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

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Citation for published version (APA):

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PART 3

GEOMORPHOLOGICAL INVESTIGATION

The Wadden islands are partly protected by ebb-tidal deltas. The spatial pattern of channels and shoals on these deltas is important for the coastal morphological development of the centres of these islands. An extensive beechplain with a large swashbar occurs at the head of Ameland. Recent changes of Ameland’s northwestern beechplain are cause for concern in land management. Yearly elevation data for the past 11 years (1985-1996) were interpolated to create elevation maps. Two spatio-temporal GISs have been used to describe the long-term development of this beechplain: a field-orientated GIS and an object-oriented GIS. The description resulted in the differentiation of three phases in the morphological development of the beechplain. The beechplain shows a regular development within these three phases, although it is irregularly cyclic in the long-run. Prediction based on long-term historical trends is therefore difficult. However, in the last phase a decrease in activity was noted—because of a lack of erodible sand; in the past, Ameland’s west coast has been stabilised with groynes. This state of inactivity might come to an end when a new phase begins, e.g., by the stagnation of a shoal in the beechplain. A sequence of storms and floods could change the stable situation for the swashbar, causing the landward migration of the swashbar and the filling of the lagoon.
PART

GEOMORPHOLOGICAL INVESTIGATION


References

International Journal of Geographical Information Science
CHAPTER 7


ABSTRACT

The Wadden islands are partly protected by ebb-tidal deltas. The spatial pattern of channels and shoals on these deltas is important for the coastal morphological development of the extremes of these islands. An extensive beachplain with a large swashbar occurs at the head of Ameland. Recent changes of Ameland’s northwestern beachplain are cause for concern for management. Yearly elevation data for the past 11 years (1985-1996) were interpolated to create elevation maps. Two spatio-temporal GISs have been used to describe the long-term development of this beachplain: a field-based GIS and an object-oriented GIS. The description resulted in the differentiation of three phases in the morphological development of the beachplain. The beachplain shows a regular development within these three phases, although it is irregularly cyclic in the long-run. Prediction based on long-term historical trends is therefore difficult. However, in the last phase a decrease in activity was noted, because of a lack of erodible sand; in the past, Ameland’s west coast has been stabilized with groynes. This state of inactivity might come to an end when a new phase begins, e.g. by the amalgamation of a shoal to the beachplain. A sequence of storm floods could change the stable situation for the swashbar; causing the landward migration of the swashbar and the filling of the lagoon.

Beachplains are present on Ameland's westerly and easterly extremes. These beachplains can be seen as extensions (or as the outer lobes) of the ebb-tidal deltas. Presently, many changes with severe consequences for management can be perceived on Ameland's northwestern beachplain (Waterloopkundig Laboratorium & Rijksinstituut voor Kust en Zee, 1996). These changes of the beachplain are related to processes in the ebb-tidal delta.

The research objectives described in this chapter are, to describe and to predict the evolution of the northwestern beachplain based on a geomorphological survey and on an automated approach. This chapter focuses on the behaviour of the beachplain. Much is already known about the relationship between the beachplain and the behaviour of the ebb-tidal delta, its shoals and its channels. This will be covered by two short literature reviews, which are presented in sections 1.1 and 1.2. Parametrisation (the attempt to describe and predict coastal behaviour with certain parameters) and the use of empirical knowledge are only possible when the link between the beachplain and ebb-tidal delta is also made. Section 1.3 introduces the behaviour of the beachplain itself. The present study mainly focuses on the use of the description of the beachplain itself as a basis for prediction, while the precise physical interpretation and explanation remains to be resolved.

1.1 Ebb-tidal deltas, inlets and backbarrier area

Tidal inlets play an important role in nearshore processes; they provide the link between the open sea and the protected embayments behind the barrier islands, exchanging water and sediments. Inlets play a major role in sediment budgets and shoreline erosion, because they interrupt the continuity of shoreline processes. Tidal inlets have been scrutinized for many years. Early work by O'Brien (1931), Escoffier (1940), Bruun and Gerritsen (1959) and others has paved the way for a better understanding of tidal inlet performance and behaviour. As with many coastal systems, however, tidal inlet behaviour is complex and hence poorly predictable from first principles (in a deterministic way), relying heavily on empirism instead (Aubrey & Weishar, 1988).

Some of the empirical mathematical equilibrium equations describe the size of the entire ebb-tidal delta (the ebb-tidal delta as an entity) in relation to the inlet and back-barrier area. Important hydrodynamic parameters in these geometric relations are: ebb and flood volumes, tidal prism and sinusoidal discharge and, mean and maximum current velocity (Biegel, 1991; Lambeek, 1993). These parameters reflect the influence of tidal forces on inlet geometry; the wave-driven component is ignored.

Walton and Adams (1976) found that the volume of the ebb-tidal delta can be related to the tidal volume. The multiplication factor in the relation differs for different classes of mean wave height and mean wave period. The volume of the ebb-tidal delta depends on both the tidal volume and the wave intensity.

