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

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CHAPTER 5

SYSTEMS APPROACH ON COASTAL MORPHOLOGY ALLOWS MODELLING

ABSTRACT

Changes in coastal morphology involve many interactions and feedback mechanisms. This study focuses on the morphological changes themselves, to reduce the complexity involved in modelling them. A new strategy, which combines several approaches, has been chosen. Morphodynamics are seen as changes in the spatial and temporal distribution of sediment volumes. Coastal areas are defined as systems with subsystems and their interrelationships, by adopting systems approach. Changes in coastal morphology are modelled on an appropriate time and space scale, by using model concepts which originate from different scales. This strategy is introduced for a geomorphological study. Three meso-scale sand-sharing systems have been defined based on differences in geomorphological appearance and behaviour. The description of these systems is elaborated by a discussion of their system boundaries, scale (cell size) and dynamics. The input of morphometric data, natural driving forces and management practices in a GIS is specified. The topic (meso-scale behaviour) and the possibilities for quantitative description with parameters that describe the input of driving forces were elaborated per system. Trends in the evolution of sand mass (or volumes) were used for prediction of future morphology. The chapter concludes with a summary of the adopted strategy.

Parts of this chapter have previously been presented as:


Coastal management on Ameland requires large investments because of the island's active coastline. Knowledge of the changing coastline, on a time scale of months to years, is still limited. This justifies research into the morphodynamics.

In a process-based definition, morphodynamics is the mutual adjustment of topography and fluid dynamics involving sediment transport (Wright & Thom, 1977). Sediment transport provides the time-dependent coupling mechanism by which this adjustment occurs (Cowell & Thom, 1994).

In this study, morphodynamics, the mutual influencing of forms and processes, can be seen as changes in the spatial and temporal distribution of sediment volumes (Eleveld et al., 1995, see Fig. 1). Important is the intercomponent sediment exchange, i.e. exchange of sediment volumes between the landscape units: nearshore zone (shallow shoreface), beach and foredunes. The main geomorphologic processes involved are erosion, transport and accumulation. They are induced by aerodynamic or hydrodynamic forces.

One of the general objectives of this thesis is to find a method for quantitative morphodynamic description and prediction of the development of Ameland's North Sea coast under the influence of natural processes and human impacts. It focuses on the morphodynamics of the area on time scales from several months to several years (Eleveld et al., 1995). This chapter relates to this objective. It aims, specifically, to outline the approach that was taken to study three complex coastal morphodynamic systems on Ameland. In general, there are two ways of approaching these complex systems: an analytical process-based approach and a more generalistic behaviour-oriented approach.

This study mainly uses a behaviour-oriented approach and a holistic view is taken. In this view, the coastal landscape is formed and changed by the results of various individual physical interactions. Similarly, LaValle (1989) and Wijnberg (1995) chose a behaviour-oriented approach for their study of morphological changes of the coast. Frequently, though, the process-based approach is opted for, and throughout the text references to the process-based approach of the subject are made as well.
2 THEORETICAL BACKGROUND

In the following sections, an overview of theoretical themes is given and for every theme (at the end of each section) reference is made to its contribution to this study.

2.1 Systems approach

The development of the theory of open, dynamic systems by for example, Von Bertalanffy (1950, 1968) was relatively quickly adopted in geomorphological research. By applying a 'systems approach', Chorley & Kennedy (1971) demonstrated that a study area can be seen as a system, with strongly interdependent sub-environments. The systems approach is a useful method that is widely applied in coastal research (Cowell and Thom, 1994). It aims at a way of thinking about coastal phenomena in terms of wholes, including all parts (components or subsystems) and their interrelationships (processes and structures) (Novosad, 1982).

The coast is a complex system characterised by an interaction of interdependent processes and entities acting in a multi-dimensional space (x, y, z) and time domain (Hoekstra, 1995). A dynamic coastal system is based on a framework, integrating and arranging a number of separate units or subsystems that vary in morphological form, pattern and configuration. This study uses the concept of sand-sharing systems that consist of landscape units sharing an amount of sediment. The structure of a system determines the spatial and temporal arrangement of the various subsystems and components. Processes determine the functioning of the system, as they are responsible for the exchange of energy and material; it may cause a change in a (sub)system or between (sub)systems from one state to another (Lakhan & Trenhaile, 1989). In this study, these processes are marine or aeolian sediment transport; they form interrelations between the various landscape units.

