Building with Nature

EcoShape

Long-term coastal dune development in the Interactive Design Tool (HK 4.1)

EcoShape – Building with Nature

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Summary
This document describes a dune model for the prediction of long-term dune response to coastal protection measures, such as regular nourishments, mega-nourishments and revetments. The model is part of the Interactive Design Tool developed in the framework of Building with Nature Holland Coast case study (HK). This document describes the model, gives background information to the choices that are made, and discusses the capabilities and limitations of the model. The final model is data driven and based on expert judgement. It gives the development of the dunes with respect to the current situation and the potential biodiversity associated with that. Optionally, management type can be given by the user, from which the dynamics of the foredune are estimated.

Contents

1. Introduction

Within the Building with Nature/Ecoshape program, an Interactive Design Tool for the Holland Coast (ITHK) is being developed. With this tool, managers and stakeholders can get a quick overview of how nourishments and other coastal management practices affect the coast on the long term (up to a century). The tool estimates coastline position, dune development and marine biodiversity. The model behind the tool is fast, taking a couple of minutes runtime for a timespan of a century, and the results are plotted in Google Earth for visualisation.

This document describes the dune module within the Interactive Design Tool. **The aim of the module is to predict the long-term response of the dunes along the Holland Coast to coastal protection measures, such as regular nourishments, mega-nourishments and revetments.** A new approach was taken to the long-term modelling: a combination of data-driven modelling (Bayesian network modelling) and rules based on expert judgement. Here we describe the dune model, give background information on the choices made, and discuss the capabilities and limitations of the model.

2. Model input and specifications

The core of the Interactive Design Tool is the UNIBEST-CL model (http://www.deltares.nl/en/software/1023766/unibest-cl/1256430). It computes alongshore sediment transport from location-specific but fixed profiles, shoreline orientation and a wave ensemble. Its output consists of the amount of volume loss or gain per profile location, which is translated into a landward or seaward shift of the profile, respectively. Dunes are treated as part of the fixed profile. The 'active height' of the profile runs mostly up to + 5 m NAP. This approach works well for situations with relative small volume changes, but is less well suited for situations in which large volumes of sand, for example introduced during mega-nourishments, allow for extensive beach and dune building. The output of the Interactive Design Tool without the dune module can be viewed in http://viewer.openearth.nl/, or in Google Earth if kml files (output data plotted in Google Earth format) are available.

The requirements for the dune model are:

- Concerning the Holland coast;
- Capable of simulating extreme situations such as mega-nourishments;
- It should fit the existing approach of the Interactive Design Tool, i.e.:
    - Computing time should be short, i.e. not adding significantly to the few minutes that a run takes now,
    - The model should use the output of the UNIBEST CL model;
- Output should be:
    - in time steps of 1 year, over a period of 100 years,
    - as compared to the starting situation,
    - directly usable for MapTable, i.e. The results should be easily visualised in Google Earth,
    - informative for stakeholders;
- Not hinder the benthos and fish module.

UNIBEST-CL in this application has alongshore grid cells of 50 m wide.

End-users are individuals and organisations meeting at so-called 'kustateliers': waterleidingbedrijven, waterschap (kustverdediging), recreatieondernemers, natuurorganisaties, recreanten, RWS, provincies, gemeenten.

Potentially interesting outcomes include therefore:

- dune foot and beach width dynamics (safety, recreation),
- dune budget (safety),
- new dune formation and dune type (ecology, recreation),
- biodiversity including the presence of vegetation (incl. green beach) (ecology, recreation),
- aeolian sand transport towards established dunes (ecology, safety, recreation).

3. Background on dune formation

3.1 Literature survey

To obtain relations between coastal profile development (e.g. volume changes such as the UNIBEST output) and dune development, a literature survey was done on which factors have the strongest influence on dune formation. Literature considering the Dutch coast was preferred.

Dunes, beach and underwater zones may have contrasting budgets, reflecting the exchange of sand between these zones. Along the Holland coast (and also the Dutch coast as a whole), virtually all cross-shore combinations of negative and positive yearly budgets occur (De Ruig and Louisse, 1991; Arens et al., 2010). Only when budgets are highly positive, such as south of the IJmuiden harbour jetties, all changes are positive. This makes predicting dune development based on total budget developments not straightforward.

Still, beach morphology and dynamics may have a large influence on dune development. They determine the availability of sediment for aeolian transport, and the degree of storm erosion by affecting wave dissipation (Sherman and Bauer, 1993; Davidson-Arnott and Law, 1996; Ruessink and Jeuken, 2002; Aagaard et al., 2004).

Individual factors that may affect dune formation are:

- *Beach width* gives most, but only limited, information about dune growth (Sherman and Bauer, 1993; Davidson-Arnott and Law, 1996; Ruessink and Jeuken, 2002; Saye et al., 2005; Damsma, 2009; De Vries et al., 2011; De Vries et al., in prep.; De Groot et al., submitted; Keijsers et al., submitted)
- *Storms* are important for erosion, but there is no consensus on whether they have predictive value for dune volumes (De Ruig and Louisse, 1991; Guillén et al., 1999; Ruessink and Jeuken, 2002; Pye and Blott, 2008; Houser, 2009; De Jong et al., 2011; De Vries et al., in prep.; Keijsers et al., submitted);
- *Variations in wind strength and direction* within the normal range have no effect on dune volumes and seem to be subordinate to transport limiting factors and beach morphology (Davidson-Arnott and Law, 1996; De Vries et al., in prep.Keijsers et al. in prep.De Vries et al., in prep.; Keijsers et al., submitted).
- *Erodibility of sediment* is very important (U.S.A.C.E., 2008; Delgado-Fernandez and Davidson-Arnott, 2011; Nordstrom et al., 2011). This is however of limited use for current model.
- *Vegetation density* is important for dune shape (Arens et al., 2001) and consequently management has clear effect on dune dynamics
- There is no relation between sand budget and area of *embryonic dunes* (Arens et al., 2010).
- *Nourishments*, most notably beach nourishments, affect the dune budget positively, and dampen variability in dune shape and budget (Stive et al., 2002; Van der Wal, 2004; Arens et al., 2010; Bochev-van der Burgh et al., 2011).

Some authors indicate a *lag* between shoreface and beach-dune volume changes (De Ruig and Louisse, 1991), others do not see a lag for beach and dune (De Vries et al., in prep., Joep Keijsers, pers. comm). Response of dune volume on nourishments is generally instantaneously (De Ruig and Louisse, 1991; Van der Wal, 2004; Arens et al., 2010), whereas dune shape lags nourishment (Bochev-van der Burgh and Wijnberg, 2009). On Ameland, dune foot and dune volume have mostly same trend (Keijsers et al., submitted), whereas also contrasting trends are found on other locations along the Dutch coast (Arens et al., 2010). Embryonic dunes may migrate towards dune foot, but are also prone to disappearance after a couple of years (Kuilder, 2010).

It should be noted that the existing Jarkus analyses have been done in several ways: using trends or deviations from the trend or volume differences; measuring dune foot or dune volume; using a fixed reference or a moving reference (De Ruig and Louisse, 1991; Guillén et al., 1999; Ruessink and Jeuken, 2002; Stive et al., 2002; Arens et al., 2010; De Vries et al., in prep.; Keijsers et al., submitted). This makes the results sometimes difficult to compare.

In case there is a very large supply of sand, relatively sheltered conditions may develop. If the beach is relatively high, strong winds may pile up the sand into unvegetated barchans and linguoid dunes. These features are ephemeral and may disappear in the next storm or high water event. In case vegetation establishes on the beach, embryonic dune fields and green beaches may develop (Bakker et al., 2005; Kers and Koppejan, 2005; Van Tooren and Krol, 2005; Smith, 2007). Vegetation establishment is observed on low-lying beaches in the lee of a seaward bar (e.g. Kwade Hoek, Ameland, west Schiermonnikoog, as derived from aerial photographs), and where the beach is so high and wide that disturbance by the sea becomes a rare event (north and east of Schiermonnikoog). The speed of vegetation colonization, and thus dune development, is strongly negatively affected by disturbance such as treading, driving, raking and beach cleaning (Smith, 2007; Nordstrom et al., 2011), as well as storms (Kers and Koppejan, 2005). The development of a green beach is often related to the establishment of microbial mats. A green beach may develop into a salt marsh or dune slack. On a large timescale, this type of development falls into the category of foredune ridges on a prograding coast (Hesp, 2002; Woodroffe, 2002).

3.2 Additional data analysis: Jarkus along Holland coast

As there is a large Jarkus dataset available for the Holland coast, additional Jakus analyses were done for this area (De Vries and De Groot, 2012). These relate volumetric changes of four sections of the coastal profile: offshore, subtidal beach, subaerial beach and dunes. All available years were used. Correlating the volume changes in the four profile sections led to the scheme shown in Figure 1. The underwater parts were strongly correlated, and the intertidal/dry areas were correlated. However, correlations crossing mean low water level (the distinction between the two parts of the beach) were weak or absent. Largest fluctuations were found in the subtidal part of the beach. Both findings are comparable to earlier, similar analyses (De Ruig and Louisse, 1991). This means that it is difficult to relate total profile developments to developments in one of the zones, e.g. the dunes.