Others see the inlet system as an interplay of forces trying to close (fill in) the inlet (e.g. littoral drift), and those which keep the inlet open (e.g. tidal current amplitude) (Van de Kreeke, 1996). The wave-driven component is acknowledged with the incorporation of littoral drift.
The significance of the large-scale behaviour of the Ameland’s ebb-tidal delta is recognised; the total volume of the ebb-tidal delta will correlate somehow to the total volume of the beachplain, but the behaviour of forms in the delta (channels and shoals) is also of importance for the evolution of the beachplain. This will be discussed below.

1.2 Channels and shoals of the ebb-tidal delta

The following sediment transport processes are quantitatively important as driving forces behind the behaviour of channels on the ebb-tidal delta:

- sediment transport by tidal currents in the channels;
- wave-driven longshore transport;
- wave-driven cross-shore transport;
- sediment transport by tidal currents over the shoals (Allersma, 1993).

The interactions can be simplified even further to tidal action perpendicular to the coast, and wave-driven sediment transport parallel to the coast.

However, both Allersma (1993) and Huijs (1993) pose that channel displacement on the ebb-tidal delta can also be an autonomous phenomenon; a channel can change because of the spatial association of channels and shoals by the internal dynamics of the system, without a change in external process parameters.

The behaviour of forms in the delta can be approached from two points of view: the migration of channels, and the migration of shoals. Allersma (1993) questions whether the channels migrate (by water movement in the channel) or the shoals migrate (by wave driven currents).

The channels move by:

- meandering;
- widening and narrowing;
- shifting sideways (sediment bypassing);
- rotating;
- changing in length.

Some empirical relations are known concerning channel geometry and water movement (flow) and their connection to sediment transport:

- tidal volume can be related to channel cross-section;
- sediment transport can be related to current velocity and to depth;
- the radius of the meander bend can be related to the width of the channel;
- secondary processes have physical relations with sediment transport. The water movement differs both along and perpendicular to the current. Also the sediment movement differs from a simple translation along the axes of the channel suggested by working with the mean velocity. In addition the tidal movement is not purely symmetrical. Thus secondary processes occur along the channel, perpendicular to it and as a result of asymmetrical residual currents (Allersma, 1993).
Systems analysis of channel migration on the ebb-tidal delta allows geometric information to be combined with knowledge of the local water movements. The influence of several physical processes within this system can be discriminated:

- **the 'tidal drive'** (original term is 'motorisch vermogen', by Van Veen, 1936)
  A tidal channel will adopt a position so that the maximum hydraulic gradient in the slope of tidal water levels will be achieved.

- **jet-effect** (original term is 'dynamic diversion', by Todd, 1968)
  The displacement of the shore parallel currents due to the outflow jet; the ebb jet is a hydrodynamic obstacle for the longshore transport and causes sediment accumulation upstream of the channel outlet.

- **sediment bypassing** (Bruun & Gerritsen, 1959; FitzGerald, 1988)
  The longshore transport of sediment over the ebb-tidal delta and across the inlet channels caused by wave-driven sediment fluxes and by tidal currents.

- **secondary flow**
  A hydraulic gradient towards the inner bend of a channel perpendicular to the main current, which forms in reaction to the centrifugal force (directed towards the outer bend). The Coriolis force can be an important component in secondary flow, but changes with the direction of flow (Berben, 1986).

For the latter two processes, empirical formulas have been developed by Bruun and Gerritsen (1959) and by Van Rijn (1990), respectively. Huijs (1993) made a conceptual model which describes the development of some main channels in relation to these physical processes with observed long-term channel migration data.

Shoals move as a result of erosion and sedimentation by:

- a channel,
- transport over the surface and along the boundaries of the shoal itself.

Shoals are more than just a fill-up between channels. Indeed, the shift in channels due to sediment bypassing indicates an active role of the shoals in the morphological interaction of the forces. Various processes play a role in water movements and the transport of sand over the shoals. Tidal currents (currents as a result of a hydraulic gradient) dominate in deep water. In shallow water, however, these currents play a role together with the orbital movement and the residual currents of waves. Drift currents only play a role during strong winds and when other factors are weak.

Allersma (1993) concludes that there is a need to describe morphological units, such as channels and shoals, in their association and movement with characteristic parameters. Furthermore, he states that modelling is only feasible at a high aggregation level; if possible without simulation of detailed sediment transport. One of the options mentioned is extrapolation of historic development, possibly supported by knowledge of the movement of water and sediments. In the present study, a prediction based on sequential analysis of digital elevation models (DEMs) will take place.