Advantages of the systems approach are that it gives a clear order, and that decomposition in subsystems can be an aid to understanding the system as a whole. There are also practical and computational benefits. The development of 'object oriented programming' can be an impulse for modelling morphodynamics, as it supports the simulation of the system with subsystem and interrelations (Cremers et al., 1995).

Systems can be isolated, closed or open, and they can be classified according to several different system types. For instance, beach morphological systems could be functionally classified as open systems, and structurally as process-response systems (Lakhan & Trenhaile, 1989). The attempt to use interpolated coastal profiles (JARKUS data) and remote sensing data, with their possibilities for overview, and their limitations on a temporal scale, influences the choice of systems and system boundaries. In this way it puts a constraint on the phenomena and processes that can be studied and predicted.
Properties of morphodynamic processes

With various examples Lakhan & Trenhaile (1989), Phillips (1992) and Cowell & Thom (1994) argue for the applicability of system theory for coastal morphological systems, but also in other geomorphological texts, indications can be found that system theory is important for the study of morphodynamics.

Carter (1988) used elements of system theory (albeit inadvertedly) in his arguments for the pursuit of the causes of coastal change. Some examples are given below.

- Antecedent conditions can exercise strong control over change.
- Sole reliance upon the indicators of response may understate the overall problem.
- Environmental reaction may be tempered or buffered by external influences.
- Reaction may be incremental, or related to thresholds.

The essential properties of morphodynamic processes comprise (Cowell & Thom, 1994):

- self-regulation (equilibrium tendencies);
- self-forcing (which leads to thresholds, self organisation and regime changes);
- Markovian inheritance (which introduces uncertainty);
- hysteresis (which causes different responses to changes in boundary conditions);
- non-linearity;
- non-stationarity;
- non-homogeneity.

The following principles and assumptions, which are included in or related to system theory (Von Bertalanffy, 1950, 1968; Chorley & Kennedy, 1971; Phillips, 1992), underlie these properties of morphodynamic processes (Wright & Thom, 1977; Lakhan & Trenhaile, 1989; Cowell & Thom, 1994; Phillips, 1992):

- positive, and negative feedback (self-organisation);
- equilibrium (steady-state, homeostasis);
- thresholds (bifurcation);
- hierarchy;
- frequency-response principles (response-time effects, relaxation-time hysteresis);
- magnitude-frequency concept;
- inheritance (Markovian properties, memory, state dependence);
- linearity, and non-linearity (chaos, deterministic complexity).

System theory and the derived systems approach are applied in the present study by defining the research areas under investigation as systems. The study reported here uses the principle of inheritance in coastal morphodynamics: the coastal morphology at a certain time is to a large extent determined by its previous morphology, and, in addition, undergoes continuous adjustments. It conforms to the concept of hierarchy, which implies that different processes are active at different scales. In addition, the data set analyzed and the approach taken in the present study incorporate autonomous behaviour of the system or subsystems; the temporal
differences in the studied elevation maps are an expression of variation in the forcing signal and changes inherent to the system.

2.2 Scale

Coastal environments are among the most dynamic on the earth's surface. Many coastal changes are circulatory in space or periodic in time. In studying coastal processes, variables need to be selected that are both sensitive and reliable enough to indicate change. It is clear that the scale of observations in both space and time is important in this context (Carter, 1988).

- Observations over short time scales (with high frequency) might show that the variable seems inert when change takes significantly longer than the provoking process; reaction and relaxation time are in excess of the time scale of the forcing agent. However, there may be a cumulative effect, especially if the forcing agent itself is undergoing change.
- Measuring at the same time intervals as the period of the process might only indicate slow change, while sampling at random time intervals is likely to introduce far greater variation into the results.
- Observations over long time scales (at low frequency) might show that the change is significant, but muted or hidden by more dynamic high frequency variations.

Given these considerations it becomes clear that the observation of coastal phenomena is not straightforward.

The study of coastal changes over the past five to ten years up to the present forms the basis for prediction of the morphology in the near future. Yearly coastal profile measurements and multitemporal remote sensing data are the main data sources for the research. The prediction of future morphology is also in the order of years, because upscaling in coastal morphodynamics is very difficult. Morphodynamics may be the result of complex, possibly even chaotic, processes and interactions in the coastal zone. Thus, trends on a lower scale may be considered as noise on a higher scale level. On the other hand, large-scale fluctuations sometimes seem to influence the outcome of smaller scale morphodynamic prediction significantly. This is often reflected in changing boundary conditions. Examples are the longshore migration of ‘sand waves’ on the foreshore in relation to cross-shore profile development, or the impact of climate change on the same profile development. For the prediction of morphodynamics on a certain scale one should have knowledge of processes acting on a larger time scale. Fig. 2 shows the theoretical concepts of the different levels of coastal behaviour within coastal geomorphic systems.