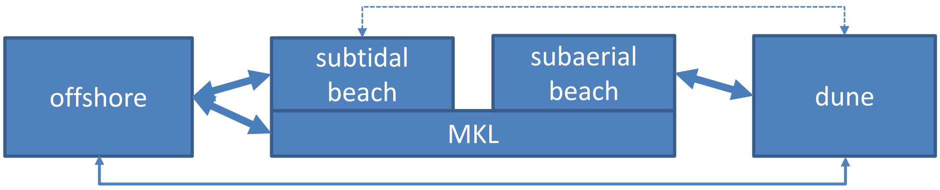

Figure 1. Correlations between volume changes of different parts of the active profile, based on analyses by Sierd de Vries. All correlations are positive, and the thickness of the arrows indicates the strength of the correlations. Dune is the volume > +3 NAP, subaerial beach between + 3 m NAP and MLW, subtidal between MLW and the +3 m NAP mirrored in MLW, and offshore lower than that. MKL is the sum of the two parts of the beach, i.e. the standard Dutch measure for beach sand volume.

3.3 Additional data analysis: barrier islands

Specifically interesting in the context of mega-nourishments are situations in which so much sediment is available locally, that the beach builds out and new dune formation is possible. We looked at recent developments on Ameland and Schiermonnikoog, where green beaches and new dunes have developed from 2000 on, and relatively good information is available. A description of the analyses can be found in Appendix 1, and a summary is given here.

The gentle slopes of accretionary locations have the consequence that often the measurements do not extend far enough seaward to capture the entire profile of interest (which by the way is not a problem for managers, as at these locations no safety issues exist). The data showed that at most locations, the developments of underwater and dunes were not synchronised. This is for a significant part related to the dynamics of tidal channels. As such channels are not common features along the Holland coast, the underwater developments of the islands were not considered relevant for the current model. Dune volumes tend to increase with time, but level off when a green beach or embryonic dune field develops. Accumulated dune volumes before such development can be used as a lower level for model thresholds.

3.4 Existing models

There exist a number of models for dune development, including DUBEVEG (De Groot et al., submitted), DUNE (Kroy et al., 2002, being adapted at Deltares), DUROSTA, DUROS+ or comparable adaptations of that (Damsma, 2009; den Heijer et al., 2012), SAFE-HILL (Van Dijk et al., 1999), an adapted version of Sbeach (Hanson et al., 2010), and an adapted version of UNIBEST (Bas Huisman pers. comm.). Damsma

(2009) gives an excellent overview of the capabilities of most of these models. However, these models are not suitable for integration in the current application. This is due to a variety of reasons, including being too detailed, focussing too much on one process, not being validated, and/or having computing times that are too long. Overall, it should be noted that the state of the art aeolian models are less advanced and successful than those concerning sediment transport in water.

3.5 Modelling considerations

Based on the above literature and data analysis, and ample discussion with Sierd de Vries (TUD), Joep Keijsers (Wageningen University) and Michel Riksen (Wageningen University), it was concluded that the beforehand expected relations (such as beach width or storm frequency) are not generally valid and/or not well understood. Subtidal and subaerial developments seem to be poorly linked, and linkages between short-term processes and long-term developments are not well enough established to make a reliable process-based model (Keijsers et al., 2012). Therefore a data-driven approach is taken instead. Care was taken that the approach gives room for including more process-based approaches in future.

The existing modelling approach of Bas Huisman (pers. comm.), that relates foredune growth and erosion to beach width, was considered. Although this is an elegant way of approaching the subject, there are some reasons for not using it:

- It depends strongly on the calculation of beach width from the UNIBEST profile. This is based on moving the profile linearly back and forth according to change in total volume. This seems valid for small volume changes, but breaks down if very wide beaches develop due to a large influx of sand.
- The relation between beach width and dune volume is less well established than often thought: it only holds for beaches between circa 50 and 150 m.
- The feedback between dune and beach budgets for narrow beaches cannot be implemented in the post-processing approach necessary in the Interactive Design Tool (see below).

4. Model approach

4.1 Model structure

The combination of UNIBEST being optimized for working standalone with standard profiles, computing time that should be as short as possible, and project size, has led to the choice for implementing dune development as post-processing module.

The output from UNIBEST consists of total volume changes. These first need to be translated into something that can be used for dune formation and ecology.
The module consists of a number of steps (Figure 2):

1. Transform profile volume changes into dune volume changes, using a Bayesian Network Model.
2. Interpret dune volume changes into dune classes or states, including temporal lags.
3. Optional (not implemented yet): given whether foredune management is implemented or not, estimate foredune dynamics, based on expert rules.
4. Optional: translate dune classes into ecological 'richness' based on expert rules.

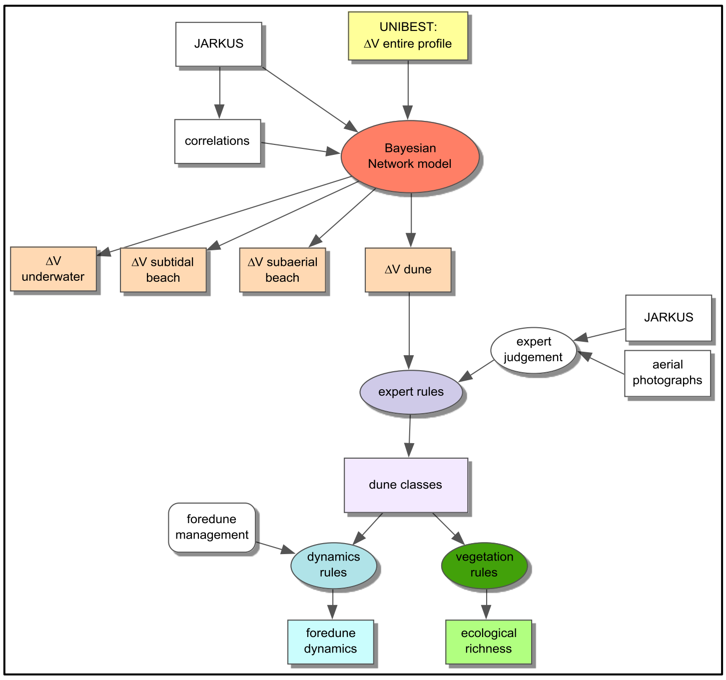

Figure 2. Model scheme.

4.2 Bayesian Network Model

The correlations identified in section 3.2 were put into a Bayesian Network Model using the program Netica, using the same data of the Holland Coast as described above (De Vries and De Groot, 2012). Selection of the variables and their linkages is a critical part of building a Bayesian Network Model for a situation like this where many data are available. Autocorrelations and cross-correlations were used to give an indication of the relation between variables and their relevance.

In this stage, volumes were chosen to represent system behaviour, but if enough process-oriented variables would become available, it would be possible to put these in as well. Because of the interaction with tidal channels, which is not expected along the Holland coast, the data from Ameland and Schiermonnikoog were not added to the Bayesian Network model.

When selecting a certain volume change, as obtained through UNIBEST, Netica gives the observed distribution of changes in each profile subsection. In the current application, we use the mean of these per volume change bin of 100 m^3 m^{-1} y^{-1} total profile change as a lookup table (Appendix 2). In future it would be possible to use information on the distribution for e.g. uncertainty modelling or Monte-Carlo approaches. The latter falls outside the scope of the current project.

A consequence of the current approach is the implicit assumption that the volume changes of the subsections are of the same sign as total volume change. That means that e.g. beach erosion is not compensated for by dune erosion. This is in line with the dominantly positive correlations between volume changes found by De Vries et al., in prep., even though there are situations known where such compensation does take place (Arens et al., 2010).

4.3 Dune classes

It was chosen to use qualitative (ordinal) classes as output. This is easier to visualise as it gives symbols instead of another line that may be confused with coastline changes. Additionally, experience is that end-users tend to overestimate the accuracy of the model outcomes and assume that the numbers are a hard prediction instead of an indication (pers. comm. Wiebe de Boer). Using classes implicitly indicates a certain uncertainty and avoids quantitative interpretation.
Dune classes are:

1. Erosive
2. Stable (within small volume fluctuations)
3. Slightly prograding
4. Prograding with new, unvegetated (mobile) dune field on beach ('Sahara-like')
5. Prograding with partly vegetated new dunes, with possibly green beach.

(A green beach is defined here as a mosaic of dune, salt-marsh and dune-slack vegetation, in an area that is occasionally flooded by the sea. It is mostly sandy, but may also have some mud deposition. It may contain dunes but this is not necessary.)
The rules for assigning the dune classes are given in Table 1. The threshold values are based on the analyses above and in the Appendix, combined with iteration.

Table 1. Rules for assigning dune classes.

cumulative dune budget (m^3/m)*	**based on**	**dune class**
< b1	expert judgement	1: erosive
b1 – b2	expert judgement	2: stable
b2 – b3	expert judgement (lower level)	3: slightly prograding
> b3	observations from Schiermonnikoog and Ameland, but increased because foredune height on Holland coast is generally larger, giving more accommodation space	4: new mobile dunes
> b3 for more than 10 consecutive years	same as class 4 time estimated from simulations (De Groot et al., submitted)	5: new vegetated beach and dunes

*b1, b2 and b3 are approximately -30, 100 and 400 m^3 m^{-1}, respectively. These are based on the sources given in the table and give plausible results when tested with UNIBEST output.

More details on dune shape are not considered. Sometimes dunes with a positive budget grow in height (on Ameland seen when beach width is relatively narrow) and other times they grow seaward (on Ameland when the beach is wide) (Keijsers et al., submitted).

Several scenarios for coastal management measures were run to test the parameters of Table 1. The resulting dune classes (and other classes discussed below) can be found in Appendix 2.