Finally, Allersma (1993) showed the limited capacity of combinations of models in trying to predict step-by-step what does not behave 'unambiguously' in nature. The natural processes are
steered by relatively weak resultant forces and are therefore sensitive to disturbances. Reactions of the system to human influences are more forceful (forced behaviour) and are therefore more suitable for modelling. Existing models can show initial morphological tendencies after interference (e.g. Van de Kreeke, 1996). These models used are not per se suitable for simulating natural processes in the long run. Ribberink & De Vriend (1995) acknowledge that the formation, migration and extinction of channels and shoals are not forced by any boundary condition or human interference: it is a manifestation of the system's inherent behaviour, which is the result of a subtle interaction between the constituent processes and bed topography. Modelling this behaviour is therefore not the same as modelling the impact of man-made works. However, process-based concepts can be used to reproduce channel/shoal dynamics; it might be possible to design a behaviour-oriented network model that includes channel migration, but this is still far from realisation.

For the current study, the following limitations must be acknowledged:

- Most of the channel data available are concerned with main flood channels between the islands.
- The migration of channels and/or shoals can be seen as the resultant driving force behind the change of the northwestern beachplain. However, no consistent theory has been formed for either resultant driving force, although some mathematical empirical relations for individual sub-processes are known. Therefore, the use of resultant driving forces for qualitative prediction of the evolution of the beachplain is hampered.

Fig. 1. shows the research location. Fig. 2. gives an overview of processes acting on an ebb-tidal delta, and Fig. 3. shows the actual changes that occurred in the Borndiep area from 1980 to 1990. In 1980 the ebb-tidal delta was directed to the NE. The delta was characterized by the presence of two major channels: Westgat (north of Terschelling), and Akkepollegat (in the elongation of the inlet), separated by Korfmansbult. East of Akkepollegat a triangular swash platform (Bornrif) was located at average depths of -1.2 to -5 m below NAP. Closer to the island this swash platform undergoes transition into Ameland's northwestern beachplain (-1.2 to 2 m). In comparison, in 1990 the ebb-tidal delta was oriented north. On the delta one clear channel, Westgat, and two less prominent channels, Akkepollegat and a new flood channel (or flood platform), were present. Korfmansbult had become less distinct. The new flood channel divided Bornrif into two parts. A smaller northwestern beachplain was still present in the NW of Ameland. Figure 3 shows the morphological changes over the period 1980 - 1990 (dif9080), i.e. erosion of the eastern part of the ebb-tidal delta, and accumulation on the western part. A reorientation of the inlet channel and of the channels on the ebb-tidal delta had occurred. Westgat and Akkepollegat had been filled and Korfmansbult eroded. Erosion had divided Bornrif, creating a new flood channel. The northwestern beachplain had eroded in the northwest and extended eastwards. (Although outside the focus of this chapter, changes occur in the flood-tidal delta, as well.)
Figure 1. Location and configuration of the ebb-tidal delta, 1990.

Figure 2. Processes acting on the ebb-tidal delta (Hoekstra, 1995).
Figure 3. Changes in the Borndiep area (1980-1990). (Values in m + NAP.)
The contour lines of topographical maps with data from 1980 and 1990, respectively were
digitised, between the RD-coordinates X: 160.000-178.000 and Y: 600.000-615.000. The digitized
contour lines were converted to DEM's by inverse distance interpolation (Van der Linden, 1997).
The 1980-DEM was subtracted from the 1990-DEM to derive the geomorphological changes.

1.3 Beachplain

The beachplain is influenced by the behaviour of the ebb-tidal delta, which is characterised by a
radial pattern of migrating channels and shallows. Fig. 4 shows the effects of these migration
processes and longshore transport on the western beachplain. The beachplain, once created by
the fusion of a shoal (shallow) is being eroded by the migrating channel that has reached the
western part of the beachplain. The beachplain is being extended eastwards (Eleveld, 1996).
The beachplain consists of a swashbar (sometimes also called a 'spit') with a lagoon (locally also
known as 'binnenmeer' or 'zwin') behind it. The borders of the lagoon and the small channel
between the end of the swashbar and the beach erode the beach and dunes.
During high tide, the beachplain is flooded. The (relatively high) swashbar protects the inner
beach. The waves dissipate on the swashbar, so the sediment can settle and there is accumulation
on the inner beach. During low tide, the water of the lagoon flows out through a small opening.
The concentrated flow erodes the beachplain. Meanwhile the end of the swashbar continues to
migrate with the longshore current and to extend eastwards. Since 1996, two channels can be
distinguished between the end of the swashbar and the beach: one for inflow (flood channel) and
one for outflow (ebb channel).
A literature study of similar features was conducted in order to predict future behaviour. A sand spit is defined as a form constructed by littoral drift of sand into the open water of a bay (Pethic, 1984; Carter, 1988), where sudden changes in wave energy occur (Pethic, 1984). Spits develop under a certain hydrological regime; they are coastal landforms related to meso- to micro-tidal conditions. In case of diminishing sediment supply spits may be breached or become beheaded (Carter, 1988).

