Chapter 6

Discussion and conclusions

This study focused on the dynamics of tide-dominated barrier coasts and ebb-tidal deltas. The main aim was to gain more fundamental physical understanding of their dynamics. Three question were formulated in Chapter 1, which formed the starting point of subsequent research.

1. Which physical mechanisms control the length scale of barrier islands?
2. Which physical processes are essential to model the symmetric ebb-tidal delta as morphodynamic equilibrium?
3. Which physical processes cause the ebb-tidal delta to be asymmetric?

The detailed results and the discussions can be found in Chapter 2 to 5. In this chapter the main findings are summarized and put into perspective. This chapter ends with suggestions for further research.

6.1 Length scale of barrier islands

It was found by *FitzGerald* (1996) and *Oost and de Boer* (1994) that the length scale of barrier islands in both the Georgia Bight (USA) and in the Wadden Sea is inversely related to the tidal range and linearly related to the wave influence. In Chapter 1 and 2 it was noted that a process-based physical explanation for this behavior is missing. Previous process-based modeling studies mainly focused on the influence of waves on the position of the coastline (*Komar*, 1998; *Ashton et al.*, 2001; *Falqués and Calvete*, 2005). The influence of tidal currents on the stability of the coastline was never studied.

Therefore, in Chapter 2 a 1-line model was developed that describes the feedback between the position of the coastline and both tidal currents and waves. The hypothesis was that an initially straight coastline can become unstable for perturbations with a length scale between zero and tens of kilometers. At locations where the coastline has retreated, the coast is more vulnerable to breaching during storms. These are locations where inlets may potentially form.

The parameter setting was chosen such that it resembled the conditions as observed along the Dutch and German Wadden coast. In the case that only the influence of the net sediment flux due to the joint action of tidal currents and waves on the evolution of the coastline was taken into account, it was found that the coastline is stable for perturbations with wavelengths larger than 8 km. For wavelengths smaller than 8 km the coastline perturbations grow. Perturbations with the smallest wavelengths grow fastest. No fastest growing mode (FGM) was obtained. The typical time scale on which perturbations grow is ∼100 years. The perturbations migrate with a typical phase speed of ∼10 m/year to the east.

The mechanism that causes the growth and decay of the coastline perturbations was explained in terms of vorticity dynamics following the method of *Zimmerman* (1981). The alongshore gradient of the alongshore component of the vorticity flux causes residual circulation cells that transport the sediment from the locations where the coastline is retreated to the locations where the coastline is protruded. This enhances the initial perturbation of the coastline. In contrast, the cross-shore gradient of the cross-shore component of the vorticity flux results in residual circulation cells that cause a decay of the coastline perturbation. The growth or decay of the coastline perturbations depends on which of the two effects dominates.

Adding the sediment flux that is solely due to waves by using the formulation of *Komar* (1998), resulted in the existence of a FGM. Varying the values of the model parameters between their extremes observed along the Dutch and German coast revealed preferred wavelengths between 0 and 15 kilometers. The model predicts that for increasing magnitude of the shore-parallel tidal currents and constant wave influence, the length scale of the barrier islands decreases. This has been tested by using the results of a large-scale model that was designed to predict the depth-averaged tidal currents and sea surface elevations in the region of the southern North Sea, the so-called ZUNO model (*Roelvink et al.*, 2001). The model results show that the long axis of the M_2 tidal current ellipse is increasing from the Island of Texel towards the German Bight. Hence, the length of the barrier islands is also inversely related to the magnitude of the alongshore tidal currents, as predicted by the model. The model results also predict that for larger wave influence the length scales of the barrier islands increase. The waves cause a diffusion of the coastline perturbations. This effect is largest for smallest wavelengths. Increasing the wave influence results in an increase of the diffusivity of the coast. Consequently, the FGM is obtained for larger wavelengths.

Model results agree well with field data, but not all observed characteristics are reproduced with the model. Observations show that barrier islands can have lengths up to tens of kilometers. The maximum wavelength of the fastest growing mode obtained with the model is 14 km.

