Exploring coastal morphodynamics of Ameland (the Netherlands) with remote sensing monitoring techniques and dynamic modelling in GIS

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CHAPTER 9

MODELLING WASHOVER LANDSCAPE DEVELOPMENT WITH AIRBORNE REMOTE SENSING DATA

ABSTRACT

An important and genetically controversial geomorphological phenomenon observed on the eastern ends of the Wadden islands is the occurrence of washovers. Through their present geomorphological function in aeolian and marine sand transport from the beach and foredunes to the saltmarsh and tidal flats, washovers also have a major ecological impact. They influence, i.e., the species composition of the saltmarsh. The study aims to describe and predict the development of a washover landscape. Several airborne sensors were used to monitor the washovers. Information on developments in the formation and stabilisation of the washovers by vegetation was extracted from multitemporal airborne videography and aerial photographs. Based on the trends derived from these sequential images, digital elevation data, and morphological parameters derived from laser altimetry, dynamic modelling in a GIS environment was applied. This resulted in the prediction of a (future) washover and saltmarsh landscape. The approach taken and the results produced were tested in several ways. The approach seems to be promising, but some of the assumptions in the model should be rejected, which means that the model could still be refined. Both sea and wind are active agents in the formation and the development of the eastern washover and saltmarsh landscapes. The presence of washovers causes environmental heterogeneity, resulting in high species diversity. Multitemporal airborne remote sensing data are not only useful for monitoring the landscape but these data also support spatio-temporal modelling.

INTRODUCTION

This chapter elaborates influence of washovers (Photo 1) on a saltmarsh (Photo 2) at the eastern point of one of the Dutch Wadden islands (Fig. 1).

1.1 Research objectives

The research objectives were:

• to use airborne remote sensing data for monitoring the input of sand as an abiotic influence on a saltmarsh landscape;

• to use these data as input for dynamic modelling to predict a future washover and saltmarsh landscape.

1.2 The Wadden area, a wetland

Since its inception in 1971, the Ramsar Convention has provided the principal intergovernmental platform for the promotion of international cooperation for wetland conservation (Clark, 1996). The Wadden area is a main Ramsar site in the north of Europe. The Wadden area comprises three main units: the North Sea, the barrier islands and the Wadden Sea (see Fig. 1). The North Sea is an arm of the northeastern Atlantic Ocean. The Wadden Sea is a shallow coastal sea, which extends along the northern coasts of The Netherlands and Germany and the western coast of Denmark. The Wadden islands, which separate the two seas, represent the central part of a barrier dune coast, extending from Sangatte in northern France to Cape Skagen in northern Denmark. This is one of the most extensive and ecologically varied dune areas in the world. Most plant communities develop under relatively undisturbed conditions, and they form outstanding and interesting landscape complexes in relation to the geomorphological development of the islands (Dijkema et al., 1993). Together with their saltmarshes, the islands measure about 1000 km². No less than 32% of the island area has the status of nature reserve (Dankelman, 1983).

1.3 Washovers at De Hon

The case study reported here comprises the monitoring and prediction of washovers at the eastern, natural part of Ameland, a coastal barrier island in the north of The Netherlands. This part of Ameland, known as 'De Hon' has developed more or less naturally, although the input of sand increased and the formation of dunes was stimulated by the construction of a sand-dike up to transect 'kilometre 23.000' (see Fig. 9) in 1962. Together with the adjacent saltmarsh area, it has had the status of 'Beschermd Natuurmonument' (protected nature reserve) since 1981 and it has been recognised as a 'Wetland' since 1984 (Abrahamse et al., 1986 in Sanderse, 1994b). The long-term development of the area might be effected by gas extraction at the seaward end of transect 23.000, which causes subsidence. The management of the island of Ameland is a typical example of the Dutch policy of dynamic preservation, adopted by the Ministry of Transport, Public Works and Water Management in 1990: 'coastal defence if it is necessary (in the inhabited central part of Ameland), let nature take its course
if possible (on the eastern natural part of the island). Therefore, management supports the natural development of the east and actively pursues monitoring research. Landscape units along a transect from north to south are: shallow shoreface, beach, horse-shoe-shaped natural foredunes mainly inhabited by marram grass (*Ammophila arenaria*), and saltmarsh with, for example, *Elymus pycnanthus*, *Festuca rubra*, *Sueda maritima* and *Salicornia*, which gradually merges into the tidal flats of the Wadden Sea.

### 1.4 Genesis

A combination of three mechanisms related to sand supply could be responsible for the genesis of the washover landscape:

- the evolution of the beachplain, related to ebb-tidal delta development and inlet sediment bypassing mechanisms (see Fig. 2 & 3);
- morphologic evolution of the foredune, as a function of beach sediment budgets and foredune sediment budgets on barrier islands (see Fig. 4);
- primary development of circular dunes (eyedunes and horse-shoe-shaped dunes), by aeolian sand transport from various directions on a beachplain (see Fig. 5).

(Please note that the presented figures only serve to illustrate the concept.)

Both sea and wind are active agents in the formation and the development of the eastern washover and saltmarsh landscape (see Photo 3). Aeolian influence on the washover landscape is acknowledged in Mader (1995); the term 'deflation channels or washover fans' is used consistently.

The occurrence of circular dune forms is a special feature of the landscape on the eastern parts of the Dutch Wadden islands. These features can be seen even better on Terschelling and Schiermonnikoog than on Ameland. In his literature review, Mader (1995) argues that areas which are specified as washover landscapes not only result from sudden fierce erosion and the breaking through of linear features during storms, but that the washovers are actually preserved regions between developed circular eye-dunes. In the eastern parts of various East and West Frisian Islands, the typical features of the deflation channels of washover fans are characterised by primary division or secondary intersection of the dune belts. Many deflation channels and washover fans do not incorporate secondary perforations, but are established in primary gaps between isolated dune patches or within more extensive dune ridges. Accretion and growth of dunes on the flat sand plates leads in many cases only to discrete dune cores that are separated by flat bands and wedges. They cause successively increasing obstruction of the washover plain of the original sand plate to the residual invasion passages of flood surges between the dune cores, which are also deflation streets. The dunes are discrete elliptical dune cores (eyedune complexes), interrupted and separated by washover passages or intertidal to supratidal creeks'. Similar views were expressed by Klijn (1981) and Sanderse (1994a).