For Ameland's easterly neighbour, Schiermonnikoog, Biegel and Hoekstra (1995) pointed out that the sandy appendix of the beachplain has to be generated by typical spit-forming processes, i.e. longshore drift, in order to be able to call it a spit. As this is not the main process in the Ameland case (see below), the term swashbar is preferred. Some theories on the development of spits, e.g. their reaction to diminishing sediment supply, may be useful when considering the swashbar, because of the close similarities between spits and swashbars.

Wave-induced sediment transport in the wake of the beachplain created a lagoon. Hoekstra et al. (1996) have shown how a positive gradient in longshore transport in the wave shadow of the ebb-tidal delta may be responsible for structural erosion of the coast. In the deeper areas of the transects close to the ebb-tidal delta, longshore sediment transport is significantly larger than in the more remote (easterly) profiles, due to the effect of breaking waves on the ebb-tidal delta shoals. Consequently, less energetic waves will enter the nearshore zone; the longshore sediment transport in this part is smaller. Therefore, sediment transport decreases from west to east in the deeper areas, but it increases from west to east in the nearshore zone. This causes accumulation offshore, and erosion in the nearshore zone, which stimulated the formation of a lagoon.

The behaviour of the beachplain can be described in several ways: geomorphologically by interpreting the multi-temporal remote sensing imagery (see above) or elevation maps; but also mathematically by assigning 'processes' (changes) such as shift, split, merge and expand to landscape units (Cheng et al., 1997). For wise management of the coast, there is also a need for prediction. In the past, hard structures and nourishments were used southwest of the beachplain to prevent further inlet migration. In 1980, sand from the beachplain near RSP 3 (PR 3 in Fig. 4a) was extracted for nourishment of Ameland's Central North Sea coast. This created a pit in the beachplain that could be perceived for many years afterwards. For several years (1989-1995) rapid erosion occurred near RSP 3. The foredunes in this region are quite broad. The most seaward row of dunes comprises a 'stuff-dike' with two 'carves'. There was a chance that the dune valley 'Lange Duinen' would be inundated by the sea. This is however an ecologically important area as it is. Therefore the management was in a dilemma: to allow the natural coastal processes and thereby destroying the existing nature, or to stop the natural coastal processes. Then, the erosion had slowed down. In 1996, the beach was nourished from RSP 7 (PR 7 in Fig. 4a) to 11 (4 km to the east of post 7). At the moment (1998), the management is confronted with questions concerning the future of the lagoon behind the swashbar in relation to touristic activities. Will the area be safe for swimming the next summer? There have been small interventions in the present situation by digging through the end of the spit, and by relocating a beach-cafe near RSP 7. The research question is therefore: is it possible to predict the behaviour of the beachplain from the descriptions?
Figure 4. Changes of the northwestern beachplain (1989-1995). (a) Horizontal changes on a backdrop rectified SPOT-PAN image of 1989. (b) Vertical changes along two transects.
2 METHOD

2.1 Data

JARKUS data from 1985 to 1996 were used for analysis of the behaviour of the beachplain. JARKUS data are elevation data and are measured each year by Rijkswaterstaat, Department of Transport, Public Works and Water Management. Every 200 m along the coast, the elevation is measured at 5 m intervals along a cross-shore line starting at about 800 m seawards to 200 m landwards from the first ridge of dunes. See Fig. 4 for examples of some profiles. Digital elevation models (DEMs) with a cell size of 60 m×60 m are created by inverse distance interpolation of the elevation data with the computer program Surfer. These DEMs were imported in two spatio-temporal GISs.

2.2 Description and modelling

Two spatio-temporal GISs were used to describe and predict the evolution of the beachplain: PCRaster, a field-based GIS, and IEMGA, an object-oriented GIS (Chapter 6).

In PCRaster, the DEMs were analyzed by visual comparison, supported by manipulations such as subtraction of the maps of subsequent years to illustrate the changes between the maps.

In addition to this raster-based approach, an analysis based on landscape units was performed. The higher aggregation level simplifies analysis, because it eliminates some of the noise. Based on elevation, several landscape units were defined. The beachplain (unit) was selected for each map (i.e. each year), and a temporal volumetric analysis was performed. The landscape units can also be treated as objects in IEMGA, an object-oriented GIS. This allows changes in objects (i.e. landscape units) to be determined.

The information gathered was subsequently used for prediction, firstly in a raster structure and then in an object structure.

PCRaster has a dynamic modelling component (Van Deursen, 1995; Karssenberg, 1996; Chapter 6). Models have been developed in PCRaster for the prediction of changes along the coast as a result of coastal processes. The DEMs are used as input maps.

- Several runs of a preliminary model for short-term prediction (five years maximum) were made (See Annex 1 for an example of the computer code of one simple model). After an examination of the data from 1993 to 1995, the active parts of the landscape, i.e. the shallow shoreface and the beach, were separated from the relatively inactive landscape unit, the foredunes in 1993. It was observed that the sediment had moved in westerly direction between 1993 and 1995. Subsequently the dynamic westerly sediment movement was simulated. The actual 1993 elevation map served as input for the model. The model was run with a varying number of timesteps (run duration). Following this, the model results were compared with the actual maps of 1993 to 1995 and an extrapolation to 1996 was made.