4.4 Foredune dynamics

Foredune management activities such as planting Marram grass and erecting sand fences have a strong impact on the shape and dynamics of the foredune, that cannot be predicted based on autonomous processes alone (Arens and Wiersma, 1994). Therefore it was not included in the dune classes, but given as separate option. The user needs to specify whether the foredune will be artificially stabilised or not. Then the degree of dynamics of the *existing* foredune (zeereep) is estimated (Table 2).

A dynamic foredune means that the vegetation is patchy, and there are aeolian dynamics with the possibility for sand to blow landwards of the foredune. A dynamic foredune logically only develops when there is no foredune stabilisation. Given the stabilised nature of the current foredune, some erosion is necessary to start off the dynamics. The rules are based on interpretation of existing literature for The Netherlands and abroad (Nordstrom and Arens, 1998; Pye and Blott, 2008; Arens et al., 2010; Bochev-van der Burgh et al., 2011).

Table 2. Rules for assigning foredune dynamics classes.

foredune stabilisation	class 1	class 2	class 3	class 4	class 5
no	dynamic	if any of past 2 years dynamic or erosive state → dynamic if not → fixed	if any of past 2 years dynamic or erosive state → dynamic if not → fixed	fixed	fixed
yes	fixed	fixed	fixed	fixed	fixed

Note: fixed does not mean that there is no change in shape of the foredune at all; even the shape of highly-managed dunes is variable over several decades (Bochev-van der Burgh et al., 2011).

Overwhelming by sand influx is not taken into account here. It is assumed that in case of a large influx of sand (dune class 4 and 5), the dune will build seawards because the existing vegetation cover is sufficiently strong to withstand the sand influx. This is a legacy of the past stabilisation (Arens et al., 2010). The rule is based on observations on Ameland, Schiermonnikoog and IJmuiden, where wide beaches and considerable sand influx has ultimately led to formation of dunes on the beach and starvation of the existing straight, intensively-managed foredune.

This option is not implemented in the September 2012 version of the ITHK yet.

4.5 Ecological richness of dune area

The ecological richness (biodiversity) of the dune area is a crude interpretation of how many habitat types dune classes can potentially support (Table 3). Possible habitat types are (E.L.I.; Van Duin et al., 2011):

- H2110 (embryonic dunes, including annual species of the strandline)
- H2120 (white dunes)
- H1310 (annual salt vegetation, green beach)
- H1320 (Spartina vegetation, green beach)
- H1330 (salt marsh, green beach)
- H2190 (dune slack, green beach)

Although grey dunes (H2130) may develop on the pre-existing foredune if new dunes develop seaward, this habitat type is not taken into account as it depends on tracking temporal developments. Given the bandwidth of the prediction of profile developments, too strong interpretation is not encouraged. Non-vegetated habitat types are not taken into account in this module, as a separate module is being developed for benthos and fish.
As the foredune-dynamics module is optional and requires additional input, the ecological richness does not take the results of that module into account.

Table 3. Rules for assigning ecological richness classes.

dune class	richness	corresponding habitat types
1	low/normal	H2120 (this is the standard for the current coast)
2	low/normal	H2120
3	intermediate	H2120 + H2110
4	intermediate	H2120 + H2110
5	rich	H2120 + H2110 + one or more of H1310, H1320, H1330, H2190

5. Visualisation

The visualisation of the output in Google Earth is done with symbols, as the classes are ordinal at best. The proposed symbols are given in Table 4.

Table 4. Symbols used for output in Google Earth

Indicator	Improvement	Similar	Worsening
Dunes classes	 Class 3 : Wide beach + potential for new dunes  Class 4 : Extremely wide beach + potential for new dunes  Class 5 : Extremely wide beach + potential for new dunes and green beach	 Class 2 : Normal + slight progradation	 Class 1 : Erosive dune front
Dunes habitat richness	 Intermediate habitat richness (class 3 and 4)  Rich habitat (class 5)	 Low / Normal habitat richness (class 1 and 2)	

6. Effect of management scenarios on dune development along the Holland coast

6.1 Scenarios and model results

Based on a Kustatelier session of June 1st, 2012, a number of scenarios for the Holland Coast were created:

- Scenario 1: Autonomous development with sea-level rise (SLR) of 2 mm y^{-1}.
- Scenario 2: Minimal consolidation with SLR (protection of coastal settlements with continuous nourishments of 5.0 million m^3 per year)
- Scenario 3: Minimal consolidation 5-year intervals with SLR (protection of coastal settlements with nourishments of 12.5 million m^3 every 5 years)
- Scenario 4: Seaward with sand engines with SLR (sand engines of 20 Mm^3 every 10 y at 5 locations along the coast)
- Scenario 5: Revetments with SLR (protect coastal settlements with revetments, no additional nourishments)

Initially, a separate set of scenarios was were run to test the model algorithm and check the parameter settings of Table 1. These scenarios of nourishments and revetments were then used to evaluate impacts. As user input, dynamic foredune management was only implemented in North Holland and not in South Holland. The simulations were run for 100 y.

In Scenario 1 with autonomous development, no nourishments or revetments are added and sea-level rise of 2 mm per year is assumed (Figure 3). Some parts of the coast will erode and others will gain sediment, but the largest part of the dunes is more or less stable. Hard structures such as the harbour of IJmuiden (around y = 55 km) clearly affect the local budget and thus dune volume. With time, the accreting areas updrift of this and other harbour moles will develop into dune fields and green beaches. In North Holland, strong coastal erosion gives locally rise to eroding, dynamic dunes, that are species-poor.

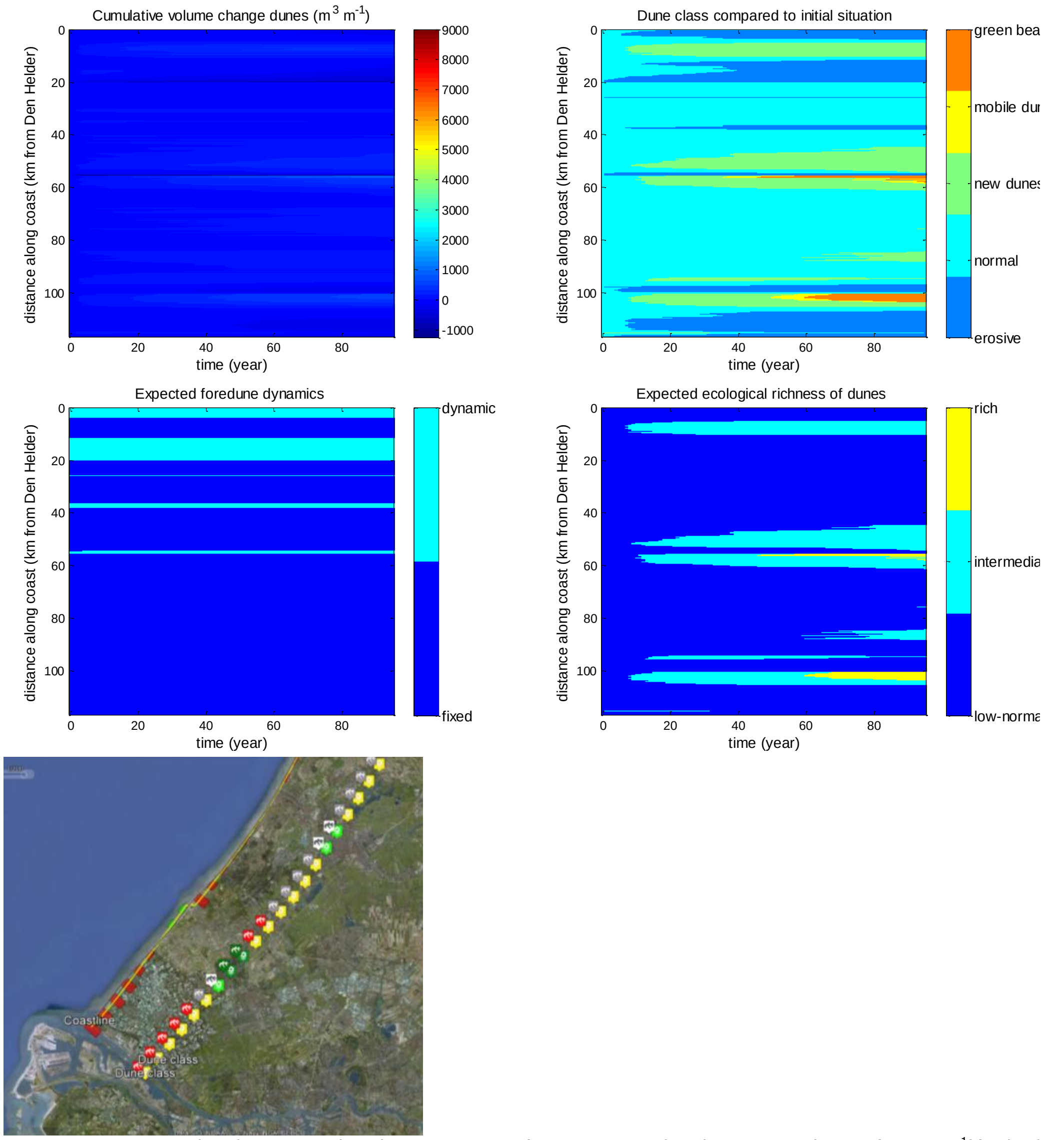

Figure 3. Dune development related to scenario 1: 'Autonomous development with SLR (2 mm y^{-1})'. The horizontal axis represents time in years, and the vertical axis distance along the coast running from north to south. The upper part of each plot therefore represents the development of the North-Holland coast and the lower part the South-Holland coast. Upper left: cumulative dune volume change (i.e. dune volume with respect to starting situation). Upper right: dune classes. Middle left: expected foredune dynamics. Middle right: expected biodiversity based on the dune classes. Lower left: corresponding screen shot of the ITHK visualised in Google Earth at t = 100 y for this scenario.

