Journal of Coastal Conservation 2: 55-62, 1996

The development of a digital terrain model for the geomorphological engineering of the 'rolling' foredune of Terschelling, the Netherlands

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Abstract. The foredunes form an important element of the line of defence which protects the low-lying parts of the Netherlands from the sea. The foredune of the eastern part of the Wadden island of Terschelling has been managed as a 'rolling' foredune to maximize the amount of sand available in times of emergency. Following a decision of the Dutch Government to maintain the coastline of 1990, this foredune will now be stabilized. A plan is made to reshape the morphology of the foredune according to a geomorphological design. A simulation model was developed to produce a Digital Terrain Model with the required geometrical information. The transformation which is on the macro-level scale can be achieved within the envisaged medium-scale planning period of five years only by applying earth-moving machinery, placing fences or planting sand-trapping vegetation.

Keywords: Dune management; Foredune morphometry; Sand dyke; Sand-trapping vegetation; Simulation model.

Introduction

The North Sea coast of the Netherlands mainly consists of dunes and dykes. Together, they protect the low-lying polders from the North Sea. Three quarters of the coast is made up of dunes, varying in width from a hundred metres to several kilometres. The foredunes, together with the beach and the foreshore, form an important element of the primary defence which must be strong enough to withstand an extremely heavy storm with an associated storm surge level (probability of occurrence once every 10 000 years). Where the foredunes do not meet the safety requirements defined in the Delta Act of 1958, they are engineered to form a continuous and regular dyke. If necessary, the dyke is reshaped and replanted, inhibiting the natural mobility of the foredune system and the spontaneous succession of vegetation.

Coastal erosion causes almost half of the coastline to recede (van Bohemen & Meesters 1991) (Fig. 1). After careful consideration of a number of alternatives, it was decided by the Dutch Government that the coastline will be preserved in its 1990 position (Anon. 1990). It is stated that allowances can be made for natural processes which contribute to the sustainable development of the coastline (Louisse & van der Meulen 1991). These include geomorphological processes such as sand-drift in the foredunes (Arens & Wiersma 1994).

One of the locations affected by the decision of the Government is a five kilometre long stretch on the north-east coast of the Wadden island of Terschelling (Fig. 2). Here, the artificial foredune comprises former foredunes and sand dykes, connecting isolated dunes and dune complexes. Such dykes are called *stuifdijk* in Dutch ('shifting dyke'), and are supposed to trap shifting sand. According to van Dieren (1934) these dunes are migrating dunes which developed from parabolic dunes. The dunes and inter-dune deflation plains have been stabilized and some parts of the valleys have been cultivated.

For many years, the dyke has been managed as a so-called 'rolling' foredune, which means that a policy of controlled retreat of the entire foredune body was applied to prevent marine erosion (Fig. 3). In this way, the maximum amount of sand remains available for an emergency storm event. Shifting of the dyke was realized by keeping the seaward slope completely free of vegetation giving the eroding northwestern wind free access to the sand. Reed fences were placed on the crest and marram grass (*Ammophila arenaria*) was planted at the inner toe to catch the sand blown in from the beach, resulting in an increased foredune volume. In this way, 250 000 m^3 of sand was gained in nine years (Fig. 4).

According to the new policy, the 'rolling' foredune has to be maintained at the position of 1990, and future coastal recession will be counteracted by an artificial shore-face nourishment (Hoekstra et al. 1994). A plan has been made to integrate the foredune into the natural development of this part of the island (Zonneveld et al. 1992; Dijkema et al. 1993). As part of this plan, the morphology of the sand dyke will be reshaped according