- Then several approaches for long-term prediction were tested (e.g. by Van der Linden, 1997) by making models that simulate changes in sediment budget by exclusively altering
the heights of cells (changes in a vertical direction only), and with a model that includes the overall flow pattern of the currents.

Cheng et al. (1997) and Cheng and Molenaar (1997) have developed a spatio-temporal GIS shell to support coastal environmental modelling. The database of a prototype system, IEMGA (Integrated Environmental Modelling and GIS Application) allows tracking of objects and their processes. Figure 9 presents a diagram of these changes and the suitability of the method for prediction is described in section 3.2.

3 RESULTS

3.1 Description of the changes

A compilation of elevation maps (Fig. 5) shows the evolution of the northwestern beachplain from 1985 to 1996. Three stages (phases) in the evolution can be distinguished:

- The redistributing phase (1985-1989)
  In 1985, the beachplain was relatively large and was connected to Bornrif in the northwest. Higher and lower areas exchanged sediment over this platform (Fig. 5 & Fig. 3). On the western side, the tidal inlet was present; its maximum depth was 25 m.

- The curving phase (1989-1995)
  On the outer edge of the beachplain, a swashbar was formed. In following years, the swashbar rotated clockwise until, in 1990, it became aligned with the beach. From then on, the spit has been moving to the east and it is approaching the beach: the western part of beachplain erodes and the sediment is deposited in the east.

- The compacting phase (1995-1996)
  The western part of the beachplain was eroded because the tidal inlet moved to the east, due to a shift in the position of the main flood channel (see Fig. 2). The tidal inlet was unable to erode the beachplain much further, because this area is stabilized with groynes.

A series of 'change maps' (Fig. 6), viz. maps of the morphological changes that have occurred in subsequent years, shows the spatial redistribution of sediment over the years. Therefore it provides insight into the evolution of the beachplain. From 1985 to 1989 much activity occurred in the east. However, major changes were alleviated in the next period; e.g. areas which had accumulated between 1985 and 1986 were eroded in the next period (1986-1987). For 1989 to 1992 accumulation can be seen in the northeast. From 1992 to 1995 erosion occurred from the southwest to the centre of the maps (along the beachplain). The main erosion between 1991 and 1992, 1992 and 1993, and 1994 and 1995 results from bar movement (see Fig. 7, transects) that accompanied the migration of the channel. From 1995 to 1996 the area was relatively stable.
The changes have also been studied on a landscape-unit level. The following boundaries are proposed relative to the Dutch Ordnance Level (NAP):

-10 m = the boundary of the ebb-tidal delta (see also Sha & Van den Berg, 1993),
-5 m = channel boundary, the boundary between the channel and the shoal/foreshore, (It is common practice to define the channel boundary at -5 m. However the boundary could also be chosen at -3 m for shallow water, near the head of the island (Huijs, 1993)),
-1.2 m = MLW. (mean low water level), the boundary between the shallow shoreface and the beach,
2 m = dunefoot, the boundary between the beach and the foredunes.

The proposed criteria are based on height. Other factors can also be of importance. Position can be important on a landscape-unit level; e.g. it depends on position whether a certain area is a shoal or a beachplain.

The development of the beachplain is of primary interest. Fig. 8 shows a decreasing trend in the volume of the beachplain from 1985 to 1988. This trend changed suddenly in 1989, possibly because of the addition of sediment by amalgamation of a small marginal shoal (see section 4, Discussion and conclusions). From 1989 to 1992 beachplain volume was high. After 1992 the volume decreased rapidly, slowing down in 1995. At the end of the data range, in 1996, the minimum value over the whole period was observed. However, this does not necessarily mean that the total volume of the beachplain actually decreased, as a part of the beachplain, the spit, had moved out of the mapping region. The volumetric changes also reflect the shift of the beachplain through the mapping region; maximum volumes occur when the beachplain was located in the middle of the mapping region.

Following Claramunt and Theriault (1996), in their semantic description of processes, Cheng et al. (1997) and Cheng and Molenaar (1997) used landscape units to describe spatio-temporal processes from an object-oriented approach (Raper & Livingstone, 1995). In map format, information is not always needed at pixel level to track coastal changes. Fig. 9 shows changes (e.g. shift, split and merge) that can be perceived at this higher aggregation level, in which the landscape units are treated as objects. Five objects (channel/shallow shoreface, beachplain, foredunes, dune valley and lagoon), which occupy certain regions, were present over the period 1989 to 1993. It were mainly the first three objects (channel/shallow shoreface, beachplain and foredunes) that shifted. In 1990 a new Object 4 (dune valley) appeared. It had split from Object 3 (foredunes). In 1991 it disappeared again by merging into Object 3. In 1992 Object 5 (lagoon) appeared (within the spatial extent of Region 3); it had split from Object 1 (beachplain) and it had expanded between 1992 and 1993.
Figure 5. Evolution of the northwestern beachplain (1985-1996). (Elevation values in m. + NAP.)
Figure 6. Change maps of the northwestern beachplain. (Values in m.)
Figure 7. Bar movements along a transect.