In the most of the literature studied, washovers are seen as a result of marine processes. The features encountered on the Wadden islands are not washovers if this definition is used. However, the washover throats are under marine influence now. During fierce storms the entire beachplain and the washover throats disappear under water. For want of a better term,
the name 'washover' is maintained in this chapter. However, both marine and aeolian influences on washover landscape development will be studied.

1.5 Ecological relevance

Studies on abiotic influences on saltmarshes frequently focus on inundation, moisture conditions of the soil, upward growth (e.g., Wiegert, 1979) and chloride content of the soil (Beeftink, 1977). Surface relief can also result from other mechanisms than from upward growth by sedimentation. A study of the sedimentary record of a coastal bar marsh on Schiermonnikoog (a neighbouring island of Ameland) showed that its surface relief was mainly determined by the relief of the sandy subsoil and less by upward growth as a result of sediment trapping by the vegetation during inundation (De Leeuw *et al.*, 1993). The importance of washovers in creating a habitat for the saltmarsh vegetation has only recently been acknowledged (Oertel & Woo, 1994). The following, traditional general view on washovers illustrates their influence on topography. Washovers consist of flat, broad expanses of sand formed during storm tides that are actively put into or on top of a saltmarsh system, thus affecting the surface relief. Washovers are common on barrier islands. The vegetation of this zone is similar to that of the foredune on the elevated portion of the washovers. Stalter (1993) mentions elevation, soil moisture and soil salinity as factors that influence species distribution in this zone. The presence of saltmarsh species indicates that soils of washovers may be saline, especially in depressions. The properties of the sand are another aspect of the input of sand by washovers (mentioned by Leatherman & Zaremba, 1987). The fresh sand will be sterile (without nematodes), which stimulates the vitality and fertility of *Ammophila arenaria* (De Rooij-Van der Goes, 1996).

Washovers are associated with dynamics and landscape diversity, which are nowadays highly valued by scientists and coastal managers. Sherman & Nordstrom (1994) give an overview of the causes and results of the new perception of migrating sand areas.

- Ecological concern for mobile dune systems reflects a shift in scientific interest from vegetation classification to population dynamics and the effects of disturbance (De Raeye, 1989).
- Scientists call for abiotic diversity in dune reserves to ensure the ecological value and richness of dune areas (Tinley, 1985 in Sherman & Nordstrom, 1994; Westhoff, 1989).
- Migrating sand areas are recognised for their recreational and ecological value (Wanders, 1989; Nordstrom & Lotstein, 1989 in Sherman & Nordstrom, 1994).
- Stabilisation measures are viewed as large-scale disruptions of ecosystems, and as spatial and temporal dislocations of sand accumulations (Sherman & Nordstrom, 1994).

Geomorphological processes result in an input of fresh sand, thereby creating new patterns in the landscape: diversity increases; the xeroserries (with i.a. *Ammophila*) penetrates into the halophytic vegetation.

Photo 2. The interwoven washover and saltmarsh landscapes. In the foreground *Sueda maritima* and *Elymus pycnanthus*, on the dune slopes in the background *Ammophila arenaria*. View towards the North Sea.
Figure 1. Study area.

Figure 2. Inlet sediment bypassing mechanisms (Hoekstra, 1995).
Figure 3. Development of eastern Ameland (after Postma, 1982 in Ehlers, 1988).
Updrift erosion supplies alongshore variation in foredune development and downdrift beach-ridge topography. Two cycles of sediment budget combinations are depicted, leading to the development of two foredune crests. The complexity of development is related to the episodes of erosion supplying sediment to support beach and foredune sediment budget combinations.

Figure 4. Morphologic evolution of the foredune. (a) As a function of the beach sediment budget and the foredune sediment budget. (b) Spatial association of foredune morphologies on a barrier island (Psuty, 1992).
The position of individual embryonic dunes determines to which degree the area between the dunes erodes during high tide, as a consequence either horse-shoe shaped dunes or eye-dunes develop. (after Klijn, 1981 and Sanderson, 1994a)

Figure 5. The influence of (a) the wind and (b) the sea on the development of eye-dunes or horse-shoe shaped dunes.
Photo 3. Carved foredunes in the washover landscape show the influence of the wind. On the foreground sand is being trapped by marram grass. View towards the North Sea beach.
I 1.6 Geomorphology of the washover landscape

The study of the washover landscape will be approached from a geomorphological point of view; it focuses on geomorphological processes in relation to sediment budgets, and on the development of forms on a time scale of years. In accordance with the philosophy behind this thesis, the focus will be on geomorphologic processes at a landscape scale; the driving forces behind these geomorphologic processes will not be discussed in detail (see Chapter 5).

Fig. 6 shows the factors influencing the washover-landscape development by geomorphic processes at a landscape level. The geomorphic processes are influenced by existing morphology and vegetation. In the background, the driving forces (hydro- and aerodynamics) and the availability of sand are mentioned.

The morphology of a certain location influences geomorphological processes through its relative height, slope and aspect, and concavity or convexity and curvature. These mathematical expressions of position are all interrelated; they can be described by derivations of x, y, z (except for the height itself). Under field conditions it is hardly possible to isolate the influence of one of these factors on the geomorphological processes or their driving forces.

The relations between the existing morphology and geomorphologic processes and their driving forces, are formally known under simplified circumstances (Bagnold, 1954; Iversen and Rasmussen, 1994). The complex morphology in the field makes quantitative prediction of landscape development with such a process-based approach a precarious assignment.

The theoretical maximum angle of repose for dry loose sand grains (33°) could be considered as a threshold value, but in reality the maximum value deviates because of variations in cohesiveness of the sediment. For example, the presence of roots increases cohesion, allowing steeper (40° to 43°) stable slopes (Carter, 1980, Greenway, 1987).

