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Morphodynamics of the Wadden Sea and its barrier island system

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ABSTRACT

The Wadden Sea and its associated barrier island system exhibit highly dynamic behaviour. Of major concern is the movement of water and air and the transport, erosion and deposition of sand and mud. These processes result in an ever-changing morphology (topography/bathymetry) of the islands, tidal channels, inter-tidal shoals and tidal flats. This dynamic development of the shape and nature of the Wadden area forms together with the biotic systems, the present Wadden system. The morphodynamic development of the Wadden Sea is influenced by changing environmental conditions e.g. sea-level rise as well as by human interferences. For the management and protection of the Wadden system knowledge on the morphodynamic development is essential. However, our present knowledge is not sufficient to predict the effects of human interferences under different climate change scenarios in sufficient detail and accuracy. This paper identifies the existing knowledge gaps, based on a review of the state of the art on morphodynamics of the Wadden Sea that is confronted with major requirements from a coastal zone management point of view. The identified knowledge gaps have to inspire and stimulate research in the fields of the large-scale sediment budgets, morphodynamic changes at smaller scales, processes and mechanisms of sediment transport, erosion and deposition and modelling tools.

1. Introduction

The Wadden Sea is a coastal wetland of exceptional size, great beauty and richness in unique natural assets (Fig. 1). It contains the largest coherent tidal flat area in the world. It has developed a unique geomorphology with its specific combination of physical factors and their interaction with the regional biota. In 2009 the Dutch and large part of the German Wadden Sea became a UNESCO World Heritage Site.

The Wadden Sea, the tidal inlets and the North Sea coasts of the Wadden Islands exhibit a dynamic behaviour. The dynamics concerns the flow of water and air, and transport, erosion and sedimentation of sand and mud. These processes result in an ever-changing morphology (topography/bathymetry) of the islands, channels and tidal flats. This dynamic development – of shape and nature of the Wadden Sea area – form, together with the biotic systems, the Wadden system.

Although the dynamic development of the morphology is a very characteristic and natural aspect of the Wadden system, there are concerns about developments due to changing environmental conditions and to human interferences. Climate change and sea-level rise – including changes in tidal range such as observed in the German Bight – are major challenges for guarantying the safety against flooding, for conserving the unique character of the morphological and ecological system and for managing the human activities in harmony with nature. Examples of human interferences in the Wadden Sea are the closures of the Zuiderzee and the Lauwerszee, land reclamation, mining of gas and salt leading to land subsidence, dredging and dumping activities including maintenance of navigation channels and sand nourishment for the maintenance of the North Sea coast. Coastal projects outside the Wadden Sea may be of influence as well. Examples of these projects include the land reclamation and harbour development of Maasvlakte 2 and all planned/proposed major works along the Dutch coast such as the construction of artificial islands or large-scale nourishments. Knowledge on the morphodynamics of the Wadden Sea is therefore essential to protect, conserve and wisely manage the Wadden Sea.

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Fig. 1. The Wadden Sea (www.waddensea-secretariat.org).

Morphodynamic research of the Wadden Sea system has to deliver the essential knowledge and tools (such as models) to assess the qualitative and quantitative coastal developments that will occur in response to changing environmental conditions and human measures.

Morphodynamical development is the result of the interaction between water movement, sediment transport and bottom changes (Fig. 2). Likewise, morphodynamic research includes studies of hydrodynamics, sediment transport, morphology and interaction with biological processes. Biological processes play an important role in (de)mobilizing sediment and in generating eco-morphological landscape units such as mussel beds and salt marshes. Hydrodynamic studies have to include the effects of tide-, wind- and density-driven flow patterns as well as the impact of waves and wave-driven currents. Sediment transport concerns sand, mud and sand-mud mixtures. Therefore morphological studies should not only concern changes of geometry and bathymetry, but also changes in substrate or bottom composition ought to be considered. The bottom composition is of great importance for the ecological system. Mud is a carrier for nutrients and contaminants and the mud content in the bottom has a substantial impact on flora and fauna. Conversely, flora and fauna may also affect water movement, sediment transport and morphological changes. Biogeomorphology is a recently developed discipline focusing on the interaction between morphological and biological processes and their impact on coastal geomorphology.

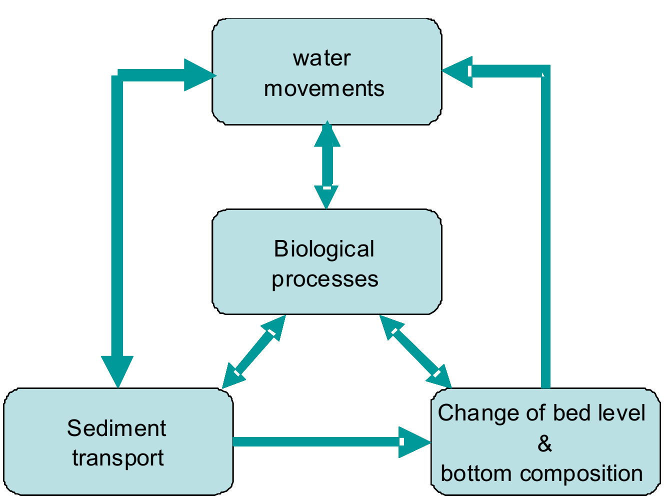


Fig. 2. The components of the morphodynamic system.

The objective of this paper is to identify gaps in our knowledge on coastal morphodynamics of the Wadden Sea area. For that purpose we present an overview of the state of the art on morphodynamic research and confront this knowledge with major questions that have to be addressed by coastal zone managers and policymakers who share a responsibility for the complex Wadden Sea ecosystem.

Although biological processes are very important for the Wadden Sea (Fig. 2) we will focus on the physical processes, i.e. the interaction between water movement, sediment transport and changes of morphology and bottom composition. First a review is given on the state of the art on the existing knowledge in Chapter 2. In Chapter 3 the knowledge requirement is evaluated from the integrated coastal zone management perspective. The knowledge gaps are identified in Chapter 4 by combining Chapter 2 and Chapter 3.

2. Research fields morphodynamics Wadden Sea

2.1. Large-scale sediment budget

By large-scale sediment budget we mean sediment volume changes due to sedimentation and erosion of large areas at the scale of an entire tidal basin in the Wadden Sea and the corresponding North Sea coastal area. These changes give insights into the import–export of sediment through the tidal inlets. Understanding of the large-scale sediment budget is important for the coastal maintenance as well as for the sustainable management of the Wadden Sea.

In 1990 the concept of Basal Coastline (“Basis Kust Lijn – BKL) was introduced in the Netherlands and the Dutch coast has to be maintained by law. Local erosion and losses of sediment have to be compensated by beach- and shore-face nourishment. As far as possible, “hard” engineering solutions such as seawalls and dikes have to be avoided to combat coastal erosion.

The frequency and amount of the nourishments depend on the rate of coastal erosion. Until 2000, only the Basal Coastline was maintained. This results in sand nourishment in the order of 6.5 million m^3 per year (Fig. 3). Under the current policy since 2000, in addition to the maintenance of the Basal Coastline also the development of the lower part of the profile is taken into account which requires an additional amount of sediment to compensate for sea-level rise. This requires sand nourishment in the order of 12 million m^3 per year (Fig. 4). If sea-level rise accelerates, and if the sediment loss from the coastal system is taken into account, even more sand should be nourished in future (De Ronde, 2008). Barrier island beaches of the Wadden coast are subject to regular and major sand nourishments. This is probably due to sediment import to the Wadden Sea caused by the sediment demand in relation to sea-level rise and human interventions (closures of Zuiderzee and Lauwerszee, etc.). The Wadden Sea is an important sediment sink of the Dutch coastal system and sediment demand in the Wadden Sea is considered as a major cause of sand loss from the Dutch North Sea coast (Stive and Eysink, 1989; Mulder, 2000; De Ronde, 2008;

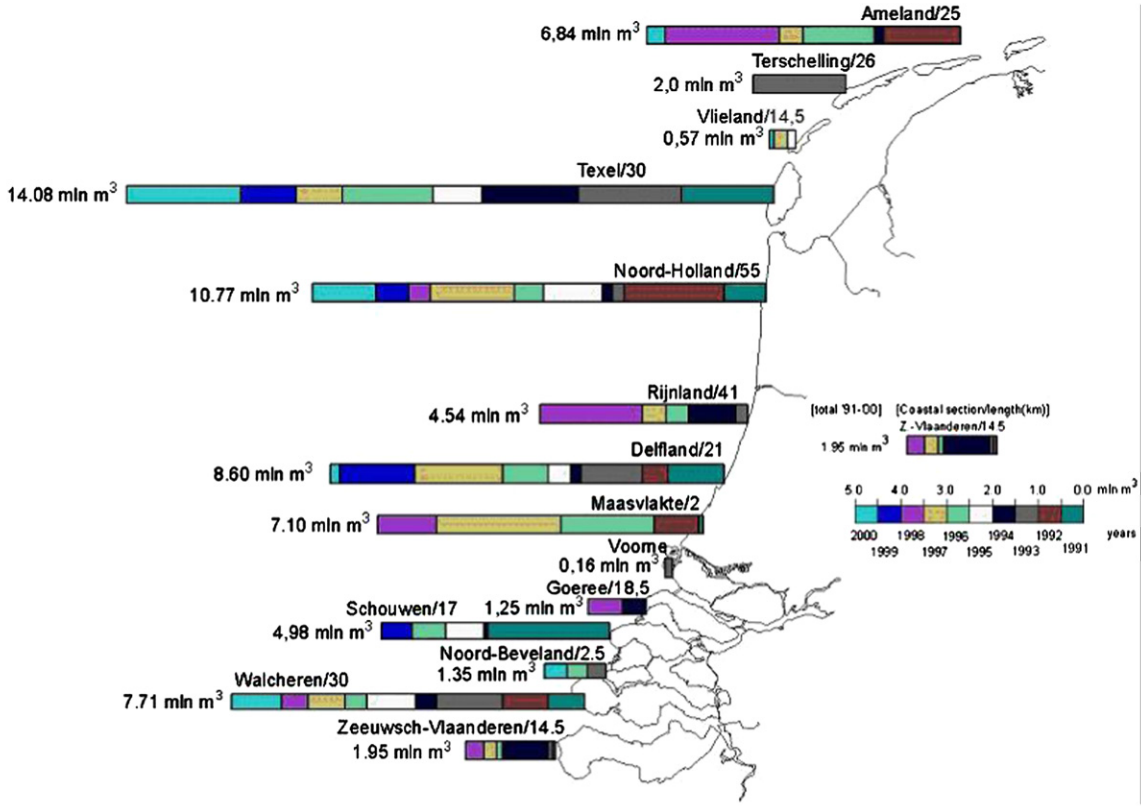


Fig. 3. Sand nourishment during the periods 1991–2000.

