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Wadden Sea Quality Status Report

Geomorphology

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1. Introduction

The hydro- and morphodynamic processes of the Wadden Sea form the foundation for the ecological, cultural and economic development of the area. Its extraordinary ecosystems, its physical and geographical values and being an outstanding example of representing major stages of the earth's history are factors why the Wadden Sea received a World Heritage area qualification (UNESCO, 2016). During its existence, the Wadden Sea has been a dynamic tidal system in which the geomorphology of the landscape continuously changed. Driving factors of the morphological changes have been: Holocene sea-level rise, geometry of the Pleistocene surface, development of accommodation space for sedimentation, sediment transport mechanisms (tides and wind) and, the relatively recent, strong human interference in the landscape.

In this report new insights into the morphology of the trilateral Wadden Sea gained since the Quality Status Report (QSR) in 2009 (Wiersma et al., 2009) are discussed. After a summary of the Holocene development (sub-section 2.1), the sand-sharing inlet system approach as a building block for understanding the morhodynamic functioning of the system with a special emphasis on the backbarrier (sub-section 2.2) is discussed, followed by other parts of the inlet-system. The foreshore and the ebb-tidal delta development is discussed in sub-section 2.3, the islands in sub-section 2.4 and the islets in sub-section 2.5. The morphology of the estuaries is discussed separately (see report on "Estuaries").

2. Status and trends

2.1 Holocene development

From 8000 BC onwards the lower parts of Pleistocene valleys of rivers, such as Elbe, Weser and Ems were inundated and changed into tidal basins. At the landward side of these basins peat was formed. During the period around 2000 BC, sea level rise slowed down and the sediment infill of the basins could keep up with it. At the borders, sedimentation was faster than sea-level rise, salt-marsh areas extended seaward and coastal peat marshes increased in size. During the period between 500 BC and 1500 AD, several marine ingressions occurred, due to subsidence of the marshland surface in the hinterland. The subsidence had natural and anthropogenic causes. A natural cause was penetration of tidal creeks which drained and lowered the peat, after which clay deposited on top of it, leading to further subsidence. In the last part of the Holocene, subsidence was mainly due to agriculture and diking. With the beginning of dike construction, coastal lowlands and marshes became decoupled from marine sedimentary processes. The peat of the farmlands compacted, but there was no compensation by clay deposition. Storm surges have had large-scale morphological effects by flooding these lands. The peat area became lower due to drainage, erosion and compaction of the peat areas leading to land loss (e.g., Jade Bay & Ems-Dollard, Figure 1). In addition, new accommodation space was created due to the on-going sea level rise, which, on the mud- and sand flats, could not always be filled up due to sediment deficits (Chang et al., 2006). Since the systematic construction of modern dykes, the coastline of the Wadden Sea has become relatively stable. as such it is a significant change in the long-term trend.

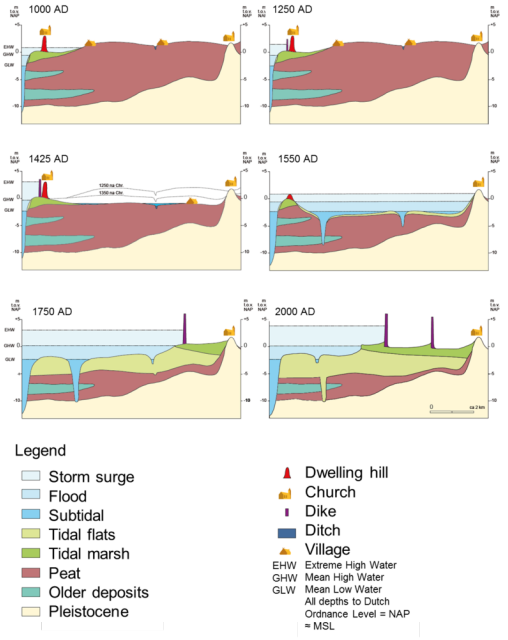


Figure 1. Schematised cross-sectional reconstruction of the Dollard area (E=W) between 1000 and 2000 AD (Vos & Knol, 2015).

