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Geomorphology

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In 1994, the countries bordering the Wadden Sea agreed upon striving towards protecting and restoring nature in the Wadden Sea area as far as possible. This implies that large-scale interventions in the Wadden Sea system should be avoided. For a good appreciation of the quality of the present day Wadden Sea system, a clear understanding of its development through time is essential. This chapter provides an overview of the geomorphological development of the Wadden Sea over the past 1,200 years, illustrated by four paleogeographical reconstructions. During this period, human influence on the development of the Wadden Sea increased steadily, for instance through the construction of dikes and the extraction of peat. The paleogeographical reconstructions place the current human impact in a historical context and provide a reference for the trilateral Wadden Sea countries to strive towards their goal of a near-to-natural situation. Recent interventions such as gas extraction causing land subsidence, enclosure and reclamation of intertidal basins, the construction of artificial sand dikes and coastal defense structures will be discussed in this context.
The Wadden Sea consists of tidal flats and tidal channels, and is separated from the North Sea by a chain of barrier islands and ebb-tidal deltas over 75% of its length. It extends from Den Helder in The Netherlands in the west, along the coast of Niedersachsen and Schleswig Holstein in Germany, to the peninsula of Skallingen in Denmark in the north. Its existence and long life span hinge on a delicate balance of the relative sea-level rise and the availability of sediment. A sediment surplus caused by an increase in sediment input or slower relative sea-level rise would silt up the Wadden Sea. On the other hand, a sediment deficit caused by a decrease in sediment input or faster relative sea-level rise would result in a gradual loss of intertidal area of the Wadden Sea.

2. Natural preconditions

The general outline of the present day Wadden Sea can be largely attributed to a combination of the pre-existing relief in the area, variations in the tidal volume and storm surge frequency and wave climate.

The pre-existing relief of the Pleistocene surface influences the general position of the present-day Wadden Sea because of its position with respect to the present-day sea level: firstly, the steepness of the slope of the Pleistocene surface underlying the Wadden Sea is of influence on the morphological development of the Wadden Sea and the availability of sediment: a gentle slope is inundated faster during periods of sea-level rise than a steeper slope, and generally results in a higher availability of sediment. Secondly, the position of paleo-valleys in the Pleistocene surface that formed during sea-level lowstands determines the position of the tidal basins reaching inland, such as the Lauwersmeer, Ems-Dollard estuary, Jadebusen and the Elbe estuary. Thirdly, several of the barrier islands developed around a core of Pleistocene or older age, for instance Texel, Amrum and Sylt. Finally, sub-marine Pleistocene ridges can influence currents and wave impacts. For example, Blåvandshuk is a cuspatate foreland which is formed on the lee-side of the sub-marine ridge of Horns Rev (Kingo Jacobsen, 1992).

In the Wadden Sea, between Den Helder and Esbjerg, the continuous shoreline is replaced by barrier islands separated from each other by tidal inlets (Ehlers, 1988). The general morphology of the barrier islands is governed by wave and tidal forces (Hayes, 1979). The tidal forces are determined by tidal basin size and height (and hence paleorelief) and tidal range. Along the Wadden Sea, there is variation in tidal range (Figure 1).
and in significant wave height (1.3 to 1.6 m), both influencing the coastal morphology of the barrier islands. Between Wangerooge and the peninsula of Eiderstedt, only shoals are present with temporary primary dunes. In this area tidal ranges exceed ~2.9 m. From the German Bight up to the north, again barrier islands stretch from Eiderstedt up to Skallingen, the northern end of the Wadden Sea.

Under the influence of strong winds, water levels of the North Sea can reach extreme heights. Such storm surges can have a considerable effect on the morphology of barrier coasts and large land areas can be flooded and sometimes eroded. Channels created during storm surges can gradually develop into large tidal channels. For instance, it has been suggested that a breach of a relatively low and narrow dune belt between Den Helder and Texel during the storm surges of AD 1164 and 1170 eventually triggered the development of a large tidal inlet (Marsdiep) and helped change the freshwater Lake Flevo into a body of brackish water, the Zuiderzee (Oost et al., 2004). In addition, the Halligen in the German Bight were probably part of a larger salt marsh area that was eroded during storm surges in the Middle Ages. Specifically, one devastating storm in AD 1362, “die Grosse Mandränke” (great drowning), is often mentioned in this context, but the alleged impact of this legendary storm is questioned in historical studies (Buisman, 1996).

