Chapter 5

Overall conclusions and further research

In this thesis, the generation and maintenance of shoreface-connected sand ridges has been investigated, based on the hypothesis that they form as an inherent instability of the coupled water-bottm system. In order to analyze these features, several numerical models have been developed. The models are based on the depth-averaged shallow water motion coupled to an erodible bed. Because of the large length/time-scale of these features, multiple length/time-scale analysis, as an approach to the long-term morphodynamic system, is required: parametrizations for the sediment transport, for the effect of the waves, for the wind or for the bottom roughness; but also different time scales for hydrodynamics and morphodynamical processes. The model includes bottom friction and Coriolis terms. A local parametrization is used for the sediment flux where it is assumed to be proportional to some power of the current and where downslope effects are accounted for. In order to deal with different weather conditions, a statistical approach to describe the sediment transport during storms and mild weather is also incorporated. In a first stage, linear stability models to study the interaction between an erodible bottom and a basic current, which consists of a steady plus a M_2 tidal current have been developed.

The hypothesis that shoreface-connected sand ridges are the result of an inherent free instability of the interaction of topography and weather motions has become more plausible as a result of the research carried out. However, shoreface-connected sand ridges are predicted only under certain conditions. Thus, depending on weather and tidal conditions and the proximity of the coast, the model predicts basically five types of bedforms:

shoreface-connected sand ridges: Elongated ridges which are trapped in the inner shelf and up-current rotated crest-lines with respect to the net current. They are mainly formed where storm weather conditions are dominant and where the steady flow component is stronger that the tidal one. The characteristic longshore spacing is $5-8$ km and the bedforms migrate downstream. Their formation is related to the deflection of the net longshore current over the bars and the transverse slope of the inner shelf. The steady longshore current has to be mainly controlled by a longshore pressure gradient and not by windstresses.

Coriolis bars: Elongated ridges which occur on the outer shelf and that are cyclonically oriented with respect to the net current. They are mainly formed if calm weather conditions are dominant and if the steady flow component is stronger that the tidal one. The characteristic longshore spacing is from 20 km to 7 km and the bedforms migrate downstream. Their formation is related to the production of vorticity by Coriolis torques and wave orbital velocities near the bottom are small compared to the velocities induced by the steady currents.

alternate bars: They are alternating shoals and pools which occur on the outer shelf. Although these bedforms are not elongated ridges, a suggestion of a cyclonically oriented pattern is still apparent through a connection between the shoals. They are mainly formed during calm weather conditions are dominant and if the steady flow component is stronger that the tidal one. The characteristic longshore spacing is 6 km and the bedforms migrate downstream. Their formation is related to the production of vorticity by frictional torques and wave orbital velocities near the bottom are small compared to the velocities induced by the steady currents.

trapped tidal ridges: Elongated ridges which are trapped in the inner shelf and that are cyclonically oriented with respect the tidal current direction. They mainly form during both storm and calm weather conditions and if the tidal flow component is stronger that the steady one. The characteristic longshore spacing is 7 km and the bedforms do not migrate. Their formation is related to the shift of tidal residual circulations due to transverse slope.

offshore tidal sandbanks: Elongated ridges which occur on the outer shelf and that are cyclonically oriented with respect the tidal current direction. They are generated if calm weather conditions are dominant and where the tidal flow component is stronger that the steady one. The characteristic longshore spacing is 7 km and the bedforms do not migrate. Their formation is related to the tidal residual circulations such thatwave orbital velocities near the bottom are small compared to the velocities induced by tides.

