Chapter 1

Introduction

This thesis discusses the physics of morphologic features in shallow seas that are formed by stirring and transport of sediment by tides and waves. Two main topics are investigated. The first one concerns systems of barrier islands and inlets with a distinct alongshore rhythmicity (length scale from a few km to tens of km). The second topic concerns the dynamics of ebb-tidal deltas, which are shallow sandy areas that are located seaward of these inlets. In section 1.1 general observational evidence of sequences of barrier islands and of ebb-tidal deltas is given. Section 1.2 motivates the choice and relevance of these topics. Two examples of sequences of barrier islands are presented that have a different hydrodynamic setting: The barrier islands of the Georgia Bight (Section 1.3) and of the Dutch and German Frisian Islands (Section 1.4). In section 1.5 the present-day knowledge with regard to the modeling and understanding of the dynamics of barrier coasts and ebb-tidal deltas is briefly discussed. Based on this information, in section 1.6 the research questions are formulated. Finally, in section 1.7 the methodology and approach that are used in this thesis are discussed.

1.1 Sequences of barrier islands and ebb-tidal deltas

A significant fraction (about 12%) of the world's coasts are sandy and are characterized by barrier islands separated by tidal inlets (*Glaesser*, 1978). Examples are the Dutch and German Wadden coast (*Ehlers*, 1988), the Atlantic coast of the Unites States (*FitzGerald*, 1996; *Davis*, 1997) and the barrier coast of New Zealand (*Hicks et al.*, 1999). The typical length of the barrier islands ranges between a few kilometers (Florida coast; *Davis* (1997)) to tens of kilometers (e.g. Wadden Sea, North Carolina and Virginia coast). An example of a chain of barrier island is presented in Figure 1.1. It shows the barrier islands located along the coast of Georgia and South Carolina (USA). The light parts are shallow and the dark parts are deep. The black line represents the zero meter contour line and indicates the transition from land to water. White parts represent land.

The water motion observed in the region of barrier islands comprises many components with different length and time scales which, mutually affect each other. The tidal wave traveling along the coast induces both variations in sea level and currents. For most coastal regions the semi-diurnal lunar tide (also called M_2 tide, period 12 h 25 m) is the dominant tidal constituent. The typical amplitudes of the sea surface variation is ~ 1 m and of the tidal currents ~ 1 ms^{-1}. The wind blowing over the water generates surface waves (periods in order of seconds and heights in the order of 1-2 m) and wind-driven currents (magnitudes of order 0.1 ms^{-1}). In shallow areas these waves break and induce wave-driven currents (order 1 ms^{-1}) and set-up of the sea level (order of 1 m). River outflow induces density differences which drive estuarine circulations (order of 0.1 ms^{-1}).

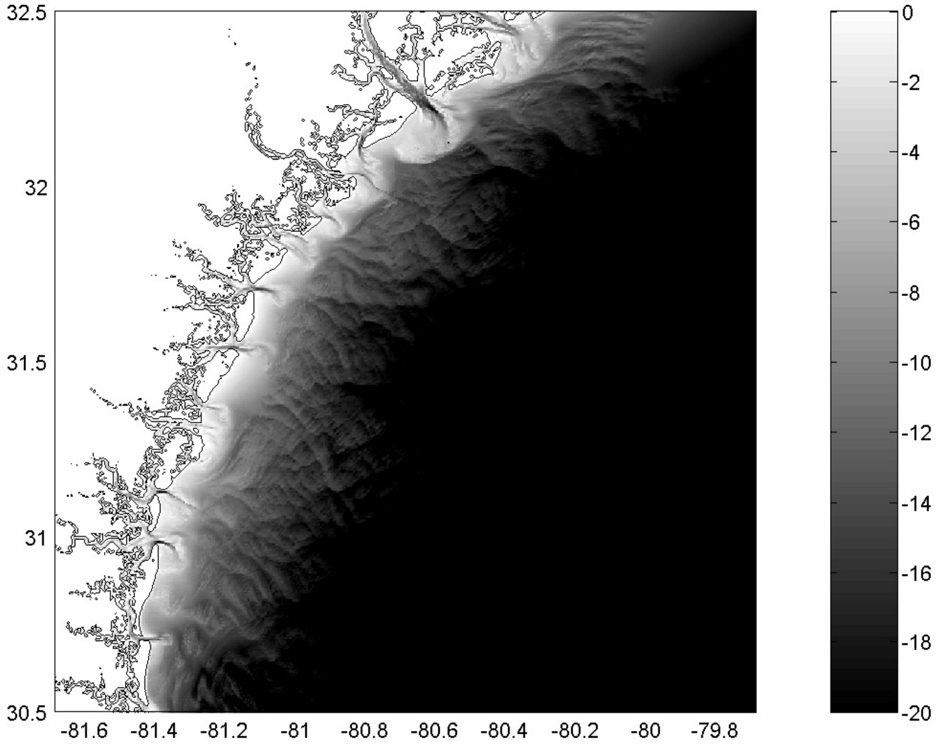


Figure 1.1: Barrier islands along the coast of Georgia and south Carolina. Dark parts are deep, light parts are shallow. Black line is zero meter contour line. Data obtained from NOAA's coastal relief model (http://www.ngdc.noaa.gov/mgg/gdas).