Through an interplay of the above-mentioned mechanisms, the present day Wadden Sea can be largely subdivided into three areas. First, a chain of barrier islands in front of a tidal basin extending from the western island of Texel, near Den Helder, up to the island of Wangerooge characterizes the western and eastern Frisian Wadden Sea. A notable feature is the decreasing length of the barrier islands towards the east, reflecting the increasing tidal range towards the east. Second, the area between the Jadebusen and the Eiderstedt peninsula is characterized by a series of mobile shoals and several large tidal inlets. The large tidal inlets are associated with a deeper Pleistocene surface representing the valley of the glacial Elbe and Weser rivers. Barrier islands are unable to develop in this area because of the macrotidal conditions. A third area encompasses the area from the Eiderstedt peninsula up to the Skallingen Peninsula in the upper north. This area consists of a chain of barrier islands, several of which enclose a core of Pleistocene or older age. The Halligen islands north of the Eiderstedt peninsula represent the remnants of a formerly extensive peat marsh and salt marsh environment.
3. Morphological development during the Holocene

1.1 Introduction
In the next chapter the morphological development of the Wadden Sea after the last Ice Age will be discussed. First in some broad steps, but in more detail for the period from 1000 AD until now, when humans exceedingly influenced the development of the area.

1.2 Holocene development
The early Holocene
During the last glacial, most of the North Sea was land and the nearest shoreline was off Bretagne in the south and near the Shetland Islands in the northwest. The rivers Ems, Weser, Elbe and Eider drained northward in a broad valley (Figge, 1980). When the continental ice-sheets started melting, sea level rose rapidly, forcing the shoreline to recede and flooding the present-day North Sea.

In The Netherlands and Niedersachsen, the deepest river valleys of the Pleistocene land surface underneath the present land area flooded around 8000 BP (Beets and Van der Spek, 2000). Sea-level was still some 20 m below its present level (Figure 2) and the coastline was much further offshore than its present position, 10 to 15 km for the Dutch coast (Vos and Van Kesteren, 2000). Smaller barrier islands or beach ridges were probably present in front of the coast as relics of Pleistocene headlands (Flemming and Davis, 1994). Because sedimentation rates were insufficient to fill the accommodation space created by the rapidly rising sea (1.0 m/century), much of the inundated surface evolved into subtidal environments, fringed at the landward side by a narrow zone intertidal sand and mud flats and pioneer salt marshes. In the course of the Holocene, the barrier islands and tidal basins shifted landward as sea level continued to rise rapidly. An increase in tidal ranges (Figure 2) resulted in stronger tidal currents which might have led to increased net sediment transport into the tidal basins (Vos and Van Kesteren, 2000). At about 5000 BP, sediment accumulation rates began to exceed the rate of sea-level rise. Thus, intertidal sand flats grew at the expense of subtidal environments, which ultimately disappeared (Van Heteren and Van der Spek, 2003). At this time, the Dutch and Niedersachsen chain of barrier islands were still situated several kilometers seaward from the present position: in the case of Terschelling about 9.5 km more seaward (Sha, 1990).

From 5000 BP to present, the chain of barrier islands has been migrating landwards with an...
average landward migration rate in the order of almost 2 m/year. The landward migration of the barrier is caused by sand loss on the seaward side. This sand was largely transported into the intertidal basins of the Wadden Sea, and more or less balanced the ongoing sea-level rise (Van der Molen and De Swart, 2001). The situation in the German Bight was and is different. In this area, sediments were partially transported off-shore during storm surges (Aigner, 1985).

During the following millennia, sea-level rise decelerated, and the infilling of the available accommodation space tipped in favour of net sedimentation. As a consequence, the landward part of the basins silted up and the salt marshes at the landward fringe of the tidal basin could advance seawards (Vos and Van Kesteren, 2000). The landward shift of the barrier islands and the seaward progression of the salt-marshes resulted in a decrease of the intertidal area of the Wadden Sea (Vos and Van Kesteren, 2000). The clastic tidal sediments accumulated in and along the Wadden Sea are interspersed with a series of peat layers representing periods of terrestrialization. Some of these peat layers reached a considerable extent (Behre, 2004). However, most of these fresh water marshes drowned again and clastic tidal sediments were deposited on top of them.