Van Koningsveld et al., 2008; Elias et al., in press). The greatest loss occurs along the coast next to Marsdiep (Texel inlet, between Texel and the mainland coast), where between 1991 and 2000 more than 25 million m^3 and between 2000 and 2010 almost 50 million m^3 of sand was nourished. In response to expected accelerating sea-level rise, the loss by import into the Wadden Sea will become even much larger. From a coastal zone management point of view knowledge of the sediment budget of the Wadden Sea is essential

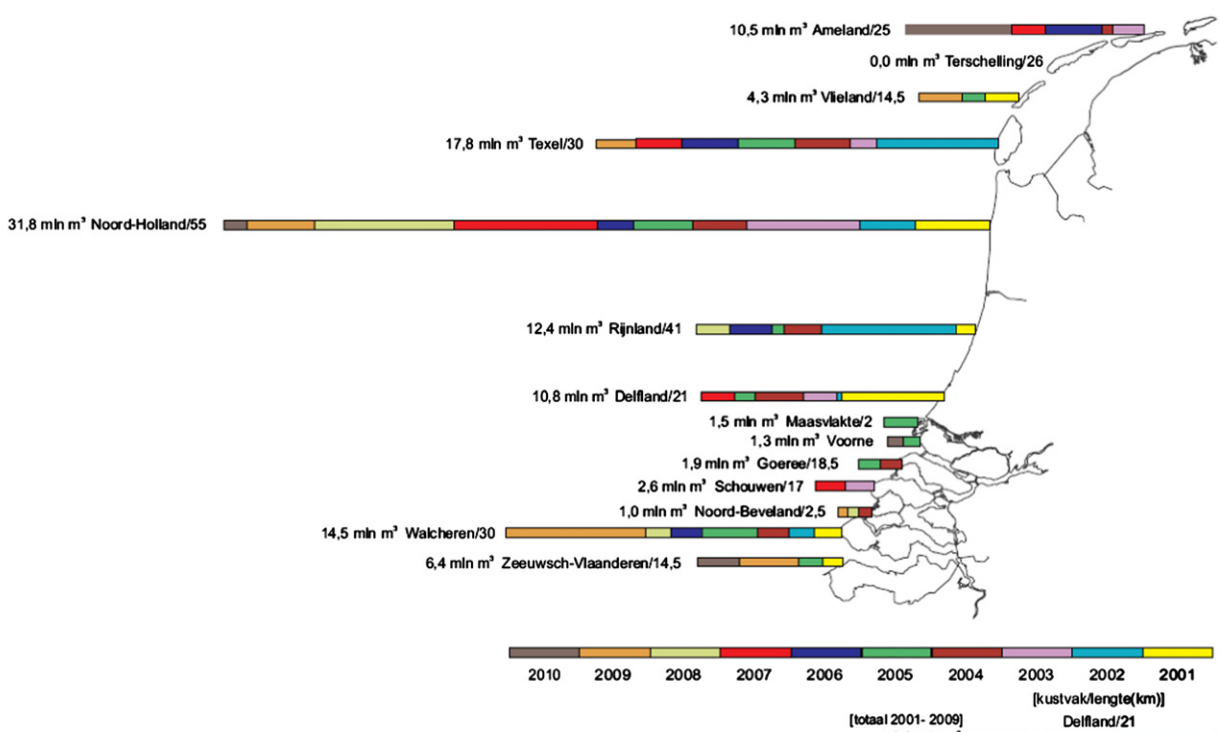


Fig. 4. Sand nourishment during the periods 2001–2010.

to establish the (potential) morphological and ecological impact of sea-level rise.

An important question is whether 'drowning', sea-level rise is faster than sedimentation, or 'infilling' – sedimentation is faster than sea-level rise – will occur.

Bathymetric Data for the Netherlands Wadden Sea (Fig. 5) area are available since 1926, stored in 10 × 12.5 km blocks called 'Vaklodingen' (Fig. 6). Based on these data, the development of sediment volumes in the tidal basins, the ebb-tidal deltas and the adjacent coasts of the various inlets (Fig. 6) can be determined. This type of sediment budget studies was carried out for different parts of the Dutch coastal system by several researchers in recent years. For the Wadden Sea area, the studies by Walburg (2006), Van Koningsveld et al. (2008) and Elias et al. (in press) are worth mentioning.

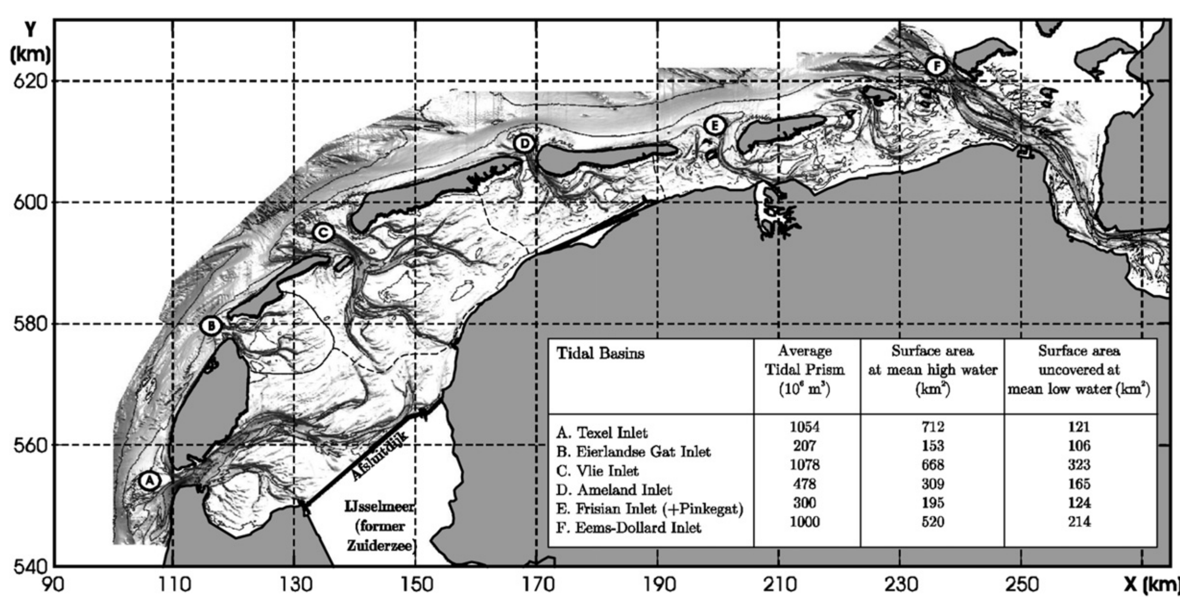
Fig. 7 shows the volume changes determined by Elias et al. (in press) for the tidal systems defined in Fig. 6. Changes before (indicated in legend with 'incl. dd') as well as after correction with dredging and dumping amounts are shown. Note also that the ebb-tidal delta (etd) is part of the coastal area. For the whole Western Wadden Sea (the five flood basins) a total sedimentation of about 500 million m^3 occurred in the period 1927–2000, i.e. averaged nearly 7 million m^3 per year. This is much more than the amount needed to compensate for the relative sea-level rise of 18 cm per century, which requires less than 4 million m^3 per year sedimentation. The cause of this ongoing infilling is among others attributed to the closure of the Zuiderzee (in 1932) and the Lauwerszee (in 1969). These closures have disturbed the morphological equilibrium in the respective basins. Additional import of sediment is required to restore the equilibrium (sand demand). Further, the sedimentation rate in the Wadden Sea shows no clear decline in time. This indicates that the effects of the closure works are still ongoing, although part of the observed changes is due to natural fluctuations. Overall, there is an almost closed budget: erosion rates found along the North Sea facing barrier island coast is of the same order of magnitude as net deposition in the Wadden Sea. However, locally the budget is not always closed between the erosion outside and sedimentation inside an individual inlet and basin. The area outside of Marsdiep erodes much more than the sedimentation inside, and the reverse applies to Vlie. Based on this observation, it is concluded that sediment is transported from Marsdiep to Vlie (Elias, 2006). The watersheds between the tidal basins are thus no real boundaries but allow for an exchange of water and sediment, in particular during storm conditions. Moreover, the positions of the watersheds are not fixed in time.

In summary, the following conclusions from the sediment budget studies are drawn:

- Under the influence of relative sea-level rise and man-induced coastal interventions in the past the Wadden Sea captures sediment: Wadden Sea is an important sediment sink of the Dutch coastal system. It is generally assumed that the import of sediment to the Wadden Sea causes erosion along the North Sea Coast.
- The current sedimentation rate in the Dutch Wadden Sea is higher than the relative sea-level rise.
- Effects of large-scale interventions such as the closure of the Zuiderzee and the Lauwerszee are still observed.
- The various inlets cannot be considered as separate systems with fixed boundaries. Transports occur across the watersheds and, subsequently, the watersheds tend to migrate in time.

In spite of these clear results, a full-scale sediment budget analysis is hampered by a number of problems:

- Inaccuracies and uncertainties in the data. In analyzing the bed level changes between different years it is shown that sometimes errors/mistakes have been introduced during the data collection and/or processing. This is obvious if one observes abnormal changes in the data in a given period for a given area. Correction of these errors is usually not possible because it is no longer possible to reconstruct the origin of these errors.
- Low frequency of the morphological measurements. The Dutch Wadden Sea is measured once every six years, but not all areas simultaneously. As a consequence, data from different years and different "Vaklodingen" are needed to construct a complete bathymetry for a certain inlet including its ebb-tidal delta and tidal basin. It is worthwhile to examine what kind of errors this can cause in the results of the analysis.



Tidal Basins	Average Tidal Prism (10^6 m^3)	Surface area at mean high water (km^2)	Surface area uncovered at mean low water (km^2)
A. Texel Inlet	1054	712	121
B. Eierlandse Gat Inlet	207	153	106
C. Vlie Inlet	1078	668	323
D. Ameland Inlet	478	309	165
E. Frisian Inlet (+Pinkegat)	300	195	124
F. Eems-Dollard Inlet	1000	520	214

Fig. 5. The Dutch Wadden Sea.

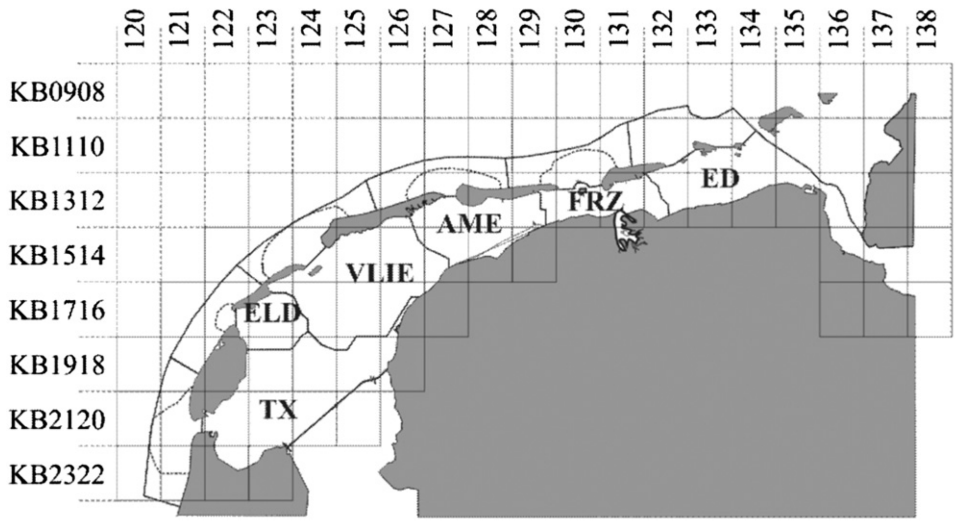


Fig. 6. Overview of 'Vaklodingen' and polygons used in the sediment budget analysis. The dotted line outside each inlet indicates the ebb-tidal delta area (etd. in Fig. 7).

- Boundaries of sub-systems (inlets) are not always clear. It has already been mentioned that the watersheds between the tidal basins have no fixed locations. However, in the analysis a fixed boundary between the systems for all years has to be assumed. For the area outside the inlets the boundaries are arbitrary. In Fig. 6 the middle of an island is used as a border between coastal areas corresponding to the two inlets. These problems may also have contributed to the non-closed budget for each inlet.

