Chapter 1

Introduction

Some undulations of the sandy bottom in many coastal seas have a rhythmic pattern. Ripples are the smallest among these bedforms (spacings of a few centimeters) and can be found both close to the shoreline as well as in deeper water (Allen, 1984; Sleath, 1984). Megaripples and sand waves (Huntley *et al.*, 1993) with length scales from ten to some hundreds of meters are often present on the inner and outer shelf. Close to the shore, surf zone sand bars are observed which have characteristics similar to those of megaripples and sand waves. Larger features are the undulations of the shoreline known as beach cusps (Kuenen, 1948; Komar, 1998), the bars in the nearshore zone (Homma & Sonu, 1963; Holman & Bowen, 1982) and the channel-shoal patterns in tidal basins (Ehlers, 1988). Their length scales vary between a few metres up to 500 m, see e.g. Komar (1998), and, as shown in table 1.1, the order of magnitude of these scales varies widely, sometimes even if only one specific type of bedform is considered.

On the outer shelf even larger bedforms occur (see e.g. figure 1.1), called tidal sand banks(Off, 1963; Stride, 1982), with wave-lengths of the order of 10 km. In this thesis the emphasis will be on shoreface–connected sand ridges (Swift *et al.*, 1978; Van de Meene, 1994), rhythmic bottom features which are observed offshore (in water depths between 5 and 30 m) and which have alongshore spacings typically between 5-10 km. Their horizontal length scales and shape are comparable to those of tidal sand banks but they are affected in some way by the presence of the coast.

1.1 Shoreface–connected sand ridges

Shoreface-connected ridges are elongated sand banks found in the inner part of some continental shelves. Early observations of shoreface-connected ridges were made on the East American continental shelf by Duane *et al.* (1972) and Swift *et al.* (1972). Later on they extended their work to other inner shelves (Swift *et al.*, 1978). The ridges are also found along the Brazilian shelf (Figuieredo *et al.*, 1982), the Argentinian shelf (Parker *et al.*, 1982), the Canadian shelf (Hoogendoorn & Dalrymple, 1986), the Central Dutch coast (Van de Meene, 1994; Van de Meene *et al.*, 1996) and along the German coast (Antia, 1996*a*,*b*). Examples of this features are shown in figures 1.1, 1.2 and 1.3.

With regard to the origin of sand ridges different hypotheses have been formulated in the past. It has sometimes been suggested that they are geological relicts, see e.g. the discussion in McBride & Moslow (1991). Although this may be true for some ridges, there is geological evidence that the US- and Dutch shoreface–connected ridges are not relict features, that is, they are active under the present hydrodynamic conditions and their growth has taken place during the Holocene, see Swift *et al.* (1985), Van de Meene (1994) and Van de Meene *et al.* (1996). For instance, on the Dutch inner shelf they started to form about 3400 years ago. This suggests that the behaviour of the ridges is determined by the interactions between the water motion, the transport of sediment and the erodible bed. Previous studies have demonstrated that especially storm-driven currents are important for the evolution of shoreface-connected ridges (Swift *et al.*, 1978; Niedoroda *et al.*, 1984) and tidal currents are essential to generate tidal sandbanks (Zimmerman, 1981; Pattiaratchi & Collins, 1987).

From the field studies mentioned above it appears that the alongshore spacing between suc-

bedform	**spacing**	**height**	**speed**	**period**
ripples	(0.1-1)m	(0.01-0.1)m	-	hours
beach cusps	(1-100)m	(0.1-1)m	-	hours-days
nearshore bars	(50-500)m	(1-5 m	(0-100)m/yr	days-weeks
shoreface-conn. sand ridges	(5-10)km	(1-5)m	(1-10)m/yr	centuries
sandwaves	(300-700) m	(1-5)m	(1-10)m/yr	decades
tidal sand banks	(5-10)km	(5-15)m	-	centuries

Table 1.1: Characteristic wave-lengths, heights, migration speeds and evolution timescales of rhythmic bedforms in coastal seas (from Dodd *et al.*, 1999).