The Danish Wadden Sea formed about 5000 BP (Jacobsen and Madsen, 1993) in a similar way to the Dutch and Niedersachsen Wadden Sea. Once formed, the barrier islands retreated eastward with the relative sea-level rise. The difference with the Dutch and Niedersachsen situation is a slower relative sea-level rise (only ~12 m in the last 8400 years [Pedersen et al., 2009]) and a Pleistocene landscape consisting of Saalien moraines and gently sloping Weichselian outwash-plain deposits (Bartholdy and Pejrup, 1994). The gentle slope and slower sea-level rise may have resulted in the formation of a tidal basin with intertidal conditions since its formation, thereby skipping the period with subtidal conditions as has occurred in the Dutch and Niedersachsen Wadden Sea between about 8000 BP and 5000 BP.

In the area of Eiderstedt and North Frisia around 4500 BP the barriers and Pleistocene cores in the area formed an inlet-segmented coastline at the western part of the North Frisian tidal flat area (Meier, 2004). On the peninsula of Eiderstedt, the cores of present-day east-west trending sand-bars probably consist of eroded Pleistocene material and are a relict of this barrier system (Hoffmann, 2004). The sandy barrier system protected the hinterland and around 2500 years ago extensive marshes formed, consisting of thick sequences of clayey and peaty sediments with small scale relief due to differential compaction (Meier, 2004). Although a large part of these marshes eroded during storm surges in the Middle Ages, its remnants still dominate the morphology of the area.

### The late Holocene: Human settlement

#### Dutch and Niedersachsen Wadden Sea

The first settlements on the marshes along this section of Wadden Sea date from the 9th/10th centuries BC in Niedersachsen (Behre, 2004) and from the 5th Century BC in The Netherlands (Vos and Knol, 2005). Around AD, there is a large increase in the number of settlements along most of these coasts. During this period, the settlers built their houses on naturally elevated levees and did not have to rely on artificial elevation of ground level. The distribution of these old settlements reflects the coastline and riversides during the initial settlement period. Shortly after AD 100, an increase in storm flood levels occurred, and until the late Middle Ages the inhabitants of the coastal marshes protected themselves against storm surges by the construction of dwelling mounds (Vos and Knol, 2005; reconstruction AD 800). Protection of the farmland, which was regularly inundated in winter, was carried out only in the close vicinity of the mounds and existed of small local dikes. The first large-scale dikes were built at the end of the 10th Century AD (Van der Spek, 1994) safeguarding arable fields and meadows from the occasional summer and spring floods. They were, however, not sufficient for protection against all winter storm surges. Gradually, these ring dikes were connected and raised, and by the 13th Century a continuous system of winter dikes had been created.

The consequence of the extensive embankments was that the storm-surge levels increased due to the reduction in space that could be inundated during storm floods, in particular in the funnel shaped estuaries of the Ems, Weser and Elbe rivers. This led to frequent dike breaches. In response to this, the dikes were elevated and new areas were reclaimed, thus leading to further rises in the levels of storm floods. During the dike breaches, the floodwaters invaded the low-lying back-swamp areas whose surfaces had subsided due to drainage and subsequent oxidation, burning of surface layers for growth of cereals, and compaction. This made it exceedingly difficult to drain the flooded areas, and dike breaches became irreversible, creating new bays (e.g., the Dollard and Jadebusen). Around AD 1500, many
larger bays reached their maximum size. From this time onward, successful land reclamation started again, from time to time set back by severe storm surges.

Northern Frisia

The recovery of flint daggers and sickles dating from the Mesolithic proves the presence of people in the northern Frisian marshes at an early stage, but there is no continuity in the following periods. In the first centuries AD, the marshes were already densely populated, but later abandoned again, possibly in response to climate deterioration (Meier, 2004). Only since the 7th Century AD has the area been permanently occupied by humans (Meier, 2004). At this time, the first houses were erected on the marsh surface, indicating that the settlements were not seriously threatened by storm floods. In the 11th Century, storm-flood layers were deposited on top of the earliest cultural layers, indicating increased marine influence.

Later on, the northern Frisian marshes were protected by dikes, which required drainage resulting in compaction due to dewatering of the underlying sediments. In 1362 AD, a catastrophic storm surge inundated extensive areas protected by dikes. In particular, the areas consisting of thick clayey and peaty sediments that had experienced increased compaction could no longer be protected against the sea. Consequently, part of the former coastal marsh area was changed into a tidal flat area.