A relationship between time scales and spatial scales, and between process scales and scales of coastal behaviour is presumed in coastal morphodynamics. The assumed relation between time scale and spatial scale is positively correlated to the amounts of sediment involved in the coastal change; for a noticeable change in a large stretch of coast more sediment has to be redistributed than for a noticeable change in a small stretch of coast (Wijnberg, 1995). Recently, ample conceptual overviews (or organisational frameworks) of time and space scales associated with behaviour at different scales have been constructed (Stive et al., 1990; De Vriend, 1991a; Larson & Kraus, 1993; Terwindt & Kroon, 1993; Cowell & Thom, 1994).
In one framework, De Vriend (1996) distinguishes three scale classes in behaviour: a (hydrodynamic) process scale, a dynamic scale and a trend scale. Behaviour can be modelled from each of these scales. Furthermore, De Vriend (1996) assumes that a different driving force is responsible for the main change in sediment budget at each scale level in the coastal system. In view of the latter, the primary-scale relationship (De Vriend, 1991a) states that a process (driving force) on a certain scale will be in dynamic interaction with coastal behaviour on a similar scale; the same process will be an extrinsic condition for coastal behaviour on a smaller scale and will be noise for coastal behaviour on a larger scale.

In this study, a certain scale level was immediately chosen. The data set consisted of annual descriptions of morphology, so this was the scale of interest. The data set and the behaviour studied act at the same scale level, which reduces the level of complexity which one has to deal with. This is in contrast to the more common practice of studying coastal processes using different scales. The study of coastal processes using different scales, both spatial and temporal, is the usual approach when hydrodynamics (e.g. turbulence, wave, tides, storm surges, currents) and morphodynamics (e.g. ripple formation, bar formation cross-shore transport, longshore transport) are studied in a non-coupled way, to be subsequently coupled in complex hydro-morphodynamic models (De Vriend, 1991a, 1991b; De Vriend et al., 1993).

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![Figure 2. Large-scale sand transport and climate change fluctuations influence prediction of morphodynamic phenomena at a smaller scale (after Terwindt & Kroon, 1993).](image)
2.3 Morphodynamic models

Models can serve as a framework or method that can help in understanding processes and interactions in our environment. In addition, they can be used to predict what a landscape will look like in the future, with or without (further) human influence. Models are used to express the essential knowledge about or to analyze the dynamic behaviour of systems subject to changes. They are required to:

- improve understanding, since they can be evaluated against alternative models and observed behaviour;
- integrate knowledge across disciplines;
- make quantitative predictions for decision making (Jakeman et al., 1995).

Categories of models

The present generation of mathematical morphodynamic models can be divided into two main categories, depending on the concepts used for describing the actual processes within the systems: process-based models and behaviour-oriented models (De Vriend et al., 1993).

Models that are based on a detailed description of the elementary physics of fluid and sediment particle motion are classified as process-based models. The majority of morphodynamic models use this classical approach. The use of these models requires detailed knowledge of the physics of the many interacting processes (Hoekstra, 1995). Input mainly consists of hydrodynamic or aerodynamic data. Hydrodynamics or aerodynamics cause changes in sediment transport, resulting in a changed morphology. This type of modelling provides much insight into the processes, but in their application for long-term prediction of morphology there are still some problems because of the chaotic (stochastic) character of the morphodynamics of coastal systems, and the increasing inaccuracy with an increase in scale (Fig. 3).

Behaviour-oriented models are becoming popular, because of their ability to predict morphology on a longer term. In these models, the physics of the processes are included at a high level of abstraction; the detailed physics of the hydrodynamic processes are no longer incorporated in the models. The morphological behaviour of large-scale coastal features is represented by relatively simple expressions, combining both process-related information and empirical data sets (Hoekstra, 1995).

This sort of models seem to be more suitable for quantitative prediction of the morphologic changes of Ameland's North Sea coast on a time scale of months or years, and for integration in a spatio-temporal GIS (i.e. a geographical information system with a spatial and a temporal component).
increasing inaccuracy

- water movements (seconds, minutes)
- sediment transport (hours)
- changes in morphology (days, weeks, months, years)

Figure 3. Increasing inaccuracy with increasing time scale of the process modelled and with an increase in the number of loops made (After Kroon, 1994).