6.2 Symmetric tide-dominated ebb-tidal deltas

Data indicate that the large-scale patterns of tide-dominated ebb-tidal deltas are quasi steady. The ebb-tidal delta is found at the end of an ebb-dominated channel. The delta is flanked by two flood-dominated channels (*Hayes*, 1975). In addition, there is a relation between the volume of sand stored in the ebb-tidal delta (ESV) and the total amount of water that enters and leaves the tidal basin during one tidal cycle, the tidal prism TP (*Walton and Adams*, 1976). Some tide-dominated deltas are (almost) symmetric with respect to the mid-axis through the inlet. These deltas occur in coastal areas where shore-parallel currents are small compared to cross-shore tidal currents. Typical examples can be found along the east US coast. The main question that was addressed in Chapter 3 and 5 was which physical mechanisms cause and maintain the symmetric ebb-tidal delta in morphodynamic equilibrium (no evolving bathymetry). It has been noted by *Stommel and Farmer* (1952) that the flow during ebb has a jet-like structure while during flood there is radial inflow. In the conceptual model of *Oertel* (1972) it is argued that the jet during the ebb-phase removes the sand from the inlet and deposits it further seaward. This results in the formation of a deep ebb-dominated channel and an ebb-tidal delta. The process-based numerical modeling study of *van Leeuwen et al.* (2003) suggested that the ebb-tidal delta might be a morphodynamic equilibrium, although true equilibrium was never reached in their simulation.

In Chapter 3 an idealized process-based morphodynamic model was developed and analyzed. It uses simplified formulations for currents, waves, sediment transport and considers the dynamics for an idealized geometry. The main assumption of the model was that the symmetric ebb-tidal delta can be modeled as a 2D morphodynamic equilibrium. Therefore, instead of performing time integrations, a continuation technique was applied to calculate the morphodynamic equilibrium solutions.

The parameter setting was chosen such that it represented the conditions as observed along the east US coast. The modeled current patterns consist of a jet-like pattern during ebb and a radial inflow during flood. This is linked to the presence of two residual circulation cells. This is consistent with field observations. The equilibrium bathymetry consists of an ebb-dominated channel in the center of the inlet. At the end of this channel the ebb-tidal delta is found. This delta is flanked by two flood-dominated channels. This is consistent with the conceptual picture of the ebb-tidal delta presented by *Hayes* (1975). Furthermore, the observed almost linear relation between ESV and TP is recovered with the model.

An analysis of the results showed that in equilibrium the ebb-tidal delta and the channels are maintained due to a balance between the net (i.e., tidally averaged) convergence of sediment transport induced by the currents and waves and the net sediment transport induced by the bed slopes. The ebb-dominated channel is formed by the sediment transport due to currents and waves which is not in the direction of the residual currents. The ebb-tidal delta is mainly caused by the stirring of sediment by waves and tides and the transport by the residual currents.

However, differences between model results and observations were noticed as well. First, the cross-shore length of the ebb-dominated channel obtained with the model is considerably smaller than observed ones. Second, the model does not recover the folding of the ebb-tidal delta around the ebb-dominated channel. The ebb-dominated channel does not protrude into the ebb-tidal delta, which is commonly observed. Third, the modeled sand volumes are a factor ~ 5 smaller than observed ones.

Therefore, in Chapter 5 it was studied whether these discrepancies between observations and model results are caused by the formulation of the waves and currents used in the idealized model. Furthermore, new aspects were studied such as the net transport of sediment due to tidal asymmetry (joint action of M_2 tidal currents and its overtides), the use of a quadratic bottom stress formulation and a more realistic wave model (including wave refraction). Experiments were performed with a numerical model based on the Delft3D software. This model was adapted such that it allowed for the calculation of morphodynamic equilibria.