The different ways of dealing with these problems have also complicated an intercomparison between the various sediment budget studies.

The sediment budget studies give an indication, but no direct answer to the question of how much residual sediment transport occurs through each inlet. Because transport occurs across the watersheds the transport field is not simply determined from the sedimentation – erosion results (Van Koningsveld et al., 2008). Imports–exports through the inlets can be determined only if additional assumptions are made. Based on a comprehensive consideration of the whole Western Wadden Sea and its coastal areas, Elias (2006) concluded that the net sediment transport through Marsdiep inlet is in the order of 6 million m^3 per year import. Data from direct transport measurements for supporting or testing such results are very scarce. The TESO measurements in the Marsdiep carried out in recent years are unique in this respect. Sediment transport derived from these measurements indicates that only the mud transport through Marsdiep is already 5-10 million tonnes per year and the influence of wind is very important (Buijsman and Ridderinkhof, 2007; Ridderinkhof, 2008; Buijsman, 2008). This suggests that the sediment imports through this inlet is much more than reported by Elias (2006), which immediately raises many questions. More studies, particularly on the basis of field measurements are needed to resolve this inconsistency.

The sediment budget studies up to now do not distinguish between different sediment fractions. If, for example in a particular area sedimentation has occurred it is still insufficiently known whether it is sand, mud or a mixture that accumulates there. The relationship between morphological changes and the transport of different sediment fractions through different inlets has not been systematically studied yet.

The current sedimentation rate in the Dutch Wadden Sea is larger than sea-level rise. Yet it is the general consensus that there is a critical rate of sea-level rise above which the Wadden Sea will 'drown' (see e.g. Van Goor et al., 2003). However, there is no agreement about what the critical rate of sea-level rise exactly is. This lack of agreement partly results from a lack of knowledge of coastal processes inside the tidal basin, for example channel–shoal interaction and the related erosion and deposition. General understanding is that a larger basin is more likely to drown than a smaller one at accelerating sea-level rise. It is noted that the studies on the critical rate of sea-level rise so far consider the different tidal basins as isolated systems from each other. Given that sediment exchanges between the basins occur and boundaries between the basins are not fixed, the question arises to what extent the conclusions of those studies remain valid.

2.2. Changes at smaller scales

A tidal inlet system in the Wadden Sea consists of a number of morphological elements (Van Veen, 2005 [1950]) (Fig. 8). A tidal inlet between two Wadden Islands connects the tidal basin to the North Sea. Seaward of the inlet there is an ebb-tidal delta, often formed around a deep channel. On the delta itself, there are smaller morphological features moving from southwest to northeast. This shows that the sediment transport along the North Sea coast also includes transport over the ebb-tidal delta. Inside the inlet a flood delta is present. In general different modes of tidal basins are determined by the extent in which the flood-tidal delta is developed over the basin. In the Wadden Sea case the current basins all display a well-developed flood-tidal delta, as sketched in Van Veen's characterisation of a Wadden Sea lagoon (Fig. 9). This is believed to be due to the combination of moderate sea-level rise and availability of sediment from the adjacent barrier coasts (Stive and Wang, 2003).

Both the ebb-tidal and the flood deltas are characterized by channels and adjacent shoals, which are counterparts in the same system. Furthermore, the morphology of the basin is characterized by a branching channel structure similar to an apple tree (Van Veen, 2005 [1950]). This channel network takes care of the water supply during flood and drainage during ebb. Along the mainland coast and the Wadden Sea coasts of the islands salt marshes are often present. A good overview of research on the morphodynamic evolution of tidal inlet system as a whole and the various morphological elements is given by De Swart and Zimmermann (2009). They successively consider the stability of the inlet, the

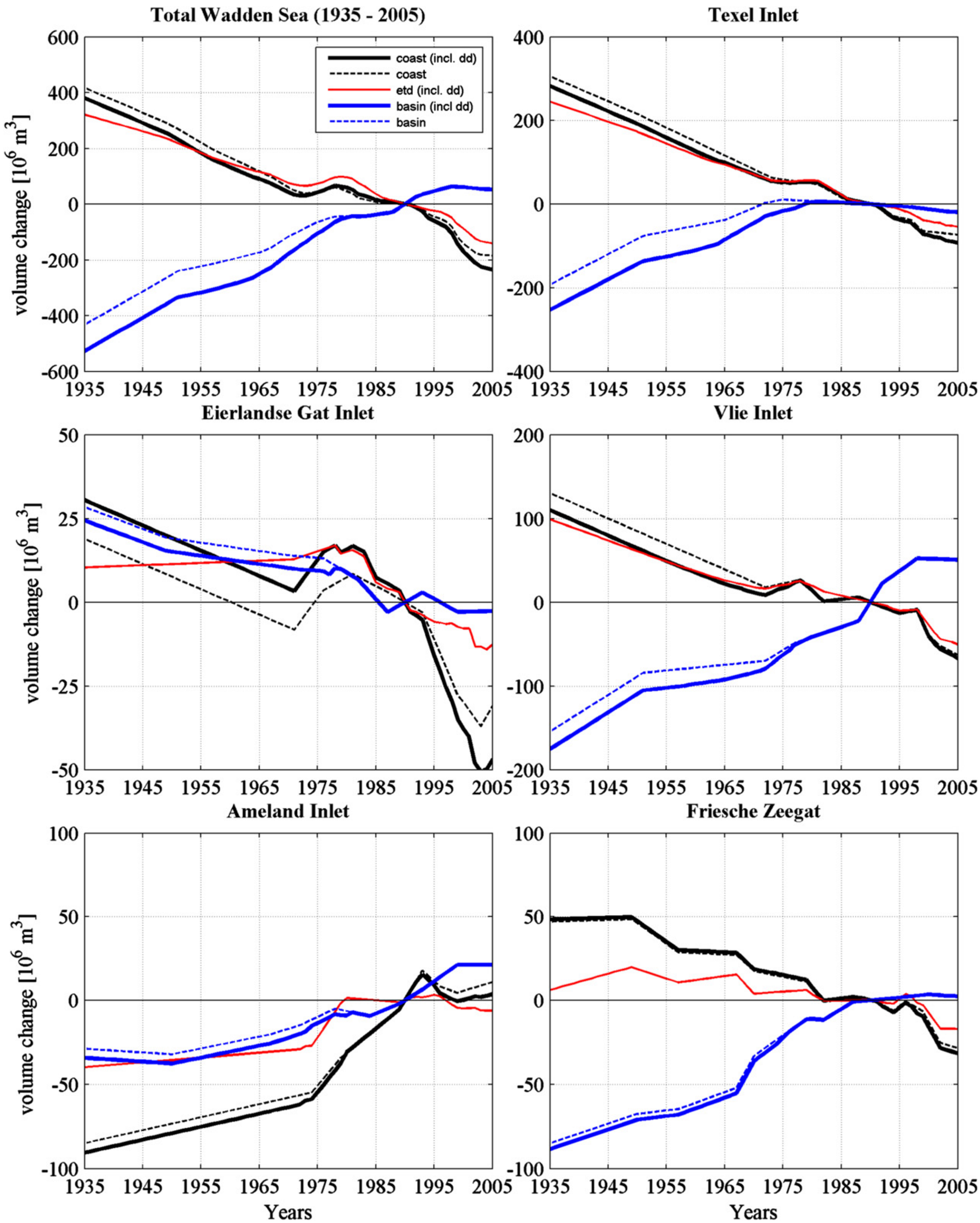


Fig. 7. Sediment volume changes (after Elias et al., in press). Note that etd = ebb-tidal delta (see Fig. 6) and dd = dredging & dumping.

development of the ebb-tidal delta, the morphological equilibrium of the tidal basin, the channel network, bars and meanders within a tidal channel, and the development of inter-tidal flats. They pay particular attention to stability analyses based on process-based models. In the following paragraphs the review of De Swart and Zimmermann (2009) is summarized for the various morphological elements.

The stability of a tidal inlet is determined by two competing processes: the tidal current which keeps it open, and the wind waves and associated littoral drift trying to close the inlet. Escoffier (1940) shows that a tidal inlet has a stable equilibrium if the tidal current (determined by the combination of tidal range and size of the basin) is sufficiently strong compared to the waves. The Wadden inlets belong to mixed energy tide-dominated inlets according

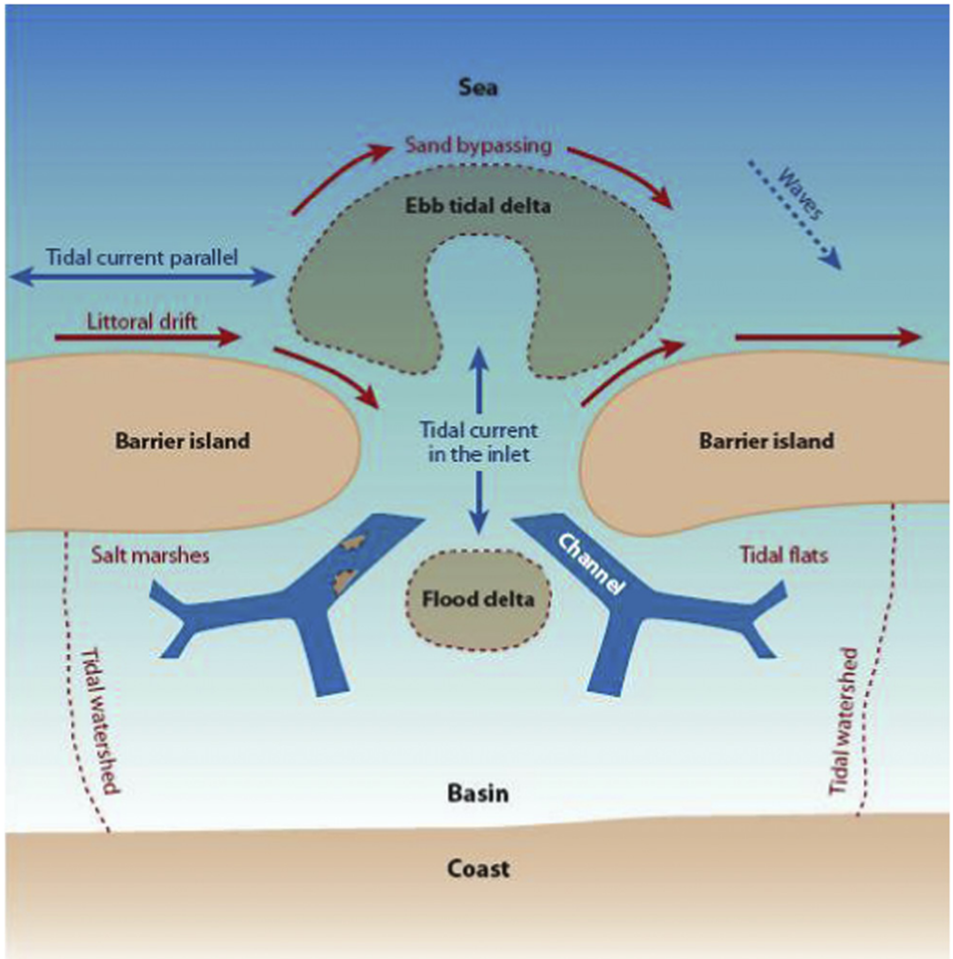


Fig. 8. Schematic sketch of a tidal inlet system, with different morphological elements and dominant physical processes and phenomena (Source: De Swart and Zimmermann, 2009).

to the classification of Hayes (1979, see Steijn, 1991), which apparently satisfy the stability condition. Extension of the analysis to system of several coupled inlets (Van de Kreeke, 1990; Tambroni and Seminara, 2006; Van de Kreeke et al., 2008) suggests that such a system tends to evolve into a single tidal inlet system, unless the interaction between the inlets themselves is weak. So this suggests that a system like the Wadden Sea can only exist because the flow

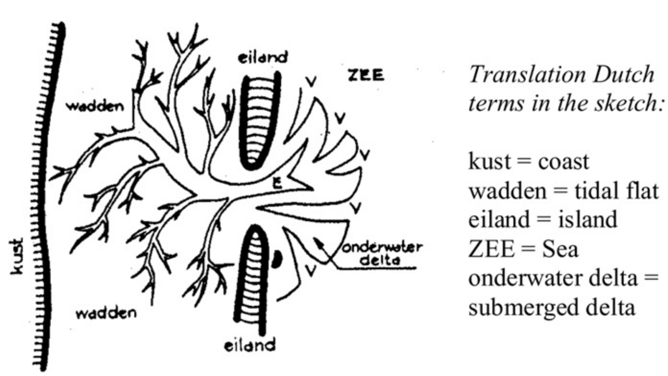


Fig. 9. Well-developed flood-tidal delta, as sketched in Van Veen's characterisation of a Wadden Sea lagoon.

and transport across the tidal watersheds are limited. Salles et al. (2005) though claim that for the stability of a multiple tidal inlets system the nonlinear processes not included in the above stability analyses, are important.