In between the barrier islands the tidal inlets are located. They connect a backbarrier basin to the sea. The bathymetry in the area seaward of the inlet is in general characterized by a deep ebb-dominated channel (meaning that peak currents during the ebb phase are stronger than during the flood phase) and two adjacent flood-dominated channels (Figure 1.2). The ebb-tidal delta is located at the end of the ebb-dominated channel. Spatial extents (alongshore and cross-shore) of the ebb-tidal delta vary from several hundreds of meters observed for tidal inlets along the Florida coast (*FitzGerald*, 1996; *Davis*, 1997) up to 10 kilometer for the Texel inlet (the Netherlands). The maximum depth of the ebb-dominated channel ranges between several meters for small tidal inlets (*FitzGerald*, 1996) and ~ 50 m for Texel inlet (*Sha*, 1989b). The region of the ebb-tidal delta is shallow, with depths in the order of several meters, while some parts can be above mean sea level. Furthermore, smaller-scale channels and shoals repetitively form in the region

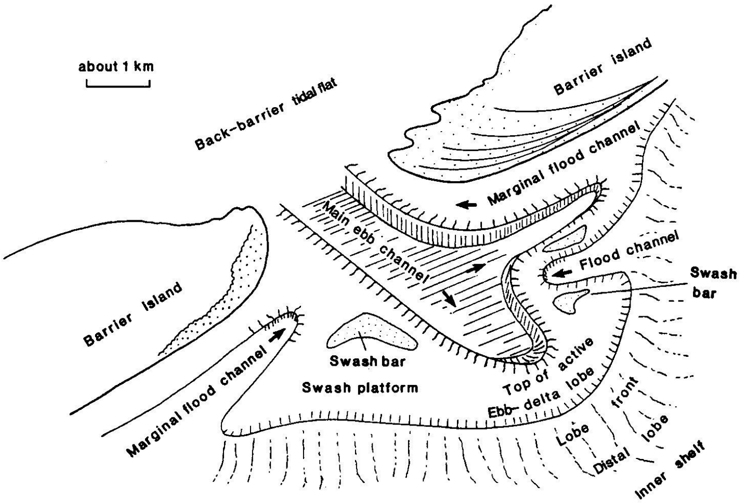


Figure 1.2: Typical spatial configuration of ebb-tidal deltas (*Hayes*, 1975). The ebb-tidal delta is the large shallow area at the seaward side of the tidal inlet. In the center it is intersected by a deep ebb-dominated channel. At both sides of the ebb-tidal delta two flood-dominated channels are seen.

of the ebb-tidal delta and subsequently migrate from one side of the inlet to the other side (*Sha*, 1989b; *Oost and de Boer*, 1994; *FitzGerald*, 1996); the ebb-tidal delta exhibits cyclic behavior. Typical time scale of this cycle ranges between decades (Ameland Inlet, the Netherlands) to centuries (Texel Inlet, the Netherlands).

In many tidal inlets the cross-shore tidal currents are in the order of ~ 1 ms^{-1}. The transport of water by these currents causes the basin to fill and empty with water during one tidal cycle. The tidal prism (TP) is defined as the volume of water that enters and leaves the tidal basin during one tidal cycle and is a function of the tidal range and of the characteristics of the backbarrier basin. The tidal prism ranges from $1 \cdot 10^6$ m^3 (*Walton and Adams*, 1976) to 10^9 m^3 for Texel Inlet (*Sha*, 1989a; *Gibeaut and Davis Jr.*, 1993). The characteristics of the morphology in the area seaward of the tidal inlets strongly depend on the magnitude of the tidal prism. Based on data of ebb-tidal deltas along the Atlantic US-coast, *Walton and Adams* (1976) concluded that there is a power-law relationship between the ebb-tidal sand volume (ESV) and the tidal prism (Figure 1.3). The ebb-tidal sand volume is defined as the amount of sediment that is stored in the ebb-tidal delta. Only the areas which are shallower than a reference bathymetry (defined as the bathymetry that would be obtained when no tidal inlet is present) are considered as a part of the ebb-tidal sand volume. *Walton and Adams* (1976) found that

$$\mathrm{ESV} = c_1 \mathrm{TP}^{c_2} \tag{1.1}$$

When making ESV and TP dimensionless by dividing them through a unit volume of 1 m^3, a best fit of the data is obtained for $c_1 = 0.0066$ and $c_2 = 1.23$. The islands along the Dutch and German Wadden coast show an almost linear relation between TP and the depth of the ebb-dominated channel (*Sha*, 1990).

Field observations indicate that the overall orientation of ebb-dominated channels is quite different for different barrier coasts. The channels located seaward of the inlets along the Atlantic coast of the USA often have a shore-normal orientation (see Figure 1.1). In contrast, the ebb-dominated channels observed off the Dutch Wadden coast bend to the left, when viewing from the inlet in the seaward direction, and those observed off the German coast bend to the right. In the rest of this thesis they will be referred to as left- (or right-) oriented channels. Since the ebb-tidal deltas are located at the end of the ebb-dominated channels the deltas of the Dutch and German Wadden coast are asymmetric with respect to reflection about the mid-axis of the inlet. Analysis and interpretation of data suggest that the orientation of the channels is controlled by three factors, viz. the tidal prism, the magnitude of shore-parallel tidal currents and the intensity of the wave-driven alongshore currents *Sha* (1989a).

