


Figure 4.28 Time stack of computed bed profiles; 400 m<sup>2</sup> shoreface nourishment case.

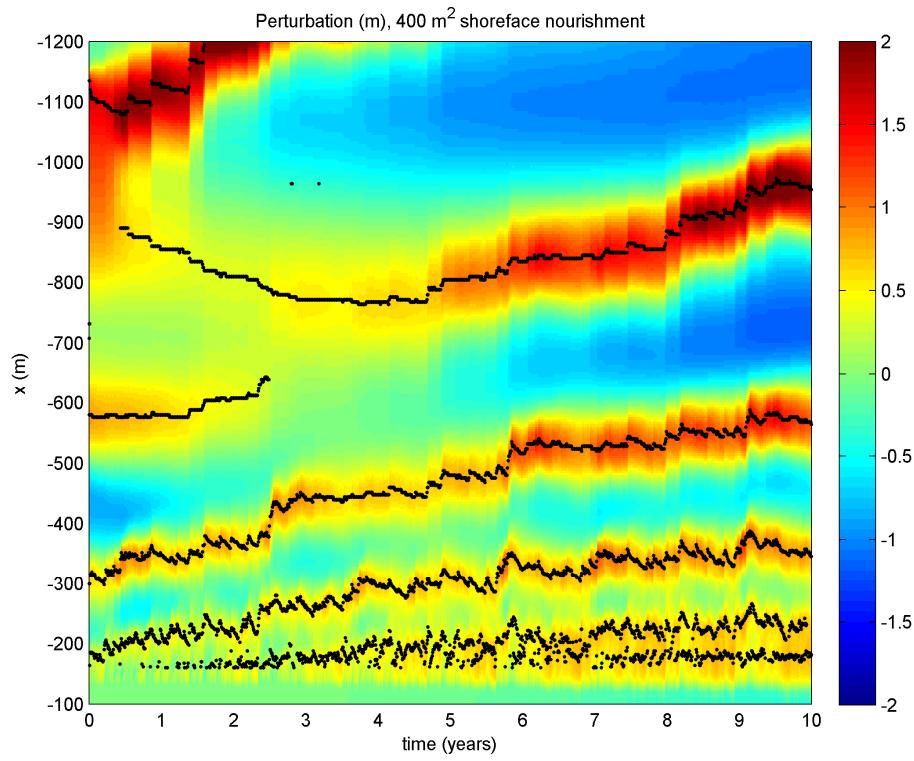


Figure 4.29 Time stack of bed level perturbations;  $400 \text{ m}^2$  shoreface nourishment case.

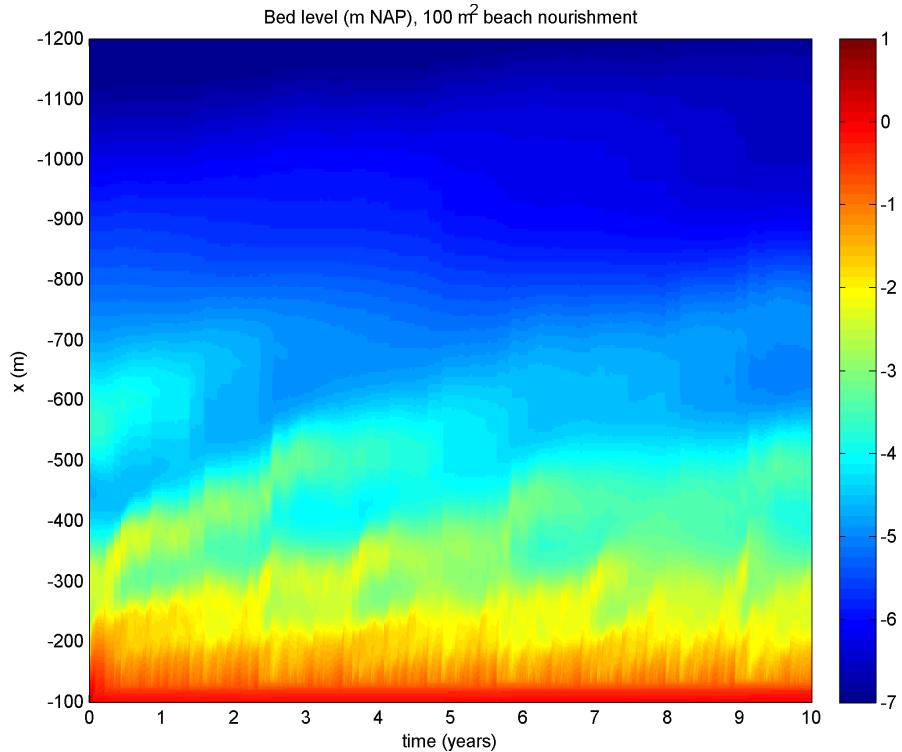


Figure 4.30 Time stack of computed bed profiles;  $100 \text{ m}^2$  beach nourishment case.

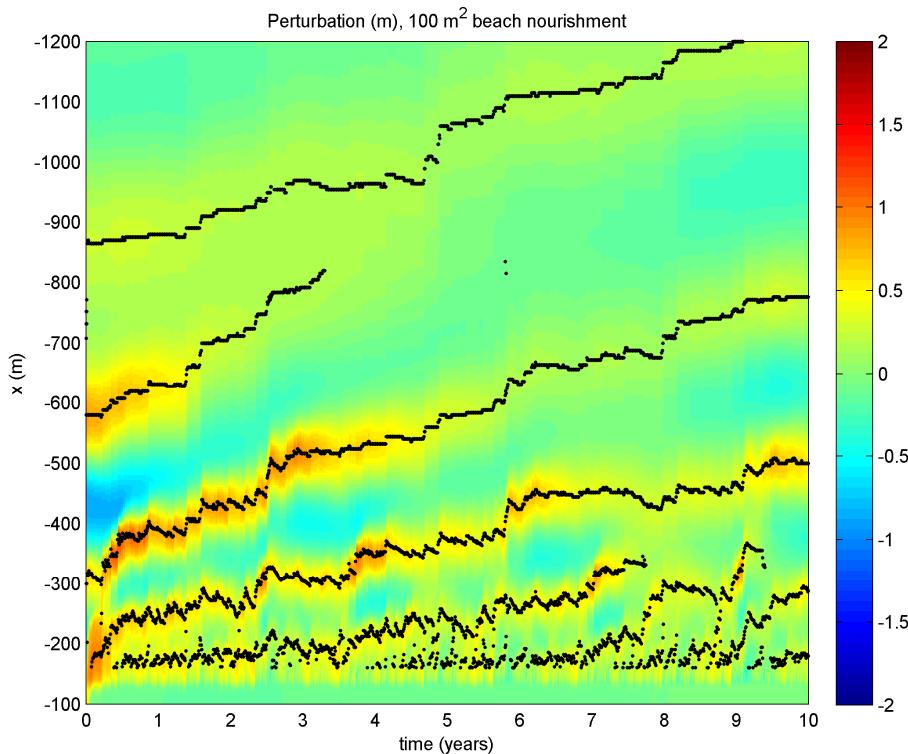


Figure 4.31 Time stack of bed level perturbations; 100 m<sup>2</sup> beach nourishment case.

Figure 4.32 and Figure 4.33 show the development of the beach width, MKL volumes, MKL position and dune foot position in time.

Figure 4.32 shows that the MKL zone mainly profits from the shoreface nourishment: after 10 years the increase in MKL volume is about 150 m<sup>2</sup> or ~40% of the nourishment sand volume. Without nourishment, the beach width is smaller than the imposed equilibrium value of 115 m, as a result of which the dune foot migrates slightly in the onshore direction (Figure 4.33). Due to the shoreface nourishment the beach becomes wider, and the dune foot migrates in the offshore direction (Figure 4.33). After 10 years of simulation, the bed profile is not yet in a new equilibrium and the impact of the shoreface nourishment is still visible. It should be noted that, as Unibest-TC is a cross-shore profile model, there are no sediment losses in the longshore direction (basically implying an infinitely long nourishment) and the nourishment impact is therefore expected to be overpredicted.

In case of beach nourishment, after 10 years the MKL volume is about 40 m<sup>2</sup> higher than in the reference case, which corresponds to ~40% of the nourishment volume. The dune foot profits from the beach nourishment the first two years, after which the trend in time is the same as for the no nourishment case. As stated above, the beach nourishment is eroded quickly: the beach width is after ~0.5 years pretty much the same as for the no nourishment case.

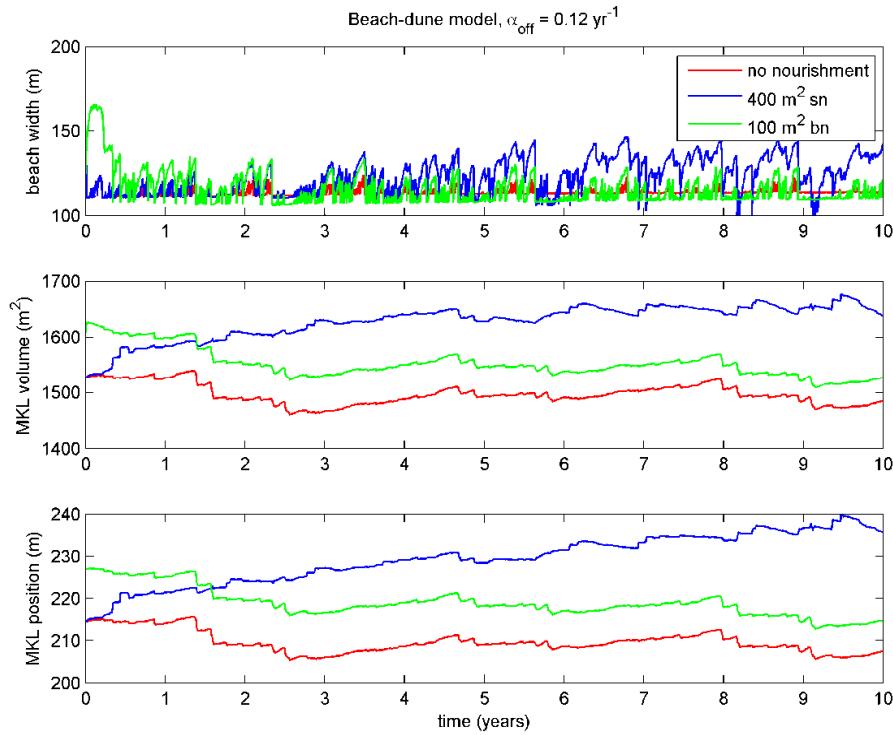


Figure 4.32 Effect of nourishments on beach width, MKL volume and MKL position computed by Unibest-TC.

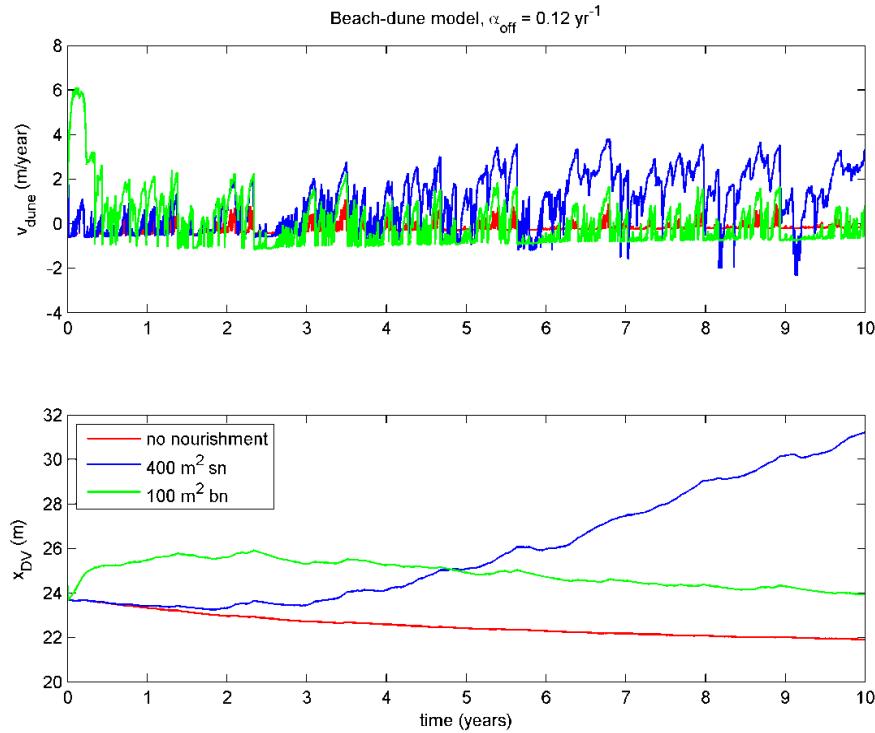


Figure 4.33 Effect of nourishments on dune migration rate and dune foot position computed by Unibest-TC.