During the Middle Ages, people produced salt by burning the peat, which occurred in the coastal marshlands under a cover of clay. The area between Langness, Hooge and the mainland was most suitable for salt production because of the presence of a thick peat layer, and hence exploited. This peat extraction made the land especially vulnerable.
Morphological development during the last 1200 years

The development of the Wadden Sea during the last 1200 years is illustrated in 4 maps. The first map represents the situation in AD 800 for the Dutch Wadden Sea only. The subsequent maps represent the situation for AD 1500, AD 1850 and AD 2000, for the entire Wadden Sea. For the reconstructions, we used a selection of historical, geological and geomorphological maps and previous reconstructions of parts of the Wadden Sea. The level of detail of the various areas on the maps reflects the confidence of the reconstructions. With respect to the mainland peat bogs, the extent in the Dutch part of the Wadden Sea is reconstructed based on soil maps, topography and land subdivision, whereas the peat bogs in Germany and Denmark reflect the current extent in a general reconstruction, because no detailed reconstructions are available. This is a first attempt to establish a comprehensive overview of the development of the whole Wadden Sea, from The Netherlands to Denmark; the authors would welcome additions and remarks.

Morphological situation of the Dutch Wadden Sea in AD 800 (Annex 1)
The reconstruction of the Dutch Wadden Sea in AD 800 shows the situation before large scale human interference in the system. The situation in the Dutch part is thought to be representative for the most of the Wadden Sea in this time period. Clearly visible is the strong interconnectedness, showing rivers which debouche in the Wadden Sea and reach deep inland. In the direction of the mainland one could, at that time, go from the tidal flats via tidal marshes and extensive brackish areas towards the peats surrounding the higher sandy areas. Another striking feature is that the Holland coast was still partly open in the north and the area of Texel was still dissected by small inlets, with the northernmost island connected to Vlie-land. Furthermore, the Marsdiep inlet, in between Texel and Den Helder, had not yet fully formed. The inter-tidal area consisting of tidal flats and salt marshes extended to the higher Pleistocene grounds. The settlements on the coastal marshes were built on dwelling mounds, having a negligible influence on the large-scale tidal dynamics.

Morphological changes between AD 800 and 1500 (Annex 2)
By AD 1500, a large area of salt marsh attached to the mainland had been embanked. Large areas of land bordering the inland bays along the Dutch and Niedersachsen coasts had been reclaimed in the period before AD 1500, following a devastating loss of land due to several dike breaches in the Middle Ages. The land reclamations also led to a decrease in tidal volume which resulted in smaller tidal inlets. The Halligen islands were still much larger than at present, although storm surges during Medieval times had already dramatically changed the landscape. The reconstruction also shows that small parts of the saltmarshes on several barrier islands had already been embanked. This might have happened as early as the 14th Century.
Morphological changes between AD 1500 and 1850 (Annex 3)

From 1500 AD onward, successful land reclamation continued. The area of embanked salt marshes gradually increased and the size of the inland bays consequently decreased. The tidal flat area has decreased with some 58% (Delafontaine et al., 2000) by the embankment of areas which rose above storm surge level due to sedimentation and due to the closure of embayments. This decrease also led to a marked decrease in muddy areas in the Wadden Sea. The Halligen area, which was especially vulnerable after peat extraction for the production of salt, was struck by catastrophic storm surges (e.g., 1634, 1825) and large areas of land were lost, largely shaping the present-day Halligen landscape (Figure 3). Only a small percentage of the inundated marsh could subsequently be reclaimed. In the early 17th Century the first large-scale attempts took place to protect dune belts on the barrier islands. The intended stimulation of a closed vegetation cover was inhibited, however, by extensive livestock grazing. In this period, extensive artificial sand dikes were erected and maintained by placing brushwood fences which trapped and stabilized wind-blown sand. As early as 1633, the islands of Ejerland and Texel were connected by an artificial dune dike.

On many maps from around AD 1650, large intertidal areas in front of the Danish barrier islands are indicated. These have disappeared by AD 1850.