Figure 8. Volume changes of the beachplain relative to -10 m NAP level.
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**Figure 9.** Identified objects and their processes (after Cheng & Molenaar, 1997).
3.2 Prediction of the changes

**Prediction with PCRaster**

- The runs with the preliminary model showed that short term prediction of morphology within one of the phases was possible (Fig. 10). When the example of a model for short-term prediction (Annex 1) was run with the data of 1993 as input, then the actual situation in 1994 agreed with the modelling result of 3 timesteps; 1995 agreed with 5 timesteps. Based on this trend, the morphology in 1996 could be predicted by taking 6 or 7 timesteps. In reality, 5 timesteps would, again, have given the best approximation. Errors occurred in the prediction of 1996, because of the compaction effect (in 1996 the compacting phase had already started). Furthermore, over this period the effect of a small southern displacement, in addition to the prominent western displacement, became apparent.

Several approaches for long-term prediction were tested (e.g. by Van der Linden, 1997). Models that simulate changes in sediment budget by changes in the vertical direction only; horizontal movements are not incorporated in the models. However, no overall pattern of loss or gain of sediment was found in parts of the area; the measured elevations in one area changed, for example, from a high sediment loss in one year to a large gain in the next year, followed by a small loss in the following year. Therefore, a model that uses the average annual change in the area was thought to be best. This is produced by calculating the differences between the real elevation maps from 1985 to 1996. The 'change maps' are then averaged. The 'average change map' shows the mean annual changes in the area. With this map, the elevation for each year is calculated by adding the average change map (several times) to the elevation map of, for example, 1985. This gave unrealistic results, especially when maps for years after 1989 were used as the input map.

Finally, a model that included the overall flow pattern of the currents was made. In the northeastern part of the study area, an east-southeasterly current was flowing alongshore (Fig. 2). In the southwestern part, a southerly or southwesterly current was present resulting from the flood stream in the tidal inlet. Hence a diverging flow pattern appeared in the northeast. The sediment from this area will, therefore, also diverge. In the flow-patterns model, a number of problems arose.

- First, in the area of diverging flow patterns, a large area with 'missing values' (i.e. a total depletion of sediment) developed.
- Secondly, as a result of sediment replacement, the flow patterns changed from year to year. The PCRaster modelling module cannot automatically adjust the flow pattern if it is not based upon flow as a result of elevation differences.
- Finally, the morphology and the processes changed over the years. For example, in 1985 the spit on the northern corner moved to the NNE. Since 1989, this spit has been bending to the east and moving parallel to the coast. These changes and the change in processes could not be included in the model. Thus, a model made in PCRaster that includes flow patterns could not be used for long-term prediction of elevation in this area.
Figure 10. Result from the preliminary model: (a) actual situation in 1995, (b) predicted situation in 1995 and (c) the predicted situation in 1996. (Values in m + NAP.)

Therefore, although it is possible to extrapolate a trend, long-term prediction is arduous, because it is not known when the inflexion point in the trend occurs. A particular problem in using PCRaster to model horizontal movements of sediment is the creation of 'missing values'. This was also a problem when flow patterns were used. The alternative, i.e. exclusion of the horizontal component, by modelling budget changes in vertical direction only, also did not work.

Possibilities for automated prediction with IEMGA

The description of the processes (Fig. 9) has been evaluated according to its usefulness for prediction. Shifting was registered for the channel/shallow shoreface, beachplain and the foredunes. This is in contradiction with the previous approach (prediction with PCRaster), in which the latter object was taken as relatively stable (for the prediction). In IEMGA, relatively small changes in region are recorded as shifting. Between 1989 to 1993, two objects split off. The dune valley (Object 4) split off in 1990 and merged into the foredunes again the year after. In reality the valley is relatively stable; it has not become much deeper; a measurement or interpolation error will have caused a slight change in height. Although they are included in the database, processes for this object should not be used for prediction.

The second object that split off was the lagoon. The splitting off and expanding of the lagoon was registered and can be used for prediction. Actually, a continuation in the trend of expansion occurred and coastal managers are waiting for this unit to merge into Object 1 (the beachplain) again.

4 DISCUSSION AND CONCLUSIONS

Recently, Ameland's northwestern beachplain has changed drastically. Literature study revealed that the behaviour of this beachplain is related to the migration of shoals and channels in the ebb-tidal delta, and that it is associated with the behaviour of this delta. This section indicates how the results of the present study are linked to this larger framework.
4.1 Description and prediction of the beachplain

This chapter shows that three phases of development of the beachplain, each with its own behaviour, can be identified.