## 4.6 Discussions and conclusions

The relation between beach width and dune foot migration of De Vriend&Roelvink (1990) was successfully implemented in UNIBEST-TC, such that the interaction between the beach and dune area is now accounted for. Those changes to the dune profile due to aeolic transport would not be simulated by the standard UNIBEST-TC code, without beach-dune module implemented. The implementation of the beach-dune module conceptually means that the morphodynamics of the cross-shore profile lower and higher than the low water line are decoupled. The first is controlled by the regular bed updating of UNIBEST-TC forced by the simulated hydrodynamic conditions, and the latter by the beach-dune module. This is not ideal as there is interaction between the two and the behaviour of the upper part of the profile is now forced towards an equilibrium defined by the pre-defined equilibrium beach width.

Simulations with the UNIBEST-TC model were run for a profile at Noordwijk for a period of 10 years and including different combinations of shoreface and beach nourishments. The best agreement between 10-year UNIBEST-TC simulations for the Noordwijk profile and data analysis on the impact of nourishments on MKL and dune foot position for the entire Holland coast was obtained with an increase of the offshore dune migration coefficient from its original value of 0.024 to 0.12 1/yr.

The main impact of the newly-implemented beach-dune module is on the beach and dune area. The breaker bar dynamics are hardly affected.

The results with the beach-dune module are sensible to the imposed equilibrium beach width and the vertical position of the low water line.

According to the UNIBEST-TC model, shoreface nourishments are more effective than beach nourishments or a combination of beach and shoreface nourishments to increase the beach width and the MKL volume after 10 years. On the other hand, combinations of beach and shoreface nourishment are more effective in promoting seaward dune foot migration. The impact of the different nourishment types on MKL position is similar.

Time stacks based on UNIBEST-TC simulations also show that the model is able to reproduce the impact of the nourishments on breaker bar dynamics in a qualitative way. In particular, shoreface nourishments tend to merge with the offshore breaker bar and to reduce the offshore migration of the inner bars.

Imposing a fixed layer in the UNIBEST-TC model proves to be necessary to prevent unrealistic erosion of the beach and dune area. This indicates the model inability to deal with sediment transport processes in shallow water.

The model set-up in this chapter will be used as a basis to build the Bayesian network in chapter 0 and to assess the influence of different nourishment designs on the morphological indicators.

## 5 Prediction of nourishments efficiency based on Bayesian approach

### 5.1 Introduction

In this chapter the planning and evaluation of different nourishment strategies is investigated using a stochastic approach based on Bayesian statistics. A Bayesian network is a method of reasoning using probabilities, where the *nodes* represent variables and *arrows* represent direct influence between the nodes. The advantage of using this approach is that by combining multiple parameters, makes it possible to make robust forecasts.

In general, the Bayes rule is expressed as:

$$p(F_i | O_j) = p(O_j | F_i) p(F_i) / p(O_j),$$

where the left-hand term is the updated conditional probability (or ‘posterior probability’) of a forecast  $F_i$ , given a particular set of observations,  $O_j$ . In this specific case, the posterior probability is described by the distribution of a certain morphological indicator, in response to a certain nourishment strategy (nourishment type + nourishment volume).

The advantages of using a Bayesian network for this purpose are that:

- A Bayesian network is a useful tool to evaluate causes and effects (i.e. nourishment and effects on coastal indicators).
- A Bayesian modeling approach gives an intuitive representation of the physical processes involved. The use of nodes and arrows makes directly visible which variables play a role and how they are correlated.
- A Bayesian network is interactive. Once the network is trained with a proper data set, different situations can be easily simulated.
- A Bayesian network is a probabilistic method and therefore allows accounting for uncertainties.

Giardino and Knipping (2012b) investigated the efficiency of different nourishment designs in North Holland using a Bayesian network approach fully based on measured data of nourishment types and volumes and changes to the probability of failure, MDV (Momentary Dune Volume) and MKL (Momentary Coastline Position). Among the recommendations from this previous study, it was suggested the use of model data alongside measured data for a number of reasons:

- With models, it is possible to simulate situations which have not yet occurred (or hardly ever and therefore not statistical significant), in reality. For example, to assess the effects of a nourishment at one transect which has never been nourished or to simulate the effects of a nourishment much larger than the ones which are generally applied. This could be relevant for the design of innovative types of nourishments.
- In a model, it is easy to separate the effect of a single nourishment from other background conditions (e.g. the effect of other nourishments in nearby transects).

## 5.2 Set-up of the network

The network used in this project has been trained based on results from a large number of UNIBEST-TC runs, using the same model set up as described in Chapter 0, but with different starting bathymetries representative of the initial situation plus specific nourishment scenarios. In total 297 runs were carried out: 185 shoreface nourishments and 115 beach nourishments. As the UNIBEST-TC model is a purely cross-shore model, it is assumed that the bathymetry is characterized by straight contour line parallel to the coast.

The volumes of the beach nourishments were supposed to vary between  $50 \text{ m}^3$  and  $400 \text{ m}^3$ , while the volumes of the shoreface nourishments between  $50 \text{ m}^3$  and  $800 \text{ m}^3$ . The probabilistic distribution of respectively beach and shoreface nourishments volumes is shown in Figure 5.1. An example of two initial bathymetry including two different nourishments is shown in Figure 5.2.

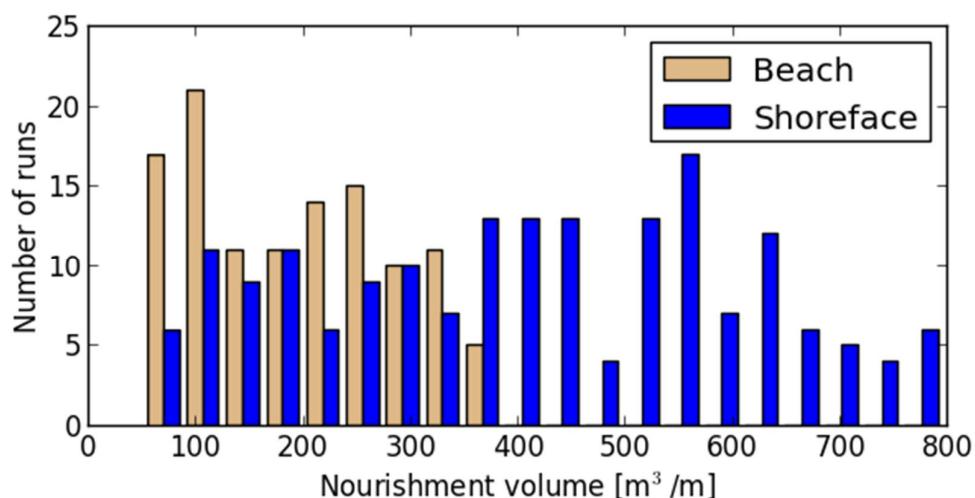


Figure 5.1 Probabilistic distribution of beach (orange bars) and shoreface (blue bars) nourishment volumes

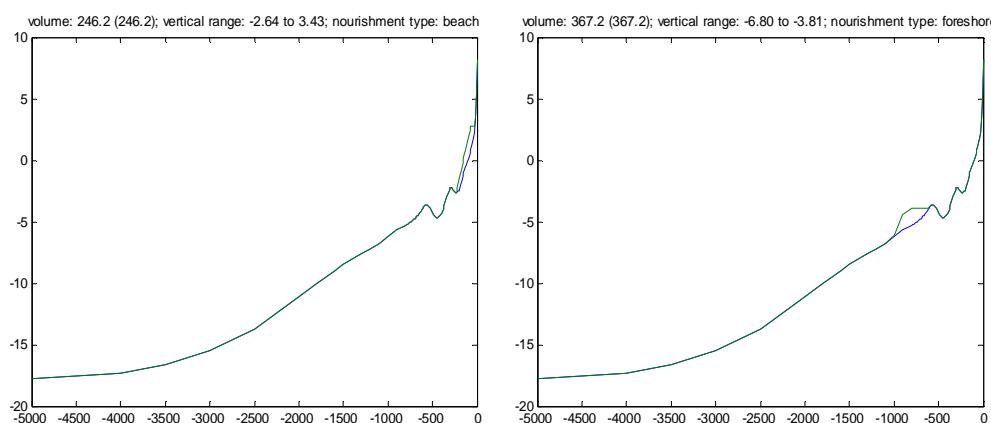


Figure 5.2 Example of two nourishment designs: a beach nourishment (left figure) and a shoreface nourishment (right figure).

To quantify the effects of different nourishment types and volumes, two morphological indicators were selected: the MKL and the dune foot position. These indicators can be considered representative of different system functions: respectively, the medium-term safety and the space available for nature and recreation (Giardino et al., 2013a). Moreover, changes in dune foot position are also closely related to changes in short term safety.

The overview of the network, with the prior distribution for each variable is shown in Figure 5.3. In general, the network can be described as a fault tree where a number of events at the top of the network leads to consequences in the nodes which come below in the tree. Each node is described through a statistical distribution, with values for different classes given in %. In the last line, the average value and the standard deviation of the distribution for a specific node is also given.

At the top of the tree, first appears the node *Time\_Horizon*, defining the time window to be analysed. In particular, in this study the effect of a nourishment was analysed *one year*, *five years* and *ten years* after a nourishment was built. The nodes *Nourishment\_Volume* and *Nourishment\_Type* are used to define the nourishment design, respectively through the volume of the nourishment to be applied and the type (*Shoreface* or *BeachNourishment*). Finally, the effects on morphological indicators is evaluated using the nodes: *MKL\_change* and *Dune\_foot\_change*, which represent changes in MKL and dune foot position with respect to the situation before the nourishment.

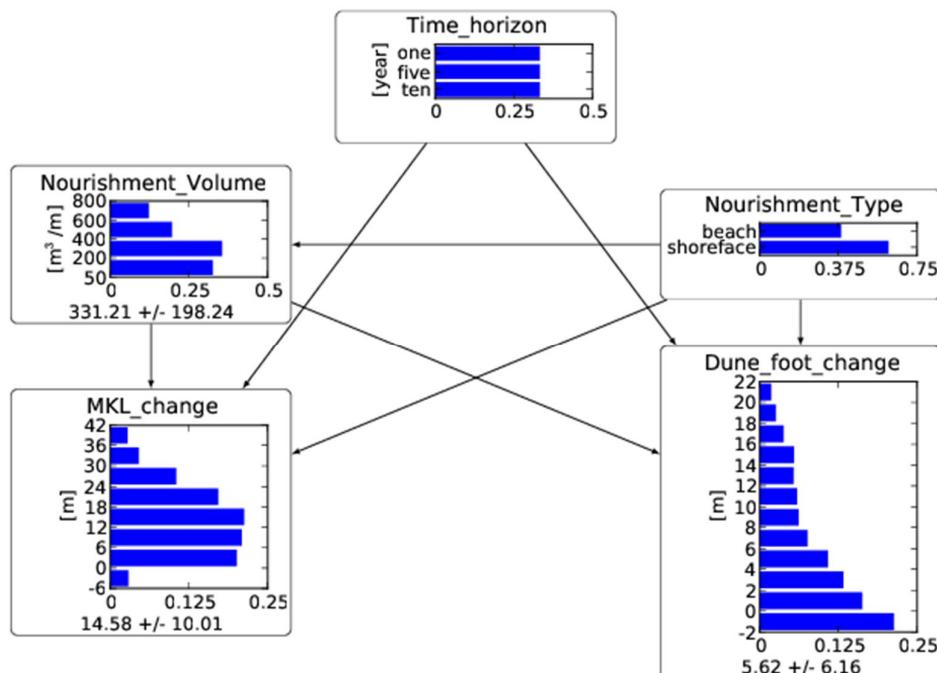


Figure 5.3 Bayesian network – prior probabilities

### 5.3 Applications

A number of applications have been described in this section (Table 5.1). For each example, one or different nodes were constrained to be certain (100% probability). Constraining is essentially the same as conditioning a variable in the network to a particular value.

As an example, we only look at the development of the morphological indicators in simulations where beach nourishments were implemented, and after a specific time (e.g. 1 year).