Many studies on ebb-tidal delta morphology are reported in the literature and many research questions have been formulated and addressed. To mention a number of these fundamental questions: How is an ebb-tidal delta generated? What factors determine the size and shape of the ebb-tidal delta? Why do the sandbanks on the ebb-tidal delta show a cyclic behaviour in time? Based on field observations one could already conclude that the formation of the ebb-tidal delta is related to the different flow structures during ebb and flood, respectively (see e.g. Sha and van den Berg, 1993). During ebb the flow behaves like a jet flow whereas during flood the flow to the inlet looks more like a potential flow. This is confirmed by the recent study by Van der Vegt et al. (2009); they demonstrate the formation of the ebb-tidal delta with an idealized process-based model. Their results also confirm the empirically found relationship between the size of the ebb-tidal delta and the tidal prism, and that the orientation of the main channel in the ebb-tidal delta is determined by the phase difference between the tidal current along the coast and that through the inlet.

The channels in the ebb-tidal delta and the inlet show dynamic behaviour. These channels migrate generally from west to east under influence of the tidal flow and the longshore sediment transport by littoral drift. The channel pattern shows a cyclic behaviour in time (Fig. 10) in which the existing channel decreases in importance as it approaches the east side of the ebb-tidal delta and eventually disappears (Oost, 1995; Isreaël and Dunsbergen, 1999). At the same time a new channel develops west of the inlet. This channel steadily grows in size and gradually takes over the role of the old channel (Oost, 1995). This process leads to a very dynamic behaviour of the channels in the inlets and the adjacent Wadden islands. Movements of hundreds of metres per year are quite normal. The cyclic behaviour of the ebb-tidal delta is closely related to the transport along the coast. However, it is also affected by the processes in the basin. Elias et al. (2005) demonstrate that due to the changes in Marsdiep caused by the closure of Zuiderzee the cyclic development of its ebb-tidal delta, as previously described by Sha (1989) no longer occurs.

The periodic supply of sediment from the ebb-tidal deltas to the North Sea coast of the down-drift Wadden islands results in a highly fluctuating coastline on a scale of years and decades. Fig. 11 shows the development of the coastline at cross-section Km5 of Schiermonnikoog. The periodic fluctuation of the mean low tide line (MLT) due to sediment supply from the ebb-tidal delta is clearly shown. The average coastline (average of annual averaged position of HW and that of LW) and the dune foot (DF) follow this behaviour with a time lag and damped amplitude. Superimposed on this cyclic behaviour the position of the coastline also shows a seaward trend.

Under the influence of tide-, wind- and wave-driven alongshore currents the sand will be moved in the eastwards direction along the islands (Houwman, 2000). Initially, this happens in the form of a more or less horizontal sand wave (see Prakken, 1989), then slowly but surely, the sand continues to be distributed and looses its coherence. Partly based on the results of the NOURTEC project (an EU pilot project on the foreshore nourishment), the following conclusions can be drawn regarding the coastal morphodynamics of the North Sea coast of the islands:

- The dynamics of the beach and the surf zone is strongly influenced by the behaviour of almost shore-parallel sand-banks along the coast at a water depth of 2–7 m. The surf zone

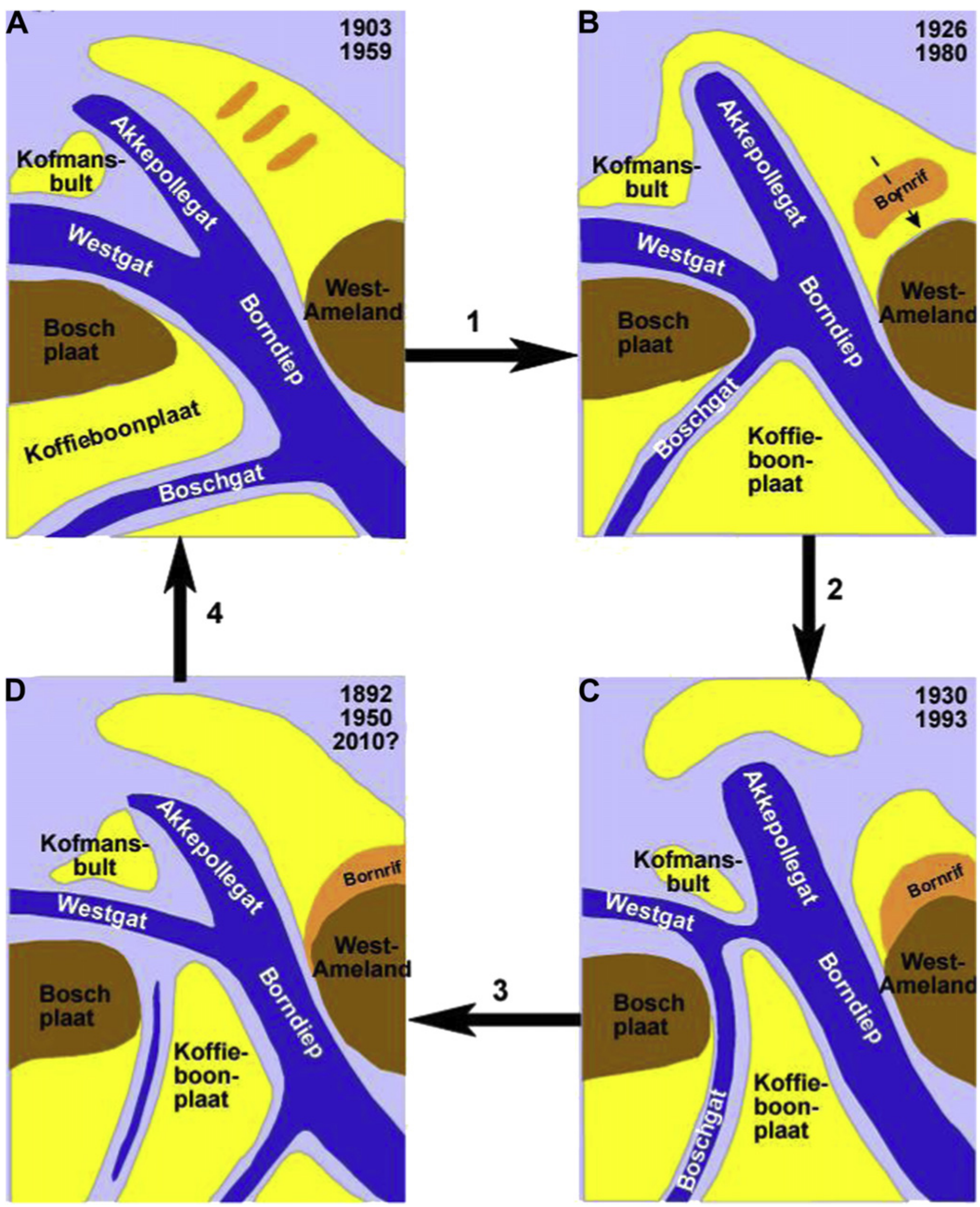


Fig. 10. Cyclic behaviour of the tidal inlet Amelander Zeegat (Dutch terms in the figure are names of shoals and channels) (Isreaël and Dunsbergen, 1999).

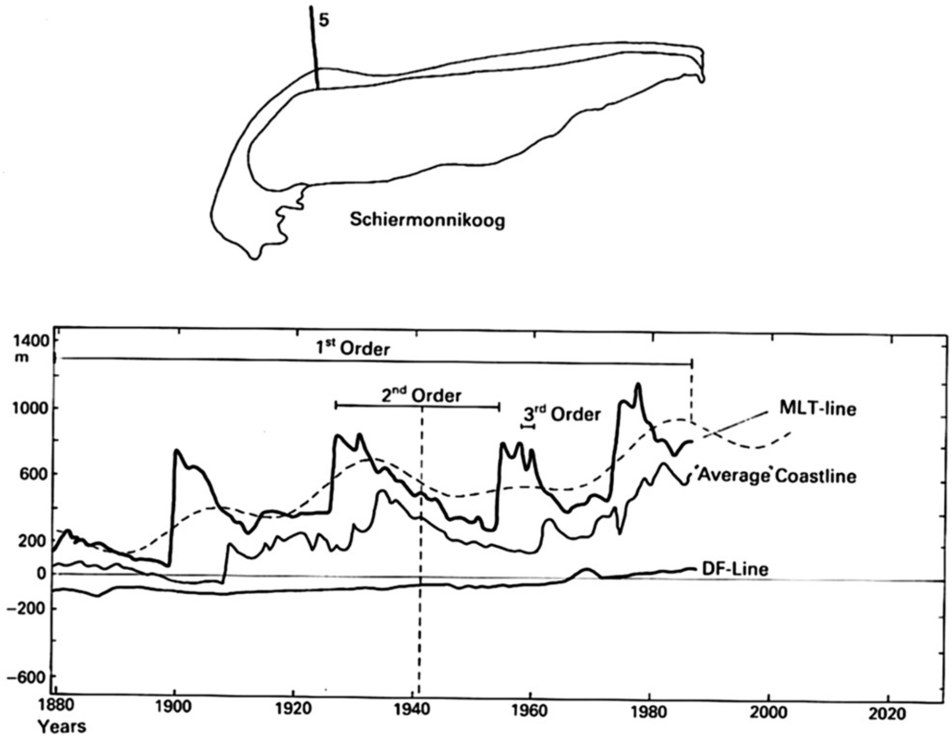


Fig. 11. Cyclic behaviour of the coastline of Schiermonnikoog (After Prakken, 1989). MLT = Mean Low Tide, "Average coastline" = mean of the Mean Low Tide and Mean High Tide line, DF = dune foot. The dashed line is a moving average of the MLT-line.

has often a strong dissipative character (Ruessink, 1998a) and extends over a distance of about 1200–2000 m offshore.