Two important types of process-based coastal models are the coastal profile (2DV) models and the coastal area (2DH) models (Hoekstra & Van Rijn, 1995).

- **Coastal profile models** have been developed for simulating the short-term evolution of beach- and surf zone profiles, particularly during and following a coastal event such as a storm.
- **Coastal area models** are usually model systems built from wave field, currents, sediment transport and seabed change models (or modules).


- **Linear and non-linear extrapolation models** extrapolate existing shoreline records in order to predict the position of the future shoreline.
- **Descriptive beach-state models** calculate variation in breaker power which determines the change from one state to another. These models explain and specify important parameters that play a role in establishing an equilibrium. The predictive power of these models is limited.
- **Equilibrium cross-shore profile models** are based on the interaction of constructive forces (initiating a landward movement of sediment particles) and destructive forces (initiating seaward directed transport). They consist of simple power functions to characterize the equilibrium beach profile. Over a time scales of years, there is no real equilibrium.
- **Parametric cross-shore profile evolution models** express the behaviour of a certain process or the passing of a threshold value in the system in a single parameter, which is based on empirical studies. Its relation with specific coastal processes is rather obscure.
- **Empirical cross-shore profile models** schematise the beach and nearshore zone by a number of representative depth contours; the rate of migration of the depth contours is proportional to the deviation of the profile from the equilibrium slope.
• **Shoreline change models** describe the development of the coastline as a function of gradients in longshore transport. The method is based on sediment budget calculations for control volumes.

• **Empirical equilibrium models for the cross-sectional area of tidal inlets** relate tidal transport of water masses to these cross-sectional areas of tidal inlets. The approaches of the *empirical cross-shore profile models* and *shoreline change models* based on sediment budget calculations are particularly interesting for the present study, because they can predict sediment volume exchanges.

### Inventory of existing models

**Dynamic models used by Rijkswaterstaat**

Dynamic models are characterised by a state which depends on both time and place. Cremers *et al.* (1995) mentioned an inventory of the dynamic models used by Rijkswaterstaat (The Ministry of Transport, Public Works and Water Management) the authority in charge of coastal zone management in the Netherlands. Only part of these models describe morphodynamics. Most of the models describe water movements, hydrodynamics (e.g. ZWENDL, WAQUA and TRIWAQ). Sometimes, water quality procedures are linked to them (DUFLOW and DELWAQ).

If morphodynamics are modelled, then this forms a part of the entire model system (built of several sub-models or modules) with an integrated approach to hydrodynamics, (water quality, salt intrusion), sediment transport and morphology. Examples of such systems are SOBEC and SIMONA. Other process-based model systems are UNIBEST and COMOR (TAW, 1995). The only exception, a real morphodynamic model in the list, is DUINAF, which is a predecessor of DUROSTA, a dynamic model that computes dune retreat given *i.a.* a certain water level and wave height. DUINAF and DUROSTA predict recession under extreme conditions. The overview of models by TAW (1995) leads to the same conclusion.

Another model available at Rijkswaterstaat, which was not presented in the overview of Cremers *et al.* (1995), is MOBIC. MOBIC roughly describes the sand balance in the Wadden Sea, and is based on linear trends from soundings.

Finally Cremers *et al.* (1995) mention that 70% of the models used by Rijkswaterstaat is 'physically distributed' and mostly process-based, whereas only 20% of the models is empirical (often more behaviour-oriented models); the status of the other 10% of models is unknown.

Many models with different characteristics are available at Rijkswaterstaat; models containing concepts that are of special importance for the current study are mentioned below.
Sediment budget models

Sediment budget modelling is an obvious choice when studying the spatial and temporal distribution of sediment volumes (see Introduction). An example of a sand budget study based on coastal profiles (JARKUS data) is given by De Ruig & Louisse (1991). The trend in the sand volume of any arbitrarily chosen area can be considered the result of the equation of mass conservation; the volumetric change in an area equals the transport over its boundaries. Quantification of these fluxes is difficult, because of the inaccuracies in sediment transport measurements (Kroon, 1994). A sediment budget analysis as previously indicated or with a multi-line model can be seen as an example of behaviour-oriented research (Van Rijn, 1995), and, as such, marine sediment budget modelling of the nearshore zone and beach has been applied in various studies.