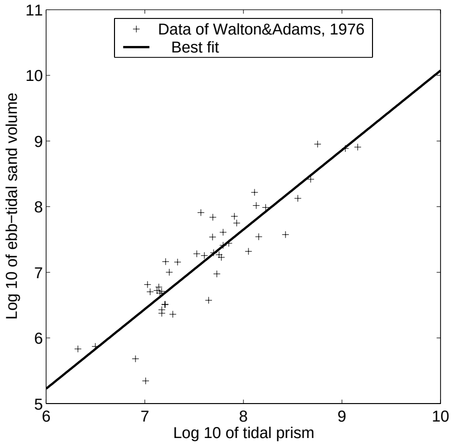


Figure 1.3: Data of ebb-tidal sand volumes and tidal prisms of tidal inlets along the Atlantic US-coast obtained by *Walton and Adams* (1976).

1.2 Focus of this thesis

Apart from being scientifically interesting features, barrier coasts and the tidal inlets with their adjacent ebb-tidal deltas are important for economic reasons. Often a harbor is situated at the landward side of the tidal inlet. Furthermore, these areas are densely populated, they are attractive for recreation and they are also important from an ecological point of view since they serve as nurseries for fish larvaes and as feeding grounds for e.g. migrating birds. In addition, human interferences in the backbarrier basin take place, which influence the dynamics of both the backbarrier basin and the the ebb-tidal delta (e.g. the closure of the Zuiderzee by the construction of the Afsluitdijk in 1927-1932, see *Sha* (1990) for a discussion). It is thus important to gain more understanding of the natural behavior of the tidal inlet and the ebb-tidal delta. In spite of the important function of ebb-tidal deltas and tidal inlets, they belong to the least studied coastal environments. This is mainly due to the complex hydro- and morphodynamics.

The general aim of this thesis is to obtain fundamental knowledge about processes that are important for the morphodynamics of (i) barrier coasts and (ii) ebb-tidal deltas. More specific, the physical mechanisms that determine the length of barrier islands and the physical mechanisms that generate and maintain ebb-tidal deltas are studied. A model approach is used. One of the problems with formulating models for the barrier coasts and ebb-tidal deltas is the difficulty in devising a model that is representative for a large population of the ebb-tidal deltas, while at the same time making the model sufficiently accurate to study the fundamental physical processes. This makes it inevitable to limit the scope of this study. This thesis focuses on barrier coasts and ebb-tidal deltas of which the morphological developments are largely induced by tides and to a lesser extent by waves.

In the following section the hydrodynamics and morphodynamics of two chains of barrier islands are discussed. Furthermore, for each case the hydrodynamics and morphodynamics of the ebb-tidal delta of one specific inlet is discussed in more detail. The first chain of barrier islands that is discussed is found along the Georgia Bight (USA). The ebb-tidal delta of Beaufort Inlet is discussed in more detail and serves as an example of an (almost) symmetric ebb-tidal delta. The second chain of barrier islands are the barrier islands of the Dutch, German and Danish Wadden Sea (Frisian Islands). The ebb-tidal delta of the Ameland inlet is discussed in more detail and serves as an example of a spatially asymmetric ebb-tidal delta.

1.3 Georgia Bight

1.3.1 Barrier Islands

The Georgia Bight stretches over 1200 km from Cape Hatteras (North Carolina) down to Cape Canaveral (Florida). Typical tidal range of the M_2 tide is $1 - 2$ m. It is maximum along Georgia and minimum along Florida and North Carolina. The tidal currents in the inlets are up to 1 ms^{-1}. The shore-parallel currents are typically one order of magnitude smaller and range between 0.05 ms^{-1} along the shelf of North Carolina to a maximum of 0.11 ms^{-1} along the shelf of Georgia (*Blanton et al.*, 2004). The deepwater average wave height is $1 - 2$ m and the waves approach from the north-east (*Davis and FitzGerald*, 2004). The bottom consists of fine to coarse sand (grain size $100 - 1000$ μm) with a median grain size of 500 μm. At large time and space scales the sediment transport is predominantly to the south. The inner shelf, which is the area just seaward of the surf zone (where the waves break), is steep near both edges of this coast and wider and less steep in the middle (Figure 1.4). A sequence of barrier islands is present with a typical distance between successive inlets that varies between a few up to tens of kilometers. The length of the barrier islands seems to be inversely related to the magnitude of the tide (Figure 1.4). In regions with small tidal range the average length of the barrier islands is larger and the number of inlets per length scale is smaller. This is typically the case in the region along the North Carolina coast. When tidal range is larger the length of the barrier islands is smaller and the number of inlets is larger.