In the previous QSR (Wiersma et al., 2009), several distinctive regional palaeogeographical maps were reconstructed for the trilateral Wadden Sea (Wiersma et al., 2009). Recently, strongly improved versions have been produced for the Dutch and German Wadden Sea (Appendix I; Vos & Bungenstock, 2013; Vos & Knol, 2013; Vos, 2015). Behre and others compiled Lower Saxony coastline maps and palaeogeographical maps of the Jadebusen (Behre 2004, 2012; Karle et al., 2016). Homeier et al. (2010) compiled historical data from the past 500 years within a GIS-based framework. In Schleswig-Holstein and in the Elbe region, valuable landscape reconstructions for the past two millennia have been made (Meier, 2006, 2014; Lindhorst, 2007; Meier et al., 2014). Pedersen et al. (2009) reconstructed the Holocene development of the Varde Å Estuary in Denmark. Fruergaard et al. (2013, 2015a, 2015b) reconstructed the Holocene development of the Danish barrier islands. Together, these reconstructions provide an overview of the major changes due to natural forcing and the interference of man.

In modelling the short- and long-term effects, palaeo-tidal landscape reconstructions are a useful tool to understand and predict morphological changes for different sea level scenarios (the past as key to the future). The palaeogeographic 4D model reconstructions can be used to calibrate numerical models for landscape changes of the Wadden Sea area in the close and more distant future. Besides for modelling purposes, the palaeo-landscape maps can also be a useful 'landscape-reference' to develop the nature policy and management of the Wadden Sea area.

2.1.1 Holocene sea level rise

For the trilateral Wadden Sea coast, several sea level curves have been published based on different methodological approaches (e.g.,

Jelgersma, 1979, Roep & Beets, 1988, van de Plassche & Roep, 1989, Denys & Baeteman, 1995, Behre, 2007, Bungenstock & Schäfer, 2009, Pedersen et al., 2009). Vink et al. (2007) show the differences of the sea level curves along the North Sea coasts of The Netherlands and Germany as a result of glacio-isostatic adjustment (GIA) during the Holocene as earlier discussed by Kiden et al. (2002). The GIA is probably one of the main reasons for differences in relative height of sea level data over time, but also local factors as tidal conditions, sediment budget and, most important, paleogeography are influencing the development of sea level induced local water levels. Therefore, coastal sections are represented by their own local sea level curves directly linked to the palaeogeographic development (Bungenstock & Weerts, 2011, 2012, Baetemann et al., 2011).

2.1.2 Formation of the Wadden Sea islands

The bulk of the sediments which form the barrier islands consist of locally reworked Pleistocene sediments selected, transported and deposited by marine processes into the Wadden Sea as demonstrated by the mineralogical composition (e.g., Winkelmolen & Veenstra, 1974, Veenstra & Winkelmolen, 1976). Mud was mainly brought in with North Sea water, whereas the deposited sand mainly derives from the North Sea coasts. About 10 % of the sediments are of fluvial origin (Hoselmann & Streif, 2004).

The bulk of the West and East Frisian barrier island chain formed between 6000-5000 BP (for budget studies see: Beets & Van der Spek, 2000; Hoselmann & Streif, 2004). At first, sedimentation rates were insufficient to fill the accommodation space created by the rapidly rising sea (1 m/century). Much of the inundated backbarrier area evolved into subtidal environments, fringed at the landward side by a narrow zone of intertidal sand and mud flats and salt marshes. At about 5000 BP, decelerating rates of sea level rise were exceeded by sediment accumulation rates so that intertidal sand flats grew at the expense of subtidal environments (Van Heteren & Van der Spek, 2003, Vos et al., 2011). As a result of the sediment transport into the backbarier area, the barrier islands coasts eroded. Due to erosion and slow flooding, the islands (which do not receive much sand from deeper water or coast parallel transport) slowly retreated. At about 5000 BP, the West and East Frisian barrier-island chain was still situated several kilometres offshore from its present position, e.g., in the case of Terschelling

about 9.5 km further to the north compared to its present position (Sha, 1990a,b, Vos et al., 2011). From 5000 BP until today, the chain of barrier islands has been retreating landward at an average migration rate in the order of 1-2 m/year.