The aeolian component is often neglected in coastal research, and there are hardly any aeolian sand transport models or aeolian sand budget models available. Yet it was this component that formed the Younger Dunes and fed the stuif-dikes, and in so doing built the primary sea defence of Ameland. The aeolian influence will be studied especially in the Eastern system (see Practical Application), therefore some attention is paid to one of these rare models. SAFE, the aeolian sand transport model of Van Dijk et al. (1995) is (partly) a process-based cross-shore profile 2DV model, and runs on a time scale of minutes. The underlying formulas provide the parameters for any aeolian model. The model describes the transport of sand on the beach and over the dunes during onshore winds, and computes the patterns of erosion and deposition. The present input for the model primarily consists of field measurements of local topography and vegetation cover and height. HILL, a supporting model of wind flow patterns, by Van Boxel & Arens (1998), is linked to the SAFE-model. HILL is based on the model of Zeman & Jensen (1987).

The sediment budget modelling approach contains many components which are required for the present study of the spatio-temporal distribution of sediment volumes. The actual use of sediment budget models for this study is limited because of the lack of knowledge on the sediment fluxes that regulate the input and output.

Long-term behaviour models

Many geomorphological and coastal engineering models are based on empirical relations that describe equilibrium situations. Sometimes they are models of long-term development (over tens or hundreds of years), as in the case of equilibria between inlet, backbarrier and ebb-tidal delta (see Chapter 7). This is not the time scale aimed at in the current research, but information on this scale is important for the meso-scale (see Scale).

The modelling of Large Scale Coastal Behaviour (LSCB) has been receiving increased interest lately (List, 1993). Indications of an increasing rate of sea level rise have stimulated this interest. Modelling LSCB aims to integrate empirical (equilibrium or trend) relations with transport processes; it uses a theoretical approach of morphodynamics. Cowell & Thom (1994) indicate that research into the morphodynamics of LSCB entails scaling up from the laws of physics and scaling down from the geological principles of coasts. This pragmatic approach combines laws obtained from deterministic studies with geostatistical relationships.
for coastal geomorphologies and their geological evolution (Terwindt & Battjes, 1990). Despite the difficulties related to up- and downscaling, that have already been mentioned (in Categories of models), some mathematical solutions are being developed. De Vriend et al. (1993) discuss some mathematical aspects of long-term modelling of coastal morphology, and in doing so they focus on two key concepts: reduction (data reduction, input reduction, model reduction) and knowledge integration (of process and empirical knowledge). Both concepts can be elaborated through behaviour-oriented models.

Geological models also simulate long-term development. Basin filling by sedimentation modelling can be performed with SEDSIM (SEDimentary Basin Simulation), which has been coupled to WAVE to simulate effects of wave-induced currents in depositional environments (Harbaugh & Bonham Carter, 1970; Martinez & Harbaugh, 1989, 1993; Harbaugh, 1994). Another example is DELTA2, a 2D response model that simulates the fill of a sedimentary basin from the growth of a prograding delta (Syvitski & Daughney, 1992).

Concepts from long-term modelling are of importance for the present study; long-term modelling also deals with the integration of multi-scale information, and it also looks for trends.

**New models in GIS**

Literature on coastal behaviour and a case study with remote sensing data and a temporal series of elevation maps provide some information on the behaviour of the coastal morphodynamics on Ameland. To predict this behaviour (in its spatial dimensions) requires the use of a model linked to a GIS. The objective of using models in this study is to increase morphological understanding and to make quantitative morphodynamical predictions. The main subject is coastal morphodynamics; the main topic is change in morphology through processes of marine and aeolian erosion, transport and accumulation, expressed as changes in sediment volumes at a specific location (sediment budgets). Model concepts from budget modelling and from long-term modelling have been used for this study; trends in the evolution of sand mass (or volumes) were used for prediction of the future morphology of three coastal systems (see Practical Application and Chapter 6).

Remote sensing provides the data needed to describe the x, y and z component of sand volumes, either directly (laser altimetry) or indirectly (JARKUS data from the DONAR database). The approach taken in quantifying the x, y and z components and the changes in these components depends on the interests and background of the model developers. If they are more interested in the physical explanations of the steering processes on the morphology, then a model based on aerodynamic and hydrodynamic transport formulas results. This requires knowledge on parameters such as wave height, wave period and wind speed and direction. If developers are (just) generally interested in the resulting morphological behaviour, then behaviour-oriented modelling might be a better approach for predicting morphological changes. In this case empirical behaviour is incorporated in the input (elevation maps which are the result of a certain behaviour) and in the equations of the model; a basic explanation of the changes is incorporated in the model in advance, whereas the process-based modelling tries to explain from model results. A behaviour-oriented budget-supported approach was chosen for this study.
Given this choice, the role of GIS in this research becomes clear: the final step will be to integrate the modelling and the GIS. This will help in the prediction and visualisation of coastal zone development for different scenarios (and alternative strategies). GISs seem to offer the capability of modelling complicated problems of complex systems. The spatial coordinates of the GIS provide the necessary spatial dimension, while historical or rate-process information in data layers or separate layers associated with different time periods provide the temporal dimension (Trovimov & Phillips, 1992). In addition, they communicate spatial information effectively, using maps as a well-understood and accepted form of spatial data display, generating a widely accepted and familiar format for sharing information (Fedra, 1993). Conceptual models will be created and simple dynamic models in GIS will be made using the Dynamic Modelling Language (Chapter 6 and Part 3).