1.3.2 Ebb-tidal delta of Beaufort Inlet

Many ebb-tidal deltas along the Georgia Bight have almost symmetric ebb-tidal deltas. One inlet is studied in more detail: Beaufort Inlet. This choice is motivated by the avail-

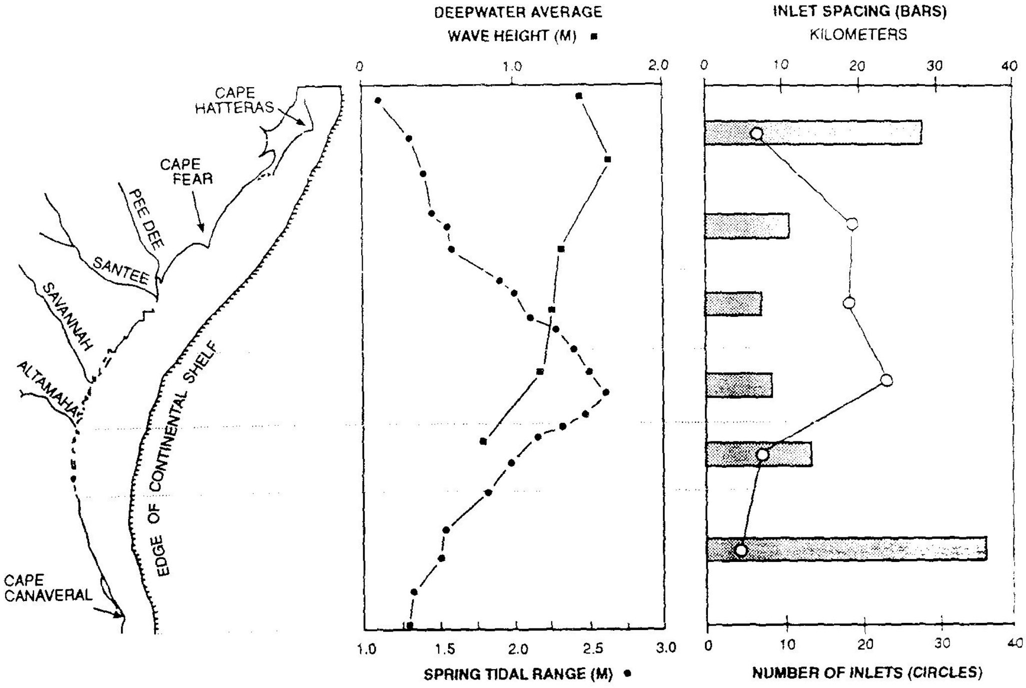


Figure 1.4: Length of barrier islands and number of tidal inlets as a function of inner shelf width, tidal range and wave amplitude for the Georgia Bight (*FitzGerald*, 1996). The left panel shows the Georgia Bight and the edge of the inner shelf. The middle panels shows the local tidal range and significant wave height. The right panel shows the number of tidal inlets and average inlet spacing.

ability of many observations and by previous modeling studies (e.g., *Hench and Luettich* (2003)). Beaufort Inlet is located at the east coast of the US with the center of the inlet at 34.7°*N*, 76.6°*W* and it has a width of 1 km. The Beaufort inlet is characterized by a small tidal range ($\sim$ 1 m) and the maximum tidal currents in the tidal inlet are up to $\sim$ 1 ms^{-1} (*Hench and Luettich*, 2003). The tidal prism is $2.8 \cdot 10^7$ m^3. Beaufort inlet is sheltered from (storm) waves from northwest by the presence of a cape. The mean offshore significant wave height is about 1 m and the mean significant wave period is about 6 s. The ebb-tidal delta is almost spatially symmetric. The spatial extent of the ebb-tidal delta is several kilometers (Figure 1.5). There is one elongated ebb-channel. This channel is maintained at 10-15 m depth and has a shore-normal orientation. The flood-dominated channels, which are often observed for ebb-tidal deltas, seem to be absent. This is probably due to fact that the tidal inlet is maintained by man. Depths of the ebb-tidal tidal delta range from 2 to 10 m. The total volume of sand stored in the ebb-tidal delta is $2.4 \cdot 10^7$ m^3.

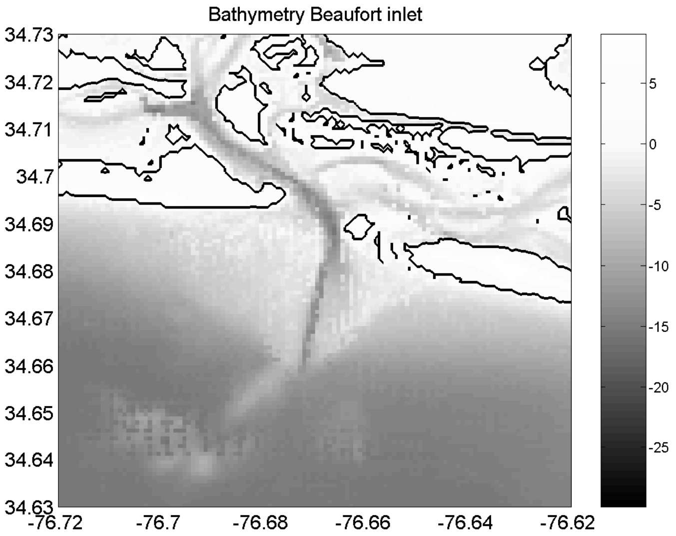


Figure 1.5: Bathymetry of Beaufort Inlet, North Carolina, USA. Data obtained from NOAA's coastal relief model (http://www.ngdc.noaa.gov/mgg/gdas).