The mere presence or absence of vegetation influences geomorphologic processes as well. Parts of vegetation above the surface modify windflow and intercept sand whereas, the binding capacity of the roots protects the underlying sand against aeolian or marine erosion. Parameterizations of these interactions have been proposed by, for example, Wasson & Nanninga (1986) and Hagen & Armbrust (1994). The distribution of the vegetation has to be considered for application of their formulas in an actual field situation. The assessment of this variable per location is difficult, in contrast to above-ground biomass and the percentage of cover, which can be derived from false colour photography (Van der Putten & Kloosterman, 1991).

Conversely, the reaction of vegetation to the input of sand can also be diverse; vegetation growth can be stimulated, growth can remain unaffected, or there could be a decline of the vegetation. The reaction of vegetation has in its turn implications for the effectiveness of the vegetation as a sandtrap (Hesp, 1989). These feedbacks will, however, not be elaborated on in this study.

In Fig. 7 some relations between the vegetation and geomorphologic processes are elaborated for aeolian processes. Recently, efforts have been made to quantify the influence of (distribution of the) vegetation on the geomorphological processes under field conditions (Sarre, 1989; Wiggs et al., 1994; Wiggs et al., 1995).
The driving forces on the sediment transport in the background of Fig. 6 are the aerodynamics (windflow over a surface) and, on an event basis, the hydrodynamics (water motion when the washover landscape is inundated during stormy conditions). Another requirement for the geomorphologic processes (in the background) is the availability of sand for transport. It can originate from within the system or it can be externally supplied.

Information on the relief can be provided by laser altimetry and coastal profile data. Information on the presence of vegetation can be retrieved from aerial photographs and video images. This has been elaborated in Chapter 2.

2 METHOD

The method aimed at behaviour-related modelling gives conceptual insights into geomorphic changes (Eleveld, 1996b) and provides information necessary to assess future ecological consequences. To develop this method, starting from the remote sensing data input and ending with a prediction, two stages were completed consecutively. First, inventories of past and present geomorphological states of the terrain were made. Then a conceptual model was formulated and incorporated in dynamic modelling in a GIS environment.

2.1 Geomorphological survey

In a search for geometric factors and geomorphological processes that might influence the development and formation of a washover landscape, inventories were made of present and past geomorphological states of eastern Ameland (see Table 1). Data collected by airborne sensors, height profile data and field checks were employed for this purpose.

2.1.1 Aerial photographs and aerial video data

Airborne remote sensing data give an indication of geomorphological activity; sometimes it is even possible to distinguish between erosion and accumulation (Eleveld, 1996a). In addition, Janssen et al. (1995) have been monitoring the vegetation on Ameland from an ecological point of view, with various types of remote sensing data (e.g. aerial photographs and CEASAR). In this study two sets of aerial photographs scale 1 : 18 000, one from April 1992 and the other from February 1995, were used. Additional information was derived from airborne video imagery from October 1995 and May 1996. A visit to the Topographical Survey (the Netherlands) allowed a historical perspective to be developed. The landscape was studied at three levels of scale with these data. In addition, multitemporal comparison was performed.
Figure 6. Factors influencing the washover landscape development: existing relief, vegetation and geomorphological processes. The driving forces (hydro- and aerodynamics) and the availability of sand act in the background.

1. Vegetated spots impede erosion, so that the vegetation can persist. If there is erosion, then the vegetation will be negatively affected.
2. Vegetation inhibits sand transport, this causes sand to accumulate.
3. The presence of vegetation stimulates accumulation, and accumulation can stimulate the prevailing dune pioneer vegetation.
4. Bare spots can erode more easily than the vegetated ones, the erosion itself causes them to remain bare at first. (Later they can be stabilised by algae.)
5. Bare stretches allow transport, and the sand blasting would impede colonisation.
6. Bare surfaces (as such) do not stimulate accumulation and therefore do not stimulate the colonisation by pioneer vegetation.

Figure 7. Interactions between geomorphological processes and vegetation.
### Table 1. Approach taken to assess the past and present geomorphological state.

<table>
<thead>
<tr>
<th>feature</th>
<th>data</th>
<th>analysis</th>
<th>results</th>
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<tbody>
<tr>
<td>patterns</td>
<td>aerial photography and videography (multi-temporal)</td>
<td>aerial photo interpretation unsupervised classification</td>
<td>discrimination of units on three scale levels:</td>
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<td></td>
<td></td>
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<td>- discrimination of active (washover) and resistant areas</td>
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<td>- distinction of three types of washovers: Fan, Creek and Plain</td>
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<td>- differentiation of separate sub-forms within the washovers</td>
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<tr>
<td>height</td>
<td>laser altimetry (uni-temporal)</td>
<td>interpolation to a digital terrain model (DTM)</td>
<td>contour map</td>
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<td></td>
<td></td>
<td>cartographic modelling</td>
<td>different views by using various derivatives of the original elevation data allows e.g. distinction of 'obstacle dunes'</td>
</tr>
<tr>
<td>height profile</td>
<td>data</td>
<td>comparing different profiles:</td>
<td>washovers tend to fill up initially steep, convex beach profiles with a high bar activity</td>
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<tr>
<td>data (multi-temporal)</td>
<td></td>
<td>- bar amplitude</td>
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<td></td>
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<td>- beach width</td>
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<td>- slope of beach and shallow shoreface</td>
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<td></td>
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<td>- number of foredune ridges, width and height of the foredunes</td>
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</table>
2.1.2 Laser altimetry and profile data

Airborne laser scanning technology for topographic terrain mapping is emerging as an attractive alternative to traditional survey techniques (Flood & Gutelius, 1997). Pre-processed laser altimetry data from 1996 were used in the software package Surfer to create a laser Digital Terrain Model (DTM) with a 5 x 5 m grid. These data were plotted as a contour map, which functioned as a base map for the analysis. The corresponding topographical map, scale 1 : 25 000 (edition of the Topographical Survey, the Netherlands), provides no information on this part of Ameland.