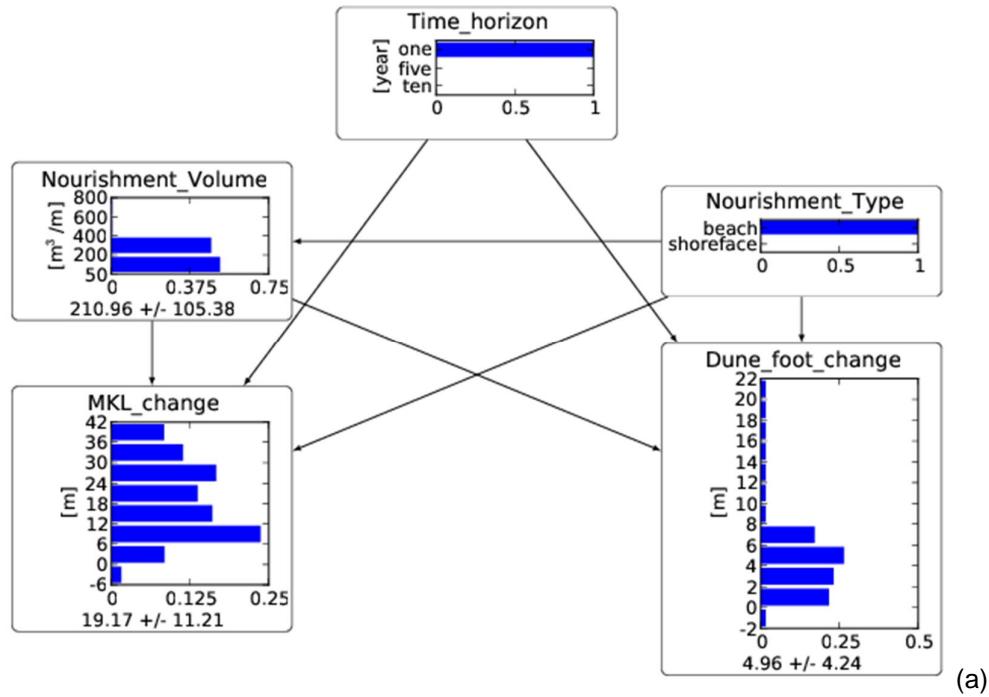
Table 5.1 Descriptions of the applications which were investigated with support of the Bayesian network.

<b>Application</b>	<b>Question to be addressed</b>
1) Response of the morphological indicators to beach nourishments after 1, 5, and 10 years	What is the effect of beach nourishments on MKL and dune foot position at different time scales?
2) Response of the morphological indicators to shoreface nourishment after 1, 5, and 10 years	What is the effect of shoreface nourishments on MKL and dune foot position at different time scales?
3) Effect of increasing nourishment volumes on morphological indicators	What is the effect of increasing the total nourishment volume on MKL and dune foot position?
4) Plan of a nourishment strategy	What is the nourishment volume necessary to reach a seaward MKL shift of 9 m, after one year using a beach nourishment or a shoreface nourishment?

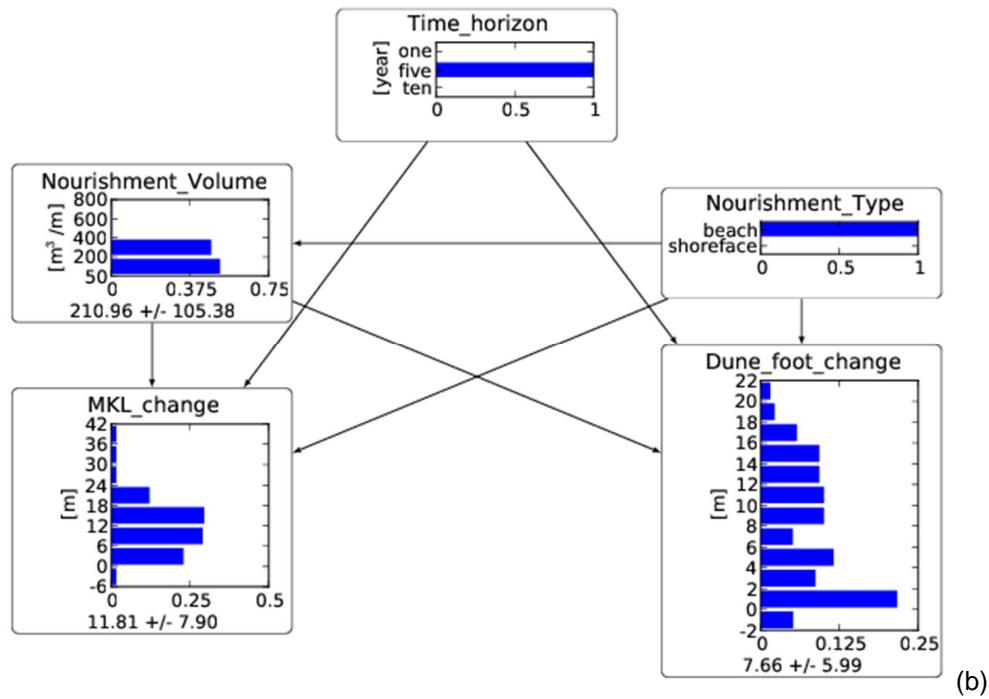
### 5.3.1 Response of the morphological indicators to beach nourishments at different time scales

In this application, the response of the morphological indicators to beach nourishments after *one*, *five* and *ten* years is investigated. Figure 5.4 shows the effects of beach nourishments for the three different situations respectively.

MKL reacts immediately to a beach nourishment, with a maximum effect observed after one year, and which decreases five and ten years after the nourishment. On the other hand, the effect on dune foot position is still quite limited one year after the nourishment, reaches its maximum five years after the nourishment as the sand get transported by aeolic transport from the beach to the dunes, and then slightly decreases after ten years due to storm erosion and redistribution across the profile. The average changes in MKL and dune foot position, reported below each node, are summarized in Table 5.2.



(a)



(b)

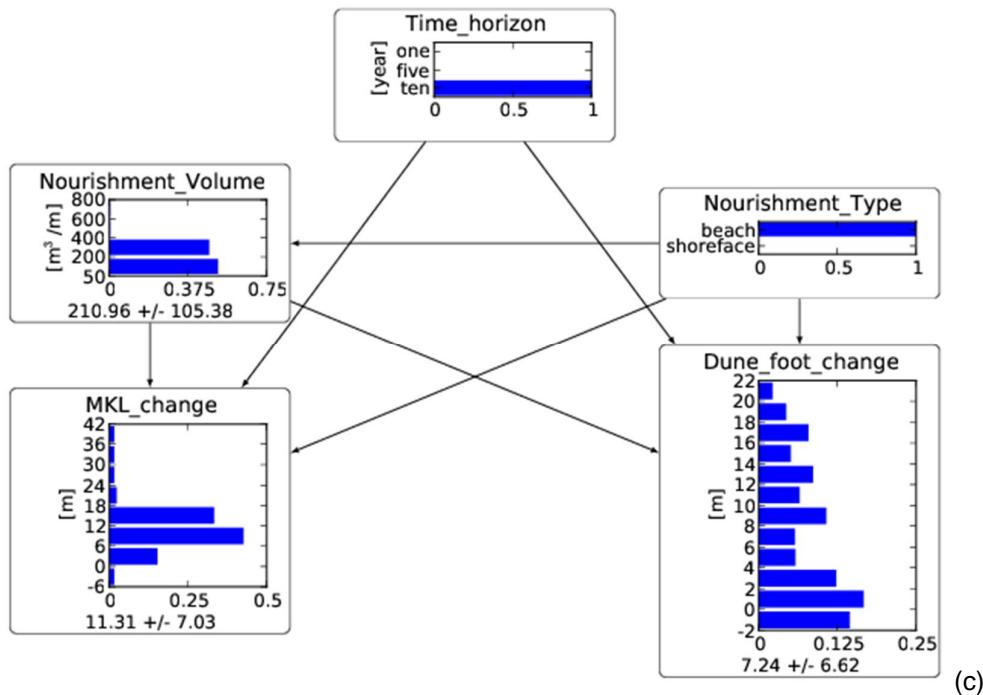


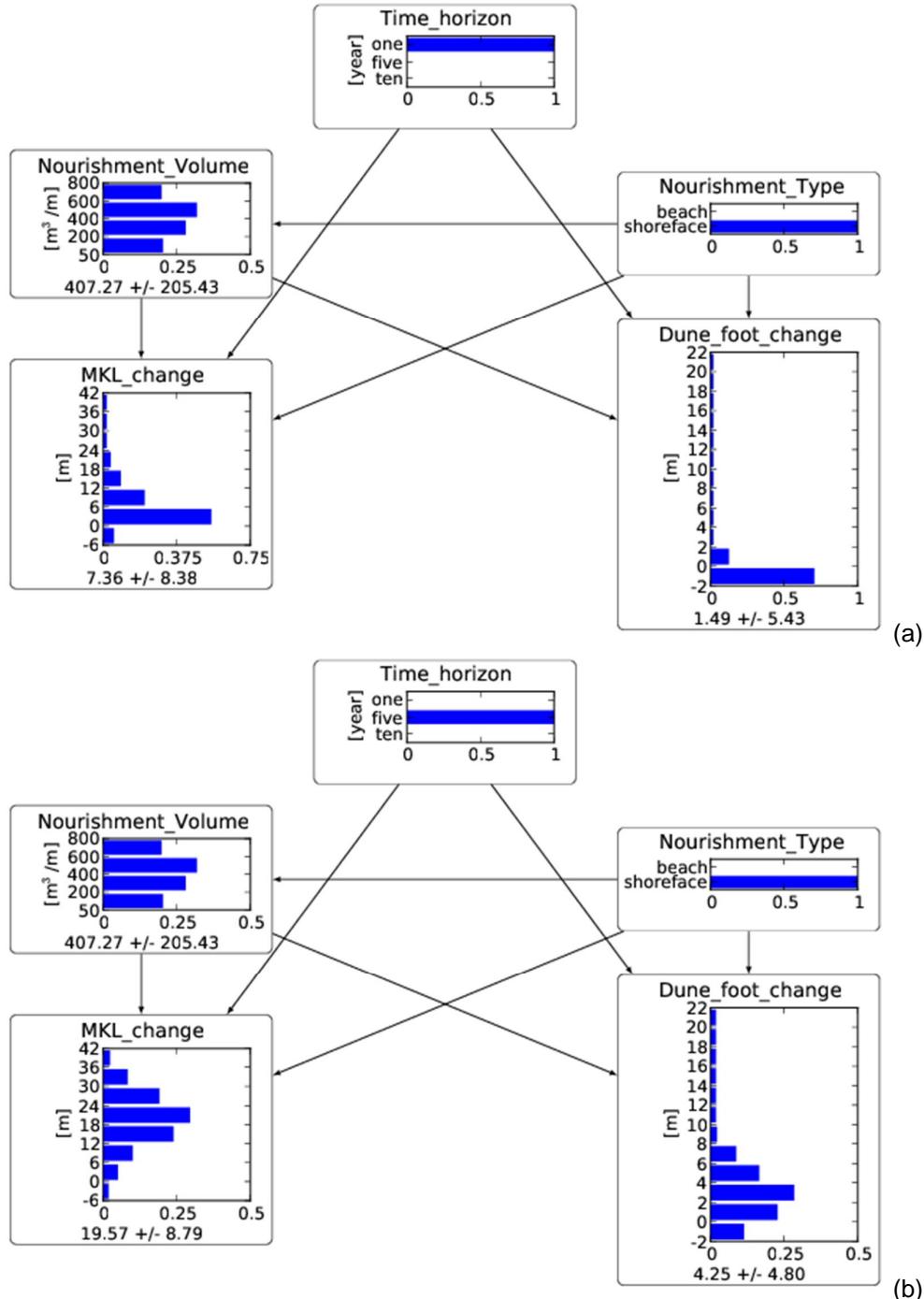
Figure 5.4 Changes in MKL and dune foot position in response to beach nourishments one (a), five (b) and ten (c) years, after the construction of the nourishment.

Table 5.2 Average changes in MKL and dune foot position, 1 5 and 10 years after beach nourishment construction

	Average MKL change (m)	Average dune foot change (m)
After 1 year	19.17	4.96
After 5 years	11.81	7.66
After 10 years	11.31	7.24

5.3.2 Response of the morphological indicators to shoreface nourishments at different time scales  
In this application, the response of *shoreface nourishments* on morphological indicators after one, five and ten years is investigated. Figure 5.5 shows the effects of shoreface nourishments for the three different situations respectively.

With respect to the case of a beach nourishment, a shoreface nourishment has a more limited effect on MKL changes one year after the nourishment, a maximum effect five years after nourishment construction, and which slightly decreases after ten years. The effect on dune foot migration one year after the nourishment is very limited, but tends to increase constantly five and ten years after nourishment construction. In both cases, the total migration of both MKL and dune foot after 10 years for a shoreface nourishment is larger than that one for a beach nourishment. However, it is important to point out that the average volume of the shoreface nourishments considered is almost twice as big as that one of beach nourishments ( $407 \text{ m}^3/\text{m}$  versus  $211 \text{ m}^3/\text{m}$ ). The average changes in MKL and dune foot position, reported below each node, are summarized in Table 5.3.