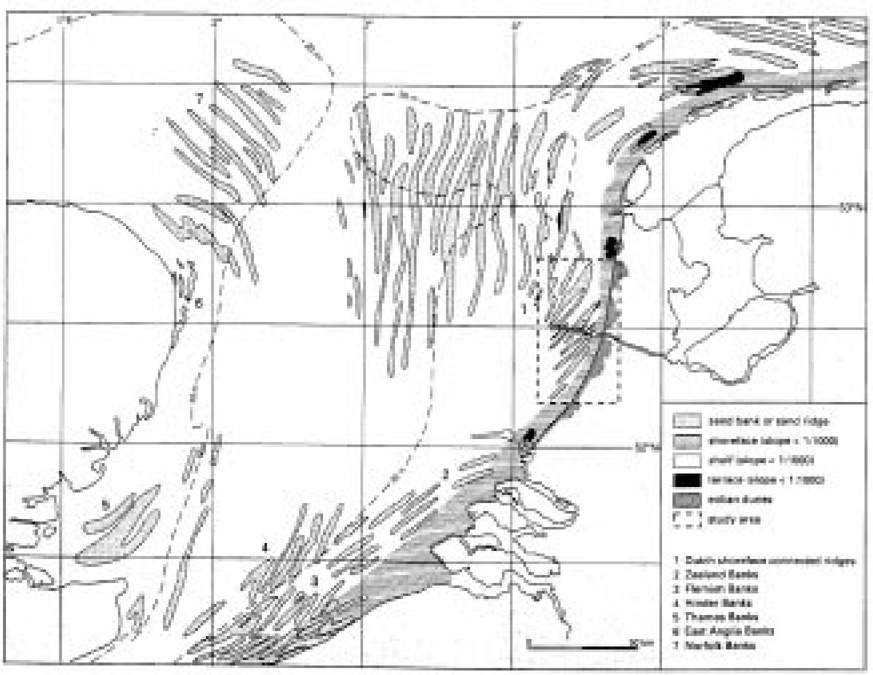

Figure 1.1: Sand banks and sand ridges in the Southern Bight of the North Sea (from Van de Meene, 1994).

cessive crests of shoreface-connected ridges ranges between 5 and 10 km. The length of individual crests is between 10 and 25 km and their height is between 1 and 5 m. They are found in the first tens of kilometers from the coast, in water depths between 5 and 30 m. They start at the offshore end of the shoreface and they extend seaward forming an angle of $20^o - 35^o$ with respect to the coastline. In these ridge areas significant net longshore currents are present (typically of order $0.5\,\mathrm{m\,s^{-1}}$) which are driven by winds, tides and density and longshore pressure gradients.

A striking property is that orientation of the crests of the ridges are related to the net current and the general rule appears to be that they rotated against this net current. In other words the seaward ends of the crests are shifted upstream with respect to their shoreface attachment. Hereafter we will refer to this as *upcurrent rotated* bars. The opposite orientation will be defined as *downcurrent rotated*. Furthermore the ridges appear to migrate downstream with typical velocities of $1 - 10\ \mathrm{m\,yr^{-1}}$, depending on local conditions. Furthermore, the seaward flanks of the ridges are often steeper than the landward sides and often dislocations are present. The latter statement means that the bottom pattern consists of local irregularities or discontinuities: in particular the splitting of crest-lines is a well-known phenomenon.