In Scenario 2 'Minimal consolidation with SLR', settlements and other risk areas are protected against erosion by continuous sand nourishments of 0.3 Mm^3 y^{-1}, whereas other locations do not receive nourishments (Figure 4). On the largest part of the coast, dunes show steady growth: more nourishment sand is blown into the dunes than is taken away by structural erosion. This excess of sand creates room for new dune development and locally the development of a species-rich green beach. Further, the sand is transported to adjacent areas, leading to additional dune growth. Dune growth as result of nourishments is indeed presently seen along part of the Dutch coast (Arens et al., 2010), although the degree that Figure 4 shows now may be an overestimation. Because there are only limited areas that exhibit dune erosion to activate dune dynamics, the areas with dynamic foredunes are also limited.

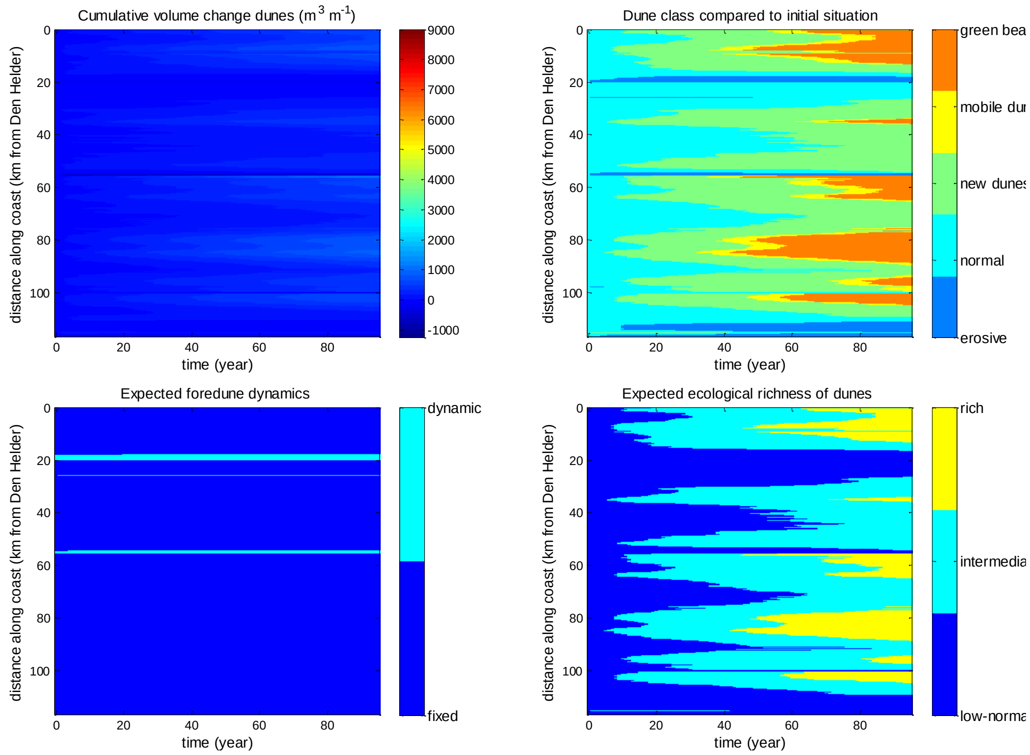

Figure 4. Dune development related to scenario 2: 'Minimal consolidation with SLR'. Panels are the same as in Figure 3. Note that the scales in the upper left panels vary between pictures.

A variation of the minimum consolidation scenario is the one where the nourishments are carried out every five years instead of yearly (1.5 Mm^3 every five years, Scenario 3, Figure 5). The nourishment sand is spread out less than in the previous scenario, leading to more variation in dune shape alongshore. Compared to the previous scenario, green beaches develop earlier as a result of the nourishments. This is related to the wider beaches that develop at the nourishment locations, functioning as source of sediment for the dunes (De Groot et al., submitted). Further there are slight differences related to the locations of the nourishments.

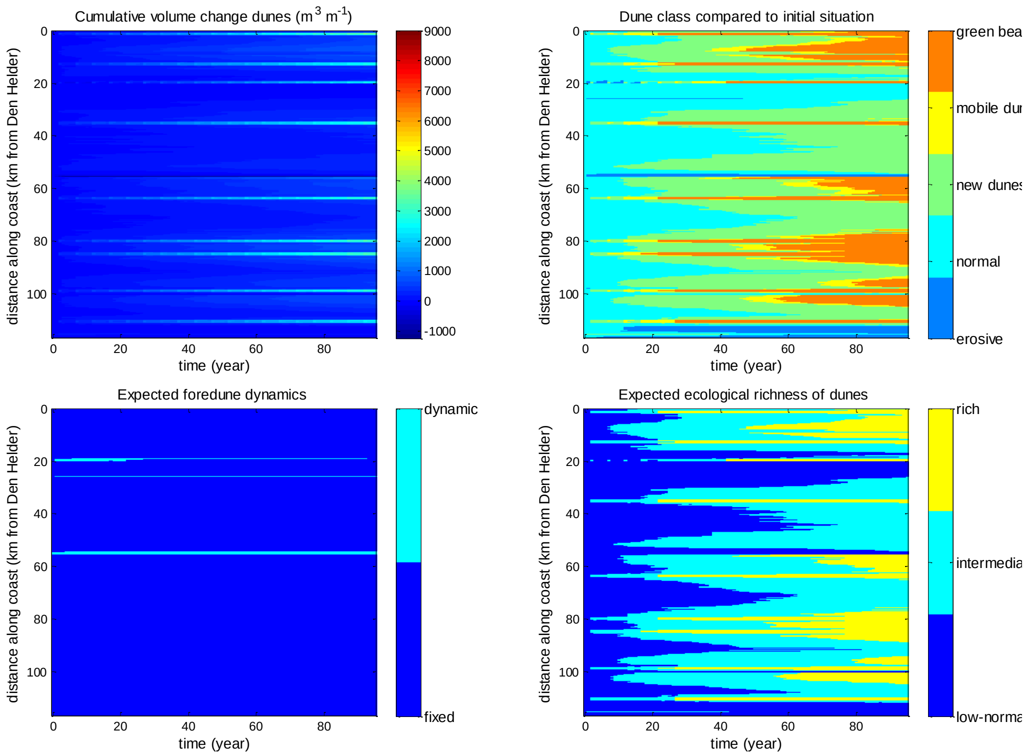

Figure 5. Dune development related to scenario 3: ‘Minimal consolidation 5-year intervals with SLR’. Panels are the same as in Figure 3.

An ambitious plan is to build the coastline gradually seawards with the help of sand engines of 20 Mm^3 that are applied every ten years at five locations along the coast (Scenario 4, Figure 6). Because these are local, in the beginning some non-nourished dune areas will be eroded, giving rise to a dynamic foredune. With time, the sand of the sand engines spreads along the coast, building virtually the entire coast seaward and giving rise to extensive dune formation. After about 60 years, green beaches, and thus new dune rows, have established everywhere. It has to be noted, though, that with such strong seaward building, other functions will undoubtedly make use of the area. The ecological expectations then may have to be tempered.

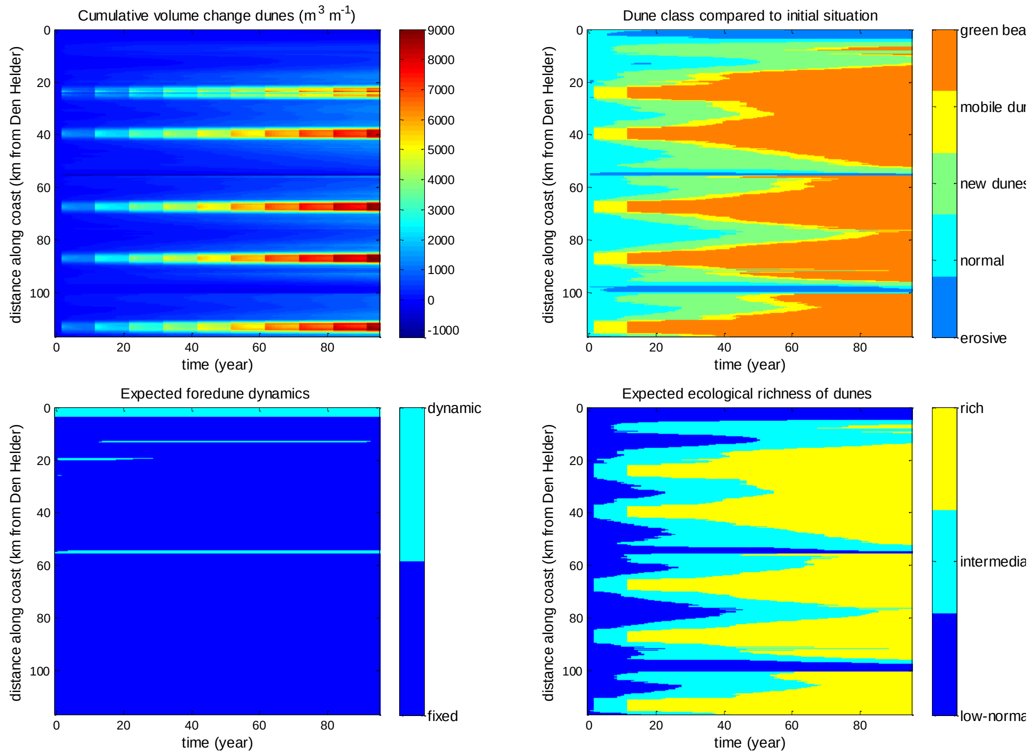

Figure 6. Dune development related to scenario 4: ‘Seaward with sand engines with SLR’. Panels are the same as in Figure 3.