Morphological changes after 1850 (Annex 4)

After 1850, land reclamation occurred as part of the industrial development. Parts of the Wadden Sea were changed into harbours, other parts (e.g., Zuiderzee and Lauwerszee) were simply diked and embanked affecting the shape and size of the associated tidal inlets for many decades after the closure. The changes in the landscape were quite significant. On the barrier islands, a series of notable morphological changes occurred, mainly between 1850 and 2000 (Ehlers, 1988). These changes concern primarily island growth and reflect excessive sand supply. During this period, the islands of Ameland, Schiermonnikoog, Juist, Norderney, Baltrum and Wangerooge, and the Ostplate of Spiekeroog started to grow rapidly eastward, and salt marshes began to develop behind dunes formed on Memmert and Mellum. On Trischen, vegetation developed on newly formed dunes. The Kniepsand began to merge with Amrum. In Denmark, the Havsand and Juvre Sand merged with Rømø. Fanø extended northwards with the formation of new dune ridges and the Skallingen spit grew thereby protecting a larger part of the back barrier basin leading to salt marsh development (Ehlers, 1988).

Some of these contemporary morphological changes may have been caused by local circumstances, but the striking coincidence of so many positive shoreline changes makes it very likely that some common processes may have caused them. Since the period discussed here marks the end of the Little Ice Age (~1450 - 1850), a change in circulation following this period has been suggested as a driving mechanism for the observed changes (Ehlers, 1988). Also an increased deposition of nitrogen associated with the industrial revolution could have enhanced vegetation development.

On the barrier islands, the increase in tourism in this period resulted in the development of first seaside resorts on the Wadden Sea coasts. These permanent structures were built in highly dynamic
locations and were soon threatened by coastal retreat (Ehlers, 1988). In response, new coastal defense structures were developed, having an important impact on the morphological development of the islands. Most influential were the hard protection measures taken at the northwest and western heads of the islands Ameland, Borkum, Norderney, Baltrum, Spiekeroog and Wangerooge. The constructions have halted the threatening migration of the tidal inlets. In some cases however, this caused extreme deepening of the inlets.

In addition to groynes, seawalls have been constructed to protect the barrier coast where vulnerable to erosion. The steep profile of these structures increases the power of the waves, and therefore they are often marked by a more smoothly sloping revetment. The earliest seawalls were built of basalt; later, asphalt mounted with stones was used in order to increase the roughness of the surface and decelerate the waves. In recent decades, there has been a growing tendency to use sand nourishment rather than hard structures to actively protect the coast. An advantage of nourishment is that the beach is maintained dynamically, keeping natural processes of erosion and sedimentation intact. A disadvantage is that the sand has to be dredged somewhere else, consequently introducing sand that is different from the sand native to the islands, and thus influencing the habitat.

Except for these smaller scale interventions stabilizing islands, several large scale construction works were built after AD 1850 influencing the remaining intertidal areas. The most notable interventions between AD 1850 and AD 2000 were the closure of the Zuiderzee by the construction of the Afsluitdijk in 1932, the construction of the dams connecting Rømø (1949) and Sylt (1927) to the mainland and the construction of the Eider barrier in 1973, protecting the mainland from storm surges. The influence of a selection of these interventions is discussed in the following section.
5. Recent interventions

Nowadays, humans influence the Wadden Sea to such an extent that the impact might be considered a "geomorphological force" in its own right. This influence causes the Wadden Sea area to deviate from its natural situation. Two major groups of influence can be distinguished:

I. Influence on morphological development that is still exerted by large-scale interventions in the past, such as:

1) the diking of the higher tidal marshes, which effectively cut off the Wadden Sea from its hinterland that would be flooded during storm surges under natural conditions. The characteristic landscape existing of high supratidal mud-rich meadows, with occasional coast-parallel sandy/silty ridges and low-lying brackish areas has largely disappeared (Esselink, 2000).

2) The loss of land due to increasing vulnerability to flooding by peat excavation (inner and outer dikes) and drainage (e.g., Jade, Dollard, Lauwersmeer, North Frisian area (Kühn, 1997), but probably also in parts of the western Wadden Sea (Oost and Kleine Punte, 2004)). Several of the largest muddy embayments of the Wadden Sea are to some extent artifacts of flooding caused by peat extraction.

3) The loss of connectivity between the mainland, especially its rivers, and the Wadden Sea, following the closure and damming of many of the estuaries in the area. This loss resulted in the loss of many characteristic estuarine environments and species specialized in colonizing and occupying these brackish conditions.