- These nearshore bars are generated close to the coastline before they migrate seaward and eventually disappear at the seaward side. With the disappearance of the most seaward bar the next bar starts to migrate seaward while a new bar near the beach is generated (Ruessink, 1998b).
- Important observation here is that during the cycle of generation, migration and disappearance of a nearshore bar neither net loss nor net gain of sediment in the surf zone occurs (Ruessink, 1998a, see also Wijnberg, 1995).
- Morphometric parameters such as bar height, depth, width and volume and migration parameters such as migration duration and migration rate vary in alongshore direction (Grunnet and Hoekstra, 2004). To the east end of the island the system of bars and troughs gradually changes into the system of channels and shoals of the ebb-tidal delta. The troughs achieve then a considerable depth.

Model experiments, in combination with measurements have shown that stirring up and transport by waves and wave-driven currents is the main mechanism of alongshore and cross-shore sediment transport. Wind-driven alongshore currents can enhance the transport but tidal currents are hardly capable of generating a residual transport (Grunnet et al., 2004, 2005). The cross-shore (suspended) sediment transport is the result of a subtle balance between the effect of the seaward wave-driven return flow due to wave breaking and the effects of short and long waves (Ruessink et al., 1998). Near and at the beach the wave field is dominated by effects of long waves (period> 20 s; Ruessink, 1998a, b), the so-called infragravity waves.

Based on measurements and calculations of sediment transport, the morphological response of the foreshore after a nourishment and the median grain size characteristics of sediment, it can be concluded that on a timescale of several years to a decade the development of the shallow foreshore to a depth of about 10 m (upper shoreface) is actually decoupled from the behaviour of the deeper foreshore (10–20 m; lower shore face, Hoekstra et al., 1999). In other words, on a time scale of years the shallow foreshore functions as a more or less closed system, while continuous transverse redistribution of sediment takes place under the effect of bar migration.

Wave processes in the cross-shore direction are responsible for a strong segregation of sediment fractions in the coastal zone with fine sediments near the dune foot (aeolian material), coarse sediment near the waterline (wave action due to swash-backwash processes) and a growing fining to deeper water (up to about −8 to −10 m) after which the median grain diameter may increase again with increasing depth. This natural distribution in median grain size is fairly robust and will, after introducing a disturbance (e.g. a nourishment of sand with deviating grain properties) quickly recover (Guillèn and Hoekstra, 1996).

Along the North Sea coasts of the Wadden islands the seasonal fluctuations in hydro-meteorological conditions play an important role. During storms, erosion of beaches and dunes takes place (Fig. 12) and under calm conditions this is wholly or largely compensated by accretion. In the foredunes aeolian deposition is stimulated by erecting fences to trap the mobile sand. These processes lead to fluctuations in bed levels, especially in the foreshore and on the beach. Bed levels may vary a few metres, for example due to the offshore migration of nearshore bars On some islands, e.g. Ameland a coastal retreat of one to a few metres per year takes place in the central part of the North Sea coast. Since 1990 this process is compensated by coastal nourishment.

Also in the Wadden Sea the bed morphology is very dynamic, partly due to a migration of channels. In or near the channels,

Fig. 12. Beach and dune erosion on Ameland after the heavy storm in 2006 (Photo by Johan Krol).

changes in bed level may occur of about 1 m/yr. Bed level changes on the tidal flats can be up to several centimetres or decimetres per year. Inter-tidal shoals, mudflats and salt marshes, are important and productive inter-tidal environments in the Wadden Sea. In the overview of De Swart and Zimmerman (2009), much attention is paid to the morphological studies of these elements. The fact is that our knowledge on the inter-tidal zone is perhaps the most restrictive compared to the other morphological elements. The development of the inter-tidal zone is determined by currents and waves, sand as well as mud transport and both physical and biological processes. As a matter of fact, the channel–shoal interaction in tidal basins should still be regarded as an unsolved problem. In addition, the special phenomenon of drying during ebb and flooding during flood tide in such areas is still difficult to handle in models. Salt marshes are vegetated areas of the inter-tidal zone. Salt marshes form the natural transition between the unvegetated mudflats and the landward located mainland coast or the Wadden Sea coast of the islands. They may be considered as an integral part of the coastal defence system because they reduce wave run-up during storms (Den Heijer et al., 2007). However, it is insufficiently known what role the marshes play in determining the boundary conditions of waves and water levels during storm surges for sea dikes along the Wadden coast. After the closure of Zuiderzee, sedimentation has taken place in the shallow parts of the Western Wadden Sea. In these areas, marshes can therefore occur. The question remains how these areas will continue to develop for different scenarios of sea-level rise. A rapid rise in sea level can easily result in a loss of inter-tidal flats and associated salt marshes. Salt marshes disappear by infilling or by cliff erosion. For the time being it is also unknown how the management of sand dikes affects the development of island marshes.

Watersheds which form more or less the boundaries between the different tidal basins will migrate in time. There is still a lack of knowledge about the processes, mechanisms and factors involved. The position of the watersheds cannot be considered apart from the positions of the inlets. Geologically, the positions of the inlets are determined (anchored) by the presence of large basins, old Pleistocene valley systems in the hinterland that determine a kind of structural control (Oost, 1995). However, nowadays the basins in the hinterland are closed by the coastal defence of the mainland. There is thus no more reason why the tidal inlets, islands and the watersheds should have a stable position in time. In fact, the whole system tends to move eastward. That is held back again by the defences of the island heads. Fixing the island heads directly stabilizes the position of the inlets and the tidal watersheds. The watersheds can still move under the influence of natural processes such as the periodic eastward growth of the islands. Furthermore, they can also move due to human interferences. The closure of the Zuiderzee caused a relocation of the watersheds between Marsdiep and Vlie and the watershed moved to the east. The same thing happened to the watersheds south of Schiermonnikoog Island after the closure of the Lauwerszee, although it is not easy to say whether it is a consequence of the closure or is simply the expression of an autonomous development in the tidal basin (Biegel and Hoekstra, 1995). It is noted that a distinction should be made between the hydraulic watershed and morphological watershed. The two do not necessarily coincide, especially for a disturbed system. The hydraulic watershed responds immediately after the introduction of a construction or disturbance but the morphological watershed has to follow with a delay. Qualitatively we can say that after a closure of a part of a basin, the basin is trying to increase in size in order to compensate the effect of the closure.

However, there is still insufficient knowledge to predict these processes and developments in the future. The results of the morphodynamic simulations by Dastgheib et al. (2008) suggest that the movement of the watershed between Marsdiep and Vlie can continue for a long time, but the predicted movement cannot be considered as reliable because of the schematisation and simplification in the used model.

In spite of the dynamic behaviour of the Wadden Sea system, a sort of morphodynamic equilibrium does seem to exist. An indication for this is that the morphological state of the system correlates well to the hydrodynamic conditions. This is partly illustrated by the following relations:

- The area of inter-tidal flats in a tidal basin relates well to the size of the basin.
- The total channel volume and the volume of the ebb-tidal delta correlate well to the tidal prism of the basin.
- The average level of tidal flats measured relative to low water relates well to the mean tidal range.

Under natural conditions, these morphological quantities change slowly or not at all. A disturbance caused by, for example, human intervention can trigger a relatively faster development, which ensures that once again the natural relationships between the morphological quantities and the hydrodynamic parameters are satisfied (see also Biegel and Hoekstra, 1995). The same applies to the disturbance caused by, for example, a change in the rate of the rise in sea level.

Empirical relationships between morphological variables and hydrodynamic parameters have existed for a long time, on both the scale of the whole basin (total volume of channels in a basin) and locally at the scale of the cross-section of a channel (O'Brien, 1969; Eysink, 1992). Only in recent studies it has been demonstrated, based on physical–mathematical formulations for flow and sediment transport processes, that morphological equilibriums exist and how they look like (Schuttelaars and De Swart, 2000; Lanzoni and Seminara, 2002). However, these theoretical considerations are limited to highly idealized cases. Less restrictive are the analyses carried out by using numerical models (Hibma et al., 2003a, b; Marciano et al., 2005; Van der Wegen and Roelvink, 2008; Dastgheib et al., 2008), see Fig. 13 for an example. Unfortunately, in these numerical simulations, even for basins of simple geometry, the aspect of large-scale morphological equilibrium is inseparable from phenomena at smaller scales, such as channel networks, tidal shoals and meanders in channels, for which also separate theoretical analyses can be found in literature (Schuttelaars and De

Swart, 1996, 1999; Seminara and Tubino, 2001; Schramkowski et al., 2002; …). An extensive review of various studies is given by De Swart and Zimmerman (2009). A critical view on the equilibrium concept and the empirical relations is also required in attempting to close the gap between the empirical knowledge and the process knowledge/process-based models.

2.3. Processes and mechanisms causing residual sediment transport

Knowledge about the basic processes that determine the import and export of sediment in the Wadden Sea system is of vital importance to understand the morphological development and ecological potential of the system. Likewise sediment transport processes in the Wadden Sea itself are equally important in explaining the behaviour of the system. However, research to improve understanding of the basic processes is not specific to the Wadden Sea but can be based on more generic studies as well. With regard to water movement it is noted that both currents and waves are important. There is as yet little research on waves in the Wadden Sea basins. The flow in the Wadden Sea is not only influenced by tides, but also by wind. The wind-driven flow is likely to provide a significant contribution to the transport across the watersheds. There is still little known about the role that storms play for the exchange of water and sediment between basins and the North Sea. With respect to sediment transport it is noted that not only sand but also mud transport is important. In the area of mud transport relatively much research into fundamental processes such as flocculation, consolidation, erosion and deposition has been carried out in recent years (see Winterwerp and Van Kesteren, 2004). Research has also been carried out for sand-mud mixtures but still limited, see for a recent overview Le Hir et al. (2011). Application of a sand-mud model to the Wadden Sea has been reported by Van Ledden (2003), Van Ledden et al. (2004) and Van Ledden et al. (2006).

Besides the physical processes, biological processes can also be relevant to the geomorphology of the Wadden Sea. Biological processes that may influence the development of morphology are investigated in biogeomorphology which can be considered as a subdiscipline in both the geomorphology and the geobiology. Biogeomorphological research consider two different questions, viz. (a) the impact of plants, animals and micro-organisms on the development of landforms and (b) the influence of geomorphology on the distribution and occurrence of plants, animals and micro-organisms. Biogeomorphology is an interdisciplinary field that links ecological processes with geomorphic processes (Naylor, 2005). Bioturbation, biostabilisation, bioprotection, biodeposition and bioconstruction are the main biogeomorphological processes that may influence both the large-scale and small-scale sediment budget. Although in the last 15 years relatively intensive biogeomorphological research has been carried out and published, so far an overall synthesis of this discipline is lacking. A good recent example of biogeomorphological research, namely the role of biofilms for sediment stabilization and its use for modelling sediment transport in the Wadden Sea, was published by Borsje et al. (2008). Biogeomorphology can provide very important contributions to the sustainable management of hydro- and morphodynamics of the Wadden Sea.