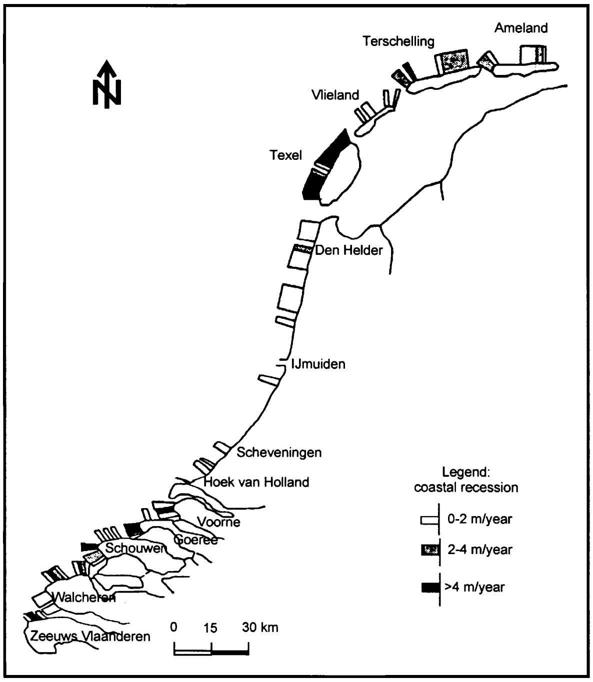

Fig. 1. Places of coastal recession on the Dutch coastline (From: van Bohemen & Meesters 1992).

to a geomorphological design. To help dune managers to attain this goal, a simulation model has been developed which produces a Digital Terrain Model (DTM) with the necessary geometrical information. Boundary conditions for the DTM are:

- the safety of the coast,
- a natural transition to the existing foredunes at the western and eastern ends,
- a limited supply of sand which is available for reshaping.

Material and Method

Two types of simulation program for geomorphological engineering of foredunes have been designed by van der Wal (1993): the PARABOLA model and the PARALLEL model. The Digital Terrain Model developed for Terschelling is generated by the PARALLEL model. In this model a number of geomorphologically representative foredune profiles is generated. This is done by selecting randomly from the range of values of the parameters found for each point of nearby ‘natural’ (reference) profiles. The tolerated slope angles between the points both on the transect and between the transects are taken into account. The main part of the computer program is governed by a number of constraints, which have been built into the model as conditional statements. One of these constraints, for example, applies to the safety of the coast. Process-related knowledge of dune building is incorporated only in an implicit manner; the model is based on the quantification of the morphometric response of the foredunes to aeolian processes. For a discussion of the merits of the model, see van der Wal (1993).

Source of the numerical data for computing the parameters is the JARKUS data base of Rijkswaterstaat of the Ministry of Transport and Public Works, the authority in charge of coastal defence. The data base comprises yearly beach and foredune profiles for the whole of the Dutch coast. A reference system has been used with an imaginary line along the coast, the so-called RSP-line (de Ruig & Louisse 1991). The profiles are oriented in a fixed network perpendicular to this line and, approximately, perpendicular to the foredunes. The profiles are 200 to 250 m apart and have a record of height for every 5 m along their length. For Terschelling,

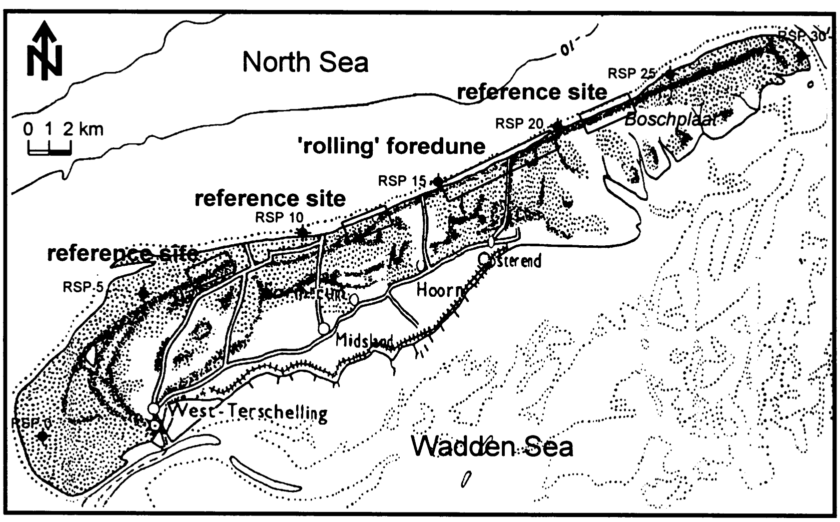

Fig. 2. The Wadden island of Terschelling. The markers indicate the position of the kilometre poles of the reference system (the ‘RSP-line’). The ‘rolling’ foredune is situated between RSP (kilometre pole) 15.000 and 20.000.