In the ridge area the sediment consists of coarse to medium-grained sand (typical size of order 1 mm), but there are also clear spatial differences in size distribution: the finer material is observed

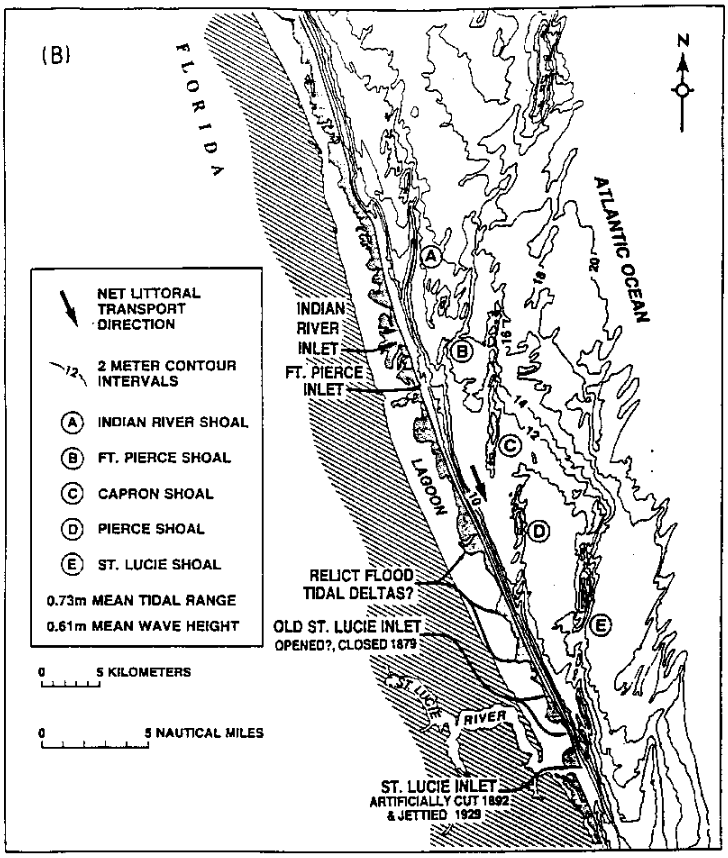

Figure 1.2: Sand ridges attached to the shoreface along the south–central Florida shoreline (from McBride & Moslow, 1991).

on the seaward sides and on the crests whereas the coarser material is found either in the troughs or on the landward flanks (Swift *et al.*, 1978; Antia, 1996*b*). It has been demonstrated by Niedoroda *et al.* (1984) and Van der Giessen *et al.* (1990) that the water motion on the inner shelf has a pronounced 3D structure. During storms offshore flow occurs near the bottom due to wind-driven Ekman circulation, whereas there is a weak onshore flow during mild weather conditions. Also the tidal flow has a vertical structure. In for instance the Dutch coastal zone there is also a significant effect of density driven circulation which causes onshore transport near the bottom (Van der Giessen *et al.*, 1990). As a consequence coarse material is transported towards the coast whereas fine sediments are transported offshore.

In principle there is a formidable problem: currents in coastal seas have a very complex spatial and temporal structure, they are driven by wind, waves, tides, pressure and density differences; bedforms are in a board range of temporal and spatial scales and they have strong nonlinear interactions, also with the flow; and, furthermore, the morphodynamic system is forced by processes, some of them are quite regular, e.g. the tides, but some other ones shows a chaotic behaviour, e.g. the weather fluctuations.

In this thesis the leading conditions for the generation of the shoreface-connected sand ridges and its long term behavior are looked into. The focus is in understanding the physical mechanisms that produce the formation of these features and their subsequent dynamics. This will be accomplished by means of theoretical models that are able of reproducing their long-scale characteristics –spacing, shape, amplitude, migration speed, growth time and conditions of ocurrence.

From various points of view it is important to obtain a better understanding of the dynamics underlying the formation and maintenance of these features. At present a major research theme is to study the effects of human interferences and sea level rise on the stability of the coastal system.