3 PRACTICAL APPLICATION

The previous sections indicate that prediction of coastal changes is an important issue in geomorphological research and for coastal management. Change in volumes over time at a certain location, or in a certain system, is a valuable model concept. This is elaborated for three geomorphological systems on Ameland. This chapter illustrates a geomorphological approach to a closer formulation of morphodynamic models for three coastal systems: the Western, Central and Eastern system on Ameland. These models work on the level of landscape units (e.g. nearshore zone, beach and foredunes) and geomorphological forms (e.g. bars, cliff and washovers) and meet the needs of realistic morphological prediction. Eventually, the ideas should also support modelling in GIS.

3.1 Description of the systems

Three systems can be distinguished, based on differences in morphological appearance and behaviour (Fig. 4). The Western system comprises the evolution of a beachplain in relation to migrating channels and shoals of the ebb-tidal delta. The Central system describes the development of a coastal stretch under influence of bar, beach and foredune dynamics. The Eastern system incorporates the dynamics in the washovers and eydunes and their influence on the saltmarsh landscape. The three main systems can be defined as meso-scale systems, with scale levels intermediate to morphologic micro-scale systems, such as coastal cells, and macro-scale systems, such as the Wadden Area system. The description of the three morphodynamic systems is elaborated below by their boundaries, scale, and dynamics; the input used in the modelling of these systems is also mentioned.

- System boundaries
  The morphological appearance and the range of the data are factors in the determination of the systems. Longshore, A change in beach width indicates the boundary between the western beachplain system, and the central coastal stretch. The presence or absence of washovers in the foredune area and the change in beach width demarcate the boundary between the Central system and the Eastern system. Cross-shore, the coastal profiles reach to a certain depth, which is often, but not always, sufficient to describe the active
region entirely. Extra boundaries within the systems delineate subsystems; e.g. the mean low-water level (MLW at -1.2 m) and the dunefoot (2 m) separate the landscape units of nearshore zone (shallow shoreface), beach and foredunes.

- **Scale (cell size)**
  Large cell sizes have been used to describe phenomena with large areal coverage (e.g. the development of the western beachplain), whereas smaller sizes were chosen when more detail was required. Their exact values depend more often than not on coincidence (e.g. the laser data was provided with a 5 m cell size).

- **Dynamics**
  The dynamics in the development of the western beachplain are governed by migrating channels and shoals of the ebb-tidal delta. The development of the central coastal stretch is influenced by migrating bars and eroding beach and foredunes. The development of washovers and foredunes, and their influence on the saltmarsh landscape, is associated with aeolian and marine sediment transport in an area with a large beachplain and low foredunes.

- **Input maps**
  The input consisted either of interpolated coastal profile data or of laser altimetry data. From a process-geomorphological point of view, the elevation maps obtained are the result of the action of a number of factors (activities by different processes), the combination of which is different and changes from one place to another. Sequential pattern analysis of remote sensing data gives additional information on these processes.

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![Figure 4. Systems approach, 'Three sand-sharing systems'.](image)

**Figure 4. Systems approach, 'Three sand-sharing systems'.**

**The Western system (W):** the evolution of a beachplain in relation to migrating channels and shoals of the ebb-tidal delta.

**The Central system (C):** bar, beach and foredune dynamics.

**The Eastern system (E):** the dynamics in washovers and eydunes and their influence on the saltmarsh landscape.

The Western system comprises the evolution of a beachplain in relation to the migrating shoals and channels of the ebb-tidal delta. It is a semi-natural situation because of the stabilisation of inlet migration with hard structures just south of the system.