In a first series of experiments the set-up of the numerical model was such that it is as close as possible to the idealized model. The idealized model and numerical model give qualitatively similar results. Main (quantitative) differences are due to the boundary condition in the tidal inlet, which could no be made equivalent. From these experiments it was concluded that the rigid lid approximation, as was applied in the idealized model, is valid. After these experiments the sensitivity of the results to extensions of the model was studied. The results show that internally generated higher harmonics are not important and only lead to quantitative (order of 10%) differences in magnitude of the bottom patterns. However, externally prescribed higher harmonics at the tidal inlet can lead to different bottom patterns. Prescribed ebb-dominated currents lead to more pronounced bottom patterns while flood-dominated currents prevent the presence of an ebb-tidal delta. Experiments performed with a quadratic bottom stress formulation showed that the linearized bottom stress formulation, as was used in the idealized model, leads to an overestimation of the dissipation of momentum in the entire domain. Therefore, the modeled residual currents are too small. Furthermore, using the quadratic bottom stress formulation results in a first indication that the ebb-tidal delta folds around the ebb-dominated channel and that this channel becomes more elongated in the cross-shore direction. In addition, the modeled sand volumes are considerably closer to the observed ones if a quadratic bottom stress formulation is used instead of linearized version. From the results obtained with the quadratic bottom stress formulation it was concluded that a bed shear-stress formulation can be used which is linear in the current, but in that case a spatially varying friction coefficient should be used (instead of the constant friction coefficient that was used in the idealized model). The use of the realistic wave model yields that already for small waves and a small delta the refraction of the waves around the delta becomes noticeable. This effect can be important if larger waves are modeled. The presence of waves causes a larger delta.

Still, several features of observed ebb-tidal deltas are not recovered with the numerical model. First, the seaward extent of the ebb-dominated channel is still smaller than those of observed ebb-dominated channels. Second, field data suggest that larger wave influence results in a smaller sand volume of the ebb-tidal delta. The model predicts that larger wave influence results in a larger sand volume of the delta.

6.3 Asymmetric tide-dominated ebb-tidal deltas

In Chapter 3 and 5 the focus was on the dynamics of symmetric tide-dominated ebb-tidal deltas. However, observations show that many tide-dominated ebb-tidal deltas are asymmetric with respect to reflection about the mid-axis through the inlet. Typical examples are found along the Dutch and German Wadden coast (*Ehlers*, 1988; *Sha and van den Berg*, 1993). In this region the strength of the shore-parallel tidal currents is of the same order of magnitude as the cross-shore tidal currents. The ebb-dominated channels have an orientation with respect to the mid-axis through the tidal inlet. Some channels are oriented to the left (Dutch Wadden Sea) and others to the right (German Wadden Sea). The main objective of Chapter 4 was therefore to study which physical mechanisms are responsible for the asymmetry properties of ebb-tidal deltas.

In previous studies two important agents were identified that render deltas asymmetric. Processes related to waves cause the ebb-dominated channel to be oriented with the direction of the wave-driven currents (*Oertel*, 1975; *FitzGerald*, 1996). Processes related to the presence of strong shore-parallel tidal currents cause the ebb-dominated channel to be oriented to the left (*Sha*, 1989a). However, the explanations rely on the use of conceptual models. So far, no process-based modeling studies were able to reproduce asymmetric ebb-tidal deltas as morphodynamic equilibrium solutions.

Therefore, in Chapter 4 the idealized model of Chapter 3 was generalized to the case that shore-parallel currents are also important. Furthermore, the effects of the Coriolis force and of large-scale residual currents at sea were included. The set-up of the model was such that it represented the situation as observed along the Dutch and German Wadden coast. The results show that the Coriolis force causes only a weak asymmetry of the ebb-tidal delta. An ebb-tidal delta located on the Northern Hemisphere will have its center of mass slightly shifted to the right (when viewing along the mid-axis of the inlet in the seaward direction). The area with ebb-dominated currents is also located at the right-hand side of the mid-axis of the inlet. The ebb-tidal delta is called right-oriented. An ebb-tidal delta located at the Southern Hemisphere will be left-oriented. The influence of the shore-parallel tidal currents on the asymmetry of the delta is much larger. In a first experiment the phase difference between the shore-parallel and cross-shore tidal currents was approximately zero. The modeled currents on the left-hand side of the inlet are ebb-dominated and are bidirectional. The tidal currents at the right-hand side are weaker, more rotary and are flood-dominated. This is consistent with observations (*Sha*, 1989b). At the end of the area with ebb-dominated currents the ebb-tidal delta is located. However, no ebb-dominated channel is modeled. Changing the phase difference between the tidal currents through the inlet and the shore-parallel currents such that the tidal currents through the straight are significantly lagging the shore-parallel currents (around 90 degrees), results in a change of the orientation of the delta. The area with ebb-dominated currents is now located at the right-hand side of the mid-axis of the inlet and the delta is right-oriented. Increasing the width of the inlet also results in a change of the orientation of the delta. Broader inlets have a stronger tendency to have ebb-dominated currents which are oriented to the right. Lastly, in Chapter 4 the influence of large-scale shore-parallel residual currents at sea on the asymmetry properties of the delta was studied. In the case of residual currents from the left-hand side of the tidal inlet to the right-hand side, the area with ebb-dominated currents is located at the right-hand side of the mid-axis of the inlet. The delta is again located at the right-hand side and no ebb-dominated channel is modeled. Changing the direction of the currents leads to a change in the orientation of the delta from right-oriented to left-oriented.