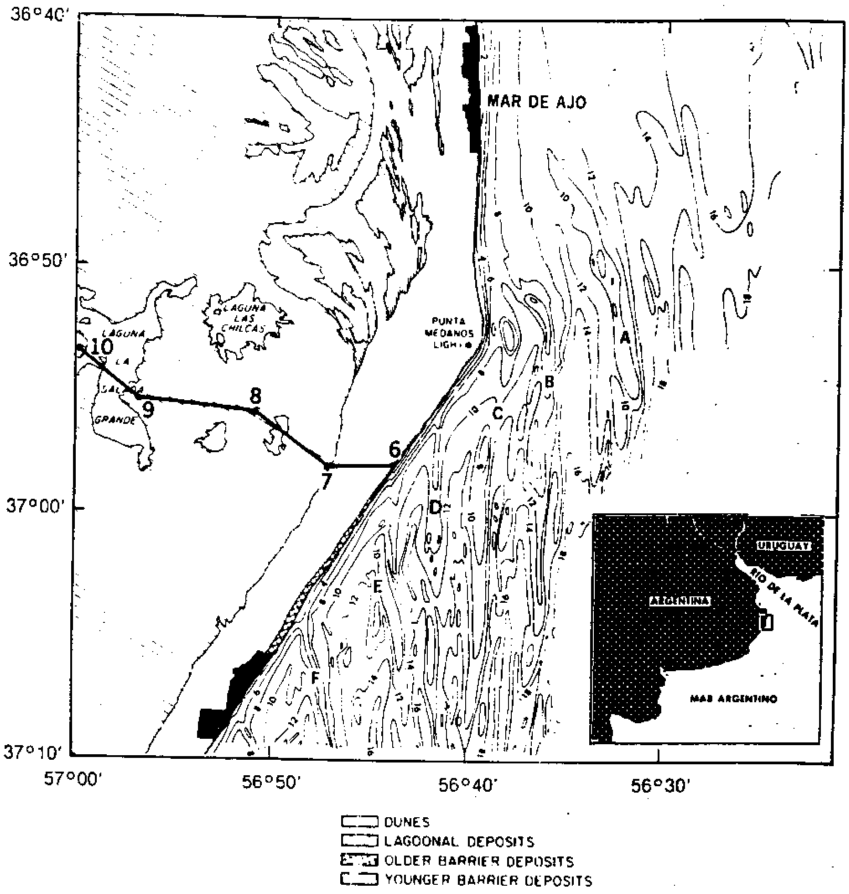

Figure 1.3: Morphologic map of the Argentinian inner shelf (from Parker *et al.*, 1982).

In general, sand banks are important, since they may form shallow areas which are hazardous for shipping traffic, they also may affect the management of shipping channels and navigation areas. Furthermore, they are important to the offshore industry, as their presence may increase the risk of buckling of pipe-lines and oilrigs or the instability of offshore constructions, due to lateral movements. They are also important as potential sources for sand mining. From a geological perspective, sand banks are of interest since they are potential oil reservoirs due to their high preservation potential and good textural characteristics.

The shoreface-connected ridges, which form the seaward boundary of the nearshore zone, play a relevant role in this coastal system (Van de Meene, 1994). Practical motivations to study these ridges are that they appear to be relevant for the stabilization of the coastline, due to wave energy dissipation over the ridges during storms. Although all the previous motivations for study the shoreface-connected ridges, these patterns do not have importance only in themselves; their investigation is a way of gaining insight into the fundamental physics of the system. Indeed, their rhythmicity seems to be the visible imprint of some physical mechanism that may dominate the coupling between water motions and bottom changes under certain circumstances.

1.2 Geographical differences: influence of tides

Shoreface-connected sand ridges are observed in both tidal and non-tidal environment. In the first case also other large-scale bedforms occur on outer shelf: tidal sandbanks. The tidal sandbanks have similar dimensions and timescales as the shoreface-connected ridges, but the former only occur when tidal currents are stronger than approximately 0.5 $\mathrm{m\,s^{-1}}$. Tidal sand banks are observed for example on the midshelf of the North Sea (Off, 1963; Stride, 1982; Pattiaratchi & Collins, 1987, and references herein), but not on the US-shelf, because the latter area is characterized by micro-tidal conditions. Two essential differences with the shoreface-connected ridges are that the crests of tidal sandbanks are always cyclonically rotated (anticlockwise on the Northern Hemisphere) with respect to the dominant tidal current direction and that these ridges do not migrate.