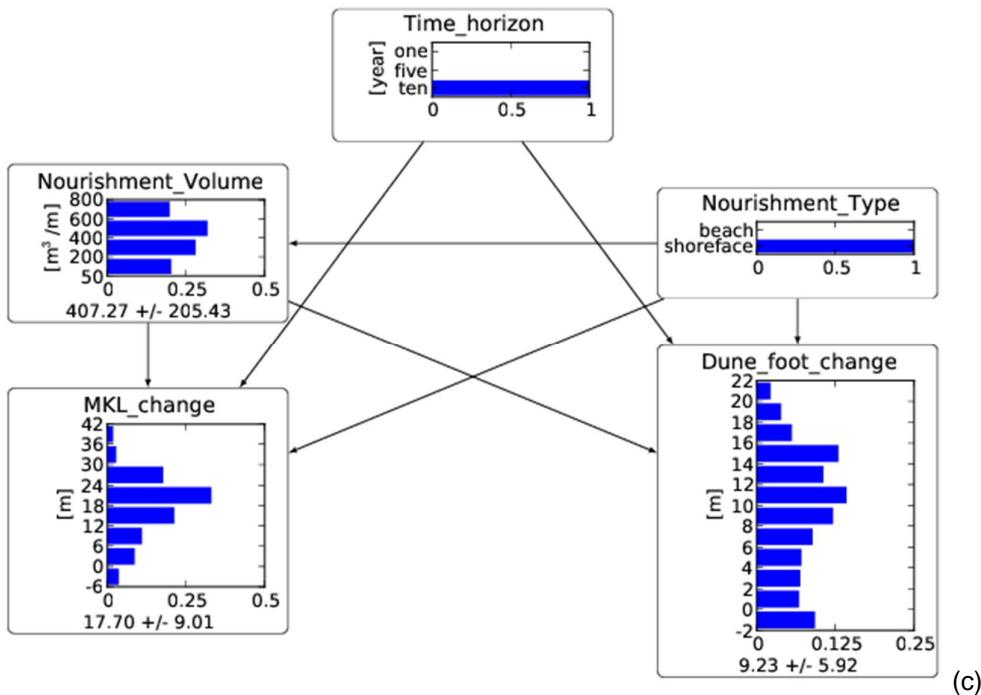


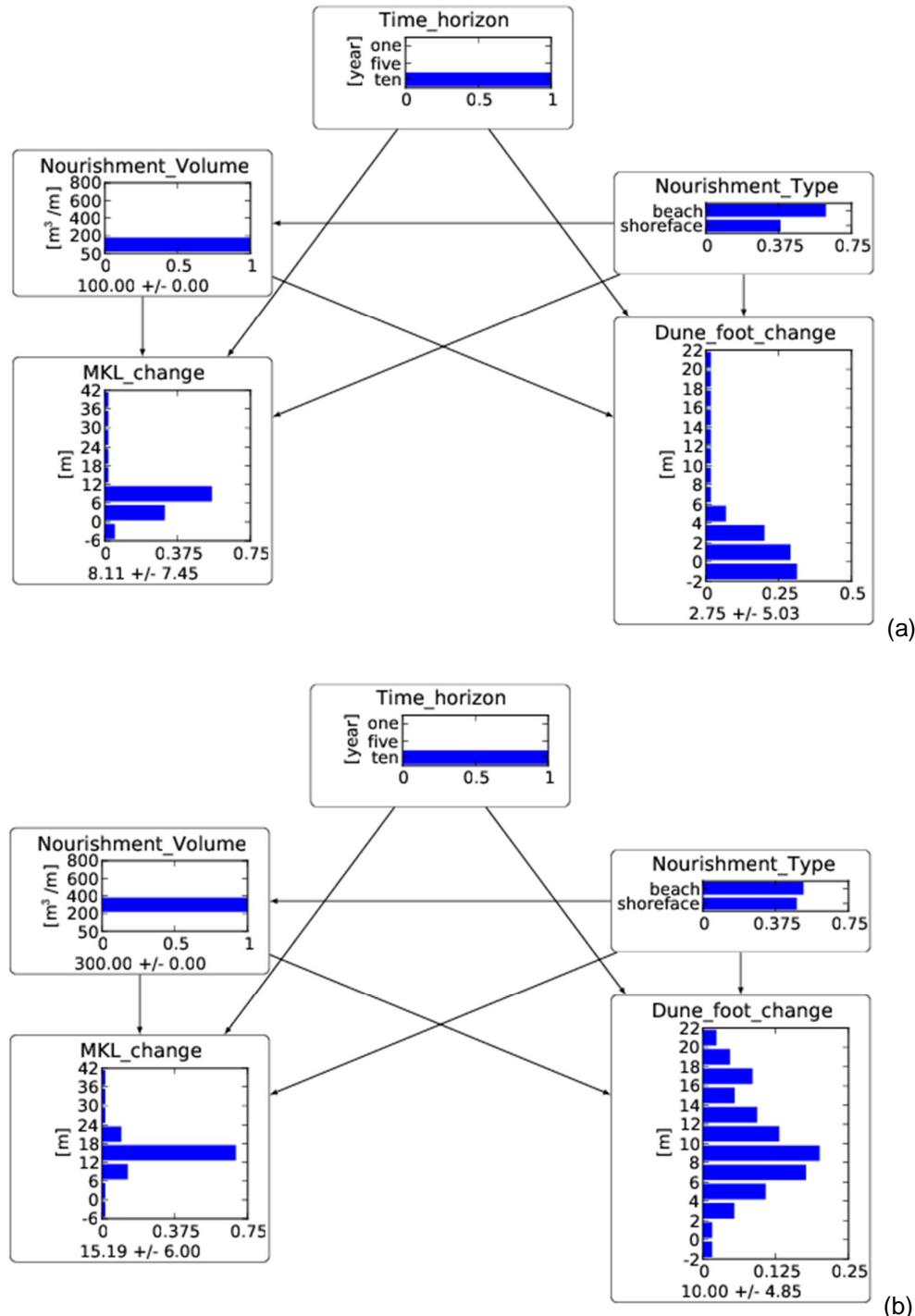
Figure 5.5 Changes in MKL and dune foot position in response to beach nourishments one (figure a), five (figure b) and ten (figure c) years, after the construction of the nourishment.

Table 5.3 Average changes in MKL and dune foot position, 1 5 and 10 years after shoreface nourishment construction

	Average MKL change (m)	Average dune foot change (m)
After 1 year	7.36	1.49
After 5 years	19.57	4.25
After 10 years	17.70	9.23

### 5.3.3 Effects of increasing nourishment volumes on MKL and dune foot position

In this application, the effect of upscaling the nourishment volumes is assessed by constraining the node *Nourishment\_Volume* to the following classes of values: from 50 to 200 m<sup>3</sup>/m, from 200 to 400 m<sup>3</sup>/m, from 400 to 600 m<sup>3</sup>/m, and from 600 to 800 m<sup>3</sup>/m, and considering a *Time\_horizon* of 10 years. In this application, the effects of both shoreface and beach nourishments are considered without distinguishing between the two. Figure 5.6 shows the effects of upscaling the nourishments for the four different situations respectively. The average changes in MKL and dune foot position, reported below each node, are summarized in Table 5.4.



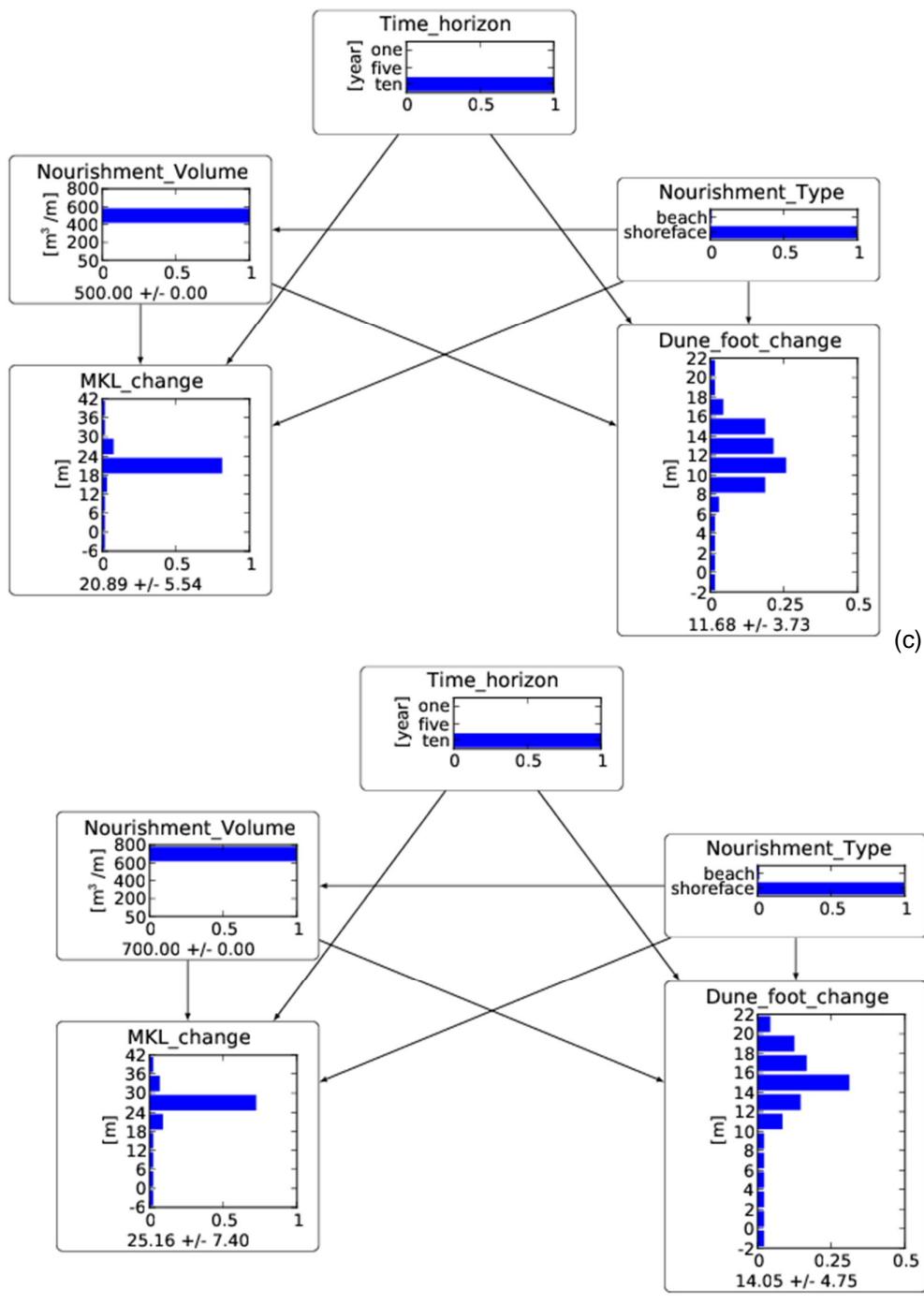


Figure 5.6 Changes in MKL and dune foot position after 10 years, in response to nourishments with increasing volumes: from 50 to 200  $\text{m}^3/\text{m}$  (figure a), from 200 to 400  $\text{m}^3/\text{m}$  (figure b), from 400 to 600  $\text{m}^3/\text{m}$  (figure c), and from 600 to 800  $\text{m}^3/\text{m}$  (figure d).

Table 5.4 Average changes in MKL and dune foot position in response to increasing nourishment volumes.

	Average MKL change (m)	Average dune foot change (m)
Average volume 100 m <sup>3</sup> /m	8.11	2.75
Average volume 300 m <sup>3</sup> /m	15.19	10.00
Average volume 500 m <sup>3</sup> /m	20.89	11.68
Average volume 700 m <sup>3</sup> /m	25.16	14.05

The relation between average nourishment volumes and relative changes in MKL and dune foot position given in Table 5.4 are shown as plot in Figure 5.7. The increase in nourishment volumes leads to an increase in MKL position after 10 years which is close to linear. A larger increase in nourishment volumes for larger nourishments is just slightly less efficient than for smaller nourishments as the slope of the fitting line tends to decrease moving towards bigger nourishments. This is even more clear, if we focus on dune foot changes, which show a much stronger response to smaller nourishments. This can be explained considering that a lot of the smaller nourishments are beach nourishments which, for the same nourishment volume, have a relative bigger effect than shoreface nourishments on dune foot changes.

The relation between nourishment volumes and changes in MKL and dune foot position in Figure 5.7 can be compared to the relations derived for the same indicators but based on data analysis for the Holland coast (Giardino et al., 2013a). Figure 5.8 show the relations which were derived based on data analysis. The slopes of the fitting line in the two figures are well comparable, with values of  $\sim 0.03$  which relate nourishment volumes and relative MKL changes after 10 years, and  $\sim 0.02$  which relate nourishment volumes to dune foot position changes. It is important to point out that the model simulations only consider nourishments built at the start of the ten year period, while the data analysis account for a total of nourishment volumes built within the 10 year time window.