For morphometric analysis of the laser altimetry data, the grid values were exported to an ASCII text file, which was imported into PCRaster (a spatio-temporal modelling package). Cartographic modelling is a geographic data processing method (Tomlin, 1990), that allows, i.a., the following morphological parameters to be derived from the laser altimetry DTM:

- height;
- slope;
- aspect;
- concavity/convexity,
- profile curvature (i.e. curvature in the direction of the slope) and planform curvature (i.e. curvature transverse to the slope).

For temporal comparison, coastal transects with a special orientation and reference system were used. The data originate from two sources: photogrammetry and traditional surveying on land, and loding and echo-sounding at sea. The transects were rectified to the Dutch Coordinate System, i.a. by programming in Turbo Pascal. Their calculated location was plotted on the contour map of the laser altimetry DTM with Surfer (see Fig. 9). Profiles of three transects that were perpendicular to the protruding foredunes and four transects in the washovers were studied with respect to:

- bar amplitude;
- beach width;
- slope of the beach and shallow shoreface;
- curvature of the beach and shallow shoreface;
- number of foredune ridges, and width and height of the foredunes.

2.2 Modelling

Knowledge obtained in the field, the results of the inventory made and additional information obtained by data processing have been combined to formulate a conceptual model. On the time-scale of the study (years, with a maximum of ten years), the washover landscape was reshaped by various agents: erosion and accumulation by the North Sea and the Wadden Sea; and wind and rain, which results in relocation of sand volumes. This was accounted for in the classification of the landscape with conditional statements (see also section 3.2).

The conceptual model is based on the following assumptions:

- there is a net growth of the beach; the beach is influenced by the sea and the wind;
- there is a small net aeolian sand flux from the beach to the foredunes;
• (vegetated) areas higher than 2 m are influenced mainly by aeolian accumulation processes;
• steep slopes are (partly) bare and therefore prone to some aeolian erosion;
• the bare surfaces allow a net transport of sand to the saltmarsh.

In PCRaster, a model can be built by using the laser altimetry DTM (section 2.1.2) in raster format, and the assumptions as formulated in the conceptual model. Subsequently, erosion and accumulation are simulated to derive a new topography. For the next time step, the new topography is classified, and so on. The time steps in the model represent half a year each. For each time step the same equations are used. The morphological consequences of the stormy season (from November to January) and of quieter periods, have therefore, to be averaged for these equations.

This dynamic modelling in a GIS (spatio-temporal modelling) aims at predicting the future washover landscape (see Annex 1 'Program'). More information on the structure of PCRaster programs is given in Chapter 6 and in Karssenberg (1996).

3 RESULTS

Two kinds of results were produced: a mainly qualitative and descriptive result, giving insight into the past and present geomorphological situation; and a semi-quantitative result, which is a map obtained by dynamic modelling.

3.1 Insight into past and present geomorphology

First, the landscape was classified on several spatial levels. Then, changes detected on aerial photographs were described. This was followed by a temporal comparison of profile changes along some transects. For further spatial analysis, cartographic modelling with the laser altimetry DTM was performed.

3.1.1 Aerial photographs and aerial video data

The landscape can be described at various levels of detail.

On Level 1 the aerial photos provide an overview of the eastern end of Ameland. (For reference: some of the features described in this section can also be distinguished in Fig. 8 and 9 which more or less cover the same area). From west to east (going towards the outer end of the island), the following stretches are encountered:

• a sand dike;
• four washovers;
• a foredune area;
• four washovers;
• another foredune area, and
• the easternmost three washovers at the end of the foredunes, where they pass into the beachplain.
The beach in front of the protruding foredune areas is narrow. The aspect of these areas is north-northeast. Their appearance varies from carved natural foredunes to distinctive horse-shoe-shaped dunes. Horse-shoe shaped dunes are erosion rests with sand input form several directions (Sanderse, 1994a). The horse-shoe shaped dunes might be a stable (or equilibrium) form in this washover environment, with much sand input from the beachplain and some from the washovers, which is stabilised by natural vegetation.

On Level 2, individual washovers within the series of washovers and foredunes can be distinguished. Three distinct types of washovers can be distinguished from west to east:
- Washovers with a clear accumulation zone immediately behind the washover throat (and flat), in this chapter referred to as 'Fan-type washovers';
- Washovers where the sand might be transported to the lower saltmarsh and tidal flats by creeks, i.e. 'Creek-type washovers';
- Washovers with throats (in this case almost gullies) intersecting the island, allowing sand transport from north to south (and back), at the eastern outer end where the foredune ridge is enclosed by the beachplain, 'Plain-type washovers'.

The differences in deposition on the saltmarsh mentioned above were probably determined by the situation before 'overwash': the elevation of the area and extensions of the saltmarsh zone. From west to east, the height of the foredunes and the extensions of the saltmarsh zone decrease.

The orientation of the washovers varies from northwest to northeast, in accordance with the direction of the strong winds on Ameland's North Sea coast. In the saltmarsh area, the creeks are oriented southeast – northwest, perpendicular to the frequent, moderate southwesterly winds which supply the Wadden sediment. In some cases this topography might influence the form of the washovers; e.g. the place of accumulation normally follows the orientation of the throat of the washovers, but is sometimes overruled by creek directions.

On Level 3, a more detailed look at the washovers allows a differentiation of forms within the washovers:
- a throat;
- a flat;
- a fan.