Fig. 3. The ‘rolling’ foredune.

the distance between the profiles is 200 m. The measurements are derived from the stereometric analysis of aerial photographs, usually taken in April and May. The vertical accuracy of the data is about 20 cm. The heights are uniquely related to the fixed Dutch ordnance datum, about mean sea level. For this study, the section above 0m is taken into account.

The construction of a DTM for the adjusted situation includes five steps.

1. *Construction of a DTM* based on the original JARKUS data of the foredune section to be reshaped.

2. *Choice of reference profiles* from the JARKUS

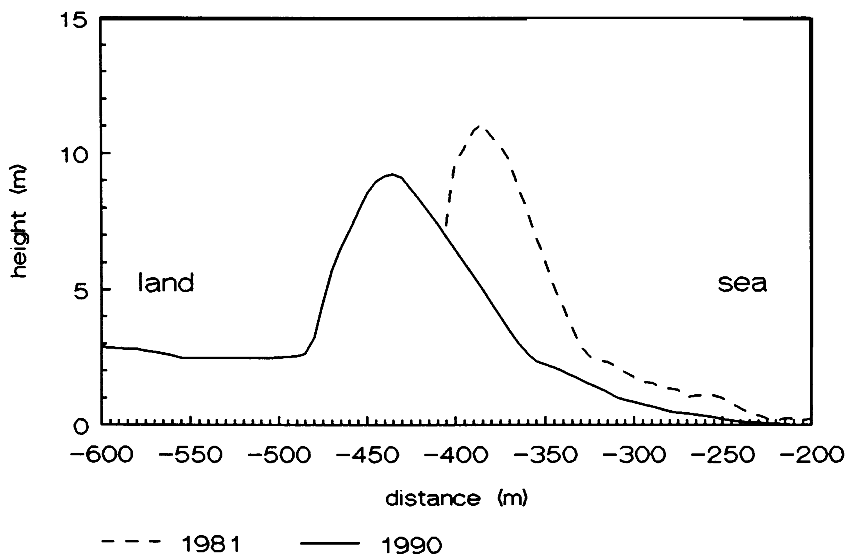

Fig. 4. Cross-sections of the ‘rolling’ foredune at RSP 17.000, for the years 1981 and 1990.

data base of Terschelling, on the basis of the geomorphological state, the behaviour of the coastline, the past management and the dimensions of the foredunes. Three reference sites have been selected (Fig. 2).

The form parameters for a dynamic foredune are derived from the coast at the western part of the island. The foredune at this site originates from the deformation of sand dykes formed between 1920 and 1929 (van Dieren 1934). Nowadays, management activities are restricted. Moderate to strong features of aeolian processes are visible (Arens & Wiersma 1994).

In order to blend the 'rolling' foredune in with the characteristic features of the area, some profiles of the two adjacent coast sections are also selected. West of the sand dyke, near Midsland, a relatively high foredune is formed. Locally, the foredune and the inner dune complexes coalesced. East of the sand dyke, a new sand dyke was formed between 1931 and 1937. This dyke separates the European Nature Reserve 'Boschplaat' from the North Sea. Up to RSP 23, this sand dyke fulfils the requirements.

3. *Input of the reference profiles* into the simulation program and generation of new profiles, taking into account:

- the range of heights for each point along the selected reference profiles,
- the range of slope angles between adjacent points along each of the selected reference profiles,
- the minimum dimensions required for the maintenance of the present strength of this part of the coastline (this requires a height of 8 metres, a crown width of 15 metres, a seaward angle of 1:10, and a landward angle of 1:5).