A relative sea level rise of circa 12 m over the past 8400 years occurred in the northern part of the North Frisian barrier coast (Pedersen et al., 2009). In combination with abundant sediment supply, Sylt developed its northern spit as of 5000 BP (Lindhorst, 2007), whereas Rømø prograded seaward since 8000 BP (Madsen et al., 2010). In the southern part of the North Frisian area (among others Eiderstedt), the barriers and Pleistocene outcrops in the area created an inlet-segmented coastline around at least 5000 BP (Vollmer et al., 2001; Meier, 2004; Lindhorst, 2007). On the peninsula of Eiderstedt, the cores of the modern east-west trending sand bars probably consist of eroded Pleistocene material and are a relic of this barrier system (Hoffmann, 2004). The sandy barrier system protected the hinterland and around 2,500 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 medieval times, remnants still dominate the morphology of the area. Seaward of the marshes, tidal flats began to form as for example, documented on Hallig Hooge and Pellworm (Vollmer et al., 2001).

2.2 Inlet systems

Since 2010, the Delta Program is carried out to safeguard the Netherlands from flooding resulting from climate change and to provide sufficient amounts of fresh water. Part of the Program focuses on the Wadden Sea, partly in cooperation with the trilateral partners. Central in all studies stands the notion that the Wadden Sea consists of sediment sharing inlet systems. Each consists of a back-barrier tidal basin (with tidal flats and channels), an ebb-tidal delta and barrier islands at either side of the inlet (Figure 2). All elements of the system are coupled and are assumed to be in, or evolving towards, a dynamic quasi-equilibrium with the hydrodynamic conditions (Dean, 1988; Eysink, 1991; Eysink & Biegel, 1992; CPSL, 2001, 2005, 2010). Changes in any part of a tidal-inlet system will primarily be compensated by sediment transport (mainly sand) to, or from, the other parts of the same system (Figure 2; Oost et al., 1998, 2012; Elias et al., 2012a; Wang et al., 2012). On the longer run net sediment import into the inlet system from adjacent systems may occur. Also, tidal flows and water shed shifts may lead to sediment transport from one basin into another one (see Table 2.3).

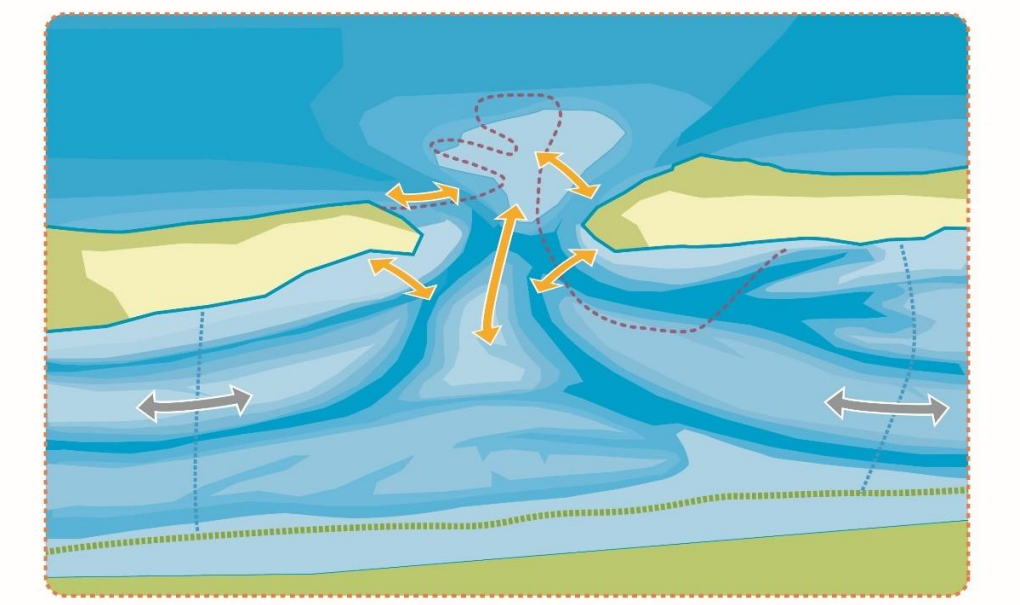
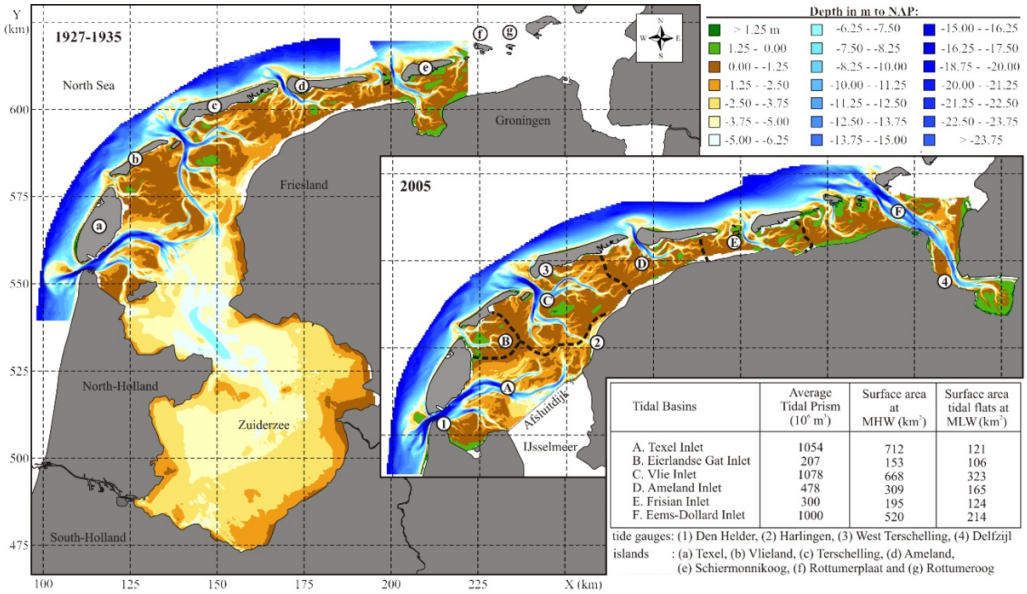