The remote sensing data did not give detailed information on the channels and shallows in the underwater part of the ebb-tidal delta, but the development of the sub-aerial western beachplain could be seen. In 1995 an eroding channel reached the western part of the sub-aerial beachplain (Eleveld, 1996; Chapter 7).
• The system boundaries enclose an area from the channel to the inner dunes (as far as the coastal profile data reach), and from the eroding western part to the accreting eastern part.
• The scale was fixed at a cell size of 60x60 m.
• The dynamics of the western beachplain are caused by erosion due to the migrating channels and accretion due to the migrating shoals of the ebb-tidal delta. The inlet migration itself is stabilised by hard structures.
• The input consisted of elevation maps constructed from interpolated coastal profile data (JARKUS).

The Central system is a coastal stretch influenced by bar, beach and foredune dynamics. This was originally a long-term eroding coast, but the system is now maintained in a steady state by artificial beach and dune nourishment. The system has breaker-bars in the nearshore zone and a swash-bar on the beach. Longshore, a net sand movement from west to east occurs. Cross-shore activities prevail in an active zone that is delimited by the closure depth (8 m) and the inner dunes. Within this zone, a sediment-volume is shared by the nearshore zone (shallow shoreface), the beach and the foredunes. Changes in the nearshore zone (e.g. the movement of bars), the beach and the foredunes were monitored and used for prediction. On the aerial photographs, video images and SPOT-PAN data, the presence of two or three bars was indicated, and their seaward movement was perceived as well. According to the 1995 data, aeolian activity on the beach was high, but the visible amount of accumulated sand in the foredunes had decreased with respect to 1992 (Chapter 2; Eleveld, 1996). An overall shortage of sand in the system has occurred several times in the past. To counteract this, extra sand was supplied by nourishments.
• The system boundaries from north to south (cross-shore) enclose an area from -8 m to the inner dunes. From west to east (long-shore) there are several coastal cells.
• The scale was fixed at a raster cell size of 20x20 m.
• The dynamics comprise the differential outwards moving trends of coastal bars. Erosion causes cliff retreat, accompanied by mass-movements and subsequent deposition on the beach. The sediment budget was replenished by beach and dune nourishments.
• The input consisted of elevation maps constructed from interpolated coastal profile data.

The Eastern system comprises the dynamics in the washovers and eydunes and their influence on the saltmarsh landscape. The bulk of the sediment deposited on the salt marshes is no longer involved in cross-shore changes. This is a natural lateral accreting system; the large beachplain and the low foredunes in the east allow the aeolian and marine sand transport to have a great influence on the sand balance.
• The developments were monitored with several aerial remote sensing techniques, which were used also for the prediction (Eleveld, 1996). In this system the main focus is on the sub-aerial part of the coast. The northern and southern system boundaries are located on the beach and in the saltmarsh area (or Wadden Sea). From east to west various washovers occur.
• The scale of 5x5 m was a minimum for accurate description of the complex morphology.
• The dynamics accompanied by the main volume change is caused by transport from the beach and foredunes to the saltmarshes (deposition in three different forms).
The input of laser altimetry provided accurate digital elevation data for the sub-aerial part of the coast. Morphological parameters can be derived from these data. The formation and stabilisation of washovers can be extracted from multitemporal airborne videography and scanned aerial photographs. Based on all this information, dynamic modelling in a GIS has been applied (Chapter 9), which aims to predict the development of the washovers and the amount of sediment that will be deposited on the saltmarsh.

3.2 Modelling morphodynamics

Fig. 5 shows the approach used for modelling morphodynamics. Trends in volume changes were based on a temporal sequence of elevation data. Extrapolation of these trends resulted in prediction (Chapters 7 and 8).

In some cases coastal systems are influenced by management practices (Fig. 5). The Dutch coastal management policy is one of 'dynamic preservation of the coastline of 1990'. For Ameland this means in practice that sand is added to the system by nourishments at erosive parts where the safety of the inhabitants and other (economic) interests are threatened. In the eastern part, which is designated to nature, allowance is made for natural dynamics. The influence of nourishments is elaborated in Chapter 8. Nourishment design parameters were translated into maps, which have been used to evaluate different scenarios in coastal development.

In addition, the input of driving forces in morphological prediction has been assessed (Fig. 5); e.g. in Chapter 8 coastal development is linked to stormflood sequences.

Parameterization is the attempt to describe and predict coastal behaviour with certain parameters. So far elevation, \( z(x,y,t) \), has been the main parameter. With the input of driving forces through the input of process knowledge, other parameters have been included (Chapter 8). The parameters correlate variables of the steering forces and net morphological responses (Terwindt & Kroon, 1993).