4) The large-scale changes by humans in the Wadden Sea after 1900 still have their effect on the morphological developments in the Wadden Sea and the adjacent North Sea coasts. A well-studied case is the closure of the Zuiderzee area in 1932. Since then the westernmost Wadden Sea in front of it has been adapting to the new hydrodynamic conditions and over the period 1927–1997 (Berger et al., 1987) nearly 400 Mm3 of sediments have accumulated in the backbarrier, especially in the tidal channels, a large part of it being derived from the North Sea coastal zone, causing strong retreat of the coastline and size reduction of the ebb-tidal deltas. From the developments, it can be judged that the effects of the damming will continue to influence the area for many decades (Elias, 2006).

5) A fifth large-scale change is brought about by all kinds of other protection works along the North Sea coasts, such as dikes and eolian dikes (probably since at least the 13th Century), groins (since at least the 18th Century), seawalls (since the 18th Century), harbour moles (since at least the 19th Century) and massive discharge sluices (since the 19th Century). Such defences have resulted in the fixation of inlets (e.g., North-Rhine-Westphalia and sandy coasts (e.g., northern Texel), which effectively limits the possibility of inlets to shift. One effect is that longshore barrier-island dynamics have become more limited than before. As a result, opportunities for pioneer vegetation have dwindled and dune belts have experienced an uninterrupted succession of the vegetation cover (Löffler et al., 2008). The range of protection measures is also known to have influenced the development of complete inlet systems (Elias, 2006).

II. Influence that is exerted by current interventions, such as:

1) The dredging of harbours and channels, leading to a higher rate of trapping of fine sediments during a large part of the year, short periods of intense turbulence during dredging activities and re-suspension from the dumping sites. The exact cumulative effects are not exactly known.

2) The deepening of channels, leading to higher tidal amplitudes, larger tidal volumes and sometimes higher current velocities (e.g., the Ems estuary).

3) The stimulation of tidal marsh formation, leading to silting up of the inner edges of backbarrier basins in particular (e.g., the mainland coasts of Niedersachsen; Ehlers, 1988; Dijkema et al., 2007).

4) Beam trawling of the sea-bed to catch demersal fish, but especially shrimp and mussel (seed). Several morphological influences are possible. Firstly, it disturbs the internal structure and layering of the sediment, with its flora and fauna. As such sediments can be considered to form an underwater soil profile that builds up over a given amount of time, this might have far reaching effects, such as a shift to more opportunistic infauna which was also observed as an effect of mechanical cockle-dredging (e.g., Piersma et al., 2001; Zwarts, 2004). Furthermore, some grades of sedimentary particles, such as shells or silts, are removed as part of the exploitation, leading to different grain size and hence to different developments.

5) The enhancement of dikes leading to prolonged morphological inactivity in the area cut off from the Wadden Sea.

6) The discharge through sluices leading to irregular brackish situations which have their effects on biota and sedimentation and small scale estuarine circulation patterns.
7) The cultivation of mussels in the Wadden Sea, leading to locally enhanced deposition of fines during quiet weather conditions (mainly during spring and summer). On the other hand, during rough weather conditions (mainly during autumn and winter) they may act as point sources and lead to enhanced turbidity of the water.

8) The import of exotic species that change the sediment characteristics. A good example is the Pacific Oyster (Crassostrea gigas), which nowadays is omnipresent in the Wadden Sea. It influences the sedimentation of fines because it is a filter feeder. It also influences the local morphological development by forming shells and reefs. However, at the same time, many of the oyster beds have displaced mussel beds, which thus have to a large extent disappeared. Another example is the introduction of Spartina anglica grass, which enhances sedimentation at the edges of salt-marshes.

9) The nourishment of sand on the coasts of the barrier islands is currently subject to debate. Locally it influences the morphological development, by preventing net coastal erosion. Any influence on the morphological development of the Wadden area as a whole at present-day volumes has not yet been proven.

10) Subsidence caused by oil and gas extraction (Niedersachsen and The Netherlands). Although the subsidence at the surface is limited in the vertical sense, it extends over large areas. Hence volumes involved are large (Mm$^3$). As a reaction extra sedimentation compensates for the subsidence in these areas, which is mainly derived from the North Sea coasts of the barrier islands (Oost et al., 1998).