- The behaviour of Phase 1, Redistributing, 1985-1989, can be explained by looking further back in history. A marginal flood channel ('kortsluitgeul'), which was formed on the swash platform, close to the island, has been closing since 1977. In 1980, sand was extracted from the channel. The influence of this pit on the patterns on the beachplain can be seen until 1989. On the undulating terrain, higher and lower areas exchanged sediment over a northwest-oriented swash platform that is connected to Bornrif.

- The sudden change in behaviour in 1989 that resulted in Phase 2, Curving, 1989-1995, can be explained by the behaviour of a shoal on the ebb-tidal delta. In 1989, a large amount of sediment was suddenly added to the beachplain (see Fig. 5). This was caused by the amalgamation of a small marginal shoal with the beachplain (Noordstra & Van den Boogaart, pers. comm.; Israël, pers. comm.). In following years the swashbar rotated clockwise until, in 1990, it was aligned with the beach. From then on the swashbar has been expanding eastwards and it is approaching the beach. Where the sediment necessary for this expansion came from will be explained in the following sub-section ‘The swashbar and the lagoon’.

- The behaviour of Phase 3, Compacting (compressing), 1995-1996 can be explained by coastal protection measures. The western part of the beachplain was eroded because the tidal inlet and the main flood channel shifted eastwards (see Fig. 3). The tidal inlet cannot erode this part of beachplain much further, because this area is stabilized with groynes.

This chapter demonstrates that it is possible to predict coastal development within a certain phase. Longer term prediction, covering several phases, is more difficult because of the non-linearity of the processes. Around tidal inlets, sediment bypassing and shoal migration commonly lead to periodical inputs of sediment into the coastal system and —logically— to a seaward displacement of the coastline (Figs. 11a & 11b). In this study, the influence of the addition of sediment by amalgamation of a small marginal shoal can be seen on the elevation maps of 1989 and later.

External factors can cause a change in these long-term trends, so their influence also has to be assessed when these trends are used for long-term prediction (decadal). Factors which have been considered in the Ameland case are: sea-level rise, coastal management, subsidence as a result of gas extraction, and silting up of the Wadden Sea by sedimentation (Klomp, 1997). Perhaps, the geometry of the ebb-tidal delta changed, e.g. as a result of eastwards displacement of the eastern tidal divide (Elorche, 1983).

In addition to this geomorphological interpretation, an automated approach of tracking processes was studied. The IEMGA database registered not only coastal change, but also processes that were not considered important for the coastal development, e.g. the splitting off of the dune valley. The automated object-oriented registration of processes (changes) also offers possibilities for prediction.
The swashbar and the lagoon

Erosion of the western part of the research area and eastwards extension of the swashbar have been observed in this study. So far, the discussion has mainly focused on erosion of the western part of the beachplain; the specific behaviour of the swashbar has not yet been described. In this subsection the behaviour of the swashbar is discussed in a broader perspective.
In the Introduction to this chapter, it was reported that a flood channel (flood platform) approached the research area in 1990. This caused the eroded sediment to be washed into the Wadden Sea, where it accumulates on shoals and tidal flats. In addition, the Introduction reported that longshore transport is relatively small in this region. Nevertheless there has been an expansion of the swashbar. Noordstra and Van den Boogaart (pers. comm.) interpolated 'vaklodingen', i.e. soundings covering the entire ebb-tidal delta, inlet and most of the backbarrier area, to create elevation maps for the KUST*2000 project. The maps for 1993 show the expansion of a large supra-tidal shoal that is located halfway between Terschelling and Ameland (see Fig. 1). It was almost connected with Korfmansbult in 1993 (a -5 m limit was used to delineate the shoal). The supra-tidal shoal became part of the drainage divide. Therefore, the inlet was actually divided into two smaller systems. These inlet systems comprised Boschgat, connected to Westgat in the west; and the larger Borndiep, connected to Akkepollegat and the flood channel in the east. Thus, ebb-transport also occurred through this formerly flood-dominated channel. The ebb transport in a seawards direction makes sediment available for longshore transport and sedimentation along the swashbar. This is in accordance with Steijn's (1991) theoretical considerations of the influence of tide and waves in the transport of sand on tide dominated delta's.

In the mean time, coastal managers are waiting for the swashbar to migrate landward by reduction of the arch of the swashbar, and for the lagoon to close. Ameland has not experienced a period with many severe storm surges since 1992. This could be a reason for the regularity in the development of the swashbar.