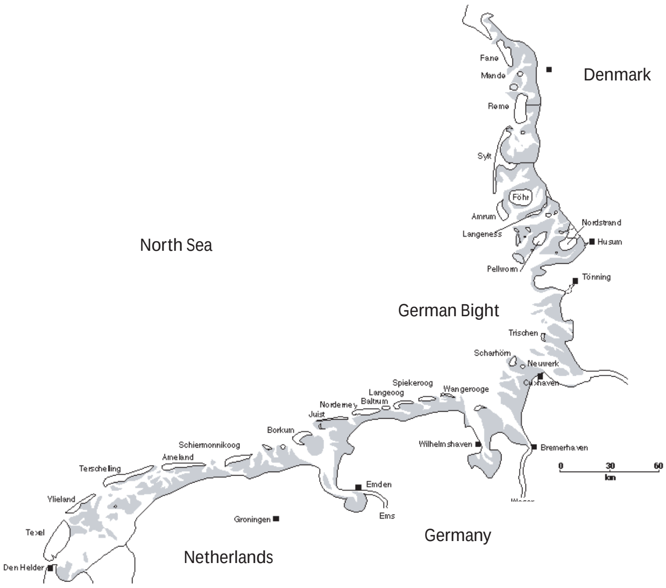


Figure 1.6: Barrier islands (Frisian Islands) and tidal inlets along the Dutch, German and Danish coast.

1.4 Wadden coast

1.4.1 Barrier islands

The second sequence of barrier islands that is discussed, is that along the Dutch, German and Danish coast (Figure 1.6). Both tides and waves are important constituents of the water motion in this area. The tidal range is minimum near the island of Texel of ~ 1.5

m and increases when moving to the German Bight, where it reaches its maximum of $3 - 4$ m. From thereon the tidal range decreases to ~ 2 m for the island of Sylt. The cross-shore tidal currents through the tidal inlets are in the order of 1 ms^{-1} while the tide-induced shore-parallel currents are also significant with magnitudes of 0.5 ms^{-1}. The mean significant wave height in the area of the Frisian Islands is ~ 1.2 m and is almost uniform (*Sha*, 1989a). The mean significant wave period is 6 s. On average, the waves approach from the north-west and at large time and space scales they transport sediment from west to east. The length of the so-called Frisian Islands is not constant. The islands of Texel and Terschelling are the longest ones ($20 - 30$ km). The length of the barrier islands gradually decreases up to the German Bight, where the barrier islands are even absent. From thereon the length of the islands increases again. Also in this area the length of the barrier islands is inversely related to the tidal range (*Oost and de Boer*, 1994).

1.4.2 Ebb-tidal delta of Ameland Inlet

The ebb-tidal deltas along the Frisian islands are asymmetric with respect to reflection about the mid-axis of the inlet. A typical example of an asymmetric ebb-tidal delta is the one that is located seaward of the Ameland Inlet (Figure 1.7). This inlet has been selected because this is one of the most natural tidal inlet systems along the Dutch coast. It is located between the islands of Terschelling and Ameland (Figure 1.6). The width of the inlet is 2 km. The mean tidal range is 2.30 m and the tidal prism is $4 \cdot 10^8$ m^3. Maximum cross-shore tidal currents are in the order of 1 ms^{-1} and the shore-parallel tidal currents outside the region of the ebb-tidal delta are 0.3 ms^{-1}. The significant wave height is 1.10 m and waves approach from the north-west (*Israel and Dunsbergen*, 1999). The deep channel that is seen in Figure 1.7 is ebb-dominated and the ebb-tidal delta is left-oriented. The depth in the main channel is about 30 m. The typical depth of the ebb-tidal delta is several meters.

1.5 Present-day knowledge

Modeling the dynamics of barrier coast and ebb-tidal deltas is a necessary way to interpret the field data and to obtain fundamental understanding about the dominant physical processes. There are several types of models (*de Vriend*, 1996; *de Vriend and Ribberink*, 1996) and in this section the present-day knowledge based on these different model concepts will be discussed.

Till 1990 most models that were used to understand the dynamics of barrier coasts and ebb-tidal deltas had a conceptual character. The aim of these models is to describe certain physical mechanisms without using equations that are based on first principles. Concerning the dynamics of barrier coasts, *FitzGerald* (1996) formulated a conceptual model for the dependence of the length of the barrier islands on tidal range. He argues that when the tidal range increases, more inlets are needed to drain the backbarrier basins. His underlying assumption is that a larger tidal range causes a larger tidal prism, which requires more openings exchange water through the tidal inlets. However, a small tidal