The modeled hydrodynamics compare well with observations. However, the modeled equilibrium bottom patterns differ in several aspects from observed patterns. The modeled ebb-tidal delta is always located at the seaward end of the area with ebb-dominated currents. This is consistent with the conceptual picture of *Hayes* (1975). However, no ebb-dominated channel is modeled. The only channel that is modeled is located at the side with flood-dominated currents. In Chapter 4 it was suggested that these discrepancies between observed bottom patterns and modeled ones are caused by the absence of a shallow backbarrier basin, by the absence of wind or wave influence, by the absence of modeling of 3D processes or by the absence of settling lag effects in the specific choice of the sediment transport formulation.

6.4 Suggestions for further research

In this section some suggestions for further research with respect to the modeling of the dynamics of barrier coasts and of ebb-tidal deltas are made. This is split up into suggestions concerning the physical processes that were included/excluded in the models, into suggestions with respect to the methodological approaches that have been used to answer the research questions and into suggestions that concern the numerical methods that were used.

6.4.1 Modeling the dynamics of barrier coasts

In the 1-line model that was developed in Chapter 2 many assumptions were made. It was assumed that the nearshore zone has a constant width, that the diffusive terms in the momentum balances can be ignored, that a linearized bottom stress formulation can be used and that the sediment transport due to the tides can approximated by a formulation which only includes the effect of stirring of sediment by waves and transport by the residual currents. The sensitivity of the results to these processes can be studied by using a complex process-based model.

Concerning the methods that have been used, it should be noted that only the evolution of small perturbations were studied in Chapter 2. No nonlinear analysis has been performed, so nothing can be said about the temporal evolution of the coastline perturbations. However, performing this nonlinear evolution is not straightforward. For instance, the evolution equation that was derived, Equation (2.27), should be revised, because it is explicitly based on the assumption that perturbations are small. A last aspect that should be mentioned here, is that the evolution of the coastline is derscibed by a 1-line model while in reality it is the result of complex three-dimensional processes. It would be interesting to extend the model formulations to 2D or even 3D formulations.

Concerning the numerical method it should be noted that the 1-line model of Chapter 2 only includes the effect of residual and M_2 tidal currents. Higher harmonics of the tide were not taken into account. The Fourier expansions of the variables were truncated after the M_2 component. However, the comparison of the results described in Chapter 3 and 5 showed that internally generated higher harmonics of the tide only lead to order 10% changes. Therefore, it is expected that using the full Fourier expansions of the variables will not lead to qualitatively different results.