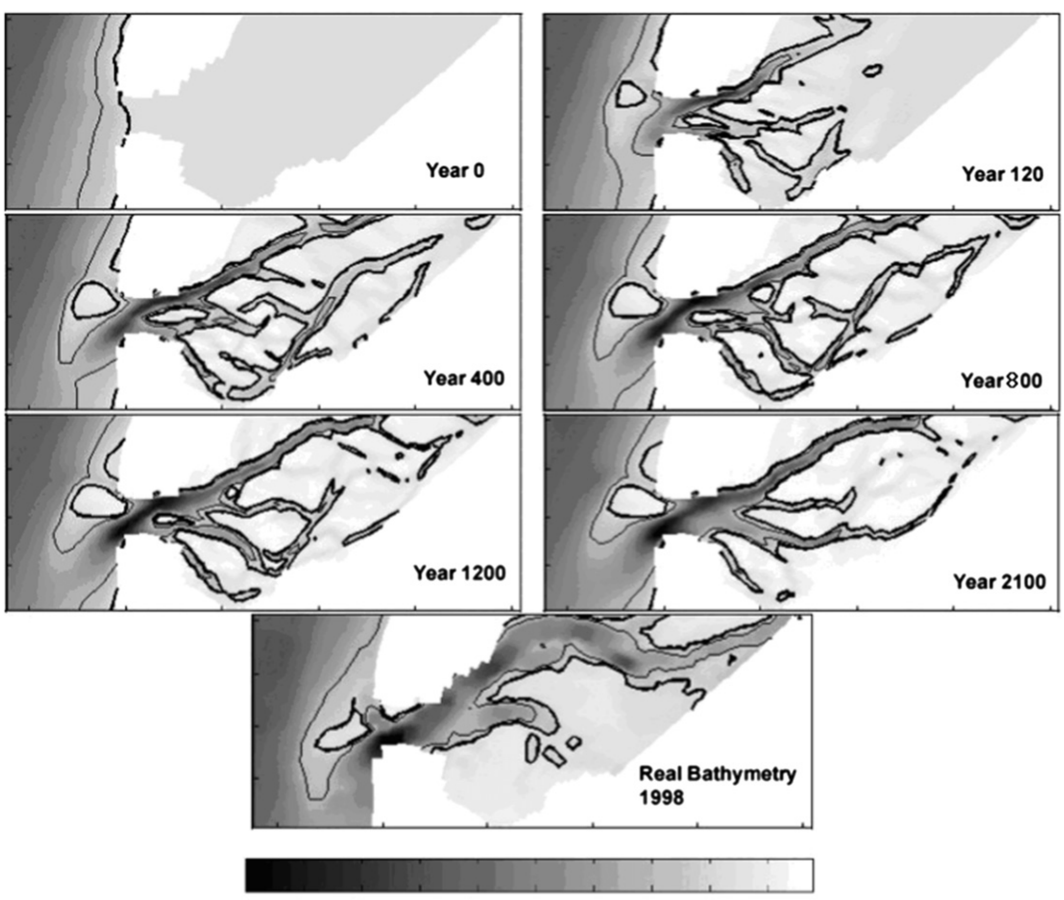


Fig. 13. Example of results of long-term numerical simulations for schematic cases (Dastgheib et al., 2008).

The mechanisms that lead to net sediment transport – either import or export – are specifically relevant to the Wadden Sea. Processes and mechanisms that affect the net sediment transport are: residual flow, tidal asymmetry, density currents, etc. (Ridderinkhof, 2008).

Tidal currents by far dominate the currents in the Wadden Sea. In analysis of long-term current measurements from a ferry in the Marsdiep tidal inlet (Buijsman and Ridderinkhof, 2007) it was shown that 98% of the variance in the water transport through the tidal inlet can be explained from the tides.

However, an 'ideal' tidal current, i.e. a current that is spatially uniform over the tidal excursion of a water parcel and has a sinusoidal varying magnitude over the tidal period, does not cause any net sediment transport simply because each sediment particle would return to its original position after a tidal period. Only deviations from such an 'ideal tidal current' cause a net transport of sediments. Such deviations are very characteristic for shallow areas like the Wadden Sea where tide–topography interactions induce residual currents and higher harmonics of the basic tidal components (Dronkers, 1986; Ridderinkhof, 1988; Friedrichs and Aubrery, 1988).

For the transport of sediments it is instructive to make a difference between the transport of relative coarse sediments (sand) and fine sediments (mud). The former are mainly transported as bed load and the latter as suspended load. For the Wadden Sea it is generally assumed that suspended load transport dominates over bed load transport.

For bed load transport difference between the magnitude of the currents during the flood and ebb period are most important since bed load transport is generally assumed to be proportional to u^n, in which u is the current speed and n a factor varying between 3 and 5. Thus a longer (shorter) flood period with lower (higher) currents than during the ebb period causes less (more) transport in the flood direction than in the ebb direction, even if the net water transport equals zero. These types of differences in the magnitude of currents during flood and ebb are mainly caused by:

- the presence of a net mean current, caused by tide–topography interactions or by wind effects and/or density gradients,
- the deformation of the tidal water level curve when it propagates through a shallow tidal basin, e.g. caused by differences in the propagation speed of a tidal wave at high and low water. If the high water tide propagates faster than the low water tide this causes a faster rising than faling tide and consequently stronger flood than ebb currents.

It is assumed that fine grained particles (mud) are transported as suspended load. Suspended particles move like water parcels with the current except for a period around slack tide when particles sink to the bottom. Depending on many characteristics of the particles, especially their size and density, the current speed at which particles start sinking to the bottom (deposition velocity) and are taken up and move with the current again (erosion velocity) may differ. In general, smaller and lighter particles spend less time on the bottom.

The fact that particles sink to the bottom around slack tide causes a net transport of particles if there are differences in the currents around slack water at the end of the flood as compared with the situation around slack tide at the end of the ebb. This was first recognised by Postma (1961) who used this mechanism to explain a net import of fine grained sediments into the Wadden Sea (see also Groen, 1967). For the Wadden Sea these kinds of asymmetries mainly arise by the decrease of the tidal current amplitude going from the tidal inlets to the land – ward end or from the tidal channels onto the tidal flats. For the Eems Dollard it was demonstrated that this is by far the dominant mechanism for the tide induced net import of fine grained sediments (Ridderinkhof, 1997). Moreover, this study clearly showed that the net transport of coarse grained sediments may be even opposite to the net transport of fine grained sediments.

For most of the Wadden Sea basins there is little freshwater inflow. Within the Dutch Wadden Sea, there is a significant river on the upstream side only for the Ems-Dollard, and Marsdiep receives some freshwater from the lake IJsselmeer (former Zuiderzee) through the locks in the Afsluitdijk. Despite the low net freshwater input into the Wadden Sea, the general existence of a horizontal density gradient between the Wadden Sea and the North Sea was proven for various parts of the German Wadden Sea, using monitoring data from pole stations (Burchard et al., 2008) and observations from the ferry in the Mardiep inlet (Ridderinkhof et al., 2002). In addition to freshwater discharges from land, differential effects of net precipitation and net heating or cooling (shallow water is heated up much stronger than deep water by the same amount of surface heat flux), have a significant influence on the establishment of horizontal density gradients in the Wadden Sea. During the warming period in spring, temperature and salinity gradients add up to result in a seasonal maximum of the horizontal density gradient (estimated as the high water to low water density difference at various pole stations). In late summer (when evaporation may be stronger than precipitation) and in autumn (when net cooling is strongest), density gradients have a seasonal minimum (see Fig. 14).

It is currently under scientific debate whether density-driven estuarine circulation (known as a major mechanism for generating turbidity maxima in tidal estuaries, Burchard and Baumert, 1998) could also be a relevant driver of net sediment transport into the Wadden Sea. Postma (1954) argued that gravitational circulation which at those times had been known as the only driver of estuarine circulation does not play a significant role in the Marsdiep (see also Zimmerman, 1976), despite its rather significant freshwater discharge from Lake IJssel. Since the work of Simpson et al. (1990) and Jay and Musiak (1994) another process is discussed as driver for estuarine circulation: tidal straining, i.e. the asymmetry in tidal mixing caused by the interaction between tidal shear and horizontal density gradients. During flood, denser offshore waters are sheared above less dense onshore waters, leading to a destabilisation of the water column. During ebb, less dense onshore waters are sheared above denser offshore waters leading to a stabilization of the water column. This tidal mixing asymmetry has the consequence of intense vertical mixing of tracers (salt, temperature, suspended matter) and of momentum during flood and suppressed mixing during ebb. As a consequence, during flood more onshore momentum is transported down to the bottom than offshore momentum is transported down to the bottom during ebb, a process which efficiently results in estuarine circulation, in addition to the gravitational circulation. Burchard and Hetland (2010) showed by means of a one-dimensional model setup that for well-mixed tidal estuaries such as the Wadden Sea tidal straining explains about 2/3 of the estuarine circulation with gravitational circulation explaining the rest. This was confirmed by idealized model simulations across a tidal channel carried out by Burchard et al. (2011): Even for situations with relatively weak horizontal buoyancy forcing, estuarine circulation was dominated by tidal straining, which was enforced by lateral advection processes as earlier described by Lerczak and Geyer (2004).

Using long-term velocity profile observations at various stations in the German Wadden Sea, Flöser et al. (2011) showed that density differences in the Wadden Sea indeed cause a significant tidal velocity profile asymmetry in favour of estuarine circulation. In an

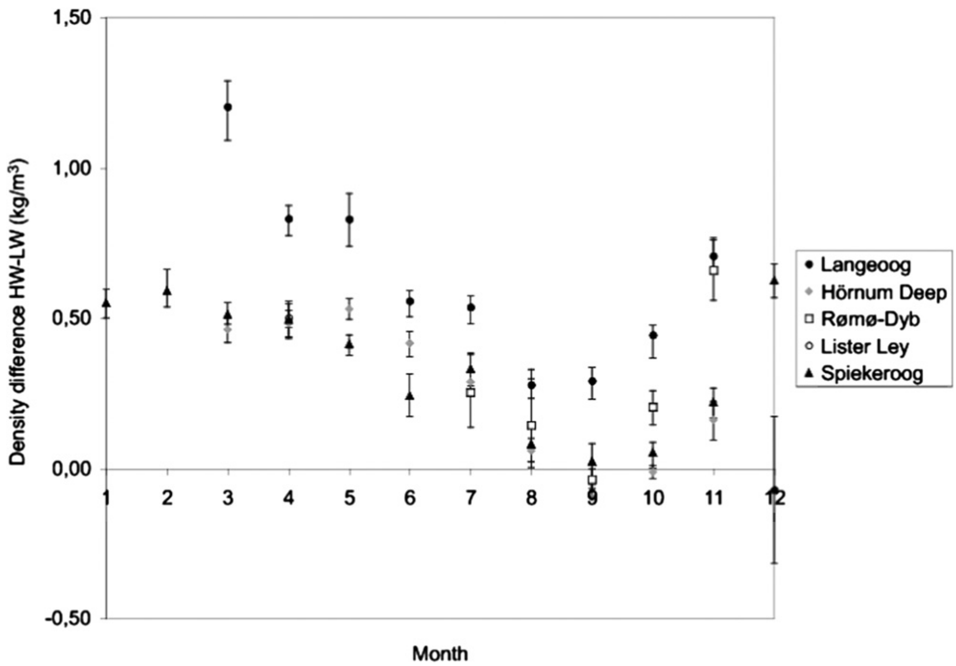


Fig. 14. Monthly climatology of density differences between high water (HW) and low water (LW) in the German Wadden Sea obtained from various long-term pole measurements. This figure has been taken from Burchard et al. (2008).

idealized three-dimensional model experiment of a tidal basin in the Wadden Sea, including freshwater discharge, Burchard et al. (2008) reproduced net sediment transport into this Wadden Sea basin only when considering the hydrodynamic effects of the density gradients on the residual circulation. Therefore, the hypothesis is justified that density-driven estuarine circulation in the Wadden Sea is a major driving force for net sediment transports into the Wadden Sea. This hypothesis needs to be further explored in the future to test its generality.