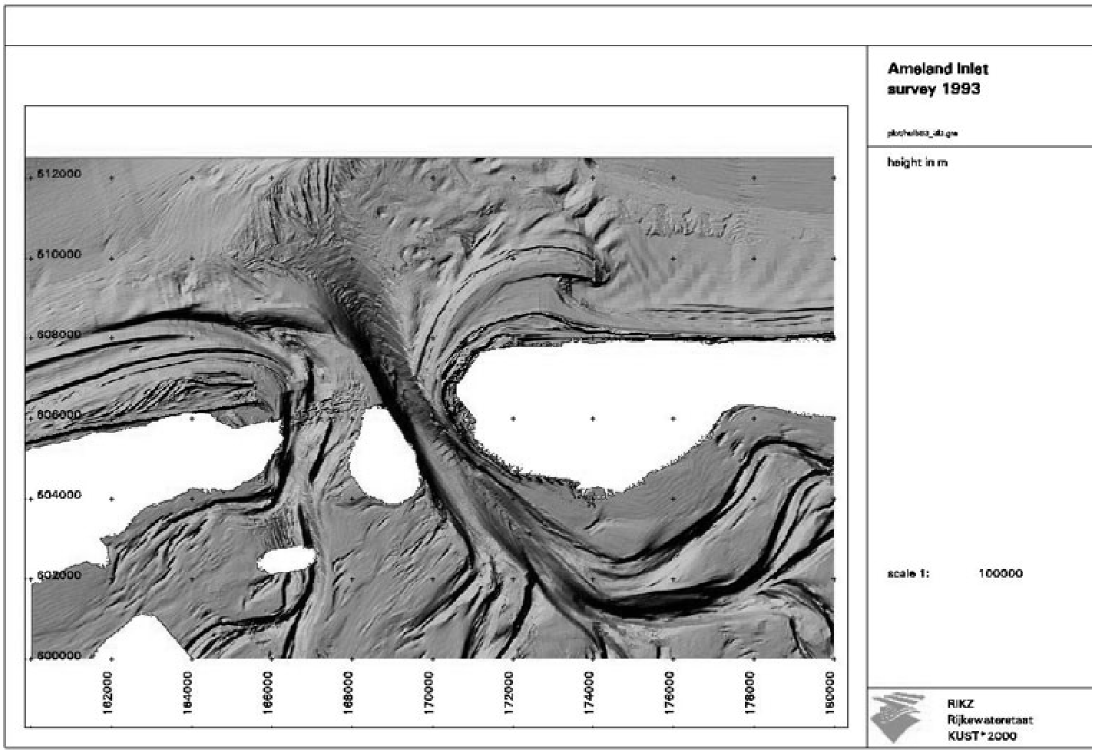
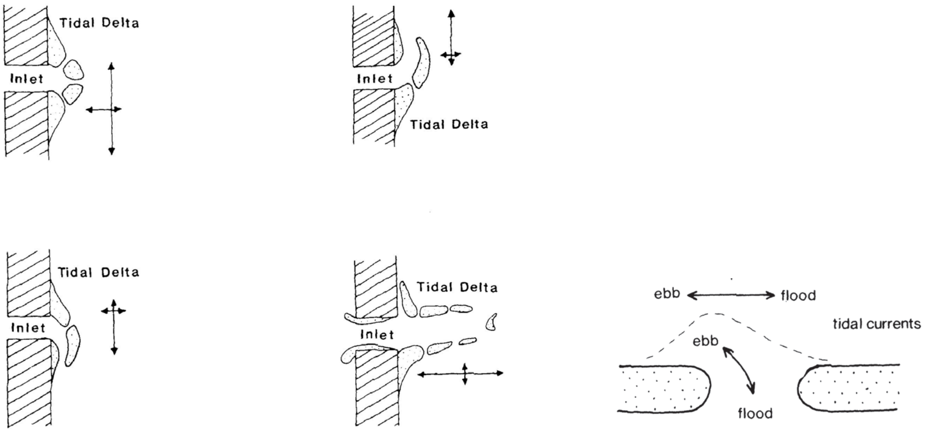


Figure 1.7: Bathymetry of Ameland Inlet in 1993. Dark parts are deep part. Light parts are shallow. White parts are above mean sea level. Barrier island on the left-hand side is the island of Terschelling, the one on the right-hand side is the island of Ameland. Source: RIKZ The Haque.

range does not automatically imply that the tidal prism is small, since the latter also depends on the size of the backbarrier basin and its resonance characteristics. Texel Inlet, for instance, has a small tidal range, but it is the inlet with the largest tidal prism of all inlets located along the Wadden coasts.

Concerning ebb-tidal deltas, *Stommel and Farmer* (1952) were the first to identify the different nature of the tidal currents during ebb and flood. During ebb, the currents are directed from the tidal inlet to the sea and are characterized by a small alongshore and a large cross-shore velocity component. Hence, the flow behaves like a jet, called the ebb-jet. During flood the inflow pattern is radial. These flow pattern have also been observed in laboratory experiments (*Wells and Van Heyst*, 2003). The different nature of the flow during ebb and flood has a strong influence on the morphology of the area seaward of the tidal inlet. During ebb sand is removed from the entrance of the tidal inlet, subsequently transported with the ebb-jet, and deposited at the seaward end of the jet (*Oertel*, 1972, 1988). During flood sand is transported from all sides towards the inlet. As a result, not all sand that is transported during ebb, is reworked during flood. On average, the sediment is removed from the tidal inlet and deposited further seaward. This gives a conceptual explanation why in the center of the inlet the ebb-dominated channel and further offshore the ebb-tidal delta are formed.