The final Scenario 5 is one where hard structures, revetments, are used to protect the settlements instead of the soft method of sand nourishments (Figure 7). For the dunes, this leads to a situation comparable to the first scenario, but with less new dune formation. Because no sand is brought to the coast, new dune development is limited and most dune areas are stable or eroding. Species richness is therefore lower than in the other scenarios. Ongoing dune erosion gives rise to dynamic foredunes, although the erosion is so strong in some cases that it may even mean removal of the seaward dune row.

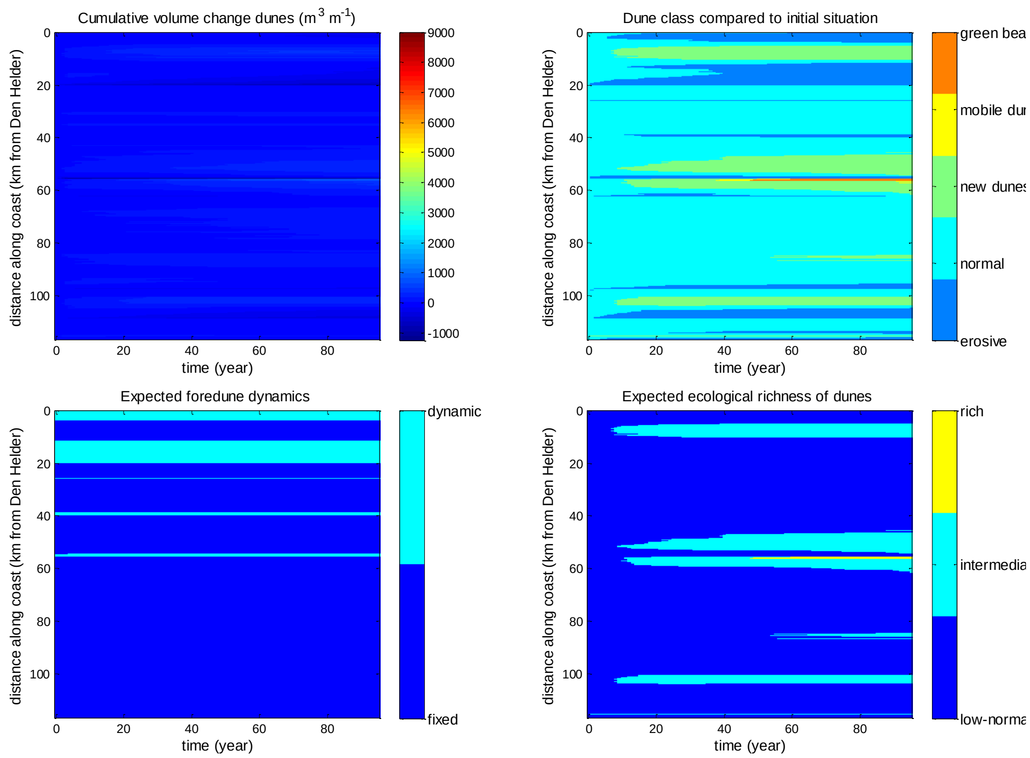

Figure 7. Dune development related to scenario 5: 'Revetments with SLR'. Panels are the same as in Figure 3.

For all scenarios it should be noted that no 'normal' nourishments are carried out. In reality, the coastline is checked every year for compliance to the Basal Coast Line, and nourishments are carried out if the Basal Coast Line is exceeded. Such management response is not included here, showing how the coast develops when regular nourishments would be stopped and only the ones in the scenarios are done.

Concluding it can be stated that the results of the contrasting scenarios are in line with what would be expected. On the longer term especially, the 'predictions' have large uncertainties, related to model schematisation and because weather and sea-level rise are not taken into account.

6.2 Notes when interpreting the model results

There are some things that need to be kept in mind when interpreting the model results. Firstly, no distinction between nourishment type was done: beach, underwater or mega-nourishment. In reality, sand from a beach nourishment is directly available for aeolian transport towards the dunes, whereas the sand from an underwater nourishment will only become available gradually. Implementing such processes would make the model increasingly complex, which would only lead to a balanced model if feedback with profile development in UNIBEST would be included. As the latter was not possible within the current project, we tried to keep the model as simple as possible.

Secondly, ‘ecological richness’ is only based on the expected dune habitats in the zone including and seaward of the original foredune. The loss of intertidal and subtidal habitat types is not taken into account. Neither is taken into account the disturbance created by a nourishment at the time of construction, nor the cessation of salt and sand spray towards the existing dunes. Both can have mild to severe detrimental effects on the ecology of the area.

Thirdly, whether mobile dunes and green beaches will develop depends on other factors that were not modelled. These include beach width, and the presence of lag deposits that may inhibit the development of mobile dunes. The development of green beaches further depends on beach usage. If there is a continuous pressure of beach driving, walking, cleaning and raking, vegetation will not establish and the area will remain in the mobile dune stage.

6.3 Ecologically optimal coastal-protection strategies

Regarding ecological richness of the dune area, the rule of thumb is simply: the more sand is available, the more diverse habitats will be created and thus the higher biodiversity is expected to be. Situations with nourishments lead therefore to more ecologically rich dunes than revetments or autonomous behaviour. A prograding coast (in this case done with Sand engines) gives most room for new dune formation and thus dune habitats. One could question the naturalness of the coast with such large nourishments, however.

Whether this ecological richness contributes to the overall nature value of the area, depends on the dune habitats presently landward of the foredune and the disturbance of intertidal and subtidal habitats (see the HK 3.8 package Baptist et al., in prep.).

For dynamics in the current foredune, erosion is necessary to get the dynamics going. This is a requirement that was already put into the model. Adding a lot of sand to the coast in the form of nourishments will therefore not lead to a significant increase in dynamic current foredunes. Theoretically, a large influx of sand could also be a cause of renewed dynamics, but field observations indicate that the development of new dunes in front of the foredune is more likely. However, as dynamic coastal development is a relatively new policy, time will tell if this is the case or that renewed dynamics will indeed occur.

7. Discussion and conclusions

7.1 General

Literature analysis, data analysis and input specifications have led to the conclusion that a relatively simple approach works best for the current long-term dune model of the Dutch coast. Although there are various good papers on the subject of long-term dune development on the Dutch coast, these papers turned out to provide insufficient information for modelling long-term development. The interactions between various parts of the coastal profile are complex, expected relations are absent or reported contradictive, and/or the investigated parameters do not match the needed parameters. Therefore a new approach was taken: a combination of data-driven modelling (Bayesian network modelling) and rules based on expert judgement.

In The Netherlands, dune growth is dominantly positive, most probably because the dunes have always been strongly managed for safety (De Ruig and Louisse, 1991). In the model, it was chosen to have negative dune budgets when overall budgets were negative. This assumes the tendency of dunes to follow a negative budget on the long term if no counter-measures are taken. This is in line with the approach in the rest of the Interactive Design Tool: large coastal erosion is sometimes predicted, whereas coastal managers will of course act before coastal erosion becomes threatening.

The Interactive Design Tool includes mega-nourishments. Nourishments on this large scale are new to the Dutch coast, with the Sand Engine at the Zuid-Holland coast as pilot project. This means that there is little information yet on the effect of such management measures. Consequently, there is considerable uncertainty in the predictions. The rules for these high-sediment-supply situations are based on developments found on for instance the beach of IJmuiden, Texel, Ameland and Schiermonnikoog. The situations on the island heads is not entirely comparable: there, waves and currents are much less uniform than on the Holland coast due to the specific morphology and dynamics of the inlets, and tidal channels may play a large role in erosion and accretion. Also the orientation with respect to the dominant wind direction is mostly different.

The development of green beaches was long absent in the Netherlands, and has only recently (past ± 10 y) started at various locations. Consequently, not much is known about the conditions required for green-beach development, except that the beach has to be wide enough and that a certain degree of sheltering is necessary. Field and aerial photograph observations from Schiermonnikoog indicate that in case there is an intertidal barrier sheltering the beach, a vegetated green beach may develop on a relatively narrow 'dry' beach (~ 200 m) and without significant dune formation. When such sheltering is absent, a large beach is necessary on which initially mobile dunes develop that shelter the beach from wave and current dynamics. Such a green beach will show a mosaic of dune, dune-slack and salt-marsh vegetation. Morphological developments in the subtidal and intertidal zone may therefore be very important for the development of a green beach. Such developments are typically something to investigate through modelling on a shorter timescale, before extrapolating to this longer term. Current modelling shows that the threshold for establishment of vegetation is an important factor (De Groot et al., submitted).

The location of a nourishment, i.e. beach or underwater nourishment, has a large influence on the response of the dunes. As the location of the nourishments is not specified, this factor has not been taken into account.