In 1997, the swashbar became connected to the beach. A -1.2 m (MLW) limit was used as lower boundary to delineate the beach. The attachment point migrated westwards between 1996 and 1997. At present, the situation is relatively stable. Nevertheless, the sea is still filling the lagoon through a small channel during flood tide, and the lagoon is drained through another small channel at ebb tide. These channels, which are located at the attachment point, close to the foredunes, still erode the beach. The lagoon functions as a (temporary) retention reservoir. Larger developments, however, seem to favour stabilisation. From 1996 onwards, Borndiep seems to have chosen a western outflow. The shoals of the delta are migrating westerly. Extra sediment will flow in the direction of the attachment point. Therefore, in the long-run the lagoon might silt up. This will cause the channels to close as well. In the end, the vast beachplain will migrate westwards. The resulting accretion will be preceded by some erosion as a result of the wave shadow of the ebb-tidal delta (Hoekstra et al., 1996).

When looking at Ameland in its spatial context as one of the Wadden islands, it appears that a similar beachplain with a differently oriented swashbar occurs on Schiermonnikoog (Biegel & Hoekstra, 1995). That similar features occur, can be expected because of a similar hydrological regime and coastal setting (large-scale morphological system). The difference in direction of the swashbar might be explained by the difference in tidal dominance of the channel bordering the swashbar and by the direction of longshore drift. The swashbar on Schiermonnikoog is influenced by a southerly-directed flood-dominated channel and by a southwesterly-directed longshore drift (Biegel & Hoekstra, 1995). The swashbar on Ameland is influenced by northwesterly directed ebb channel; the longshore drift is relatively weak.
This implies that a differently-oriented swashbar could cause Ameland's beachplain to expand (again) in another direction in future.

4.2 Recommendations for further research

Data
This discussion illustrates that a large amount of data is needed to explain coastal dynamic features related to ebb-tidal delta behaviour. Remote sensing is an ideal tool for the study of these large systems, because of the large coverage it offers. In addition to this areal information, information on height is needed. JARKUS data have a limited spatial range, and the 'vaklodingen' (soundings) have large temporal and spatial sampling distances between them. In some cases height can be extracted from remote sensing imagery. Hesselmans (1997) used the Bathymetry Assessment System (BAS) to extract height from ERS SAR imagery. More research on this particular application of remote sensing data is still necessary. (See Chapter 2, for more information on the use of remote sensing data).

Description and prediction
Allersma (1993) indicated that there is a need for formalisation, to be able to recognise characteristic parameters of the movement of morphological units. As a first step, some possible boundaries have been indicated in this chapter. Furthermore, it has been shown that temporal changes (processes) can be tracked with a prototype GIS shell (Cheng et al., 1997), and the relevance of the registered changes, and their use for prediction have been evaluated in this thesis. Further research on using an automated approach is recommended, since formalisation is the solution for consistent evaluation of coastal dynamics.

To get to know more about the steering forces causing morphological changes, a combination of a large-scale descriptive and a detailed quantitative process analysis, as proposed by Huijs (1993), seems to be the solution. The description can be used to indicate which process parameters have to be measured and at which locations. In addition, both process-based modelling and behaviour-oriented modelling can give further insights into the complex mechanisms (Ribberink & De Vriend, 1993). An analysis with both types of models, based on the presented descriptions, deserves further attention.

ACKNOWLEDGEMENTS

I gratefully acknowledge Dr. P. Hoekstra of Utrecht University for his scientific advice. During my studies, Bornrif became a KUST*2000 project site, Ir. P. Noordstra, J.M. van den Boogert, Drs. D. Timmer, Dr. D.W. Dunsbergen, and Ir.ing. C.G. Israel of Rijkswaterstaat are thanked for their interest and support. Prof.dr. P.D. Jungerius of the University of Amsterdam, Dr. A. Kroon of Utrecht University and Dr.ir. E.J. Huising of Rijkswaterstaat reviewed this chapter.
REFERENCES


# modlw1c, a coastal elevation simulation model
# by Marieke A. Eleveld
# May 1996

binding
W93=w93.map; # elevation map of 1993
Ldd6=ldd6.map; # local drain direction according to longshore current and main
# wind direction
Mask93=mask93.map; # mask over active part
Elevation=elev; # elevation map input, first w93.map, then result upstream
# operation
Lupst=lupstm; # maps with longshore transported sediment with regards to the
# situation in 1993
# lupst0.003 shows the longshore transported sediment over 3
# timesteps, predicting the situation in 1994.
# lupst0.005 shows the longshore transported sediment over 5
# timesteps, predicting the situation in 1995.
# lupst0.007 possibly predicts the situation in 1996.

Composit=composit; # map with the overlay of the part affected by the longshore
# transport and the stable dune area.

areamap
cclone60.map;

timer
1 7 1;

initial
ldd6.map=ldd(6); # constant sediment transport direction
mask93.map=if(lsc93.map lt 2 then w93.map); # active part
Elevation=w93.map; # initial elevation

dynamic
report Lupst=upstream(Ldd6,Elevation); # assigns the value of the upstream cell
Elevation=timeinput(Lupst); # second and third elevations, for the
# upstream operation
report Composit=cover(Lupst,w93.map); # overlay of the active and the inactive part