The following changes were detected on the aerial photographs when the photographs of 1992 and 1995 were compared. The accumulation zones of the washovers located in the foredune area were most rapidly stabilised, probably because on that side the vegetation is adapted to respond to incoming sand fluxes. A sheet of sand is visible in the foredunes on the photos of 1992. This sand came mainly from the beach, not from the washovers. The landscape matured after deposition of the sand sheet; aeolian processes formed steep slopes and differences in accumulation and deflation became more prominent. The throat of the washovers will in general remain an active (aeolian and/or marine) barren area for years, although in one of the 'Fan-type washovers' a lag in the form of a shell pavement, hindering aeolian activity, was found. In 1995, the bare sand bordering the marsh creeks extended further south than in 1992, indicating active southerly transport of sand. Washovers
connected to marsh creeks in the south (Creek-type washovers), and washovers located at the most easterly end of the foredunes (Plain-type washovers) can function as a conveyer-belt for sediment, transporting sand from north to south. In the latter case the sediment possibly reaches the Wadden Sea. The sand does not reach the tidal flats in the case of washovers with fans behind them (Fan-type washovers).

3.1.2 Laser altimetry and profile data

Fig. 9 illustrates the cartographic potential of laser altimetry data; the frame indicates the modelling area. Cartographic modelling allows a different view of the same data; after processing, often features can be found that were not apparent before (see Fig. 10). However, it must be realized that all information presented is derived from 5 x 5 m rasters, and that a different cell size could give slightly dissimilar results.

- The pattern of aspects reflects the creek systems. Furthermore, the aspect map can provide information on the fronts of the foredunes, which can be attacked by the northwesterly winds to which they are exposed.
- The steepest slope observed is 14.5°. This is less than the expected angle of repose of dry sand of 33°, and less than slope angles encountered in the field. A smaller cell-size might lead to higher values for this parameter.
- The concavity/convexity changes at the dunefoot: at a height of about 2 m, a transition from concave to convex occurs. This phenomenon, which shows up especially well on the profile curvature map, could be interpreted as an obstacle dune (Gegendüne, Van Dieren, 1934). The transition from foredune to a washover throat ('a washover foot') would be at a height of approximately 2.7 m. Obstacle dunes are sometimes also present at this washover foot. Finally, the maps show that the valley bottoms formed by the washover throats are relatively flat.
- The profile and planform curvature, which are closely related to concavity/convexity, support the information described under concavity/convexity.

Some relevant morphometric differences established by comparing ten annual profiles of three transects perpendicular to the resistant foredunes and four transects in the washovers were obtained. From these ten profiles, two representative transects, 23.800 (resistant) and 24.000 (washover) were selected to illustrate the developments (see Fig. 11). An analysis of a time series of differences between the corresponding profiles was made. The older profiles in the washovers had large variations in beach height. These are stepped, steep profiles. Probably steep beach profiles induce the formation of washovers. The average slope angle of the profiles decreases gradually over time. Washing over implies much activity on the beach. Washovers tend to fill up the foreshore part of the initially convex mean beach profiles. During the studied period foredunes in a washover area were comparatively smaller and wider (the height/width ratio is lower) than in stable areas.

Fig. 12 shows the situation before (1986), during (1989, 1990) and after (1991) formation of the washover. Temporal comparison demonstrates a change in beach slope when the washover was formed. The original foredunes in the washover area were located more seawards than the foredunes of the stable part, but as a result of washing over this situation was reversed.

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Figure 8. Analysis of a video mosaic: unsupervised classification.
Figure 10. Cartographic modelling with laser altimetry data. (a) Elevation (m); (b) aspect (degrees); (c) slope (degrees); (d) concavity / convexity (m/m$^2$); (e) profile curvature (m/m$^2$); (f) planform curvature (m/m$^2$).
Figure 11. Comparison of various profiles from two representative transects through a foredune area (23.800) and a washover area (24.000). For the washover area, the profiles of beach and foreshore were initially very steep (convex) and stepped; the foredunes were relatively low and wide. Washovers tend to fill up the initially convex profiles.

Figure 12. A washover is formed. Comparison of profiles from two representative transects through a foredune area (23.800) and a washover area (24.000).
3.2 Results of modelling

Fig. 13 shows a map of the actual situation in 1996, and a map with the predicted topography for 1998. Visual comparison of the two maps shows that the height of the saltmarsh will locally increase more. This is generated by the model as follows. Through the addition or removal of a certain sediment budget a cell can become a member of a different class. To this class, a different sediment budget will be allocated, thus altering the differences.

A minor error in the model causes the flat valley to broaden on the inland side of the washover throats. This is caused by assigning erosion to some of the slopes flanking the washover throat, and the filling in of some of the lower areas within the washover throat.

4 VALIDATION

In this section the quantitative results (i.e. the predicted situation in Fig. 13) reported in section 3 are verified. The approach taken is verified by testing whether temporal trends in sediment budgets actually occurred. Then the prediction itself has been verified. Finally, GIS and geostatistical tools are used for verification of the statement that the outcome of the model shows an increase in morphometric diversity of the washover landscape.

4.1 The modelling approach

The inherent assumption behind the dynamic model is that some trends can be perceived (see section 2.2). Another possible approach to modelling would be to assume complete random behaviour of sediment volume changes (stochastic modelling). Trends are present in the model as an addition or subtraction per time step. Negative feedback loops are included in the model as well. This can be explained as follows. After one to a few time steps in the model, a
cell can be assigned to a different class. For this class a new rule, in which a different sign (-/+) occurs, can be imposed. The rest of this section serves to test if the initial trend approach was justified.

The laser data, which cover the entire area of investigation, were originally only available for one year, so that possible trends in volumetric change in time could not be determined. Substantial multitemporal data are nevertheless available for various transects within in the washover/saltmarsh landscape. Therefore, the validity of the model has been verified by a study on trends in volume change along several transects.

To show these trends, 'maps' were created with a matrix filling procedure in Turbo Pascal. Then, the differences per landscape unit (foreshore, beach and foredunes) were calculated and visualised in PCRaster. On the x-axes, 14 individual transects (from 22.400 to 25.000) are shown. These discrete transects are 200 m apart. To increase the visibility of the individual transects, 5 cells in the x-direction were used, for every transect. The y-axis is perpendicular to the basal coast line. In the y-direction the measurements are 5 m apart. The result consists of a collection of individual transects depicted on a scale 1:50. The shades of grey of the raster cells represent the absolute z-values (above and below NAP, Dutch Ordnance Level).