2.4. Modelling tools

Models for the morphological developments in the Wadden Sea can be divided into the following types:

- Empirical and semi-empirical models, also known as behaviour-oriented models. These models make explicit use of empirical relations to define the morphological equilibrium. An important assumption is that the morphological system after a disturbance (through natural evolution or by human interference) always tends to develop into a state satisfying the empirical equilibrium relations. The Asmita model (Stive et al., 1998; Stive and Wang, 2003), which is used as an important tool for determining the effects of interferences in the Wadden Sea, is a typical example of this type of models. The model uses a schematisation in which a tidal inlet system is divided into the main morphological elements ebb-tidal delta, channels in the basin and inter-tidal shoals and flats (Fig. 15). These elements exchange sediment with each other and with the surrounding morphological elements to develop into morphological equilibrium defined by the empirical relations. The model is easy to handle to simulate long-term developments. This makes it suitable to study the effects of sea-level rise (Van Goor et al., 2003) and large-scale human interferences (Kragtwijk et al., 2004) on the morphology of the Wadden Sea. This type of models, though, typically represents a black-box approach and does not specify the processes that are relevant for establishing a new equilibrium. Therefore, sufficient historical data for the calibration and validation is essential for this type of models. In a certain sense this can be considered as an example of data model integration (DMI).
- Process-based models. Such models aim at the best possible description of the relevant processes. An example is the Delft3D system (Lesser et al., 2004), in which the mathematical equations representing the physical processes of water movement and sediment transport are solved numerically to determine the morphological changes based on mass-balance for sediment. Such models can be used for detailed presentation for the morphological changes. Therefore they are also indicated as “complex” and “quasi-realistic” in the literature. This type of models is particularly well suited for short-term detailed simulations to understand the system (Elias, 2006). In recent years there has also been significant progress in long-term morphodynamic modelling with process-based models (Wang et al., 1995; Hibma et al., 2003a, b, 2004 Marciano et al., 2005; Van der Wegen et al., 2008; Dastgheib et al., 2008). For practical applications, the suitability of this type of models for long-term predictions is still limited. This is not just related to

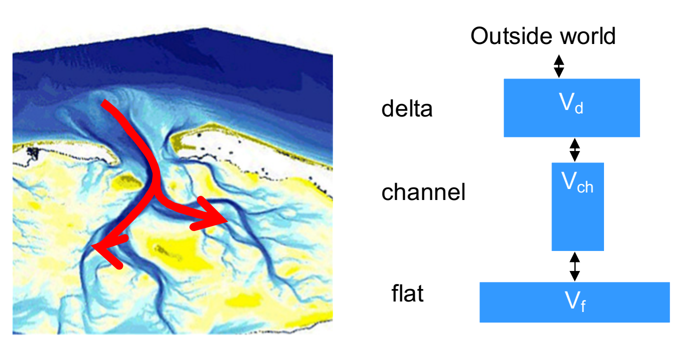


Fig. 15. Typical schematisation of an ASMITA model for a tidal inlet system in the Wadden Sea.

the required computing power, but also due to the limited insight into the behaviour of these models. One problem is that a long-term simulation often does not end in a morphological equilibrium as the empirical relations indicate. Other problems are the schematisation of the ever-varying driving forces (tide, wind and waves), representation of the "secondary" phenomena that determine the residual sediment transport, such as tidal asymmetry. A fundamental question here is: how predictable are the morphological changes? DMI techniques, e.g. by using remote sensing in combination with models, may improve the prediction capability of the models.

- Idealized models. This type of model is in fact a process-based model that makes use of simplified physical and mathematical descriptions to analyse the behaviour of a morphodynamic system. The difference with the 'complex' models is that they do not pursue full description of all processes, but try to reduce it to only the essential things that are relevant. An example of this type of models is the conceptual model of Postma (1961) on inland sediment transport in the Wadden Sea. The various models developed at IMAU for the different morphological elements within the Wadden Sea system (see review in De Swart and Zimmermann, 2009) belong to this type.

The different types of models should not be considered as competitors of each other, but rather as complementary to each other. To satisfy research objectives and to answer coastal zone management questions a combination of different models is often required.

Improving modelling should be achieved not only by improvements in the modelling tools themselves via e.g. implementing better physical and mathematical formulations, but also by improving the application of the models. A particular problem is the schematisation of driving forces. Simplifying the ever-changing tide by a representative tide and taking into account a more stochastic approach in driving forces such as wind and waves is still not a completely solved problem for morphological modelling. Especially the role of extreme events like storms is largely unknown.

3. Knowledge requirements

Knowledge of the morphological development is primarily needed for policy and management, not only for current affairs, but also for the long-term. Furthermore, knowledge requirements also arise from scientific research and the curiosity-driven wish to understand the behaviour of a system. Therefore, it appears to be difficult to clearly distinguish the need for knowledge based on these two different categories. The same understanding can be used to understand the behaviour of a system and to assess the effect of policy and management options. In that sense there is no distinction between the knowledge requirements for policy and management and those from scientific ideas. However, the priorities may differ: drowning marshes for example, may be just one of the many subjects worthwhile studying from a scientific point of view. In relation to societal issues (flora, fauna, biodiversity, ecosystem services), though, it may be a top priority.

Relevant policy and management issues in the Wadden Sea region are coastal safety and protection, degree of natural behaviour of the system, ecological values and biodiversity and the economic use as well as value of natural resources.

To guarantee coastal safety the Dutch North Sea coast of the islands has to be maintained by regular nourishments. The coastline is not allowed to move farther inland than the basal coastline (BKL) and the coastal foundation should keep pace with the sea-level rise. To plan, design and execute these nourishments proper knowledge of the behaviour of the coasts of the Wadden Islands in conjunction with the morphological evolution of tidal inlets is required. Understanding the alternation of sedimentation and erosion patterns of the coastline under the influence of the cyclic behaviour of the ebb-tidal deltas (see Fig. 11) is for example important for planning the nourishments in both time and space. Conversely, it is necessary to know what impact the beach and shoreface nourishments have on the development of the inlets. In addition, coastal nourishments can also have far reaching consequences for the local ecology and hydrology of a barrier island system, such as the fresh water bodies in the dunes.

The morphological development of the coast is also relevant to evaluate and understand the way in which extreme hydraulic conditions such as high waves and storm surge levels will affect the coast. A specific question is, for example, what role do marshes play in wave dissipation and coastal protection during severe storms?

The unique characteristics of the Wadden Sea can be threatened by both changing boundary conditions and human interference. If the rate of relative sea-level rise exceeds a critical value the Wadden Sea will eventually drown. This implies that the typical Wadden Sea inter-tidal shoals and mudflats, which are of great importance for the ecological system, would then disappear. A typical question is then: what will be the critical rate of sea-level rise? It is noted that effects of accelerating sea-level rise will not only occur when the critical rate is exceeded. In fact it is a gradual process. With accelerating sea-level rise, the morphological characteristics of the Wadden Sea will change. It is of interest to know how the morphological evolution of the Wadden Sea will be affected by sea-level rise at different rates. For the management of the Wadden Sea, the natural changes such as sea-level rise are considered as given boundary conditions. What can be done though is to investigate measures that can be taken to mitigate the negative effects. Additional coastal nourishments may be an option. But this will require a profound knowledge of sediment transport mechanisms in the Wadden Sea and the way in which these processes contribute to net deposition and morphological change.

To assess the impact of human interferences on local ecosystems not only changes in morphology (bathymetry/geometry) are relevant but also changes in substrate (sediment grain size composition) have to be considered. For distinguishing and assessing the impacts of human interferences the understanding of autonomous developments is a prerequisite since the effect of human activities has to be judged against the natural development. Not only the long-term trends but also the fluctuations on different time scales of the development are important.

Economic activities in the Wadden Sea also include navigation, fishery and mining. Here again knowledge of the system is a vital component in determining how the morphological evolution of the Wadden Sea affects these activities and vice versa. For navigation sedimentation in navigation channels and harbours is an important aspect. The related dredging activities have a direct influence on the morphology and the ecology. An increase in turbidity, for example, will reduce the primary production. To understand the influence of e.g. shellfish catch on sediment transport, knowledge of the interaction between the morphological and biological processes (biogeomorphology) is required.

In summary, for policy and management objectives knowledge of morphological development under the influence of natural processes and human interferences at different scales is essential. From a scientific point of view, our need for morphological knowledge can also be classified according to scale. To address the large-scale sediment budget of the Wadden Sea major questions are:

- Which sediment fractions appear to be relevant for deposition in the Wadden Sea tidal basins?

- How much import of each sediment fraction occurs in each tidal inlet?
- What are the dominant sediment transport mechanisms in a tidal inlet and what is their impact on sediment transport rates, directions and grain size composition?
- What determines the exchange of sediment between adjacent tidal basins?
- What role do extreme events like storms play in erosion and deposition of sediment?
- What are the consequences of various aspects of climate change (sea-level rise, global warming, changed wind patterns, changed precipitation/evaporation patterns) to net sediment transport into the Wadden Sea?

For the morphological changes at smaller scales, there are many intriguing questions:

- What determines the shape and size of the ebb-tidal delta?
- Which factors determine the typical tree-structure of the channels in the basin?
- What causes the cyclic behaviour of the ebb-tidal delta?
- Is there an interaction between this behaviour and development in the basin?
- What factors determine the location and migration of the watersheds between the basins?
- Which processes govern the transport of sediments between tidal channels and tidal flats?

To answer these questions fundamental knowledge of basic physical processes concerning water movement, sediment transport and morphological response is required.

In the coming decades sea-level rise, climate change and changing societal issues will determine a more policy-oriented research agenda for the Wadden Sea. Coastal zone management has to deliver proper answers to a number of “burning” questions: 1) How can we guarantee coastal safety and, simultaneously, maintain the dynamic and natural character of the Wadden Sea region? Can we use the present Wadden Sea system as a climate buffer to protect our coast? 2) Will we encourage and stimulate the natural character of the region or are we aiming at conservation in terms of (biogeo)morphology and ecology. If sea-level rise accelerates a fundamental question will be: are we acting against the adverse effects of sea-level rise or should we simply accept the natural response of the Wadden Sea ecosystem? And: what measures can we actually develop to preserve the present system? 3) How can we combine economic activities such as tourism, recreation and the exploitation of natural resources and the natural values of the system?

4. Knowledge gaps

The knowledge gaps are identified by combining the previous two chapters. They are summarized below using the same outline as is used in Chapter 2.