4. *Converting the DTM* of the recent situation by manually replacing the profiles of the JARKUS data base with the new profiles, 200m apart, taking into account:

- the difference in height with the original point, in order to minimize the efforts needed to realize the new profile,
- the topography surrounding the stretch of foredune that has to be remodelled,
- the land use and infrastructure landwards of the sand dyke.

5. *Creating a more detailed DTM* by repeating steps 3 and 4. Simulated profiles, with a mutual distance of less than 200 m, are fitted in to generate a denser network of profiles. If the profile spacing is small, the simulation program considers the slope angles between corresponding points on adjacent generated profiles. Data on tolerated slope angles of along-shore variation in topography are derived from survey measurements in the reference foredune areas. In addition, no accumulation slope is steeper than the angle of the rest of the dune sand, which has a value of about 31 degrees.

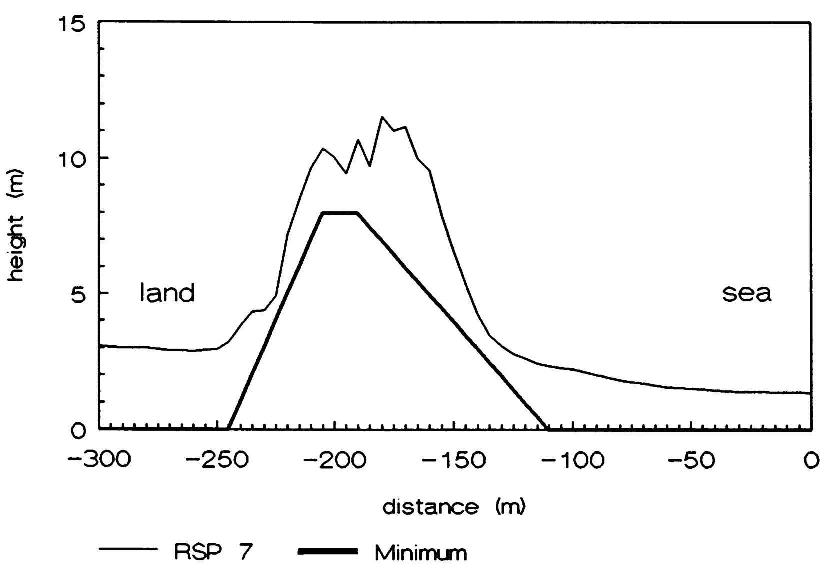

Fig. 5. The profile of the reference foredune at RSP 7.000, derived from the JARKUS data base. The bold line represents the minimum profile required for the safety of the coast.

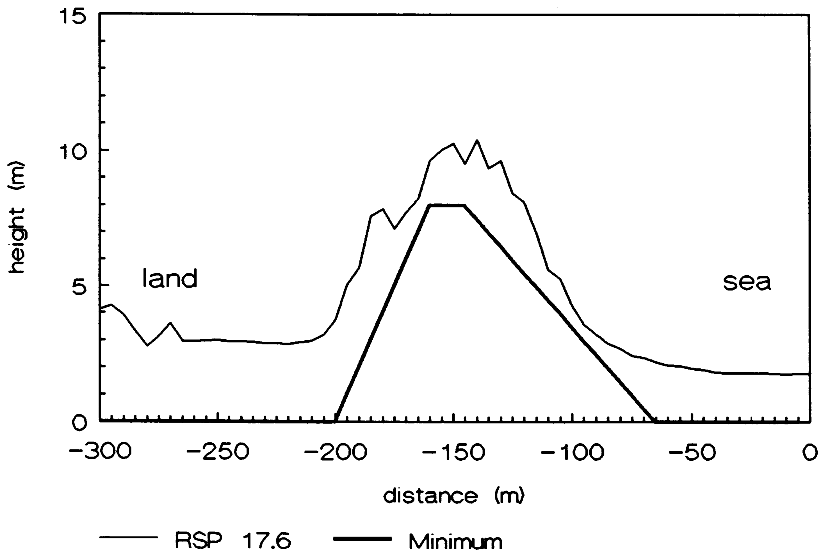

Fig. 6. The foredune profile generated by the PARALLEL model for RSP 17.600.