(a) (b)

Figure 1.8: (a) Conceptual model of *Oertel* (1975) to explain (a)symmetry of ebb-tidal deltas. Cross-shore arrows indicate strength of cross-shore tidal currents and alongshore arrows indicate strength and direction of wave-induced currents. (b) Conceptual model of *Sha* (1989a) to explain the asymmetry of ebb-tidal deltas along the Dutch Wadden Sea. Due to interaction of shore-parallel tidal currents and cross-shore tidal currents are maximum ebb-currents oriented to the left of the inlet.

Several processes related to the influence of waves and tides can render the ebb-tidal delta asymmetric. In the conceptual model of *Oertel* (1975) it is argued that the asymmetry of the ebb-tidal delta is caused by processes related to waves. Obliquely incident waves refract and break in the surf zone and this results in a wave-driven current. Assume that far away from the tidal inlet the wave-drive currents are from left to right and transport sediment. The presence of the tidal inlet causes an interruption of the wave-driven currents, because the waves do not break in the inlet where the depths are large. This interruption causes deposition at the left-hand side of the tidal inlet and erosion of sediment at the right-hand side. Hence, the ebb-dominated channel will be right-oriented (Figure 1.8(a)).

The influence of the interaction of the shore-parallel and cross-shore tidal currents on the asymmetry of the ebb-tidal delta was first noted by *Sha* (1989a). His conceptual model can be applied to the tidal inlet systems of the of the Dutch Wadden Sea. The interaction of the shore-parallel and cross-shore tidal currents leads to strong bi-directional tidal currents at the left-hand side of a tidal inlet (viewing from the inlet in seaward direction) and smaller, rotary, currents at the righthand side (Figure 1.8(b)). Furthermore, he argued that the strong bi-directional currents will result in erosion of sediment and that this sediment is deposited in the area where the currents are weak and rotary. Hence, the ebb-dominated channel is left-oriented.

The conceptual models are not based on an explicit description of the physical processes. The concepts have to be tested by using process-based models that are based on physical first principles. The objective is to gain physical insight in the dominant physical processes that are important for the morphodynamics of barrier coasts and ebb-tidal deltas. In principle, process-based morphodynamic models consist of three separated modules. In the first module the water motion (tides, waves and density-driven currents and their interaction) is calculated for a specific bathymetry. In the next module these currents are used to calculate the sediment transport. In the last module the new bottom is calculated from the divergence of the sediment transport. When the sediment transport is divergent, sediment is removed from the bed; when the sediment transport is convergent, sediment is deposited at the bed.

Before 1990 only process-based models have been developed that describe the hydrodynamics in the area seaward of the tidal inlet (e.g., *Awaji et al.* (1980); *Ridderinkhof* (1989)). Together with more recent studies of *van Leeuwen and de Swart* (2002); *Hench and Luettich* (2003), these studies identified, explained and analyzed important aspects of the currents in the seaward region of a tidal inlet. An important aspect is the presence of residual circulation cells, as was already discussed by *Stommel and Farmer* (1952). The cells can be symmetric in the case of a model for the Beaufort Inlet (*Hench and Luettich*, 2003) or they can have asymmetric properties in the case of models based on the Dutch Wadden Sea (*Ridderinkhof*, 1989; *van Leeuwen and de Swart*, 2002).

After 1990 computers became powerful enough to study the morphodynamic evolution of ebb-tidal deltas by direct simulation. In *Wang* (1991); *Wang et al.* (1995) the Delft2D-MOR model was used to study the long-term evolution of the backbarrier basin of the Frisian Inlet. Wave effects were modeled in a heuristic manner by assuming that they cause a spatially uniform stirring of sediment from the bed. The simulations reproduced some observed gross features of the Frisian Inlet, such as the presence of channels and shoals. The results for the evolution of the ebb-tidal delta were less satisfactory. *Cayocca* (2001) used a two-dimensional horizontal model to study several stages of the evolution of the Arcachon inlet (France). Both waves, tidal currents and their interaction were modeled for a realistic geometry. The model reproduced several observed features such as the opening of a new channel. A detailed study for the sediment transport patterns in the Teignmouth estuary was carried out by *Siegle et al.* (2004). They showed that waves are important for the migration of shoals.

In *van Leeuwen et al.* (2003) the evolution of the asymmetric ebb-tidal delta of the Frisian Inlet was modeled, starting from a situation without an ebb-tidal delta. The model was only forced by M_2 tidal currents. After a long simulation time (hundreds of years) the system evolved to a configuration that compared reasonably well with the Frisian Inlet system. Furthermore, at the end of the simulation the evolution of the ebb-tidal delta was slowing down. This suggested that an equilibrium configuration was achieved. However, due to numerical problems a real equilibrium (no evolving bathymetry) was not reached.

A drawback of the complex process-based morphodynamic models is the difficulty to analyze the results. The models are too complicated to study fundamental processes in isolation and to perform a large number of sensitivity experiments. Therefore it is hard to reveal which processes are causing the observed phenomena. These models are not very suitable to test the ideas that are obtained from the conceptual models.