The relative importance and cumulative effects of all these short- and long-term influences will remain subject to debate in the years to come. Comparison between the countries bordering the Wadden Sea and learning from past reconstructions might strongly enhance the understanding of process-response relationships and of measures needed to minimize negative impact of existing and future actions.
In 2009, much of the Dutch and German Wadden Sea and its barrier islands became a World Heritage Site as a tribute of its geomorphological and ecological values. This designation brings an obligation for the responsible countries to keep natural values at the present level. Since the larger part of the Wadden Sea already is highly protected, this obligation will be met by enforcing existing laws. Within the Wadden Sea, some areas are entirely protected, such as Hörnum Deep, where no exploitation is allowed, and the islands Rottumerplaat en Rottumeroog, where all coastal protection measures were terminated. Here, the natural dynamics prevail.

Nowadays, for a number of interventions, mitigation measures are taken. For instance the velocity of subsidence of new gas fields is limited to what is considered a safe limit in The Netherlands, thus minimizing the effects on the morphological development (NAM, 2006). Furthermore, studies are carried out to minimize the effects of nourishments, channel maintenance (Hartsuiker and Grasmeijer, 2008) and trawling fisheries. Also studies are carried out to increase natural dynamics on a larger scale on the barrier islands.

In the previous overview, we made a first attempt to reconstruct the development of the Wadden Sea from AD 1500 onwards. We are well aware of the shortcomings which are still present and welcome any suggestions. But even from this first attempt some general conclusions can be drawn. Summarizing:

1) The earliest reconstructions of the Dutch Wadden Sea of AD 800 and the entire Wadden Sea of AD 1500 reflect a situation of a natural and largely natural Wadden Sea, respectively. The following maps of AD 1850 and AD 2000 illustrate the increasing human interference with the Wadden Sea system.

2) In its main characteristics, the Wadden Sea coastal configuration has, by and large, remained much the same over the past 500 years as is apparent from the similarity between the reconstructions. For example, the area of tidal flats and island size is largely comparable in the reconstructions of AD 1500, 1850 and 2000. This suggests that the Wadden Sea system as a whole seems to be largely in a kind of dynamical equilibrium over this period, morphologically speaking.

3) However, if one looks more closely, it shows that all the mainland coasts have become straighter and therefore shorter, partly due to natural sedimentation and erosion, and partly due to human interference, which became very significant in the 20th Century.

4) Also, all the mainly sandy, barrier islands have changed to some extent in form and some (e.g., Buis) have disappeared. The coast is clearly receiving the full brunt of the North Sea hydrodynamics and will continue to do so. Comparison of the changes on all the barrier islands through time might provide clues as to what to expect in the future when climate is expected to change.

5) Also, there is a marked difference between the development of the east-west trending Wadden Sea of The Netherlands and Niedersachsen and the north-south trending Wadden Sea of Schleswig-Holstein and Denmark. Whereas the first Wadden area is rather stable, the northern Wadden Sea area has undergone significant drowning and land-loss (e.g., the Halligen and intertidal areas in front of the Danish barrier islands). It is not completely clear why these differences occur.

These reconstructions of the entire Wadden Sea provide a first overview of the various morphological developments occurring in the Wadden Sea system through time: from a fully natural system around AD 800 to a human influenced system by AD 2000. Hence, we suggest they are used as a "morphological reference guide" when striving towards a near-to-natural situation. We hope that these reconstructions will further discussions on which situation is natural. We propose to produce more extensive reconstructions of the morphological development, both in spatial resolution and in time, preferably going back all the way to 5000 BP, when the Wadden Sea started to form.


Literature used for the construction of the paleogeographical maps

The following list contains additional sources used for the construction of the Paleogeographical maps.


Legend

- Dwelling mounds
- Dunes and higher shoals
- Intertidal areas and salt marshes
- Peat bogs
- Pleistocene and older
- Water
- Germany

AD 800
Annex 2: A.D. 1500

AD 1500
Legend
- Dunes and higher shoals
- Intertidal areas and salt marshes
- Endiked areas and high marsh area
- Peat bogs
- Pleistocene and older
- Water

Pleistocene and older
Water
Annex 4: A.D. 2000

AD 2000

Legend
- Dunes and higher shoals
- Intertidal areas and salt marshes
- Endiked areas and high marsh area
- Peat bogs
- Pleistocene and older
- Water