Results

Fig. 5 shows one of the reference profiles from the JARKUS data base, whereas Fig. 6 is a profile generated from the reference profiles by the PARALLEL model.

Apart from a DTM with the same grid cells as the JARKUS data base, i.e. 200m $\times$ 5 m, more detailed DTMs have been made to facilitate remodelling the foredune. Part of a DTM with a 50m $\times$ 5 m grid, made by the PARALLEL model is presented in Fig. 7. The various adaptations proposed are shown on the contour maps that have been made of the original and the simulated foredune (Fig. 8). They include:

- restoration of the foredune characteristics,
- a more gradual transition between the foredune and adjacent dune complexes which existed before the sand dyke was formed.

The model can also calculate the number of cubic

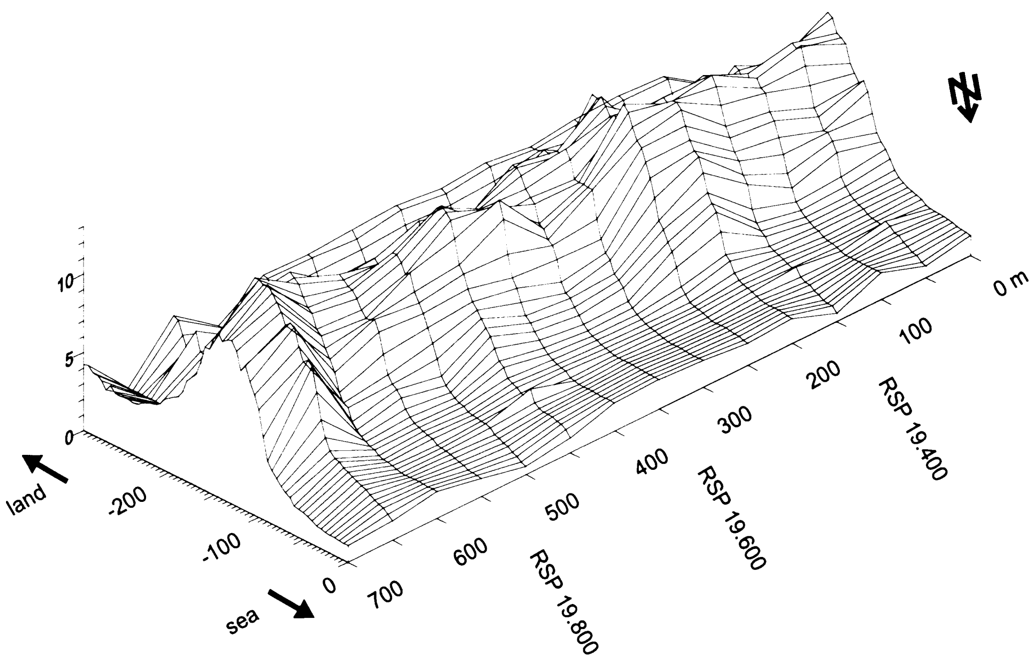

Fig. 7. A part of the Digital Terrain Model generated by the PARALLEL model. Grid cells are 50 by 5 m.