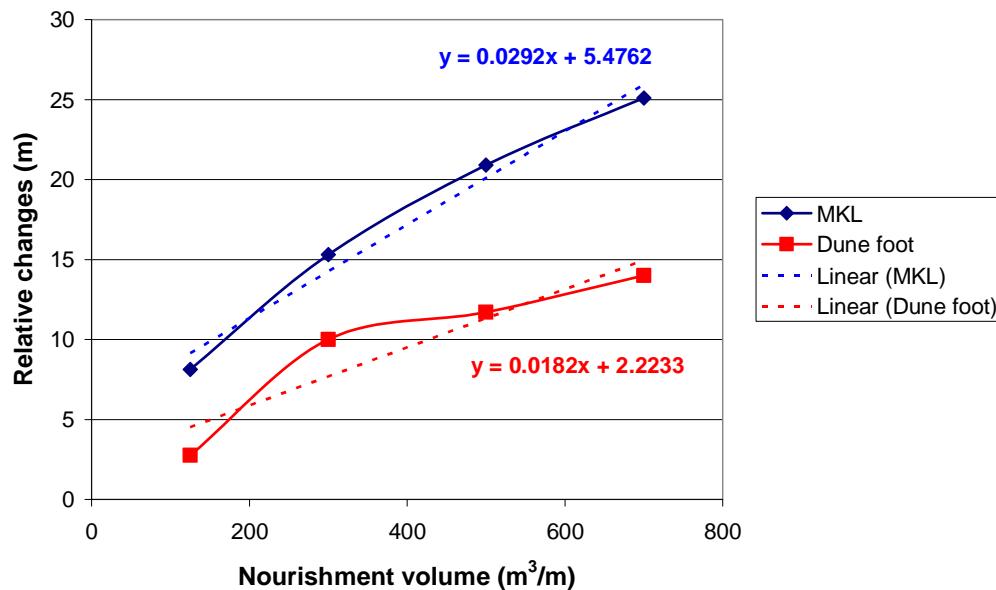


Figure 5.7 Effect of nourishment volumes on relative MKL and dune foot changes.

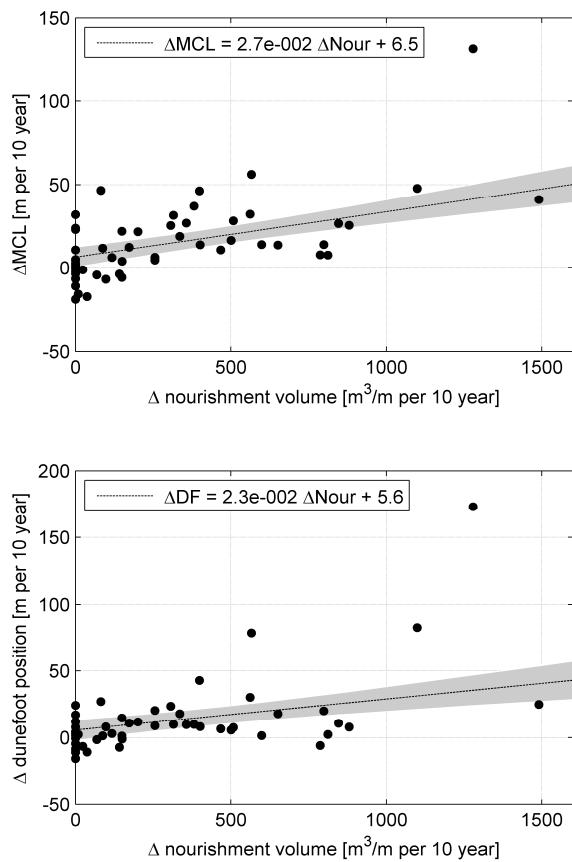


Figure 5.8 Effects of nourishment volumes on MKL and dune foot position changes for a 10-year time window at the Holland coast (Giardino et al, 2013a)

#### 5.3.4 Plan of a nourishment strategy

In this application, the network was used to plan a nourishment strategy in order to reach a predefined policy objective. The objective is an average seaward shift in MKL of 9 m after 1 year, either using a beach or a shoreface nourishment. To do that, the node *MKL\_change* was constrained to the class between 6 and 12 m (average value = 9 m), the node *Time\_horizon* to a value of *one* and finally the *Nourishment\_Typerespectively to beach and shoreface nourishments*. Figure 5.9 shows the results for the calculations, respectively in case of the use of beach and shoreface nourishments. The figure shows that to reach the predefined policy objective after 10 years, a beach nourishment volume of ~170 m<sup>3</sup>/m is necessary. On the other hand, to reach the same objective with a shoreface nourishment, it is necessary to use approximately ~190 m<sup>3</sup>/m of sand. The beach nourishment will also promote a seaward dune foot migration of ~4.9 m, against a migration of~4.3 m in case of a shoreface nourishment. Those results are specific for the transect at Noordwijk, where the different nourishment designs were tested, but could be made more general by running the same simulations for other representative transects.

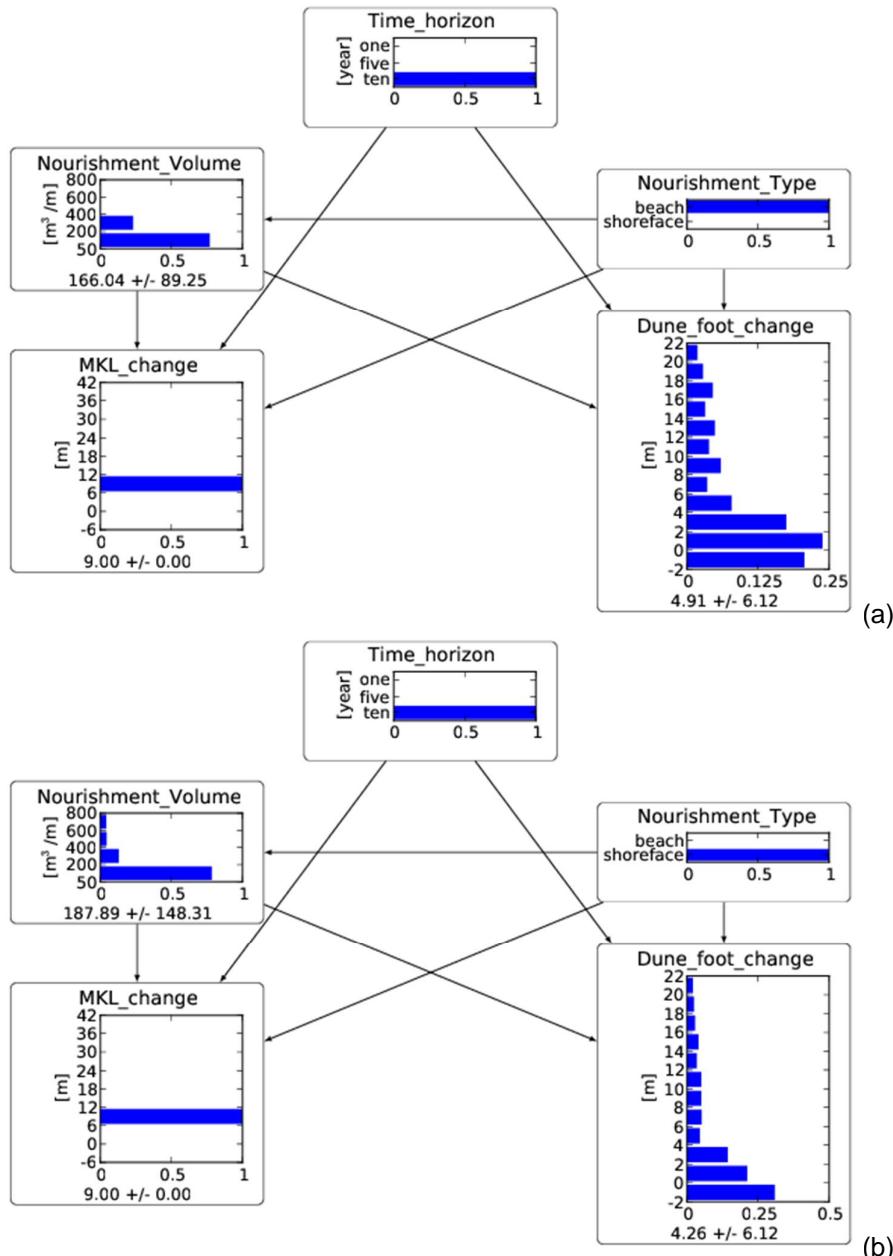


Figure 5.9 Plan of a nourishment strategy to reach a pre-defined policy objective. The policy objective is a seaward shift in MKL of 9 m after 1 year. The objective is reached: (a) with the implementation of a beach nourishment (b) with the implementation of a shoreface nourishment.

## 5.4 Discussions and conclusions

A Bayesian approach has been used in this chapter to assess the effects of different nourishment designs on a number of morphological indicators: the MKL position and the dune foot position. The network has been trained with data derived from a large number of model simulations carried out with a cross-shore UNIBEST-TC model. In the model, representative of a profile at Noordwijk, the morphological response of different types of nourishment designs has been simulated, comprising shoreface and beach nourishments with different volumes. The network has been tested for a number of different applications.

The applications have shown that:

- Beach nourishments have an immediate effect on a seaward MKL migration, which then strongly decreases 5 and 10 years after nourishment construction. On the other hand, the dune foot position has a delayed response, with a maximum effect visible 5 years after nourishment construction, and which only slightly decreases 10 years after nourishment construction.
- Shoreface nourishments have a delayed effects both on MKL and dune foot position changes. The maximum effect on MKL changes can be observed 5 years after nourishment construction, while the maximum effect on dune foot position changes can be observed 10 years after nourishment construction.
- An increase in nourishment volume leads to an almost linear seaward migration of the MKL position. Considering the effects for a 10-year time window, this follows a almost linear relation which can be described as:  
$$\Delta\text{MKL} (\text{m}) = \sim 0.03 \Delta\text{Nourishment Volume} (\text{m}^3/\text{m})$$

This behaviour is also confirmed by data analysis

- An increase in nourishment volume leads to increasing seaward dune foot migration. Smaller beach nourishments contribute to relatively larger shift in dune foot with respect to larger shoreface nourishments (i.e. relative effect defined as shift in dune foot per  $\text{m}^3$  of sand nourished). Considering the effects for a 10-year time window, the relation between nourishment volumes and dune foot migration can be described as:  
$$\Delta\text{Dune foot position} (\text{m}) = \sim 0.02 \Delta\text{Nourishment Volume} (\text{m}^3/\text{m})$$

This behaviour is also confirmed by data analysis

- The tool can be used to predict the most suitable nourishment strategy in order to achieve a certain policy objective (e.g. a certain shift in MKL position after a certain number of years).

As a Bayesian network is just a way of looking at data and relations between variables using a statistical approach, it is important to point out that the output of the network fully depends on the data used to train the network. In this case, the data were derived using the UNIBEST-TC model for one specific transect. Therefore, the assumptions and limitations relate to the model discussed in Chapter 0 are directly transferred to the network. In particular, the followings assumptions are important to point out:

- The model is a cross-shore model, which therefore assumes contour lines which are parallel to the coastline. Also nourishments are assumed to be built parallel to the coastline and to continue indefinitely in alongshore direction.
- The UNIBEST-TC simulations were carried out for a period 10 years, forcing the model with time series of wave conditions and water levels which were observed for a period of 3 years and repeating them about 3 times. The results could be different if the model was forced using different hydrodynamic conditions as input data.
- To avoid excessive erosion, the UNIBEST-TC model contains a fixed layer. The position of this layer has a large influence on the output results.

- The model was calibrated for a specific transect and using specific forcing in terms of hydrodynamic conditions. This might limit the application of the same model to other situations (e.g. other transects or other hydrodynamic conditions).

A possibility of generalizing the results from this application, would be the setting up of models for different classes of representative profiles (e.g. with different steepness, different number of breaker bars, different grain size, etc.). In the same way, also the hydrodynamic forcing could be used as additional variable to evaluate the effects of nourishments in situations characterized by different wave conditions. In this way, a more general Bayesian network could be built, including a larger number of nodes corresponding to these new variables.



## 6 Validation of the “Nourishment Impact Tool” based on 30 years data from the Holland coast

### 6.1 Introduction

Within the framework of the Building with Nature (BwN HK4.1) and Alternative Long Term Nourishment Strategies (ALS) projects, a modelling tool for the assessment of long-term and large-scale nourishment strategies has been developed. The model covers the entire Dutch coast, including the tidal basins in the Wadden Zee (Huisman et al., 2012). The model allows computing coastal changes as a function of gradients in alongshore transport and specific nourishment strategies. The model accounts for land loss due to sea level rise effects, offshore sediment losses, dune growth, and interaction with tidal basins computed by means of the ASMITA model (Stive et al., 1998 and Stive and Wang, 2003).