The previous description already indicates that tidal conditions may strongly influence the characteristics of sand ridges on the shelf. Indeed, apart from many similarities, there are also striking differences between different shoreface-connected sand ridge systems, specially between those on the American shelf and those observed in the North Sea, associate with the tides. Near the US coast, where tidal effects are small (they cause no reversal of the flow direction during storms), only shoreface-connected ridges are present, which move rather slow (less than 1 $\mathrm{m\,yr^{-1}}$) and which are observed in water depths as shallow as $2-5$ m. Furthermore, a consistent fining of sediment is observed when moving in the direction of the net current (i.e., to the Southwest).

In contrast, the ridges in the North Sea occur in regions where tidal conditions are rather strong: typical flow amplitudes are 0.6 $\mathrm{m\,s^{-1}}$ at 1 m from the bottom. Here the tidal signal merely consists of the semi-diurnal $\mathrm{M_2}$-component, as well as a strong $\mathrm{M_4}$ overtide, which causes flood currents to be larger than the ebb currents. The shoreface-connected ridges in the North Sea appear to have slightly smaller spacings than their US counter parts, they have larger migration velocities and they occur in much deeper water (depths of at least 8 m). Moreover, a coarsening of sediment in the downstream direction, i.e. towards the Northwest,(Antia, 1996*b*) is observed.

Furthermore, towards the midshelf these ridges are connected to a field of tidal sandbanks. As an example figure 1.1 shows the location of shoreface-connected ridges along the central part of the Dutch coast. Note that the tidal sandbanks and the shoreface-connected ridges have different orientations with respect to the coastline.

The North American ridges and some of the Argentinian ridges are asymmetric, with the seaward side steeper than their landward side. In the area where the ridges appear often smaller-scale bedforms are simultaneously observed, such as ripples and megaripples. The crests of the latter features are perpendicular to the principal current. Sand waves are rare and are only present in the southern part of the Dutch area. Smaller ridges appear in the troughs between the Argentinian ridges.

1.3 Stability analysis

Recently some first steps have been made in trying to to find out which physical mechanisms are responsible for the initial formation of the ridges. This has been done by the development and analysis of idealized models which only describe a limited number of processes, to identify which physical mechanisms are responsible for the generation of bedforms. The advantage of such models is that a specific phenomenon is studied in isolation and that they can be analyzed using mathematical methods. The principal disadvantage is that in nature this reduced number of processes analysed are in competition with many other processes which are not taken into account. The modelization of all processes together should be done by means of a complex models. Results of idealized models must be evaluated by complex models and semi-empirical models.

Many bottom patterns have been successfully explained as inherent free instabilities of the coupled water-bottom system under the action of some current. In such stability models given a small disturbance of a reference topography the response of the flow to this perturbation can result in a sediment transport pattern which reinforces the bottom undulation. Then a positive feedback is induced and both disturbances, in the topography and in the flow, will grow exponentially in time. There is no direct relation between the spatial scales of the dominant forced water motions and that of the resulting morphological patterns, and the feedback from the bottom to the water motion is the essential mechanism. The hypothesis that the observed bedform is a result of an inherent instability mechanism has been aplied to sea ripples (Blondeaux, 1990; Vittori & Blondeaux, 1990, 1992), beach cusps (Werner & Fink, 1993), nearshore obliqe and transverse bars (Falqués *et al.*, 1996), bars in rivers (Schielen *et al.*, 1993), channel-shoal formation in tidal embayments (Schuttelaars & De Swart, 1999), crescentic bars (Vittori *et al.*, 1999) or tidal sandbanks and sandwaves (Hulscher *et al.*, 1993).