For the ecological potential of the foredunes holds that, in general, the more sand is added to the system, the better. Large nourishments with a larger interval perform better than yearly nourishments in this respect, also because of disturbance considerations. The effects on the rest of the existing dune field have not been taken into account.

7.2 Lessons learned

- Be aware of the limitations in process knowledge. In this specific case, that meant that there were much less useful relations between factors, processes and natural development known than assumed within the community. It was tried to solve this by going back to the basis, i.e. the data.
- It is important to clearly communicate the possibilities and limitations of existing models when these models are used as input for new models. In this case, the assumptions and output of

UNIBEST impose boundary conditions to the dune model or marine habitat model (HK 3.8) that build further upon it.
- Qualitative output (classes) is sometimes just as informative for end-users as quantitative output (numbers).

8. Future improvements

This model is a first attempt to come to a long-term dune model, realised within the boundary conditions of the project. There are a number of possible improvements and additions possible for further development of the model.

- Include feedback between the UNIBEST module and dune formation, so that the profile adapts if the system changes. There are developments to include more detail on profile development in UNIBEST. This might partly replace the division of volumes used here, so that more attention could be given to the processes that directly act on the dunes. This would also include a better estimate for beach width than the current profile movement.
- Include the type of nourishment and its consequences for the calculations of dune volume.
- The Bayesian Network Model is now used in a very simple way. The method however gives the opportunity to do e.g. Monte-Carlo modelling or uncertainty estimates. With the current setup of the model, such things should be straightforward to add in a later phase.
- Include storm scenarios. This could be done by adding a table to Netica: add years with large storms to category 'storms', and select during runs for whether it is a storm year or not.
- Include 'foredune dynamics' and include more foredune management options. The absence and presence of vehicles, beach raking and cleaning, and tourist pressure has similar implications for the development of a green beach.
- Allow tracking of dune dynamics through time. This requires more parameterisation.

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Appendix 1: additional data analysis

Aim

The aim of these data analyses is to obtain values for dune growth associated with typical dune states, such as eroding, stable and prograding dunes.

Data from Arens et al. (2010)

The data given in the extensive report of (Arens et al., 2010) was evaluated for its use in the current model. The report gives a wealth of data based on Jarkus and aerial photograph analysis, but focuses on nourished areas and does not include areas with extensive new dunes formation. Observed dune development includes both vertically growing and diminishing dunes (the latter not so common), and dune foot behaviour varies between retreat and growth. At some locations there are large spatial variations in dune behaviour on short distances.

Further they relate MCL (-5 to + 3 m NAP) and dune (> +3 m NAP) volume changes for part of their study areas. Initially, the relations and directions of development (growing or diminishing) of these volumes vary between locations. After an area is nourished, the correlations turns to positive. Our analysis (see below) however shows that this lumping of the MCL zone may not be optimal for detecting changes and exchanges.

When combining volumes, profiles and descriptions given on the report, the shape of the dunes and dunefoot movement were not convincingly linked, except for the obvious large positive and negative budgets. Therefore, no threshold values for going from erosional to stable, and from stable to slightly prograding dunes could be derived.

Dune and green-beach development on Ameland and Schiermonnikoog

Large-scale formation of new dunes and green beaches has taken place on several locations around the Dutch coast. We use Ameland and Schiermonnikoog as example. Data consisted of Jarkus data (from Rijkswaterstaat, now available through OpenEarth) and several aerial photographs between 2000 and 2010 (available from Alterra) with resolutions between 0.5 and 4 m.

Large influxes of sand are often related with a gentle profile slope, so that the profile becomes too long and falls partly outside the Jarkus measurements. If e.g. the lower boundary is not included in the profile, not all volumes can be calculated reliably. Therefore, information on dune growth at these sites is not always available.

On *Schiermonnikoog*, development of green beach and new seaward dunes has taken place between transects 100 and 500 (sheltered green beach) and from 500 till the eastern end of the island (dune-related green beach). It started around 2000 (Bakker et al., 2005). The island tail is not regarded here, as dune development here is discontinuous and associated with washover complexes, which are expected to have different dynamics than the dunes on the straight Holland coast.

Visual interpretation of trends in volumes of the entire profile (in this case: underwater beach + intertidal/dry beach + dune), from 1990 – 2010, shows that yearly volume changes exhibit too much scatter to be useful (Figure A 1). Total volumes, although not comparable between transects, give better information on trends. Despite the sheltering, between transects 100 – 400 (km 1 – 4), dune volumes have clear positive trends. Total volumes vary: some are stable and others declining. In the more exposed area (5000 – 7400), dune volumes generally increase. In part of the transects, dune volume levels off when the green beach forms (around 2000, Figure A 2), indicating starvation dune to reduction in aeolian transport by vegetation growth. In 5400 and 6000 the low values after 2005 may indicate erosion by a major storm in 2006. Total volumes also exhibit the strong dip around 2006 – 2008. Part of the area has been stable since 1970. For transects more to the east (800 – 1000), less data is available, and the available data has more scatter. Total dune growth from the beginning of the measurements till the development of a green beach is in the order of 150 – 250 m^3/m. Although it is not clear if there is a strong link between obtained dune volume and the development of a green beach, we will use these values as starting point in our model.

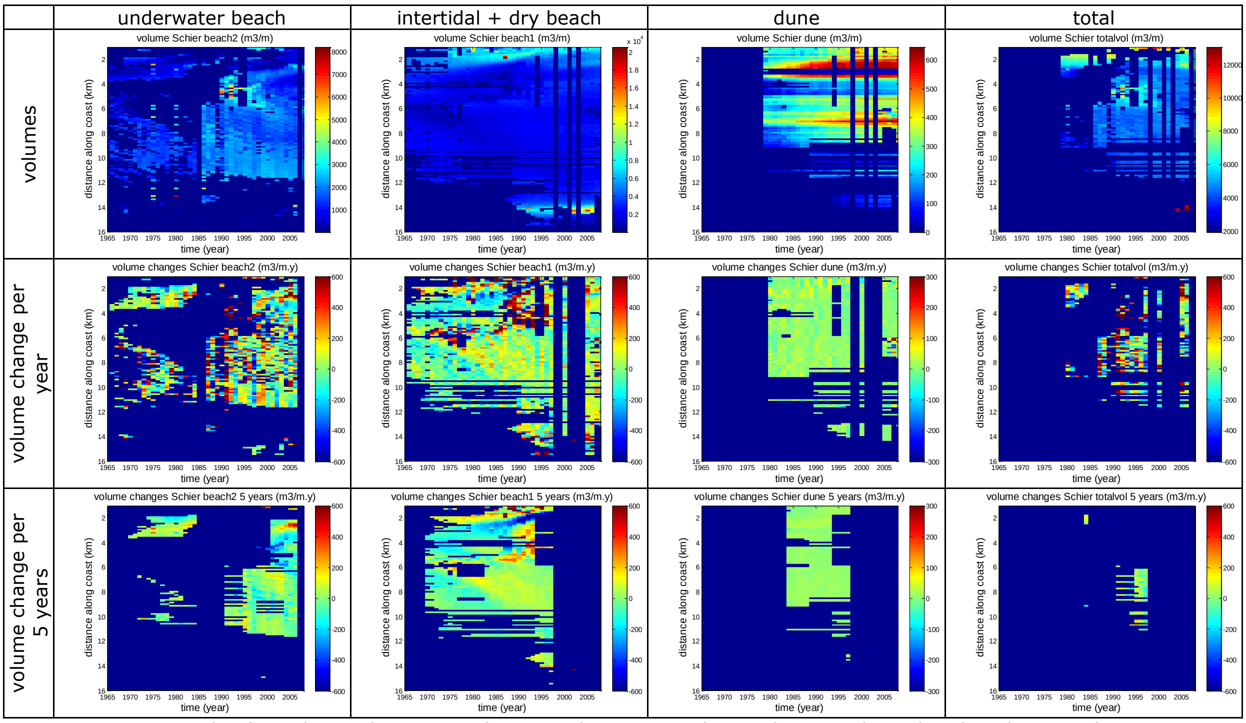

Figure A 1. Example of trends in volumes on Schiermonnikoog. Vertical axis: distance along shoreline, horizontal axis: time. Dark blue indicates no data. Volumes (upper panels) can only be compared within one transect location.