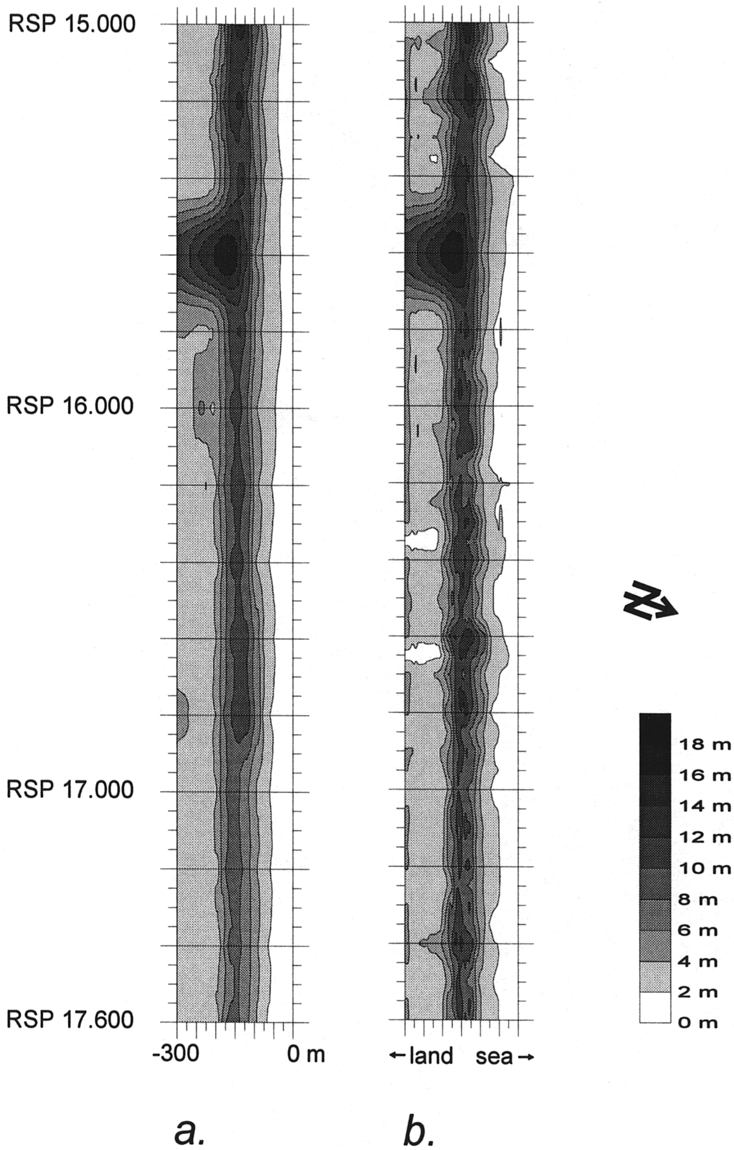

Fig. 8. Contour maps of the foredune between RSP 15.000 and 17.600. **a.** Interpolation of the JARKUS profiles of 1990. **b.** Interpolation of the simulated profiles of the PARALLEL model.

metres of sand needed for landscaping at each location. For the entire stretch it has been found that $2.02 \cdot 10^{6} m^{3}$ of sand was available in 1990, on top of the minimum of $3.00 \cdot 10^{6}$ m^3 of sand required to meet the safety standard. For the simulated situation, $2.24 \cdot 10^{6}$ m^3 of sand was required, on top of the minimum. The $0.22 \cdot 10^{6}$ m^3 of sand needed to convert the present dyke into the idealized DTM is comparable with the supply of sand to the foredune in the period of 1981-1990.

Discussion

Aeolian dune-building processes act at different scales of space and time. In a spontaneously developing dune, these scales are superimposed over each other. They are identifiable in the field or on aerial photographs of appropriate scale. Overlap between the scales may exist. There is also mutual interaction between the scales, in the sense that the relief formed at one scale, is a factor influencing the formation of the relief at other scales (Jungerius 1989). Time and spatial scales are linked (Sherman & Bauer 1993). Both are dependent on the amount of available sand, on the rate of sand movement (which in its turn is influenced by, for instance wind velocity, direction and fetch, and on the humidity of the sand), on vegetation characteristics and on other factors. The type of management measurements to be taken in the foredunes depend very much on these conditions (Psuty 1986). Likewise, the feasibility of geomorphological engineering is different for each of the scales.