These studies consist of a stability analysis of a simple equilibrium solution of the equations of motion (often a flat bed or an alongshore uniform beach profile) with respect to small periodic

Parameters Provided by a Linear Stability Analysis	Description of Parameter
Instability (/stability)	Indicates whether (or not) the basic state is adequated, the model catches the essential physics and the feature arises from a free instability (of small amplitude)
Wavelength	Gives the predicted spacing between the features
Growth Rate	Gives a spin-up time for the growth of the features
Spatial structure of normal modes	Gives the shape and the orientation of the bedform with respect to the periodic direction

Table 1.2: The information obtainable from a linear stability analysis (from Dodd *et al.*, 1999).

Parameters Provided by a Nonlinear Stability Analysis	Description of Parameter
Amplitude	The heigth of the bedforms
Actual spatial structure	The shape and spacing of the bedforms to be compared with the features in Nature
Actual flow	flow characteristics to be compared with velocity measurements
Type of Instability	Indicates the qualitative type of the bed form regime, which may constitute a series of bifurcations
Long-term evolution	The sometimes complex evolution of the bed form beyond linear theory.

Table 1.3: The information obtainable from a nonlinear stability analysis (from Dodd *et al.*, 1999).

bottom perturbations with arbitrary spatial scales. Initially, such perturbations will decay or grow exponentially and both the growth rate and spatial pattern of the perturbations are solutions of an eigenvalue problem of the linearized governing equations. The pattern with the largest growth rate is called the *preferred* or *fastest-growing* mode and its characteristics are usually compared with field observations. The information that a linear (temporal) stability analysis can provide is summarized in table 1.2.

The prediction of instability given by the linear analysis reveals the presence in the system of a physical mechanism which tends to produce a certain pattern. However, the rest of the predictions of linear stability analysis are always subject to the validity of the small amplitude assumption. Thus, linear theory does not give any information on the actual amplitude of the features or their long-term behavior. This information is essential for fundamental reasons (e.g. to determine which are the dynamical properties of the complex morphodynamical system) as well as practical ones (long-term predictions; the prediction of a long-term predictability horizon). Yet it is true that in some cases the shape and the spacing of the bedforms given by the linear analysis (if the arbitrary amplitude is adequately chosen) compare well with the observed bedforms in nature. In other cases, the characteristics of the finite-amplitude features may be very different from the predictions of linear theory. To determine whether this is so, requires a nonlinear analysis, capable of describing the nonlinear interactions. The purpose of nonlinear stability analysis is to provide predictions of the characterisitics that the linear analysis cannot. These are summarized in table 1.3.

1.4 Previous models

For tidal sandbanks such models have been developed and analyzed by Huthnance (1982), Hulscher *et al.* (1993) and de Swart & Hulscher (1995). The water motion is modelled by depth-averaged shallow water equations, the basic state describes a pure tidal current over a flat bottom and sediment transport is modelled as a local parametrization. The formation of sandbanks appears to be due to the combined effect of residual circulations, which develop due to tide-topography interactions, and a sediment flux which is a 'faster than linear' function of the current velocity (as occurs during fair weather conditions).

With regard to shoreface-connected sand ridges the first model of this kind was presented by Trowbridge (1995). The model is also based on the shallow water equations and a local sediment transport parametrization. Essential differences with the tidal sandbank model are that the basic state describes a steady current over a shelf with a transverse slope. Trowbridge studied the morphologic stability properties of a storm-driven alongshore current, with a cross-shore gradient, on a shelf bounded by a straight coast and with a transverse slope.

A severe assumption in this model is the condition of irrotational flow. This implies that production of vorticity due to bottom frictional torques and Coriolis terms, which has been proven to be very important for tidal sand banks dynamics (Zimmerman, 1981; Huthnance, 1982; Hulscher *et al.*, 1993) is neglected. In addition, a crude sediment transport parametrization is used, where the sediment flux is assumed to be linear in the mean flow velocity and the downslope effect on the transport direction is not accounted for. Despite these limitations, the model is able to predict the growth of topographic features similar in shape to the observed ones and with the correct orientation with respect to the current and he was able to explain the up-current rotation of the ridges.