Fig. 14a shows the significant differences in topography between 1995 and 1987, '89, '91 and '93, respectively, per landscape unit. The minimum and maximum values occurring in the 'maps' were studied. There is a trend (in time) in maximum changes on the beach; the reported maxima (see legends) decrease as the difference in years becomes less. For the minimum values this trend is not apparent. In the foredunes a similar trend in maxima and lack of trend in minima can be perceived.

The shades of grey in the 'maps' indicate how these maxima and minima relate to (the distribution) of the other values in the 'map'. This has been presented in graphs of the significant differences in topography as well (see Fig. 14b). If the interval in years becomes less, then the number of measurements and the range of the measurements tends to decrease (for both the beach and the foredunes). From the above, it can be concluded that there is a (weak) basis for the assumption of a trend in the behaviour of the eastern system.

The 'maps' of the shallow shoreface (or foreshore) show relatively much activity as a result of the movement of coastal bars, possibly due to a trend in bar behaviour (See chapter 8). The shallow shoreface was not included in the modelled area (see Fig. 13) because there were no laser data available for this unit; the laser beam (wavelength 1047 mm) cannot penetrate turbid water.
Figure 14a. Volume changes along transects for validation of the model. Significant differences in surface height between 1995 and 1987, 1989, 1991 and 1993 per landscape unit (m).
Figure 14b. Distributions of the values in the volume change maps of beach and foredunes (Fig. 14a).
4.2 Prediction for 1997

In the course of this study, new pre-processed laser altimetry data (for 1997) became available, which offered new opportunities for validation of the prediction. Fig. 15 shows a comparison of the actual situation in 1997 with the predicted situation of 1997 on a cell by cell bases. The differences shown in this map are, however, not solely related to geomorphological processes (e.g. Fig. 15, value 6.20). The comparison of these data is hampered because:

- The data were collected with different point densities, and they were interpolated (to different raster sizes) and filtered (to remove backscatter from the vegetation) by different companies, which possibly use different algorithms;
- There are inaccuracies in both z-values and position (x, y-coordinates) of the data (Vaessen et al., 1998).

Therefore, the prediction will also be evaluated in another way.

Figure 15. Comparison of (a) the actual and (b) the predicted topography of 1997. The lower map (c) equals the actual topography minus the predicted topography. (Values in m.)
Fig. 16 shows how laser altimetry and overlay operations can be used to study a system in which geomorphological processes, vegetation and existing morphology are the main components. A similar strategy will be used to evaluate the model employed.

In the model (see Annex 1) certain geomorphological processes (e.g. 20 cm accumulation, 10 cm erosion) have been assigned per class (e.g. dune, steep dune slope or throat in a washover). Overlaying the maps of these classes with a map of the geomorphological processes (created by subtracting the laser data of 1996 from the data of 1997) makes evaluation per class possible.

In Table 2 the changes produced by the modelling are compared to the modi of the distributions of the actual changes. For three classes (dune, steep slope/washover throat, and marsh to dune) it has been proven with 95% confidence that the difference between the changes produced by modelling and the actual changes is too large. For these classes the model performed badly. For the other five classes the numerical differences were between 0.51 and +0.51 m with 95% confidence. Therefore, the hypothesis of this test that the numerical differences could be zero would have to be accepted for these five classes. However, this confidence interval of [-0.51 m, 0.51 m] is large with respect to the changes produced by the model [0.00 m, 0.40 m]. This situation persists when a lower confidence (80%) is chosen, resulting in an interval of [-0.33 m, 0.33 m]. For the reason mentioned, no final statement regarding model performance will be made for these five cases, although the results of this test are positive for them.

4.3 Increase in landscape diversity

Visual comparison of the actual map of the original topography of 1996, with the map of the predicted situation for 1998, indicated that morphometric diversity is increasing (section 3.2., Fig. 13). Two ways were used to express qualitatively the observed increase in morphometric landscape diversity or heterogeneity: a window operation (in GIS) and a geostatistical approach. A third way to express heterogeneity could be to use fractal dimensions: the larger the fractal dimension, the more irregular is the object under study (In Pachepsky et al., 1997). This was not further explored, however.

4.3.1 Diversity within a specified square neighbourhood

First, use was made of the option 'windowdiversity' in PCRaster. With this option the number of unique values within a specified square neighbourhood (moving window) are counted and assigned to the cell in the centre of the window (Karssenberg, 1996). Different window lengths were tried for the two data sets, the map of 1996 (map96) and the prediction for 1998 (pred98). Then the sum of all cell values, i.e. the 'maptotals', were calculated to see in which map the total diversity was the greatest. The results have been expressed in Fig. 17 and Table 3.
Figure 16. GIS-based strategy for model validation. (a) Assessing the influences of existing relief and vegetation on the geomorphological processes by overlaying. (b) Assessing the associated errors.
### Table 2. Evaluation of model performance.

<table>
<thead>
<tr>
<th>Classes</th>
<th>Changes produced by modelling</th>
<th>Actual changes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>after 2 steps (m) process standard</td>
<td>mode</td>
</tr>
<tr>
<td></td>
<td>error$^a$ (m)</td>
<td></td>
</tr>
<tr>
<td>dune</td>
<td>0.40 acc 0.15</td>
<td>-0.50 ero</td>
</tr>
<tr>
<td>steep slope/throat</td>
<td>-0.20 ero 0.15</td>
<td>0.50 acc 0.21</td>
</tr>
<tr>
<td>beach</td>
<td>0.05 acc 0.15</td>
<td>0.05 acc 0.21</td>
</tr>
<tr>
<td>marsh</td>
<td>0.04 acc 0.15</td>
<td>-0.25 ero 0.21</td>
</tr>
<tr>
<td>stable</td>
<td>0.00 stable 0.15</td>
<td>-0.05 ero 0.21</td>
</tr>
<tr>
<td>beach to dune</td>
<td>0.25 acc 0.15</td>
<td>0.05 acc 0.21</td>
</tr>
<tr>
<td>dune to st.slope/throat</td>
<td>0.10 acc 0.15</td>
<td>-0.05 ero 0.21</td>
</tr>
<tr>
<td>marsh to dune</td>
<td>0.22 acc 0.15</td>
<td>-0.35 ero 0.21</td>
</tr>
</tbody>
</table>