4.1. Large-scale sediment budget

Regarding the large-scale sediment budget the following knowledge gaps are identified:

- Transport field. Purely based on the sedimentation and erosion rates in the tidal basins it is very hard to determine the net sediment transports through the various inlets, between the basins and along the North Sea coast. In addition data from sediment transport measurements are only partly available and are not sufficient to provide accurate information on these sediment transport fields. The results of the TESO measurements up to now raise more questions and are not consistent with model results. Moreover, so far the sediment budget analysis is based on fixed boundaries and does not incorporate the migration of the tidal watersheds.
- Sediment budget per sediment fraction. Until now, sediment budget studies only determine the total amounts of sedimentation and erosion. Little is known about which sediment fractions have caused the changes. In fact a budget is needed per sediment fraction and at least a distinction is required between mud and sand. This will probably generate further research questions. The results of the sediment budget studies suggest that sedimentation in the Dutch Wadden Sea basins is more or less in balance with the erosion outside the Wadden Sea, along the North Sea coast. But the erosion at the North Sea coast will mainly supply sand, whereas a substantial part of the import is a result of mud deposition. As such, the distinction between mud and sand reveals a lack of balance in erosion and deposition rates.
- The uncertainties in the results of the sediment budget studies. Based on the bathymetric data sedimentation and erosion volumes are determined for various areas (tidal basins and associated coastal areas). However, this information is subjected to errors and uncertainties. Future research has to address these errors and uncertainties.
- The exact critical rate of sea-level rise. The present sedimentation rate in the Dutch Wadden Sea is larger than the rate of sea-level rise. However, if the relative sea-level rise accelerates it can reach a critical value. Important questions are:
  - What is the critical rate of sea-level rise per basin?
  - What factors influence this critical rate?
- The character and effect of mitigation. It is insufficiently known what measures can be effective in controlling undesired developments such as local drowning of shoals and tidal flats in response to accelerated sea-level rise.

4.2. Changes on a smaller scale

On a smaller scale, more knowledge has to be developed to understand the various morphological elements, in particular their size, shape and behaviour. The following morphological elements have to be considered:

- Channels in basins. What factors determine the typical tree-like or branching structure of the channels in the basin? What determines the shape of the cross-sections of the channels? Are we able to estimate or predict the amount of dredging that is essential to maintain the navigation channels?
- Inter-tidal flats. What factors determine the size, shape and bed level of inter-tidal flats? What determines the sediment grain size composition on these tidal flats and how relevant is the exchange of sediment between channels and shoals?
- Ebb-tidal delta. What determines the shape and size of the ebb-tidal delta? What determines the cyclic behaviour of the ebb-tidal delta? Is there an interaction between this behaviour and development in the basin?
- Interaction foreshore-beach-dunes. Most of the barrier islands have a drumstick shape with a broad head at the updrift side. As a result, the beaches are a-typical and are very different in morphology and behaviour when compared to “normal” North Sea beaches, such as observed along the Holland coast. Beaches are very wide and dissipative and the wave field is strongly 3D in character and very much affected by the nearshore

morphology and bathymetry of the ebb-tidal delta. It results in specific refraction patterns and the convergence and divergence of wave energy. In addition, the wave field on the beach is almost always dominated by low-frequency (or infragravity) waves, waves with a wave period > 20 s. (Ruessink et al., 1998). Due to this complexity of the coast, the safety levels of this part of the islands are difficult to assess and the present methodology – as established by law – fails in determining this safety level. According to this methodology, coastal stretches that are supposed to erode (accrete) show accretion (erosion).

- Coastal nourishment and other forms of nourishment in the future. The morphological, ecological and hydrological impact of coastal nourishments has to be determined in response to their design, dimensions and location.
- Watershed. What factors determine the location and migration of a watershed between two tidal basins?

4.3. Processes and mechanisms

Fundamental research into physical processes and mechanisms is essential to understand the role of sediment transport gradients in generating morphological change. Here only the knowledge gaps that are very relevant for the Wadden Sea system are summarized

- Wind-driven currents. For the shallow water areas such as the Wadden Sea wind-driven currents play an important role. The same applies to local wind-generated waves in the tidal basins. In both cases though, the impact of wind-driven processes is far from understood
- Mud transport processes. More knowledge is needed about the erosion of mud and especially sand-mud mixtures and associated processes such as resuspension, flocculation and consolidation.
- Interaction between water movement and sediment transport. Water motion affects sediment transport. However, at high concentrations a feedback may occur and a high concentration of sediment will also affect the water motion. There are indications that this is already the case in the Ems-Dollard estuary, where the turbidity levels have shown a dramatic increase. These turbidity levels may have an impact on hydrodynamic processes such as tidal mixing and the degree of turbulence.
- Mechanisms that lead to residual sediment transport. Qualitatively it is known which mechanisms are responsible for the residual sediment transport in the Wadden Sea (Van Straaten and Kuenen, 1957; Postma, 1961), but it is not known what contribution each mechanism has for various inlets. Each mechanism may also have a different impact depending on the grain size involved. Another important question is: are we still missing certain processes or mechanisms? For example: the impact of density gradients due to freshwater runoff and direct atmospheric freshwater and heat fluxes on estuarine circulation and net sediment transport needs to be further investigated on a regional scale.
- Biogeomorphological processes. In the last decades it has become clear that biological processes play an important role in the morphodynamics of the Wadden Sea. It is therefore important to know these processes and their variations in time and space in detail. “Bio-engineers” play an important role in (de)stabilizing the local substrate and are able to modify their own abiotic environment, e.g. by inducing bed friction, a deceleration of the flow, a reduction of turbulent kinetic energy and by encouraging deposition. For the time being, only a limited part of the ecological processes is already implemented in hydro- and morphodynamic models.

4.4. Modelling tools

For morphological modelling in tidal areas such as the Wadden Sea, in general a number of aspects are crucial and we should be able to tackle the following problems:

- Morphological equilibrium. There is still a gap between the theoretical and empirical knowledge about the existence of morphological equilibriums and the physical characteristics of these equilibriums. Observations suggest that morphological equilibriums exist and empirical relations are defined to link morphological properties in equilibrium conditions to hydrodynamic parameters. However, for a process-based morphodynamic model it is far from obvious that a morphological equilibrium is reproduced by the model. The groundbreaking work of Escoffier (1940) about the stability of tidal inlets already demonstrates that a morphological system may be characterized by multiple equilibriums, in this case a stable and unstable equilibrium.
- Parameters in behaviour-oriented models. Behaviour-oriented models use empirical relations for morphological equilibrium as the basis. The problem here is how the model parameters that describe the morphological evolution are related to the physical processes and the way in which we can derive these parameters.
- Schematisation of driving forces. Driving forces for morphological changes can be both deterministic (e.g. tide) as well as stochastic (e.g. wind) in nature. In a model, these aspects can only be included in a simplified manner. As an example, the issue how stochastic events like storms should be combined with deterministic processes such as tides is still under discussion and a standard approach is lacking.
- Predictability and uncertainty. Because of the stochastic nature of components in the driving forces the morphological development will not always be predictable. Or in other words: future driving forces are by definition almost unpredictable. We can only rely on realistic scenarios with a certain probability of occurrence. This probability of occurrence will tell us something about the degree of uncertainty in the morphological analysis and results.
- The interactive coupling between three-dimensional baroclinic hydrodynamic models and morphodynamic models needs to be further investigated and developed, a promising task in the light of further massive increase of computer resources.
- The proper implementation of closure models for turbulence and mixing is essential to quantitatively predict dynamics of sediment and the resulting net fluxes into the Wadden Sea. Processes like settling lag depend in a sensitive way on the dynamics of turbulence breakdown and subsequent turbulence generation in the course of slack tides. Effects of turbulence damping and enhancement by stable or instable stratification, respectively, are keys to the sediment transport processes such as the interaction between turbulence and water column stability due to high sediment loads or dynamics of tidal straining. Also the consistent two-way coupling between wave models and turbulence closure models is an important issue.

More specifically for the Wadden Sea, each type of models described in 2.4 have their own shortcomings:

- For the (semi-) empirical models a problem is the changing basin boundaries (migration of tidal watersheds). All the existing ASMITA models for the Wadden Sea are setup for a single inlet system having a basin with fixed morphological and hydraulic boundaries. Because of the dynamic nature of basin boundaries and the transport across the boundaries it may be necessary to improve these models and include more flexible boundaries.

- For the process-based models the points morphological equilibrium, schematisation of driving forces and predictability & uncertainty mentioned above are relevant. Further an additional problem is the representation of the relevant (secondary) signals. The residual transport, for example through a tidal inlet, is determined by secondary features of water movements such as tidal asymmetry. Many existing models for water movement are not well designed/calibrated to reproduce these properties of water motion. Proper representation of tidal asymmetry by a flow model with changing morphology, which is essential for process-based morphodynamic modelling, is still a major challenge. Gravitational circulation driven by horizontal density gradient is a 3D feature of the flow. Therefore it can only be represented in 3D flow models, whereas many tidal flow models for the Wadden Sea are 2DH models.
- The idealized models for the Wadden Sea can be improved by better schematisations of the geometry. Many of this type of models use a 1D-schematisation with constant width. A consequence is that the inter-tidal flats are insufficiently represented.

4.5. Recommended research

Obviously, extensive research is required to close the identified knowledge gaps. Presenting a plan/programme for the required research is beyond the scope of this paper. Here we only make some remarks on what types of research is recommended.

Research on the morphodynamics of the Wadden Sea and its barrier island systems can be done by data analysis, laboratory experiments, field survey, theoretical analysis and numerical modelling. A good combination of these various types of research will be essential for success. Analysis of existing data can still help us to learn more about the development of the system in the past. Laboratory experiments are especially useful for fundamental understanding of the basic processes which are not only relevant for the Wadden Sea system. Field survey will be an essential mean for improving our understanding of the system. There are still many questions which can only be answered with the help of measurements in field. Furthermore, the data from the field survey will be indispensable for setup and calibrating numerical models. New measurement techniques, especially remote sensing techniques, should be more explored and employed to obtain e.g. synoptic picture of the relevant processes/parameters. Theoretical analysis, with e.g. idealized models, is important because it can help us to understand the observed features and phenomenon and because it can help us to understand the behaviour of complex numerical models. Understanding of both the physical system and the used model is essential for numerical modelling. Numerical models, when well validated, are powerful tools for research and for supporting management of the system. Modelling results can be used to extrapolate the field survey data to complete and larger time-space domain and they can be used for making predictions.

The required research will be a continuing major effort involving various disciplines. An intensification of the research to the morphodynamics of the Wadden Sea system will be more than worthy given the importance of the area and the challenging problems to be expected.

Although the Wadden Sea is a unique natural system, the required research is not unique. In fact, many of the identified knowledge gaps apply to the tidal lagoons and estuaries in general. This is especially the case for the knowledge gaps concerning the processes and mechanisms and those concerning modelling in general. Therefore the required knowledge may also be obtained from the research to other systems. As an example, Friedrichs (in press) gives a review on the research to mudflats in general, a subject that is very important for the Wadden Sea. Although we cannot fully rely on the research elsewhere, the research to the Wadden Sea may benefit a lot from the research to other similar systems like the estuaries in UK, the Venice Lagoon, the East and Gulf Coast of USA, the Central Coast of Vietnam and the Jiansu Coast in China. Especially international cooperation research programmes in which different systems in the world are considered can be very helpful (see e.g. De Vriend et al., 2011).

Ethical statement

The work described in or manuscript has not been published previously. It is not under consideration for publication elsewhere. Its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere including electronically in the same form, in English or in any other language, without the written consent of the copyright-holder.

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This paper is based on a previous document or position paper (in Dutch) initiated by the Wadden Academy (part of the Royal Dutch Academy of Arts and Sciences) to discuss relevant geoscientific issues of the Wadden Sea (see Speelman et al., 2009; Wadden Academy, 2009). This position paper addresses three major subjects: the geological development and structure of the region (including the presence and development of mineral/natural resources), the Holocene coastal evolution and “present-day” coastal morphodynamics. The position paper was almost entirely based on data from the Dutch part of the Wadden system. Our present paper is an extended and strongly edited version of the position paper on coastal morphodynamics and includes an update of available information and additional text about processes and mechanisms relevant for residual sediment transport in the Dutch, German and Danish Wadden Sea.

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