Table 1 lists the topics (behaviour) and their possible parameterization or empirical behaviour are listed. (Parameterization and empirical behaviour are presented in italics). The main interest in this study was in meso-scale behaviour. Very little is known on this scale: parameterization on this time scale is still scarcely available, and empirical knowledge on this scale is also limited. Sometimes information from other time scales can be used. Table 1 shows that parameterization is possible on a micro-scale (or small-scale). On a macro-scale or (large-scale) empirical knowledge is available in the form of equilibrium relations.

The implications of the table for the present study have been elaborated in Part 3, Chapters 7, 8 and 9.
Figure 5. Modelling coastal behaviour in a spatio-temporal GIS environment.
Table 1. Description of coastal behaviour with parameters: input of driving forces.

<table>
<thead>
<tr>
<th>MICRO-SCALE</th>
<th>MESO-SCALE</th>
<th>MACRO-SCALE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>boundary conditions</strong></td>
<td>scale of interest</td>
<td><strong>boundary conditions</strong></td>
</tr>
<tr>
<td><strong>days-weeks</strong></td>
<td>months-years</td>
<td>decades</td>
</tr>
<tr>
<td>WESTERN SYSTEM</td>
<td>interaction water flow - hydraulic sediment transport - morphology</td>
<td>development of the western beach plain</td>
</tr>
<tr>
<td></td>
<td>1) secondary flow in the channels (related to, e.g., the centrifugal force and Coriolis force) (Alersma, 1993; Huijs, 1993)</td>
<td>1) channel migration</td>
</tr>
<tr>
<td></td>
<td>2) water flow over shoals, e.g., rest currents, tidal currents (hydraulic gradient) and drift currents (Alersma, 1993; Huijs, 1993)</td>
<td>2) shoal migration</td>
</tr>
<tr>
<td>CENTRAL SYSTEM</td>
<td>interaction water flow - hydraulic sediment transport - morphology</td>
<td>development of a coastal stretch</td>
</tr>
<tr>
<td></td>
<td>1) hydrodynamics near the outer nearshore bar (Kroon, 1994), the ratio between bar-degenerating asymmetric waves and bar-maintaining breaking waves (Winberg, 1995)</td>
<td>1) bar migration</td>
</tr>
<tr>
<td></td>
<td>2) storm erosion of the beach and foredunes related to, e.g., water level and wave height, period and type (Steetzel, 1993)</td>
<td>storm parameter (Kroon, 1994)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>stormflood parameter (Eleved, this thesis)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2) beach and foredune erosion</td>
</tr>
<tr>
<td>EASTERN SYSTEM</td>
<td>interaction wind flow - aeolian sediment transport - morphology and vegetation, and interaction water flow - hydraulic sediment transport - morphology</td>
<td>development of a washover / eydune landscape</td>
</tr>
<tr>
<td></td>
<td>1) aeolian sand transport related to, e.g., friction velocity, slope and roughness (Van Dijk et al., 1995)</td>
<td>1) dune development</td>
</tr>
<tr>
<td></td>
<td>2) storm erosion of the foredunes related to, e.g., water level and wave height, period and type (Steetzel, 1993)</td>
<td>2) dune development and deepening of the washover throat</td>
</tr>
</tbody>
</table>
4 CONCLUDING REMARKS

A new approach has been developed for the study of three sand-sharing systems. Recent theoretical developments were found to support this approach. A summary of the adopted strategy, which is applied in Part 3, is given below:

- Formulate topic;
- Define the system;
- Choose right scale level;
- Formalize existing knowledge of interactions in equations;
- If necessary, shift a scale level and try to use that knowledge;
- Apply the equations to modelling in GIS (Chapter 6);
- Predict morphodynamics (Part 3).

In this research, behaviour-oriented modelling using trends in sediment budgets was opted for. Nowadays, the behaviour-oriented approach is being used in research on large-scale coastal behaviour (Wijnberg, 1995). In meso-scale studies, which are on a scale of direct relevance to present day management, process-oriented research is usually opted for to solve any morphological management problems. Studies concerned with these kind of problems would benefit from the additional use of the behaviour-oriented approach. Similarly, sediment budget modelling can be applied. Although a sediment budget approach is accepted in large-scale coastal research (Cowell et al., 1993), it is hardly being used in meso-scale studies. This thesis presents some possibilities of a budget approach for meso-scale modelling of coastal morphology, and aims at increasing knowledge of morphodynamics on Ameland.

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REFERENCES