The underlying physical mechanism is *the offshore deflection of the flow over the shoals and the related loss of sediment carrying capacity in the offshore direction*. The latter is due to the transverse bottom slope. However, as a result of the simplifications the model does not predict a preferred spacing between ridge crests. Furthermore, since the hydrodynamic equations are not solved, the offshore deflection of the flow, which is a key point of the model, is shown only by means of the approximate streamlines rather than by the exact flow.

The morphological effect of a steady current along the coast as a result of the instability due to the interaction of the longshore currents and the bottom irregularities, is studied in Falqués *et al.* (1996). The numerical model is based on the depth-averaged shallow water equations and sediment transport is modelled as a local parametrization that includes the local bedslope. Due this parametrization of the sediment transport, wich is also used in the model of Hulscher *et al.* (1993), a preferred mode is found.

1.5 Objectives and outline of the thesis

The ultimate objective of this thesis is to find out the mechanisms wich are responsible of the generation and maintenance of the shoreface-connected sand ridges. To this end, a series of numerical stability analysis models wich are able to describe the linear and the non-linear dynamics of the shelf large scale bedforms has been developed.

The earlier studies of Hulscher *et al.* (1993), Trowbridge (1995) and Falqués *et al.* (1996) suggest that a model based on the depth-averaged shallow water equations, which includes bottom friction and Coriolis terms with sediment flux assumed to be proportional to some power of the current and including downslope effects, takes acount of all the potential instability mechanisms and therefore will be able to model the shoreface-connected sand ridges as a result of an inherent instability. Consequently, this model is an extension of Trowbridge (1995) and Hulscher *et al.* (1993).

As a first stage in the research, a linear stability model for steady basic currents has been developed in chapter 2. The steady current is driven by longshore winds and pressure gradients. It is able to explain the initial growth of bedforms with the main characteristics of the shoreface-connected sand ridges. The principal results of this model are that the leading conditions for the initial growth of the ridges are: current generated by a longshore pressure gradient, sediment transport mainly due to wave stirring and the basic mechanism which produce the instability is the offshore deflection of the flow over the ridges on the transversely sloping bottom (the inner shelf). Therefore, the processes and mechanisms involved in its initial growth are different from the mechanism responsible for the formation of other bedforms such as the tidal sand banks.

Because shoreface-connected sand ridges are present on inner shelves with significant tidal currents, such as along the Dutch coast, a second linear stability model including steady and oscillatory currents is developed in chapter 3. In order to deal with differents weather conditions, a statistical approach to describe the sediment transport during storms and mild weather was also incorporated. For high storm fractions only bedforms trapped to the inner shelf are generated. These bedforms, which resemble shoreface-connected sand ridges, have growth rates and migration speeds which decrease if the relative contribution of tides in the total current profile increases. Nevertheless, formation of bedforms still occurs even in case of a pure oscillatory current, due to the presence of the transversely sloping bottom. If also the effects of fair weather conditions are incorporated it is found that, in addition to the shoreface-connected sand ridges, four other bottom modes can be generated: shoreface-, Coriolis and frictionally-induced bars related to steady currents, trapped tidal ridges and tidal sandbanks. Their growth rates strongly depend on the weather climate and the geometrical characteristics of the shelf area. It will be demonstrated that these bedforms are related to different physical instability mechanisms.

Because linear stability only predict the initial growth and characteristics of the perturbations, a nonlinear analysis is needed to find a finite amplitude solution. In chapter 4, as an extension of the model discussed in the chapter 2, a nonlinear stability analysis for steady basic current has been developed to investigate the long-term behaviour of finite-amplitude shoreface-connected sand ridges. Here the characteristic amplitudes of the bed forms are studied, the feedback to the net currents and the existence of multiple equilibira as well as the periodic and aperiodic behaviour. Furthermore, it will be shown that in this model for realistic parameter, when typical amplitudes and corresponding bottom and flow patterns correspond quite well with observations, and the long-term behaviour is not dominated by the linearly most preferred mode.

In chapter 5 overall conclusions and considerations for further research are presented.