Figure 2. Schematic sediment exchange between the three main elements of a sediment sharing tidal inlet system given by arrows. In reality sediment exchange paths can be very complicated and strongly depend on local morphology, since tidal currents as well as waves are driving the transport. This is illustrated by a schematic path of sediment exchange given by the dashed red line. Furthermore, the tidal inlet systems also exchange sediment via the watersheds; here illustrated with grey arrows.

When changes in boundary conditions/drivers are temporary (e.g., perturbations by storm surges) or limited (e.g., subsidence by mining activities or dredging), the morphodynamic quasi-equilibrium may be restored. If changes are more permanent (e.g., higher rates of sea level rise or decrease in tidal volumes), a new dynamic quasi-equilibrium may develop. Several tidal basins in the Wadden Sea (but not all, e.g., Lister Tief, Reise et al., 1996) are nowadays silting up faster (up to four times) than the observed sea level rise. This is often the result of human-induced perturbations, such as at the Ley Bay, Zuiderzee and Lauwerszee (Dissanayake & Wurpts, 2013; Dissanayake et al., 2012, Figures 2.3, Table 2.I; Elias et al., 2012a). How fast a dynamic quasi-equilibrium can (re-)establish depends on the magnitude of the perturbation, the sediment availability and transport capacity. At the moment it is not clear which of the two latter is the most important. The limits to the extent to which a basin can keep up with relative sea level rise are one of the major focus points in trilateral sea level rise research (CPSL, 2001, 2005, 2010; Oost et al., 2014).



Tidal Basins	Average Tidal Prism (10^6 m^3)	Surface area at MHW (km^2)	Surface area tidal flats at MLW (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	300	195	124
F. Eems-Dollard Inlet	1000	520	214

tide gauges: (1) Den Helder, (2) Harlingen, (3) West Terschelling, (4) Delfzijl
islands : (a) Texel, (b) Vlieland, (c) Terschelling, (d) Ameland, (e) Schiermonnikoog, (f) Rottumerplaat and (g) Rottumeroog

Figure 3. Maps of the Dutch Wadden Sea illustrating the configuration of the inlets, basins, channels and shoals for the years 1927-1935 (large Figure) and 2005 (lower right; Elias et al., 2012a).

Many mechanisms drive net import such as tidal asymmetries, estuarine circulation, temperature driven sedimentation, biota, wind-wave-driven transport, settling and scour lag etc. It is assumed that an increase in sediment transport is mainly possible by an increase in the volumes of tidal- or storm-surge water transport (Hofstede, 2015) or if sediment availability increases. Reversely, fine-grained sediment might not be able to deposit if changes occur as increases in turbulence hinder this. Under relatively higher sea levels, hydrodynamic energy no longer fades out in a transitional zone and mudflats and salt marshes may disappear (Mai & Bartholomä, 2000; Wehrmann, 2014).