Although other classifications have been proposed (Jungerius 1989; Sherman & Bauer 1993), four scales are suggested here. In this section, potentials for aeolian processes and geomorphological engineering with respect to the Terschelling case are presented for each of these scales.

(a) Microscale

This is the level of the direct interaction between wind, sand and the individual plant. Examples include shadow dunes formed on the beach within a few hours up to a few days in times of strong winds, around sand binders such as sand couch-grass (*Elymus farctus*) and marram grass (*Ammophila arenaria*) (Hesp 1981). They occupy not more than a few square metres at most. These developments take place without human intervention.

(b) Lower mesoscale

Aeolian features at this scale include the new low dune ridges formed within a few days up to a few months, in front of older coastal ridges. Formation of these new ridges can be stimulated by placing fences (Adriani & Terwindt 1974). Another process at this scale is the formation and extinction of deflation patches in the inner dunes. The diameter of these patches is usually less than five metres. Management measures include the planting of marram grass to immobilize the blowing sand.

(c) Higher mesoscale

The developments at this scale need anything from several months to about ten years. Deflation features such as blowouts and associated accumulation forms develop in this span (Jungerius et al. 1981; Gares & Nordstrom 1991). The corresponding lengths of these features vary from about ten to a hundred metres. A possibility for geomorphological engineering at this level is the removal of vegetation and soil by earth-moving equipment to (re-)activate the blowouts. Although in this case the onset is artificial, the finishing touch can be left to the wind.

For reshaping the 'rolling' foredune of Terschelling at this level, artificial measures may not be needed. The activity of the onshore northwesterly winds is probably such that the surface of the foredune will be remodelled with secondary deflation and accumulation features within the medium-term planning period of about five years planned for integrating the foredune in a naturally developing dune landscape. If the rate of change is too small, the natural processes could be guided by bulldozers or fences. Guiding in this sense means either restriction or stimulation of the geomorphological processes, depending on the required effect.

(d) Macroscale

This is the scale of dune complexes and foredunes of the Terschelling case. Apart from primary dune formations, there are deflation features and associated deposits at this level, for instance caused by parabolization of a foredune ridge (Hesp & Thom 1990). The evolution of the aeolian features at this scale requires more than the medium-term planning period and presumably much more than a decade. Usually, an area of more than a thousand square metres is involved. To help the processes on their way necessitates geomorphological engineering. This envisaged conversion can be achieved in two ways: by using heavy earth-moving machinery, or by trapping sand with fences or marram grass and other sand-binding vegetation. Technical skill is required for both methods. The latter technique is preferable, because use can be made of the natural mechanisms of dune building.

The PARALLEL model has been designed to quantify the morphometry of a foredune. An example of the product of this model, a Digital Terrain Model, is presented in this paper. The DTM has been developed to assist the dune manager in reshaping the foredune at the higher mesoscale and the macroscale level. Its application is an interactive process: by intensive cooperation of field workers, planners and modellers the ultimate goal must be reached, i.e. to realize a 'natural' landscape of which the former sand dyke forms an integral part.
The PARALLEL model can also be applied to other cases. For instance, it can be used to provide the terrain parameters required to reshape artificial dune nourishment. A profound field study, a proper choice of reference foredune development, a careful implementation in the landscape, adjustments of the plans during the operation, and evaluation of the project are essential.

Acknowledgements. Part of this work was carried out for the Noord-Nederland Directorate of Rijkswaterstaat of the Dutch Ministry of Transport, Public Works and Water Management. I am particularly indebted to J.H.B.W. Elgershuizen of the Noord-Nederland Directorate for his cooperation. The JARKUS data were kindly made available by the National Institute for Coastal and Marine Management of Rijkswaterstaat.

I am also grateful to Prof. Dr. P.D. Jungerius for his help with various phases of the study. Finally, I thank Dr. F. van der Meulen and two anonymous reviewers for their valuable comments on the manuscript.

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Received 2 May 1995;
Revision received 2 August 1996;
Accepted 13 August 1996.