The model is being used for addressing specific questions on the effects of long-term nourishment strategies (e.g. Giardino et al., 2013b). The model can in principle also be used as support tool to address some of the questions of the project Toestand van de Kust, specifically concerning the optimization of the nourishment strategy. Nevertheless, the model has so far not been fully calibrated using the actual coastline changes and nourishment volumes, which have been implemented along the Dutch coast. Within the framework of the KPP-B&O Kust a wide range of data has been collected, including nourishment volumes and coastal changes represented by a number of coastal indicators. This data will be used within this study to verify the quality of the predictions of the Nourishment Impact Tool and to assess at what extent the tool could be used to address the main questions of the Toestand van de Kust project.

In particular, the prediction and verification will focus on the effects of the actual nourishment volumes which have been implemented along the Dutch coast between 1980 and 2010 on the following morphological indicators: MKL positions and dune foot position.

### 6.2 Parameter settings

A number of free parameter has been set in the Nourishment Impact Tool for a proper discussion of the Holland case study. The main parameters are shown in Table 6.1.

In particular, the actual nourishment volumes implemented along the Holland coast between 1980 and 2010 have been used as input in the tool. The slope of the profile between +3 m and -5 m NAP was set to 1:100 as representative of an average slope for the Holland coast. The sea level rise was set to 1.9 mm/year, which is representative of the actual sea level rise. The representative active height was set to 8 m, from the dune foot position (+3 m NAP) to -5 m NAP. These limits are approximately the same as the ones defining the MKL volume. In this way, changes to the MKL position can be easily associated to changes in active height.

The definition of the active height is a crucial parameter as it defines the height on which the nourishments are supposed to spread uniformly in a certain period of time. The longer the time scale under consideration, the bigger is the active height to be considered. Considering a time scale of 30 years, a active height of 8 m can be considered realistic. The effective height of the dunes, representative of the dune height affected by sand input due to aeolic transport coming from the beach, was fixed to 5 m (i.e. from the dune foot position to +8 m).

Table 6.1 Main parameter settings for tool validation.

Parameter	Value
Simulation time	[1980 - 2010]
Distribution of nourishment	predefined
Sea Level Rise	1.9 mm/year
Active Height	8 m (from +3 m to -5 m NAP)
Effective height of dunes	5 m
Slope of the active height	1:100
Slope of the dune face	1:3

### 6.3 Validation of the Nourishment Impact Tool versus measured data

The Nourishment Impact Tool has been validated against measured data of nourishments and change in indicators analysed for the Holland.

The validation was at first carried out for all JarKus transects looking at three different periods of time: 1980-1990, 1991-2000 and 2001-2010. The tree periods of time correspond to periods when the nourishment policy was modified (Giardino et al, 2013a). As a consequence of these policy changes, the total nourishment volume for the Holland coast was increased respectively from  $8.7 \times 10^6 \text{ m}^3$  to  $26 \times 10^6 \text{ m}^3$  and then to  $77 \times 10^6 \text{ m}^3$  for the total duration of the three periods under consideration.

The evolution of the coastline and dune foot position computed with the Nourishment Impact Tool are shown respectively in Figure 6.1 and Figure 6.2. The two figures show that between 1980 and 1990, the coastline was in average stable but with some hot spots characterized by erosion. After the implementation of the Policy of Dynamic Preservation of the coastline in 1990 and the further increase in nourishment volume in the year 2000 to counterbalance the effects of sea level rise within the coastal foundation, the erosive trend has been replaced by a general trend toward an accretive coastline.

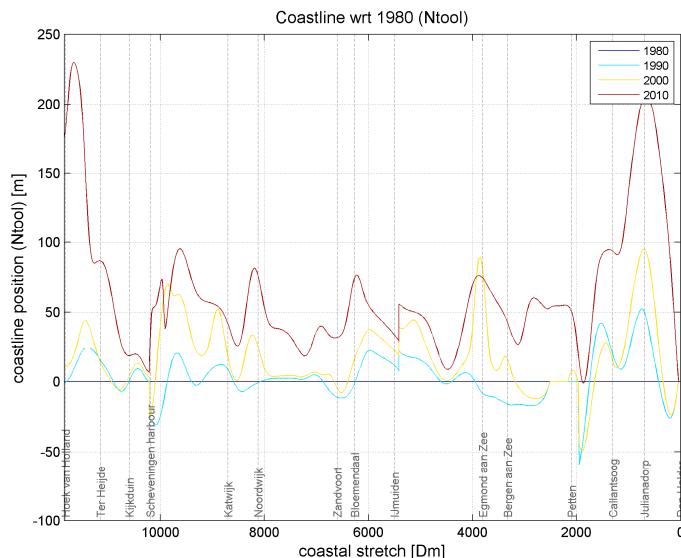


Figure 6.1 Relative changes in coastline position computed with the Nourishment Impact Tool and referred to year 1980.

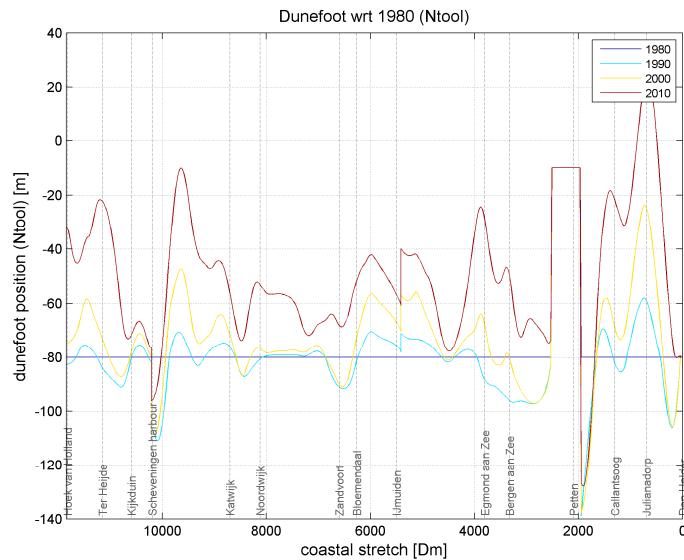


Figure 6.2 Relative changes in dune foot position computed with the Nourishment Impact Tool and referred to year 1980.

Scatter plots showing the comparison of measured and computed changes in MKL and dune foot position are shown respectively in Figure 6.3 and Figure 6.4. Both figures show a very wide spread of the data, with almost no correlation between computed and measured data. This can be explained considering that the nourishment tool has been developed to assess the large scale and long term impact of a nourishment strategy, rather than providing a detail description of the morphological development of a single JarKus transect. The physics in the models are in fact too simplistic to provide realistic results at the local scale.

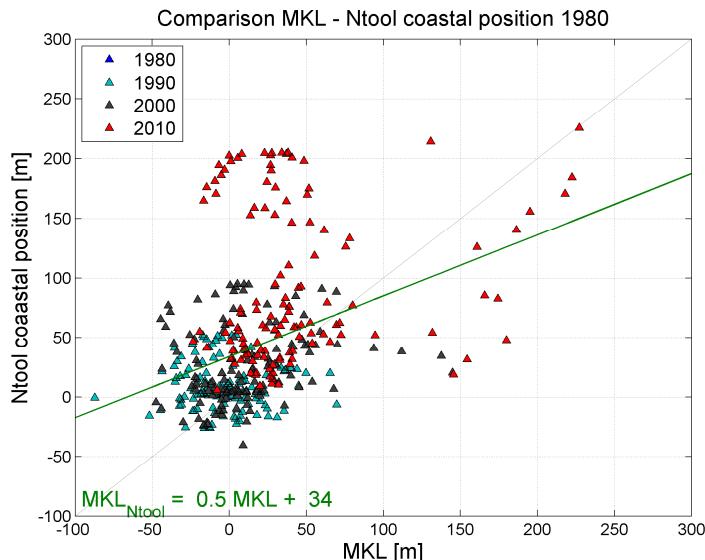


Figure 6.3 Scatter plot showing computed relative changes in MKL position, versus measured changes. Different colours show the relative changes at different years with respect to the reference year 1980.

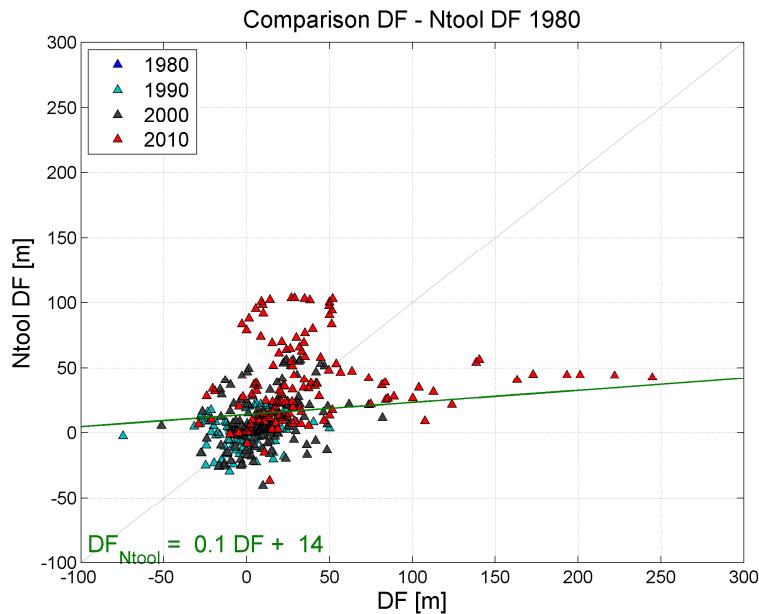


Figure 6.4 Scatter plot showing computed relative changes in dune foot position, versus measured changes.  
Different colours show the relative changes at different years with respect to the reference year 1980.

Therefore, the validation was repeated considering larger areas characterized by a homogeneous nourishment strategy and autonomous trends before that nourishments were implemented at that area. The definitions of the sub-areas is described in Giardino et al. (2012) and Giardino et al. (2013b). In total 21 sub-areas have been distinguished, of which 8 lie in Noord-Holland, 8 in Rijnland and 5 in Delfland. Trends in MKL and dune foot position have been derived at JarKus transect level and then averaged in space within each sub-area. The comparison between relative changes in computed coastline position and data derived changes in MKL position for the 21 sub-areas is shown in Figure 6.5. The same comparison was repeated considering computed and measured relative changes in dune foot position (Figure 6.6). The general accretive trends induced by nourishments can be well reproduced by the Nourishment Impact Tool. Nevertheless, a number of outliers with remarkable differences between the two data sets can be identified:

- Sub-area in front of *Ter Heijde*. Changes in measured MKL position are much larger than the computed ones in the year 2010. The same holds for the measured dune foot position in this area and in the area next to it, in front of Hoek van Holland. This can be explained considering that those areas were characterized by extremely large nourishments which were placed on the dune face or on the beach, at the end of the time window 2009-2010. In particular, the dune compensation project and the "Zwakke Schakel" (Weak Links) project which were executed between 2009 and 2010 with nourishment volumes respectively of 5.1 and  $10.1 \times 10^6 \text{ m}^3$  of sand. Those volumes produced a clear jump in the data as they directly influence the dune foot and the MKL position at the end of the time window 2000 and 2010. On the other hand, the effect of those large nourishments on computed MKL and dune foot position is less clear. In particular, changes in dune foot position in the model are derived based on an empirical relation, which simulate the effect of aeolian transport by linking changes in beach width to shift in dune foot position (Chapter 0). Therefore, changes in dune foot position computed in this way will be delayed, with respect to the immediate response of the dune foot to a nourishment which is placed exactly on

the dunes or on the beach. Also the computed shift in MKL position consider a nourishment volume which is always spread over the entire active height and which start diffusing immediately after the nourishment is built. The real situation at these sub-areas is different as in 2010 the nourishments were still under construction. The difference between computed and measured MKL and dune foot position will be most likely smaller some years after the implementation of the nourishments.

- Sub-areas south of *Scheveningen* and *IJmuiden*. Measured MKL and dune foot position are larger than the computed ones. This is related to the very simplistic approach in the model to simulate the effect of hard structures such as the harbour jetties of Scheveningen and IJmuiden on alongshore transport.
- Sub-areas in front of *Callantsoog* and *Den Helder*. Modelled changes in MKL and dune foot position are overpredicted. This might be explained considering that offshore losses in cross-shore direction are very large at these sub-areas due to the presence of the Nieuwe Schulpengat gully close to the shore and the very steep profile. Although offshore losses are included in the model, this is done following a very simple approach and which might require further calibration for these specific situations. Moreover, the loss of sediment in the Marsdiep tidal inlet also might be underestimated in the model.