It is remarkable that the model predicts five different types of preferred bottom modes, whereas only two of them (shoreface-connected ridges and offshore tidal sandbanks) are well-known from field observations. This is probably due to the fact that the parameter values for which the other bedforms are most favourably excited correspond to situations which usually do not occur in nature. Indeed most shelves are either storm-dominated and characterized by strong steady currents (like the US and Argentinian shelf) or calm weather conditions prevail together with strong tidal currents (like the outer shelf of the North Sea). Likewise, although the analisys show that Coriolis efects are not important, shoreface-connected sand ridges are only observed at locations where $fV < 0$. The simultaneous presence of offshore tidal sandbanks and shoreface-connected ridges on the shelf along the central Dutch coast can be understood from the characteristics of one preferred mode, which is formed during different weather conditions.

The results of the linear stability analysis has been extended to the nonlinear regime to study the long-term behaviour of the shoreface-connected ridges. First results indicate that there are multiple attractors, in other words, the long-term behaviour depends on the initial conditions. It turns out that the final solutions are often dominated by a mode which is not the initially most preferred mode. The spatial patterns of the final state have the typical characteristics of nonlinear features: steep bottom gradients on the downstream side, the presence dislocations and the mixture of large-scale and smaller-scale patterns. The final amplitudes and corresponding bottom and flow patterns correspond quite well with the observations.

5.1 Further research

Despite the progress that has been made, still a considerable amount of work should be done for gaining a better understanding of the system. To this end, present models can be improved in several aspects. In the linearized model, the reference flow consists of a steady component and only one tidal constituent; overtides are only generated internally due to tide-topography interaction. However, both observations and models of tidal currents in the North Sea, cf. Sinha & Pingree (1997), demonstrate that the water motion along the central part of the Dutch coast also has a strong external M_4-component. Thus it is worthwhile to investigate the sensitivity of model results to incorporation of this second tidal harmonic. It should be realized that the discussion in appendix E indicates that this is quite a substantial amount of work, because of the computation of the Galerkin integrals. A striking relation between the basic flow and the basic topography, to be analysed, is that the shoreface-connected ridges are generated when the ratio V/H is almost constant.

The linearized model for both steady and oscillatory flow should be extended to the nonlinear regime to compare the observed amplitudes with field data in regions where tidal currents are important as well as to analyze the long-term behaviour different weather conditions. The actual non-linear model should be completed by including the dynamics of the $k = 0$ mode and changing the code to allow a more flexible selection of the modes and their initial amplitudes. In particular, the quasi-periodic behaviour has to be studied in more depth.

The field observations suggest more substantial modifications. Field observations of Swift *et al.* (1978) and Antia (1996*a*) indicate that sorting effects are important: the finer material is observed on the seaward sides and on the crests whereas the coarser material is found either in the troughs or on the landward flanks. Hence it is worthwhile to study the effects of sorting on 2D dynamics (initial stage and long-term behaviour) of the ridges with the water motion forced by steady and tidal components.

The variability of the wave conditions is also an important point that should be included in the models. It is well-known that both the water motion and sediment transport strongly depend on the wave and wind conditions. During storms transports are much larger than during fair weather conditions. On the other hand the latter conditions occur much more often. Therefore it is important to develop a probabilistic formulation of the morphodynamic model in which a distinction is made between severe and mild weather conditions. The required probability distributions can be obtained from field data. During storms waves are very important because they induce sediment stirring at the bottom. Moreover the wave intensity affects the local roughness experienced by the tidal and steady flow. Since the near-bottom wave velocitites depend on the water depth a wave transformation model should be used to compute the dependence of the coefficients of bottom friction, sediment stirring and bedslope correction term on the water depth and to study their effect on the characteristics of the ridges.

Finaly, I would like to emphasize that one of the limitations of the present model is that the vertical structure of the currents is neglected. As shown by e.g. Niedoroda *et al.* (1984) and Niedoroda & Swift (1991) the three-dimensional flow structure during storm leads to an offshore directed sediment transport during storms. This will modify the 2D mechanisms analyzed in the present study. Besides, a 3D-model will probably generate new bed-flow couplings. The analysis of a 3D flow over an uneven bed, which is a complicated problem, is considered to be an important topic for future research.