Idealized process-based models are more suitable to test conceptual ideas and to obtain fundamental physical understanding about the dynamics of barrier coasts and ebb-tidal deltas. In these kind of models simplified equations are derived from first principles in which only processes are retained that are believed to be important for the specific phenomena studied. They allow for a systematic analysis of the basic mechanisms. The fundamental knowledge that is obtained by these kind of models can be used to validate the conceptual models and to interpret the results obtained with complex process-based models. Idealized process-based models have mainly been used to study the channel-shoal dynamics in tidal basins and estuaries (*Schuttelaars and de Swart* (2000); *Schramkowski et al.* (2004)) and the morphodynamics of tidal sand ridges, shoreface-connected ridges and sand waves (e.g., *Huthnance* (1982); *Hulscher et al.* (1993); *Calvete et al.* (2001); *Roos et al.* (2004)).

1.6 Research questions

From the previous sections it follows that there is still a lack in our understanding of barrier coast and ebb-tidal deltas. Concerning the morphodynamics of barrier island sequences, there is no satisfactory explanation for the observed length of the barrier islands. Concerning the morphodynamics of ebb-tidal deltas, observations by *Hayes* (1975) and *Walton and Adams* (1976) and the results described in *van Leeuwen et al.* (2003) suggest that the ebb-tidal delta is a part of the equilibrium morphology at the seaward side of the tidal inlet, but this has never been proved. Furthermore, many conceptual models for the dynamics of ebb-tidal deltas as discussed by *Oertel* (1972, 1988); *Sha* (1989a) have not been tested with process-based models. Therefore, in this thesis the following research questions are addressed:.

1. Which physical mechanisms can cause an initial straight coastline to develop into an undulating one, with spacing between successive undulations in the order 1-30 km, thereby crudely mimicking the initial formation of a barrier coast? Can such mechanisms be modeled and does the model explain why the length of barrier islands is inversely related to the tidal range, as observations suggest?

2. Which physical processes are required to model the presence of a spatially symmetric ebb-tidal delta as a part of a morphodynamic equilibrium bathymetry at the seaward side of a tidal inlet? Can such a model quantitatively explain observed empirical relationships between e.g. ebb-tidal sand volume and tidal prism?

3. Which physical mechanisms cause the spatial asymmetry of ebb-tidal deltas with respect to their mid-axis through the tidal inlet and can this be simulated by a process-based model?

1.7 Research approach

To find answers to the research questions 1,2 and 3, both idealized and complex process-based models are used. In Chapter 2, the first question is addressed. An idealized model is developed to study the stability of a straight coastline under influence of tides and waves. It describes the feedback between tides, waves and the small-amplitude undulations of a sandy coastline. The model employs a so-called linear stability analysis, i.e., the evolution of small perturbations evolving on a known equilibrium state of the system is studied. Because the perturbations are small the equations can be linearized. The small perturbations can grow or decay and migrate. The main assumption in Chapter 2 is that the joint action of tidal currents and waves cause growing initial undulations of the coastline. Spots where the coastline has retreated are more vulnerable to breaching during storms and are the spots where tidal inlets may form.

In Chapter 3 and 4 and 5 the focus is on the dynamics of ebb-tidal deltas. One of the key issues addressed is whether the ebb-tidal delta can be modeled as a part of the morphodynamic equilibrium (a state characterized by a steady bottom pattern) in the area seaward of the tidal inlet. A continuation technique is used. This technique requires the knowledge of one morphodynamic equilibrium for a certain choice of parameter values. Next, a parameter is slightly changed. It is assumed that the previous equilibrium is a good estimate of the equilibrium state for the new parameter setting. This estimate is used to calculate the hydrodynamics, the sediment transport and its divergence and convergence for the new parameter setting. From this a new estimate of the morphodynamic equilibrium state for the parameter setting is obtained. If the difference with the previous estimate of the equilibrium is small the equilibrium state for the new parameter setting is reached and a parameter can be changed again. The success of this technique for morphodynamic problems was already demonstrated in the context of models that calculated the morphodynamic equilibrium states of the backbarrier basin (*Schuttelaars and de Swart*, 2000; *Schramkowski et al.*, 2004).

In Chapter 3 and 5 the dynamics of the symmetric ebb-tidal delta is studied. First, in Chapter 3 an idealized process-based model is developed and analyzed. Many assumptions and limitations in the description of the hydrodynamics are introduced. These concern the adoption of a rigid-lid approximation, the use of a linearized bed shear-stress formulation, the neglect of higher harmonics of the tide in computing the net sediment transport and the use of a heuristic wave model. The model described in Chapter 3 is used to quantify the concepts of *Stommel and Farmer* (1952) and *Oertel* (1972, 1988). Second, in Chapter 5 a complex process-based numerical model is developed to validate the idealizations that were used in the idealized model of Chapter 3. The results obtained with the idealized and the numerical model are compared. Furthermore, the sensitivity of the results to aspects that could not be studied with the idealized model (such as a quadratic bed shear-stress formulation, higher harmonics of the tide and waves calculated with a sophisticated wave model) are studied.

In Chapter 4 the focus is on the processes that cause spatially asymmetric ebb-tidal deltas. The idealized model of Chapter 3 is extended with tide-related processes that lead to asymmetry. In Chapter 6 the results of this thesis are summarized and discussed and a perspective on new ways to study the morphodynamics of ebb-tidal deltas is presented.