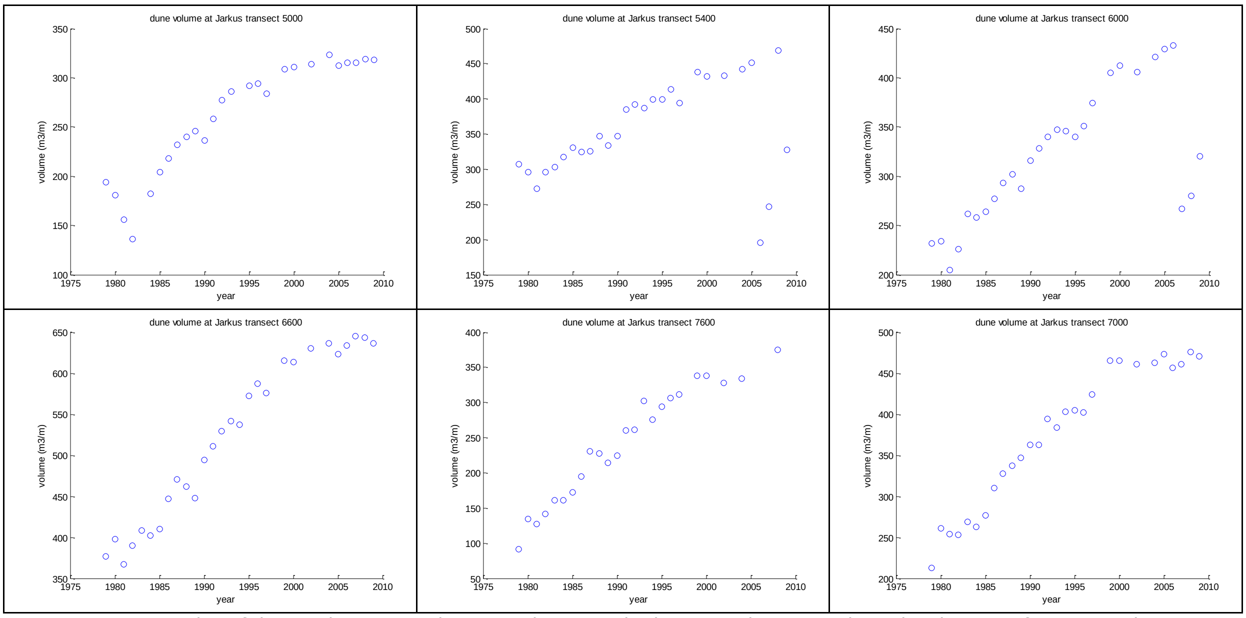

Figure A 2. Examples of dune volumes at Schiermonnikoog, at the location where new dune development from around 2000 on resulted in a green beach. NB: the landward reference varies between transects. Therefore only trends can be compared and not absolute volumes.

On *Ameland*, an embryonic dune field is present around between 4200 – 5000, and a salt-marsh type green beach between 5000 and 7000, both having developed since 2000 (Van Tooren and Krol, 2005). Again, the embryonic dunes on the island tail are not regarded here. In the first area, total volumes are declining whereas dune volumes are mostly increasing. This is related to the dynamics of tidal channels in this area, and makes the interpretation from total volumes to dune volumes not straightforward. The same levelling off of dune volumes with the development of embryonic dune field and green beach is observed as on Schiermonnikoog. Total volumes do not show a trend in the remainder of the area.

From these analyses of data and literature arises the impression that dune height, vegetation, history, and time lags between underwater and above water (e.g. tidal channel erosion) may have strong impact on dune development and the size of volume changes. These fall outside the scope of this work and were not pursued further.

To find 'threshold' volumes between slightly prograding dunes and extensive new embryonic dune formation, the 150 – 250 m^3/m from Schiermonnikoog were compared to reported transport rates towards the dunes from the Dutch coast vary between 1 to 75 $m^3\ m^{-1}\ y^{-1}$ (Arens and Wiersma, 1994; Van der Wal, 2000; Arens et al., 2001; Van der Wal, 2004; Arens et al., 2010), with values between 5 and 15 $m^3\ m^{-1}\ y^{-1}$ being most common. It should be noted that the Dutch foredunes do not present a fully natural situation due to nourishments and the tradition of fixation by planting marram grass and erecting sand fences (e.g. Nordstrom and Arens, 1998). This results in a larger sand supply and stronger 'catching' capability of the foredune, respectively. Therefore the reported values may be on the high side.

A technical note: in Netica the numbering of BV1 and BV2 is the opposite as done here and in the report of De Vries (in prep). Here, 1 = dry, 2 = wet.

Appendix 2: Model code (standalone version)