### Differences between modelled and actual changes

<table>
<thead>
<tr>
<th>Classes</th>
<th>num. diff (m) process</th>
<th>standard error$^{a,c}$ (m)</th>
<th>$^{95%}$ (m)</th>
<th>$^{80%}$ (m)</th>
<th>perform.</th>
</tr>
</thead>
<tbody>
<tr>
<td>dune</td>
<td>0.90 acc vs ero</td>
<td>0.26</td>
<td>0.51</td>
<td>0.33</td>
<td>reject</td>
</tr>
<tr>
<td>steep slope/throat</td>
<td>-0.70 ero vs acc</td>
<td>0.26</td>
<td>0.51</td>
<td>0.33</td>
<td>reject</td>
</tr>
<tr>
<td>beach</td>
<td>0.00 acc</td>
<td>0.26</td>
<td>0.51</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>marsh</td>
<td>0.29 acc vs ero</td>
<td>0.26</td>
<td>0.51</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>stable</td>
<td>0.05 sta vs ero</td>
<td>0.26</td>
<td>0.51</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>beach to dune</td>
<td>0.20 acc</td>
<td>0.26</td>
<td>0.51</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>dune to st.slope/throat</td>
<td>0.15 acc vs ero</td>
<td>0.26</td>
<td>0.51</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>marsh to dune</td>
<td>0.57 acc vs ero</td>
<td>0.26</td>
<td>0.51</td>
<td>0.33</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ The overall error deviation ($\sigma=0.15$) given by the data providers for the two entire maps (map96 and map97) has been used for this analysis. The errors in laser scanning data values per class (Huising & Vaessen, 1998) were higher ($\sigma=[0.24-0.76]$) than the ones used in this study. The errors increased with augmenting relief and increasing vegetation coverage.

$^b$ Standard error: $\sqrt{0.15^2+0.15^2}=0.21$ m

$^c$ Standard error: $\sqrt{(0.15^2+0.21^2)}=0.26$ m

$^d$ 95% confidence interval: $0.01960\times0.25=0.51$ m

$^e$ 80% confidence interval: $0.01282\times0.26=0.33$ m
Figure 17. Diversity. (a) Elevation map of 1996 and (b) predicted elevation map of 1998 (dm); (c) and (d), their 3×3 window diversities (cells). (e) Changes in window diversity, i.e. the window diversity of the predicted elevation minus the window diversity of the actual elevation (cells).
In all cases the total diversity of the predicted map (pred98) is smaller than that of the actual map (map96). According to this method there is no indication that diversity will increase. From this result, the hypothesis that diversity increases would have to be rejected. If the actual map is subtracted from the predicted map then the resulting map expresses where diversity decreases and increases (Fig. 17). Smoothening of the steep regions and inland expansion of the flat throat causes the decrease. There is an increase in diversity in the dune and high saltmarsh areas.

Table 3. Diversity of the original map of 1996 and the predicted map of 1998

<table>
<thead>
<tr>
<th>scale level (cm/dm)</th>
<th>window length (m, pixels)</th>
<th>total window diversity in map96</th>
<th>total window diversity in pred98</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm</td>
<td>15, 3</td>
<td>78,950</td>
<td>78,690</td>
</tr>
<tr>
<td>dm</td>
<td>15, 3</td>
<td>45,100</td>
<td>44,660</td>
</tr>
<tr>
<td>cm</td>
<td>25, 5</td>
<td>192,800</td>
<td>190,700</td>
</tr>
<tr>
<td>dm</td>
<td>25, 5</td>
<td>78,310</td>
<td>76,640</td>
</tr>
</tbody>
</table>

4.3.2 Geostatistical analysis

Surface elevation is a regionalised variable describing a natural phenomenon that has a geographic distribution (Davis, 1986). Semivariance is one of the basic statistical tools of geostatistics. It is used to express the degree of spatial dependence between samples (measurements of the regionalised variable) as a function of distance. The variograms for the measured topography of 1996 (map96) and the predicted topography of 1998 (pred98) were compared to see if geostatistical analysis would point to a difference in spatial variability. For this, a randomly sampled map was created with the PCRaster option 'uniform'. This option assigns a value, taken from a uniform distribution between 0 and 1, to all (true) cells of the map (Karssenberg, 1996). This map was used in conditional statements for random extraction of z values, and their corresponding x and y coordinates, for the actual map of 1996 (map96) and for the predicted map of 1998 (pred98). These values were used in the construction of the input files for VARIOWIN, a freeware program for exploratory variography and variogram modelling (Pannatier, 1994). Two types of variograms are shown: experimental variograms, which show the means of combined point pairs, are displayed in Fig. 18; variogram surfaces, which show variograms in the X and the Y direction are displayed in Fig. 19.

The experimental variogram of the predicted map (pred98) is slightly higher than that of the actual map of 1996. There is no nugget effect, which indicates that there is a good correlation of height at a small distance. Therefore, the 5 m grid was not too coarse to describe the washover/saltmarsh system. The sill increased, without an increase in range. The higher sill of the predicted map confirms that this map has a higher spatial variability.

The variogram surface shows in both cases a lower variability in the x-direction, parallel to the coastline, than perpendicular to it. This conforms with the predominantly E-W orientation of the foredunes and the shore-normal position of the washovers (see Fig. 13).
Figure 18. Experimental variograms of the original map of 1996 and the predicted map of 1998.

Figure 19. Variogram surfaces of the original map of 1996 and the predicted map of 1998.
5 DISCUSSION AND CONCLUSIONS

A washover landscape is composed of spatio-temporally changing topography with dune and saltmarsh vegetation. This chapter shows the attempt at predicting the future topography of a washover area with a geomorphological approach.