6.4.2 Modeling the dynamics of ebb-tidal deltas

A main shortcoming of the models that were used in Chapter 3, 4 and 5 was that the tidal currents through the tidal inlet had to be prescribed. This aspect can be improved by adding a tidal basin to the model geometry. This tidal basin is connected to the sea by a strait. A big advantage is that in that case the tidal currents in the inlet follow from physical laws and do not have to be imposed anymore. However, this approach is not straightforward. One has to take into account that the sediment in the area of the ebb-tidal delta is much coarser than the sediment in the tidal basin. This would imply that one has to calculate with non-uniform sediment distributions. Furthermore, considering a geometry that includes the coastal sea, the strait and the tidal basin implies that the morphodynamic equilibrium of the inner basin and the strait has to be calculated as well. This might cause problems if the typical time-scales in the tidal basin are much smaller than the typical time scale of the ebb-tidal delta. Other problems might occur if bifurcations in parameter space exist related to process that are only important in the tidal basin (they exist, see *Schuttelaars and de Swart* (2000); *Schramkowski et al.* (2004)) or in the region of the ebb-tidal delta. Nevertheless, it is tempting to connect the tidal basin with the ebb-tidal delta, since both the models that describe the dynamics of the tidal basin (*Schuttelaars and de Swart*, 2000; *Hibma et al.*, 2003) and the models described in this thesis suffer from the same problem: the boundary conditions in the tidal inlet. Other improvements of the physics can be achieved by including 3D effects such as curvature and the veering of the velocity due to Ekman processes. Furthermore, the imposed sediment transport formulation can be improved. In Chapter 4 no ebb-dominated channel was modeled. This might be caused by the fact that only bedload sediment transport is taken into account. No suspended load formulation has been studied. *Murray* (2004) showed that neglecting such effects prevented the formation of channels in his morphodynamic model of the nearshore zone. The influence of different sediment transport formulations on the morphodynamic equilibria should be studied. Furthermore, no critical velocity for erosion was included. For coarse sediment this critical velocity can be in the order of $0.2 - 0.3$ ms^{-1}. When the maximum tidal currents in the inlet are in the order of 0.5 ms^{-1} it might be very important to add this effect, especially in the case of asymmetric deltas. For a hydrodynamic setting that is typical for the Dutch Wadden Sea it was found that the tidal currents on the left-hand side of the inlet are much stronger than the tidal currents on the right-hand side.

From a methodological point of view, it should be noted that, although morphodynamic equilibria have been calculated, the question whether these equilibria are stable with respect to small 2D perturbations of the bed, has not been studied. In addition, if the maximum tidal current magnitude exceeds a critical value, no equilibria could be found. This might be caused by the way the continuation method is applied. At present, after calculating a morphodynamic equilibrium a parameter is changed with certain fixed magnitude. If a fold bifurcation exists, it might be that the change in the parameter is too large and the old equilibrium is not a good estimate for the morphodynamic equilibrium for the new parameter. An arc-length method (cf. *Seydel* (1994)) might give better results since with this method the magnitude of the parameter change is calculated. The possible existence of bifurcations sets another motivation to perform a 2D stability analysis of the 2D morphodynamic equilibria. The existence of bifurcations is related to the eigenvalues that follow from the stability analysis. A first set-up of a model that calculates the eigenvalues and eigenvectors of the generalized eigenvalue problem that follows from the 2D stability analysis has been developed, but no satisfactory results were obtained due to numerical problems (see next paragraph). Another possible way to calculate the stability of the ebb-tidal deltas would be to perturb the morphodynamic equilibrium and calculate the initial erosion deposition rate. With various techniques an estimation of the eigenfunction and growth rate with largest real part can be obtained (*Deigaard et al.*, 1999; *Klein and Schuttelaars*, 2005). A last method to gain insight in the stability characteristics of the modeled ebb-tidal deltas that is mentioned here is to perform time-integrations. The calculated equilibria are never in "true" equilibrium. Instead, a condition is applied that states that if the relative change of the new bottom is less than 1% with respect to the old estimate of the equilibrium bottom, equilibrium is reached. If the evolution of the ebb-tidal delta is immediately slowing down the equilibrium is stable. If the evolution of the delta is increasing when time evolves, the equilibrium is unstable.

The fact that no satisfactory results were obtained for the 2D stability analysis is caused by numerical problems. In the models of Chapter 3 and 4 a pseudospectral method is used. The stability of the morphodynamic equilibria is described by a generalized eigenvalue problem. The dimensions of the matrices are large and the condition number is very large. The numerical approximations are inaccurate and it is not possible to calculate the eigenvalues and eigenvectors. It is probably better to use a different numerical schematization of the spatial part of the variables. For instance, finite elements of finite differences can be used. This results in matrices with banded structures and many mathematical techniques are known which can solve the resulting generalized eigenvalue problem.