The model is coded in Matlab, and may be run standalone (such as given here), or in combination with the ITHK.

```
% dunerules_20june12.m

% ------------------------------------------------------------------
% Alma de Groot
% Ecoshape, WUR
% funded by Ecoshape and Knowledge for Climate
% 12 June 2012
%
% This code is used in the Interactive Design Tool
% in de Building with Nature program
% It calculates potential for dune formation based on Unibest outcomes,
% in a post-processing mode.
%
% INPUT
%   UNIBEST output read from ...
%   time                Timeframe
%   stored              total volume of sediment stored in a cell due to accretion or erosion (Stored volume in each cell
[10^6 m3]
%   xdist               alongshore distance
%   neticaJarkusLUT     a lookuptable that gives volume changes of parts of
%   the profile as function of total volume change, based on a Bayesian
%   network model of JARKUS data of the Holland Coast. Read from
%   neticaJarkusLUT.mat
%
%
% OUTPUT
%   cumdunes    cumulatieve dune volume compared to initial situation
%   duneclass   type of dunes that develop as a result of volume changes
%   richness    expected ecological richness of foredune area
%   dynamic     whether or not dunes are dynamic
%
%  Additional information can be found in the accompanying report
%  "Long-term dune development in the Interactive Design Tool"
%  by Alma de Groot
%  available through the Building with Nature online wiki
%
% ------------------------------------------------------------------

 %% Housekeeping

clear all
close all

 %% EXTRACT AND INITIALISE MATRICES FOR COMPUTATIONS
% this is a temporary datafile stored locally
% => needs to be changed into correct local matrix

% scenario = '0_autonoom_SLR=2mm_yr_dunes';
% scenario = '1_minimaal_consolideren_SLR_2mm_yr_dunes';
% scenario = '1_minimaal_consolideren_int_5yr_SLR_2mm_yr_dunes';
% scenario = '2_vooruit_met_zandmotoren_dunes';
scenario = '3_revetments_dunes';

eval (['load D:\Alma\EcoshapeBwN\01_Maptable_duinmodel_41\14_Model\scenarios\', scenario])
stored = UB.results.PRNdata.stored;               % total volume of sediment stored in a cell due to accretion or erosion
(Stored volume in each cell [10^6 m3]
% zminz0 = UB.results.PRNdata.zminz0;               % Offset of coastline from initial coastline [m]
year   = UB.results.PRNdata.year;                 % year from beginning
% duneclasstemp = ones(size(stored(1),1));  % initialise matrix for calculations
% these matrices normally have rows = transects, columns = years.

cellwidth = round(UB.results.PRNdata.xdist(2) - UB.results.PRNdata.xdist(1)) ;            % longshore width of cells in m,
assumed they are all same size
coastposition = (0:1:size(stored,1)-1).*cellwidth./1000;            % location alongshore in km from south to north
coastpositionRSP = max(coastposition) - coastposition;              % locatation alongshore in RSP numbers (approximately,
assuming the first location is RSP = 0)

% ------------------------------------------------------------------------
%% STEP 1 DISTRIBUTE THE TOTAL VOLUME OVER THE BEACH, DUNES AND UNDERWATER

% calculate values per year

volumeyear = (stored - circshift(stored, [0 1])).*1e+006./cellwidth;  % transform into deltaV per year, in m3/m*year
volumeyear (:,1) = stored(:,1).*1e+006./cellwidth;                    % correct for the effect of circshift

% calculate volume changes per profile section per year
% obtain values from Netica lookuptable (LUT)
[offshoreyear, beach2year, beach1year, dunesyear] = neticareadLUT(volumeyear);

% calculate cumulative values with respect to initial situation
cumdunes = dunesyear;
cumbeach = beach1year;
cumunderwater = offshoreyear;
for p = 2:size(cumdunes,2)
    cumdunes(:,p) = cumdunes(:,p) + cumdunes(:,p-1) ;
    cumbeach(:,p) = cumbeach(:,p) + cumbeach(:,p-1) ;
    cumunderwater(:,p) = cumunderwater(:,p) + cumunderwater(:,p-1) ;
end
```

```matlab
% -------------------------------------------------------------------------
%% STEP 2 TRANSLATE CHANGES INTO DUNE CLASSES

% underwater is not taken into account, can be done for other applications
% if necessary

% Classes:
% - class 1 = erosive
% - class 2 = normal and slight progradation
% - class 3 = wide beach with potential for new dunes at the foot of the old
%             dune
% - class 4 = extremely wide beach with potential for new dunes
% - class 5 = extremely wide beach with potential for new dunes including
%             green beach
% classes are compared to the current situation

% threshold values from one class to another (cumulatieve and yearly(?) volumes)
% and other settings
b1 = -30;                % from neutral to erosive (cumulative m3/m)
b2 = 100;                % upper boundary of stable situation
b3 = 400;                % upper boundary for slightly prograding situation

% assign classes
duneclass = ones(size(cumdunes));
duneclass (cumdunes < b1)                      = 1;    % erosive
duneclass((cumdunes >= b1) & (cumdunes < b2)) = 2;    % stable
duneclass((cumdunes >= b2) & (cumdunes < b3)) = 3;    % potential for new dunes adjacent to dune foot
duneclass (cumdunes >= b3)                     = 4;    % mobile dunes

% taking into account temporal effects of vegetation establishment for
% classes 4 and 5
thresholdyear = 10;                                    % how many years it takes before a wide beach becomes vegetated
for q = thresholdyear+1 : size(duneclass,2)
    duneclass_q = duneclass(:,q);                      % select only this year
    duneclass_temp = duneclass(:, q-thresholdyear: q-1);  % select previous couple of years
    duneclass_temp_sum = sum(duneclass_temp , 2);         % add up the ordinal classes

    % everywhere where at least 5 years with duneclass 4 have been => class 5
    % but when eroding, a beach that has gone from 5 to 3, it cannot shift back to 5 again.
    thresholdcrossed = (duneclass_temp_sum >= thresholdyear.*4) & (duneclass_temp(:, end) > 3);
    duneclass_q(thresholdcrossed) = 5;
    duneclass(:,q) = duneclass_q;
end


% ------------------------------------------------------------------------
%% STEP 3: ECOLOGICAL VARIATION
% roughly: estimate number of habitat types expected
% H2110 (embryonic dunes % annuals)
% H2120 (white dunes)
% H1310 (green beach)
% H1330 (green beach)
% H2190 (green beach)
% grey dunes not taken into account

richness = duneclass.*0;        % initialise resultsmatrix
richness (duneclass == 1) = 1;
richness (duneclass == 2) = 1;
richness (duneclass == 3) = 2;
richness (duneclass == 4) = 2;
richness (duneclass == 5) = 3;
% 1 = low/normal (low is the standard for the current coast)
% 2 = intermediate
% 3 = rich
% see report for explanation



% -------------------------------------------------------------------------
%% STEP 4: DUNE DYNAMICS RELATED TO MANAGEMENT
% dynamics of current foredune
% dynamics means: open places and aeolian dynamics with possibility for
% sand to blow landwards of the foredune

% % just for trial
% dyna = ones(292,96);
% fix = zeros(292,96);
% foredunemanagement = vertcat (fix, dyna);
% save foredunemanagement foredunemanagement

load foredunemanagement                     % matrix with 0 =  stabilisation, 1 = no stabilisation

dynamic = zeros(size(foredunemanagement));  % initialise results matrix

% assing classes
% 0 = fixed, 1 = dynamic
% management: 0 =  stabilisation, 1 = no stabilisation
dynamic(duneclass == 1 & foredunemanagement == 1) = 1;
dynamic(duneclass == 1 & foredunemanagement == 0) = 0;
dynamic(duneclass == 2 ...
    & (circshift(duneclass, [0 1]) == 1 | circshift(duneclass, [0 2]) == 1 ) ...
    & foredunemanagement == 1) = 1;  % if recent erosion, then dynamic, otherwise assume current vegetation cover is too
dense
dynamic(duneclass == 2 & foredunemanagement == 0) = 0;
dynamic(duneclass == 3 ...
    & (circshift(duneclass, [0 1]) == 1 | circshift(duneclass, [0 2]) == 1)...
```

```matlab
    & forudunemanagement == 1) = 1;
dynamic(duneclass == 3 & foredunemanagement == 0) = 0;
dynamic(duneclass == 4 & foredunemanagement == 1) = 0;
dynamic(duneclass == 4 & foredunemanagement == 0) = 0;
dynamic(duneclass == 5 & foredunemanagement == 1) = 0;
dynamic(duneclass == 5 & foredunemanagement == 0) = 0;
% add to the above: if there has been recent dynamic in classes 2 and 3,
% then again dynamic the year after
 potentialdynamic = ((duneclass == 2 | duneclass == 3) ...
     & foredunemanagement == 1);
for q2 = 2 : size(duneclass,2)
    newdynamic = (potentialdynamic(:,q2) == 1) & (dynamic(:, q2 - 1) == 1);
    dynamic(:, q2) = dynamic(:, q2) | newdynamic;
end
% summary: dynamics only happen when there is no foredune stabilisation,
% and when there is erosion or has been erosion recently.
% based on expert judgement: interpretation of existing literature for NL.
% Other option is to track dynamics through time, but that asks for a lot more
% parameterisation and there is not enough data for that, yet.


%% PLOTTING THE RESULTS

% plot cumulative volume changes
figure
% imagesc(cumdunes)
imagesc(year, coastpositionRSP, cumdunes, [-1250 9000])
colorbar
xlabel('time (year)', 'FontSize', 12)
ylabel('distance along coast (km from Den Helder)', 'FontSize', 12)
title('Cumulative volume change dunes (m^3  m^Aagaard,  )', 'FontSize', 12)
text(-17.5, -4, 'A', 'FontSize', 26, 'FontWeight', 'bold')
% axis xy

% plot dune classes
figure
imagesc(year, coastpositionRSP, duneclass, [1 5]);
xlabel('time (year)', 'FontSize', 12)
ylabel('distance along coast (km from Den Helder)', 'FontSize', 12)
colormap(jet(5))
colorbar('Ytick', [1 2 3 4 5], 'YTickLabel',...
    {'erosive','normal','new dunes','mobile dune field', 'green beach'}, 'FontSize', 8)
title('Dune class compared to initial situation', 'FontSize', 12)
text(-17.5, -4, 'E', 'FontSize', 26, 'FontWeight', 'bold')
% axis xy



% % plot cumulative volume change total profile
% figure; imagesc(stored.*1e+006./cellwidth); colorbar
% xlabel('time (year)')
% ylabel('distance along coast')
% title('cumulative volume change (stored) (m3/m)')
% axis xy

% plot dune dynamics
figure
imagesc(year, coastpositionRSP, dynamic);
colormap(jet(2))
xlabel('time (year)', 'FontSize', 12)
ylabel('distance along coast (km from Den Helder)', 'FontSize', 12)
colorbar('Ytick', [0 1], 'YTickLabel',...
    {'fixed','dynamic'}, 'FontSize', 12)
title('Expected foredune dynamics', 'FontSize', 12)
text(-17.5, -4, 'A', 'FontSize', 26, 'FontWeight', 'bold')
% axis xy

% plot ecological richness
figure
imagesc(year, coastpositionRSP, richness);
xlabel('time (year)', 'FontSize', 12)
ylabel('distance along coast (km from Den Helder)', 'FontSize', 12)
colormap(jet(3))
colorbar('Ytick', [1 2 3], 'YTickLabel',...
    {'low-normal','intermediate','rich'}, 'FontSize', 8)
title('Expected ecological richness of dunes', 'FontSize', 12)
text(-17.5, -4, 'F', 'FontSize', 26, 'FontWeight', 'bold')
% axis xy



%% SAVE THE RESULTS

% outfilename = [scenario '_out'];
% eval(['save ', outfilename, ' cumdunes duneclass richness dynamic'])




function [offshoreyear, beach2year, beach1year, dunesyear] = neticareadLUT(volumeyear)
% function to extract data from netica

%    14 June 2012
%    Alma de Groot
%    Wageningen University, Land Degradation and Development Group
%    IMARES
%    Building with Nature HK 4.1
```

```
load neticaJarkusLUT
% a table that gives the percentages of change of the 4 zones as
% function of the total change in the zones
% this tabel is derived from Jarkus data in netica
% background see De Groot et al 2012 HK 4.1
% outline:
% col 1: upper class boundary
% col 2: dune change (percentage)
% col 3: intertidal (aeolian) beach change (beach 1) (percentage)
% col 4: subtidal (marine) beach change (beach 2) (percentage)
% col 5: offshore change (percentage)

% initialise result matrices
percdune = NaN(size(volumeyear));
percbeach1 = NaN(size(volumeyear));
percbeach2 = NaN(size(volumeyear));
percoffshore = NaN(size(volumeyear));

% calculate number of cells that need to be evaluated,
% which will be used as index for the loop
allcells = size(volumeyear,1).*size(volumeyear,2);
allcells = round(allcells);                  % just to make matlab happy

for p = 1:allcells
   % handle NaN's first
    if isnan(volumeyear(p))                  % if error then use 1:1:1:1 and continue
        percdune(p) = 25;                    % dune is all above +3 m NAP
        percbeach1(p) = 25;                  % beach1 is intertidal + dry beach with MLW as boundary
        percbeach2(p)= 25;                   % beach2 is subtidal beach under MLW and above * (see Sierd)
        percoffshore(p) = 25;                % offshore is below -.. m NAP (see Sierd)
        continue
    end

    % the real looking up of the percentages
    r = find(volumeyear(p) <= neticaJarkusLUT(:,1), 1, 'first'); %#ok<NODEF>
    % retrieve percentages change from lookuptable
    percdune(p) = neticaJarkusLUT(r, 2);   % dune is all above +3 m NAP
    percbeach1(p) = neticaJarkusLUT(r, 3); % beach1 is intertidal + dry beach with MLW as boundary
    percbeach2(p)= neticaJarkusLUT(r, 4);  % beach2 is subtidal beach under MLW and above * (see Sierd)
    percoffshore(p) = neticaJarkusLUT(r, 5); % offshore is below -.. m NAP (see Sierd)
end

% calculate volume changes
dunesyear = volumeyear.* percdune./100;
beach1year = volumeyear.* percbeach1./100;
beach2year = volumeyear.* percbeach2./100;
offshoreyear = volumeyear.* percoffshore./100;
```

Appendix 3: Lookuptable based on JARKUS data

The table is based on JARKUS data of the Holland Coast, put into a Bayesian Network Model. This table is used as lookup table to determine volume changes of the four profile sections with. They are allotted the percentage of the total profile change.

total volume change (upper bin)	**dune (%)**	**subaerial beach (%)**	**subtidal beach (%)**	**offshore (%)**
-500	21.9	23.6	30.5	24
-400	17.6	18.8	37.8	25.8
-300	11.3	15.7	41.9	31.1
-200	5.7	13	53	28.3
-100	5.3	16.2	51.7	26.8
0	5.1	21.4	46.6	26.9
100	18.3	12.1	46.5	23.1
200	10.5	14.5	56.5	18.5
300	8.7	10.9	52.3	28.1
400	11	14.4	49.5	25.1
500	17.9	20	36.5	25.6
600	22.6	22.2	28.7	26.5

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