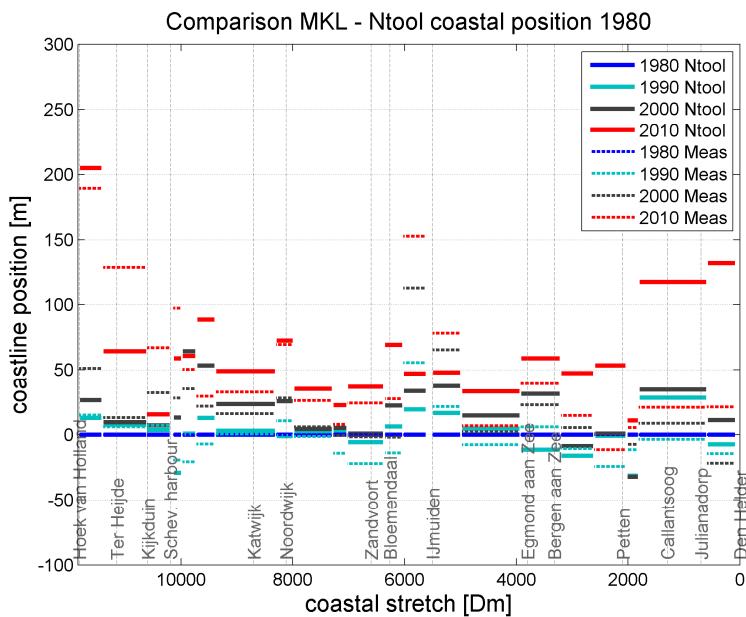


Figure 6.5 Comparison between relative changes in computed coastline position (solid line) and data derived changes in MKL position (dashed line) for different sub-areas. The reference year is 1980.

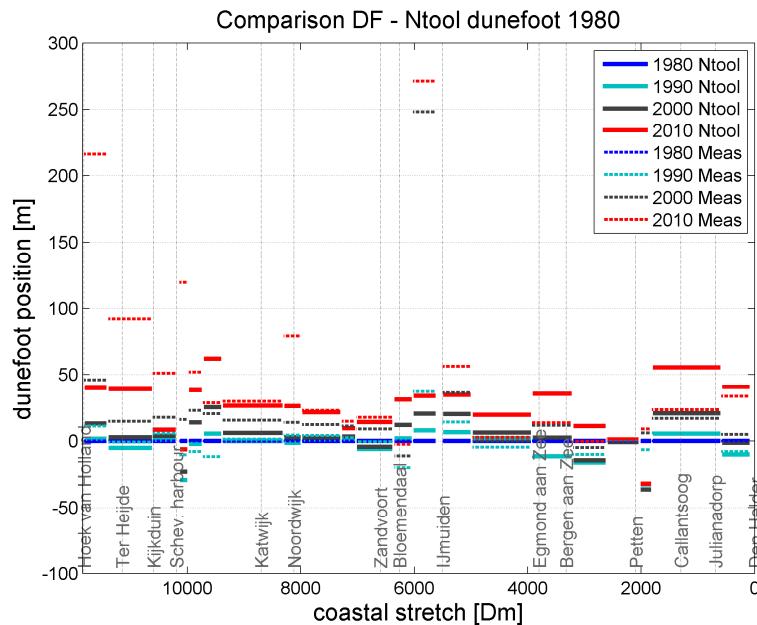


Figure 6.6 Comparison between computed and data derived relative changes in dune foot position (solid line and dashed line) for different sub-areas. The reference year is 1980.

The same types of figures can also be presented as scatter plots respectively for the MKL and dune foot position (Figure 6.7 and Figure 6.8). The tool seems capable to reproduce the average development of the MKL for the entire coast, with a slope of the trend line between modelled and data derived MKL changes of 1.2 (Figure 6.7). The number of outliers which were discussed above can also be tracked back in the scatter plot (e.g. sub-area in front of Callantsoog and Den Helder, and in the south of Ijmuiden). The effects of these outliers at the two side of the trend line balance out their effects so that the slope of the trend line remains close to 1.

It is also interesting to point out that the intersect of the trend line has a value equal to -17. This means that when data show no change in MKL, the model still predicts an erosion equal to minus 17 m. Although, several factors influence this offset, a possible explanation might be an overestimation of the sea level rise, which directly leads to an overprediction of the erosion rate following a Bruun rule<sup>2</sup> approach.

The scatter plot for the dune foot position changes show a much less clear trend (Figure 6.9). The same outliers as discussed above have also been indicated. It is clear that the model largely underestimate the changes in dune foot position as shown by the slope of the trend line which is much lower than 1 (0.2). As mentioned above, this is partly related with the formulation used in the model to predict the changes in dune foot position, which are assumed to be driven by aeolian transport only. In reality, large changes in dune foot position along the Holland coast have occurred because of beach nourishments or dune reinforcements, which immediately lead to a shift in dune foot position. A possibility to improve this in the model, would be to separate the effects of shoreface and beach nourishments instead of spreading them both on the entire active zone.

<sup>2</sup>The Bruun rule is a parametric representation of the effects of sea level rise on coastal retreat. According to this formula the coastal retreat "R" can be described as  $R=(SL)/(h+b)$ , where "S" is the sea level rise, "L" is the cross-shore width of the active profile, "h" is the closure depth, and "b" is the elevation of the beach or dune crest.

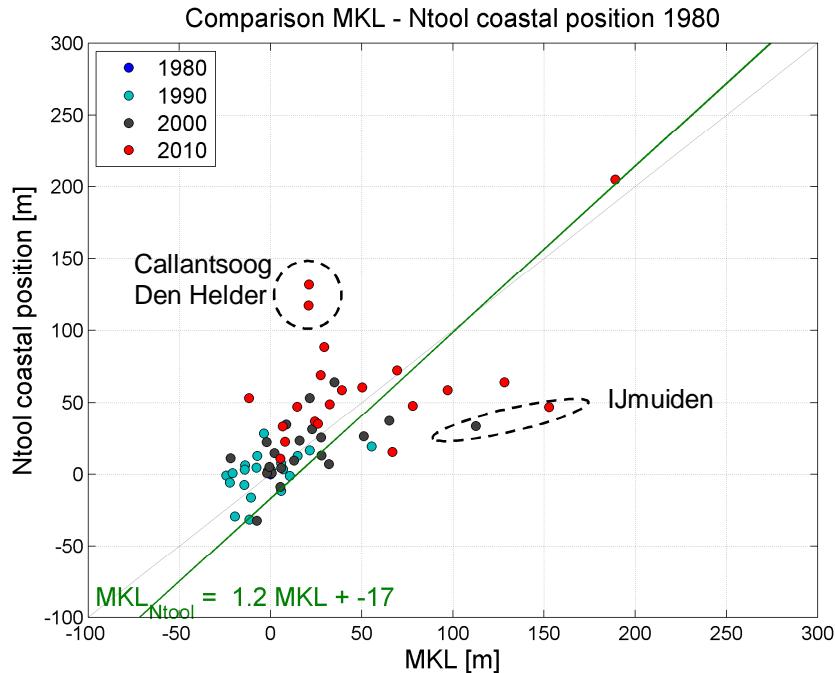


Figure 6.7 Scatter plot showing computed relative changes in MKL position, versus measured changes at sub-area level. Different colours show the relative changes at different years with respect to the reference year 1980.

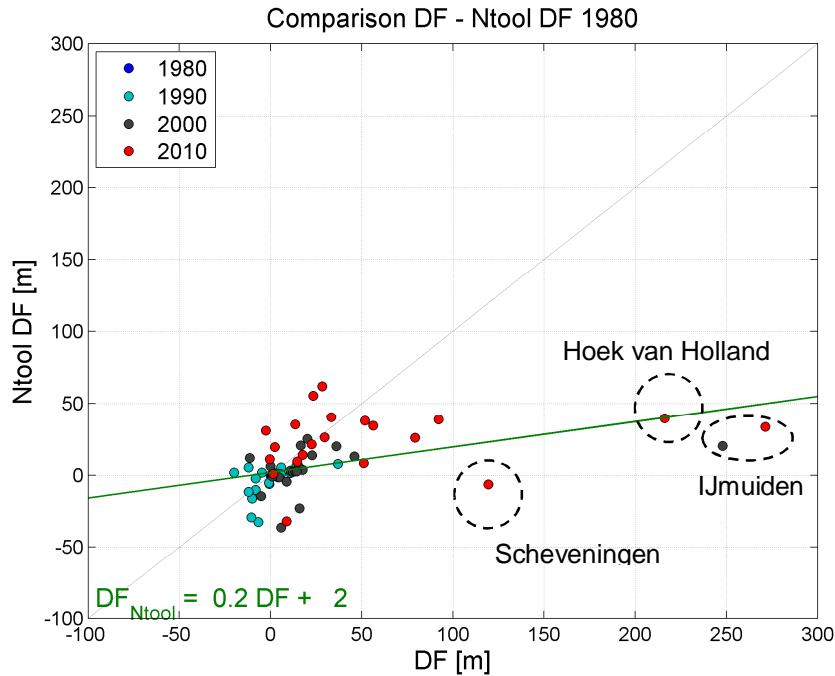


Figure 6.8 Scatter plot showing computed relative changes in dune foot position, versus measured changes at sub-area level. Different colours show the relative changes at different years with respect to the reference year 1980.

#### 6.4 Relations between nourishment volumes and computed indicators

To evaluate the efficiency of applied nourishments, the changes in MKL and dune foot position with respect to the nourishment volumes were plotted in Figure 6.9Figure 6.12, both for model and data. Figure 6.9 and Figure 6.10 show that the predicted impact of nourishments on MKL changes is very close to the information derived by data, as the slopes of the two trend lines are very close (0.028 and 0.027). This means that a nourishment volume of 1000 m<sup>3</sup> spread over a 10-year time window can lead to a shift in MKL position of about 30 m.

On the other hand, the effect of nourishment volumes on modelled dune foot position changes are underpredicted as the slope of the trend line from modelled data is 0.013 versus a slope of 0.023 derived from data. As mentioned above, this is related to the formulation used in the model to compute the dune foot position changes, which are always considered due to aeolic transport, neglecting the effects of nourishment built directly on the beach or dune front, and which would lead to much larger changes.

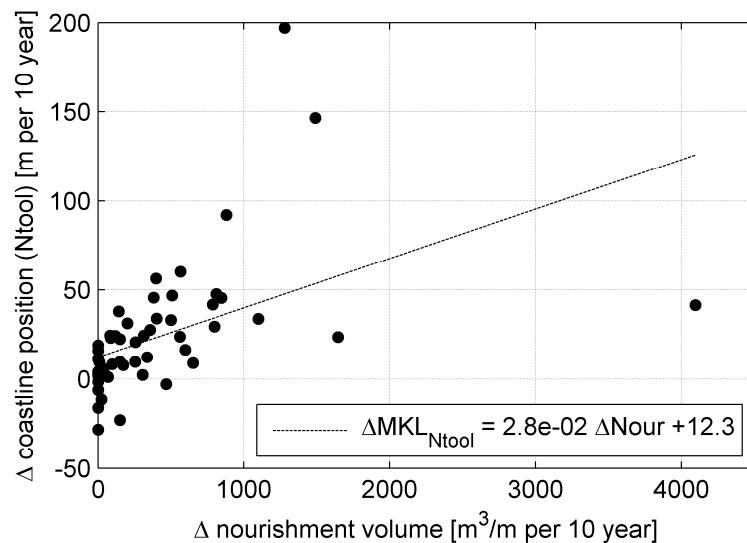


Figure 6.9 Modelled variation of coastline position as a function of the nourishment volumes. Each point represents the average value of the coastal position in one sub-area, within a time interval (1980-1990, 1990-2000 and 2000-2010).

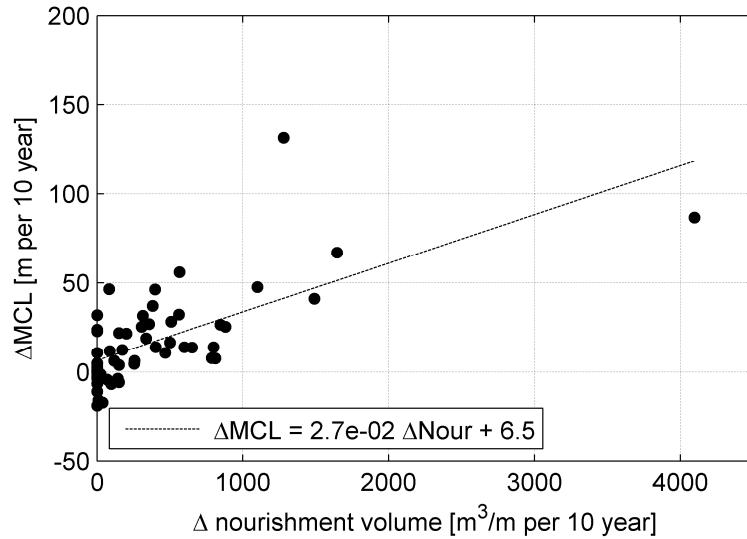


Figure 6.10 Data derived variation of coastline position as a function of the nourishment volumes. Each point represents the average value of the coastal position in one sub-area, within a time interval (1980-1990, 1990-2000 and 2000-2010) (Giardino et al., 2013a).