Method
The method was tested extensively and seems promising. It is different from the traditional research methods that have been used on washovers because it is not based on the extrapolation of process measurements at a limited number of points in the field (e.g. Leatherman & Zaremba, 1987). Compared to the traditional method of surveying sediment budgets by weekly measurements of surface changes along erosion pins (e.g. Sarre, 1989; Jungerius et al., 1981; Wiggs et al., 1995 and Davidson-Arnott & Law, 1996), which is very labour intensive and can barely be continued for several years, laser altimetry seems a good alternative – despite problems with accuracy (Vaessen et al., 1998).

A remark frequently made about spatio-temporal modelling is that there is a lack of accurate data to test the model. This paper shows that airborne remote sensing data can be used as input for spatio-temporal models.

Results
The study resulted in the prediction of a (future) washover and saltmarsh landscape. The results were tested in various ways. The prediction of the situation in 1997 was, i.a., verified with new laser data of 1997. Based on this comparison, some of the assumptions in the model should be rejected. This means that the model still needs to be refined.

Both sea and wind are active agents in the formation and development of the eastern washover and saltmarsh landscapes. An elaboration of their influences could be made if results from the multitemporal study of the profiles and the cartographic modelling (subsections 3.1.1 and 3.1.2 respectively) are related to process research. The presence of washovers causes an environmental heterogeneity that could result in high species diversity. A next step would have to be an assessment of the vegetative response to changing topography. For a longer-term prediction it must be realized that, the new vegetation will in its turn influence the geomorphological processes that form the landscape.

Genesis
A prediction of the evolution of a washover and saltmarsh landscape has been made (see Fig. 13). To predict the formation of washovers, studies should focus on the long-term sediment dynamics, because they form the preconditions for the development of the foredunes and their intervening lower parts, and their roles during storm conditions (see section 1.4). Furthermore, the presence of trends is assumed in the dynamic modelling of the evolution of a washover landscape (section 4.1). This assumes that the influencing factors will remain more or less constant. Event-based influences can, however, not be excluded in the formation of washovers.
Ecology
For managers and ecologists it is important to note that input of sand is an important abiotic factor in the genesis and evolution of a saltmarsh.

- Washovers are major sources of sand transfer on barrier islands. Cross-island transfer is the main process, providing platforms (e.g. washover fans) suitable for marsh colonisation (Oertel & Woo, 1994). That is why the understanding of washovers is very important for those studying these marshes.
- An active landscape with washovers increases landscape diversity.
- Wind is a factor that is frequently underestimated in the creation of a washover landscape.

Geomorphology
Within the saltmarsh/washover landscape, aeolian and marine geomorphological processes that occur are: erosion (deflation), sand transport and deposition (accumulation). Erosion and accumulation can easily be modelled by subtraction and addition. Simulation of sand transport, which forms the spatio-temporal connection between the two, is more difficult, however. PCRaster software was initially intended for the study of river flow in catchments, therefore the operators available are limited (Karssenberg, 1996). The use of cellular automata may provide more means for expressing transport (Chapter 6).

ACKNOWLEDGEMENTS

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Annex 1. Main program and auxiliary programs.

# wo1, parameters of future wo landscape
# by Marieke A. Eleveld
# 13-12-1996

binding
Topo.map=topo.map;
Slopedeg.map=slopedeg.map;
Catchms.map=catchms.map;

areamap
clopt5.map;

timer
1 1 1;

initial
isdunx.map=(topo.map eq 2) or (topo.map gt 2);
stslox.map=(scalar(slopedeg.map) eq 10) or (scalar(slopedeg.map) gt 10);
isdu27.map=(topo.map eq 2.7) or (topo.map gt 2.7);
ismatchx.map=((catchms.map eq 22) and (isdu27.map) or (catchms.map eq 25) and (isdu27.map));
islox.map=(topo.map lt 2); # dummy
beachcx.map=clump(islox.map); # dummy
isbeacx.map=(beachcx.map eq 3);
ismarsh.map=(beachcx.map eq 42);

hidunx.map=if(isdunx.map then topo.map);
hislox.map=if(stslox.map then topo.map);
hithrox.map=if(ismatchx.map then topo.map);
hithroxx.map=if(hithrox.map lt 6 then topo.map);
hibeacx.map=if(isbeacx.map then topo.map);
himarsh.map=if(ismarsh.map then topo.map);

aeolacc.map=hidunx.map+0.20;
erosio1.map=hislox.map-0.10;
erosio2.map=hithroxx.map-0.10;
marbeac.map=hibeacx.map+0.05;
strooi.map=himarsh.map+0.02;

erosios.map=if(erosio1.map> 0 and erosio2.map>0 then erosio1.map); # dummy
erosiod.map=(erosio1.map-erosios.map); # dummy
erosioh.map=cover(erosiod.map,erosio1.map); # dummy

erosior.map=cover(erosios.map,erosioh.map,erosio2.map);
topotus.map=cover(marbeac.map,erosior.map,aeolacc.map);
report topocn1.map=cover(topotus.map,strooi.map,topo.map);

dynamic

# moslope1, aux. program
# by Marieke A. Eleveld
# 10-12-1996

binding
Topocn1.map=topocnn.map;   # elevation map of 1996
Sloped1.map=sloped1.map;   # slopes in deg.
areamap
clonept5.map;
timer
  1 1 1;
initial
  slope1.map=slope(topocn1.map);
  sloped1.map=atan(slope1.map);

dynamic

# catchments, aux. program
# by Marieke A. Eleveld
# 10-12-1996

binding
Topocn1.map=topocn1.map;   # elevation map of 1996
Catchm1.map=catchm1.map;   # catchments
areamap
clonept5.map;
timer
  1 1 1;
initial
  lddch1.map=lddcreate(topocn1.map,1e31,1e31,1e31,1e31);
  outpchl.map=pit(lddch1.map);
  catchm1.map=catchment(lddch1.map,outpchl.map);

dynamic