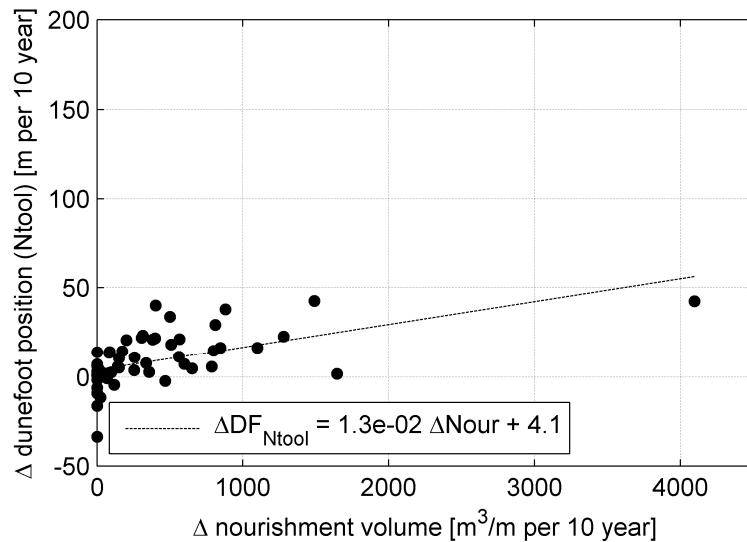


Figure 6.11 Modelled variation of the dune foot as a function of the nourishment volumes. Each point represents the average value of the dune foot position in one sub-area, within a time interval (1980-1990, 1990-2000 and 2000-2010).

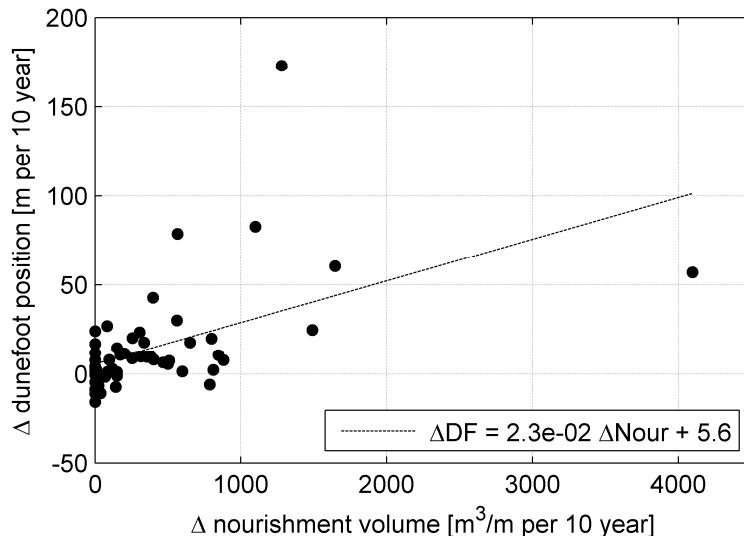


Figure 6.12 Data derived variation of the dune foot position as a function of the nourishment volumes. Each point represents the average value of the dune foot position in one sub-area, within a time interval (1980-1990, 1990-2000 and 2000-2010) (Giardino et al., 2013a).

## 6.5 Discussions and conclusions

In this chapter, a validation of the Nourishment Impact Tool has been carried out using data of MKL and dune foot position analysed within the project Toestand van de Kust.

The validation has shown that the tool can not be used to study the morphological changes at JarKus transect level as the assumptions and physics in the tool are too simplistic. On the other hand, the tool is able to predict the medium-term changes in MKL position due to the effects of nourishments on the larger scale. Local morphological changes as the one possibly due to the effects of hard structures (e.g. jetties), or where the effects of cross-shore transport is very large (e.g. gully close to the shore), or close to tidal inlets can not be properly described. Moreover, performances can increase looking at larger time scale, rather than immediate after a nourishment is built.

Dune foot migration is instead largely underpredicted by the tool as this is computed in the model by using an empirical relation which simulate the effects of aeolian transport, by relating it to the beach width. In reality, nourishments which are placed directly on the beach or on the dune front lead to much larger and immediate changes in dune foot as those due to aeolian transport.

A number of suggestions to improve the model prediction are given below:

- Distinguish in the tool between the effects of shoreface and beach/dune nourishments. In particular, the prediction of dune foot migration can be much more accurate if the volumes of sand placed exactly on the dune foot are accounted for.
- Although the tool was initially meant to simulate the effects of nourishments at the large spatial and temporal scale, the tool include a number of coefficients which can be calibrated based on data to better describe the presence of hard structure (e.g. tuning the by-pass rates), the offshore losses (e.g. for the presence of a gully close to the coastline), and the losses due to presence of tidal inlets. This would make the tools more accurate also for specific situations.
- Another parameter which can induce a possible offset between model and measured MKL changes is the sea level rise rate, which can also be tuned.

Finally, it is important to remark that also the analysis of the changes in MKL and dune foot position based on data shows a wide data scattering as the entire Holland coast includes the presence of several differences and singularities within the region. Moreover, also the data analysis included a number of assumptions as for example the use of predefined sub-areas and average trends within different time windows to define the changes in morphological indicators.



## 7 Summary and conclusions

In this study, a number of tools have been tested and applied with the aim of assessing the morphological development of the coastal zone, in the medium- (years) and long (decades) - tem, in response to nourishment works. The response was assessed in terms of changes to a number of easy-to-use coastal indicators: the MKL position, the dune foot position and the beach width.

In particular, the standard cross-shore UNIBEST-TC model, with the addition of the beach-dune module for simulating changes in the dry part of the profile, was applied to investigate the response of different nourishment designs at different time scales. A large number of runs (~300) have been carried out and the output from those runs analysed using a Bayesian approach. This approach allows to easily identifying relations between variables (e.g. between nourishment volumes and consequent changes to the indicators) and test different nourishment designs.

Moreover, the alongshore Nourishment Impact Tool has been applied and validated using data from nourishments and measured changes in the indicators collected during 30 years along the Dutch coast.

The main conclusions from this study are here summarized:

- The use of the cross-shore UNIBEST-TC model combined with an analysis based on a Bayesian approach provided useful information on the qualitative development of the coastal indicators at different time scales, as a function of different nourishment designs. In particular, the effects of beach nourishments on MKL position are much more pronounced than those of shoreface nourishments after one year. The effects of the two types of nourishments, considering the same nourishment volume, becomes nearly comparable after 10 years. On the other hand, the effects of beach nourishments on dune position reach a maximum after 5 years, but even after 10 years are still considerable higher than those of shoreface nourishments (Section 5.3.1 and 5.3.2). These conclusions can support coastal managers in the choice of the most suitable nourishment, given the result to be achieved and the time scale when this result should be achieved.
- Rules-of-thumb relations between nourishment volumes and changes in MKL and dune foot position predicted with the models, are consistent with the results derived based on data analysis (Section 5.3.3).
- The beach-dune module was successfully implemented within UNIBEST-TC. This additional module is necessary to be able to quantify morphological changes within the dry part of the profile, which is not directly modelled by UNIBEST. Nevertheless, this also means splitting the profile in two parts, one where changes are directly computed in response of the hydrodynamic forcing derived by UNIBEST, and the other one where the changes are derived from the empirically based beach-dune module (Section 4.5.3).
- The quality of the results derived with the Bayesian network are fully dependent on the quality of the UNIBEST-TC results. Those are influenced for examples by model calibration, the position of a fixed layer to avoid excessive erosion during storm conditions, and the hydrodynamics forcing used as input in the model.

The use of a fixed layer, in particular, is purely a modelling trick and does not have any physical meaning (Section 4.5.4).

- Although this was not the main focus of the study, the use of the UNIBEST-TC model has shown promising qualitative results on the influence of nourishments on the breaker bar dynamics (Section 4.5.5).
- The development of the morphological indicators along the Dutch coast during a period of 30 years using the Nourishment Impact Tool has shown that this simple coastline model is able to predict the large scale changes in MKL position, due to the past nourishment works. On the other hand, the large scale changes in dune foot position can not be predicted accurately because in the model there is no distinction between shoreface and beach nourishments, which in reality affect very differently the dune foot position. Changes in MKL and dune foot position at the local scale can not be predicted as the assumptions in the model are too strong to allow the simulations of a number of more local processes (e.g. the effects of hard structures, cross-shore sediment losses in gullies, sediment losses in tidal basins) (Chapter 0).
- To be able to assess the effects of different nourishment designs in the medium- and long- terms, the use of simplified models is required. The study was based on one cross-shore model, implemented for one specific transect, and one alongshore coastline model. Both cases, are a simplification of the reality with direct effects also on the prediction of the effects of nourishments. A cross-shore model implies the assumption of a straight coastline. Therefore also nourishments are assumed to continue indefinitely in alongshore direction, leading to an overestimation of the effects of the nourishments itself. A coastline model can not properly simulate the sediment losses and the spreading of a nourishment in the cross-shore direction.

## 8 Applicability of the prediction tools in support to WVL work

This report has described the development and application of different tools to assess the efficiency of various nourishment schemes on the coastal development. Although those tools are still under development at Deltires, feedback from the policy makers is crucial to investigate how those tools should be developed, for supporting the daily work of coastal maintenance and policy making. One of the main tasks of Rijkswaterstaat consists in deciding how to distribute the sand nourishments, in order to achieve optimal predefined objectives. In this Chapter, a number of suggestions for the application of those tools are put forward to reach these objectives:

- 1) The combination of UNIBEST + beach-dune model was used to predict the medium-term effects (up to 10-years) of various nourishment schemes (beach and shoreface with different volumes) on the development of a number of indicators (i.e. beach width, dune foot position, MKL). The implementation was tested for one specific transect but the same methodology could be applied to other representative transects, in order to cover the variability of the coastline. This tool could be used during the decision-making process to choose between different nourishment schemes (volumes and types) to reach a predefined objective (i.e. a predefined beach width, dune foot position, MKL).
- 2) A Bayesian network approach by itself is not a tool. It is a way of presenting results derived from a different model (this report) or from measurements (Giardino and Knipping, 2012b). This instrument can be used to point out visually cause-effect relationships (i.e. between nourishments and coastal indicators) and deriving rule-of-thumbs expressions relating for example nourishment volumes and changes to those indicators. Rule-of-thumb relationships could be used to get ideas on the larger scale (spatial and temporal) effects of nourishments. As an example, to predict what kind of development could be expected by nourishing with pre-defined amounts of sand the coast for the coming years. Moreover, rule-of-thumb relationships between different indicators could be used to estimate the values of certain indicators requiring the use of models for their computation (e.g. the probability of breaching) from other ones which can be easily derived from measurements (e.g. dune foot position, dune volumes).
- 3) The prediction of bar position and morphodynamic development can support in the detail design of nourishments. Breaker bars function in fact as a kind of natural submerged breakwater. Therefore it is important to assess the effects of nourishments on their cycles, to be able to use them in the most efficient way as possible.
- 4) The coastline Nourishment Impact Tool model can be helpful in investigating the effects of future nourishment policies in areas which might expect erosion (i.e. different spatial distribution of the nourishments, different volumes).



## 9 Recommendations for further work

Based on the conclusions in Chapter 7, the following recommendations for further work are here given:

- The Bayesian network as it was set up for the present study, only provides information on the effects of different nourishment designs at one specific transect, and using one specific hydrodynamic forcing at the boundary. The same types of simulations could be set up for different representative profiles, for example including different ranges of steepness or different types of profile (e.g. with one, two or more breaker bars). In the same way, different ranges of hydrodynamics forcing could be tested. This would make the Bayesian network more general, allowing to derive observations for a larger range of situations.
- At the moment the nourishment effects have been assessed either using a cross-shore model or an alongshore coastline model. Those assumptions hamper an accurate prediction of the nourishment development. A better parameterization respectively of the sediment losses in alongshore and cross-shore direction would help a more accurate prediction.
- The use of a fixed layer in the UNIBEST-TC model to avoid excessive erosion during storm conditions could be avoided with improvement of the physics in the model.
- Some improvements are still necessary within the UNIBEST-TC model, especially when used to produce a large number of runs as required when used in combination with a Bayesian approach to investigate the model results. Several runs, especially in combination with very large nourishments, crashed without clear explanation.
- As the effects of shoreface and beach nourishments, especially on the dune foot position development are very different, it is advised to separate those nourishments inside the Nourishment Impact Tool, to achieve a better prediction of the dune foot position changes.
- Based on the comparison between data and coastline development derived using the Nourishment Impact Tool, an improved calibration of the tool could be achieved.
- Although only qualitative, the simulation of the impact of nourishments on the breaker bar development has shown promising results, which should be further analysed and possibly compared to observations related to bar development at transects where nourishments were carried out.



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