At the moment there is trilateral discussion on the mechanisms and the upper limits of sediment transport. Both are essential to understand the resilience of the sedimentary systems to climate change (i.e., sea level rise) and to human use (such as subsidence due to gas mining).

Table 1. Overview of sedimentation in the Dutch Wadden Area (Elias et al., 2012). Note for the period 1935-2005 that the coast of Texel erodes with 376 million m^3, whereas the backbarrier basin silts up with 234 million m^3: a large part of the sediment is carried over the watershed into the Vlie Basin.

Inlet	Coast[2] (million m3)			Ebb-tidal deltas (million m3)			Basins (million m3)		
	1935-1990	1990-2005	1935-2005	1935-1990	1990-2005	1935-2005	1935-1990	1990-2005	1935-2005
Texel[1]	–282.2	–93.4	–375.6	–244.9	–54.7	–299.6	253.0	–19.1	233.9
Eilanderbalg	–30.5	–46.8	–77.3	–10.4	–12.7	–23.0	–24.4	–2.7	–27.1
Vlie Inlet	–110.0	–36.3	–146.3	–99.1	–26.3	–125.4	166.5	52.7	219.2
Ameland Inlet	90.5	3.7	94.2	39.8	–6.1	33.7	34.2	21.4	55.6
Frisian Inlet	–48.4	–31.7	–80.1	–6.1	–17.1	–23.2	88.5	2.4	90.9
Total	**–380.6**	**–204.5**	**–585.1**	**–320.7**	**–116.9**	**–437.5**	**517.8**	**54.7**	**572.5**

1 Volumes in Marsdiep between 1985-2005 exclude the Noorderhaaks volume above mean sea level (MSL) that accretes at a 0.35 million m3/yr rate (Walburg, 2001).

2 Coast volumes include the ebb deltas.

Closed sediment balance

Based on erosion-sedimentation patterns it is concluded that the Wadden Area (up to -20 m line in the North Sea nowadays (and probably also in the past) forms a nearly closed system for sand transport (Oost et al., 1998; Elias et al., 2012a). There is a small net sediment transport from West to East along the West- and East Frisian Islands and a small net sediment transport from North to South along the North Frisian Islands. Furthermore, the clastic material brought in by the Ems, Weser, and Elbe rivers during the last 7500 years is only 10 % from the total Wadden Sea deposits (Hoselmann & Streif, 2004). In the German Bight, storm surges are known to transport a small volume of sand offshore (Aigner, 1985). Furthermore, it has been shown that during exteme events of short time scales only, transports can go in both directions (Bartholomä et al. 2008).

As a result, the major part of the Wadden Sea sediments consists of Pleistocene sands which have been re-worked several times during Holocene transgression. Sand deposited in the back-barrier area is mainly derived from the North Sea coasts of the barrier islands and the ebb-tidal deltas. As a result the island's coasts and ebb-tidal deltas have a long-term tendency to retreat in a landward direction. Nowadays this is countered by sand nourishments and other coastal protection measures.

Mud is mainly brought in with North Sea water. It originates mainly from the rivers Rhine, Meuse, Thames, Ems, Wese, Elbe, or is eroded from the Canal Coast. A tenth of the total deposits consists of mud.

2.3 Shoreface area and ebb-tidal deltas

The shoreface reach is situated between the low water line and the depth of closure, which is defined as the position on a coastal profile beyond which there is no significant change in bottom elevation or sediment transport between the nearshore and the shoreface for a characteristic time interval (Krauss et al., 1998). The concept was established on the observation that the magnitude of sediment transport becomes increasingly smaller with increasing depth, implying that the effects on morphology could be neglected below a certain depth (Bruun, 1962). The concept of the depth of closure is widely used in practical applications (sand extraction, coastal stability) as it defines the extent of the active (dynamic) coastal profile (Capobianco et al., 1997). In the Wadden Sea, this notion is influential to management. For instance, the Netherlands currently use the -20 m Dutch Ordnance Level line as a "safe" depth of closure. However, recently it was argued that this depth might be too large based on

various arguments (Koomans, 2000; Schroevers et al., 2014; van Oeveren-Theeuwes et al., 2015). Up to now there is not an official trilateral agreement on the depth of closure.

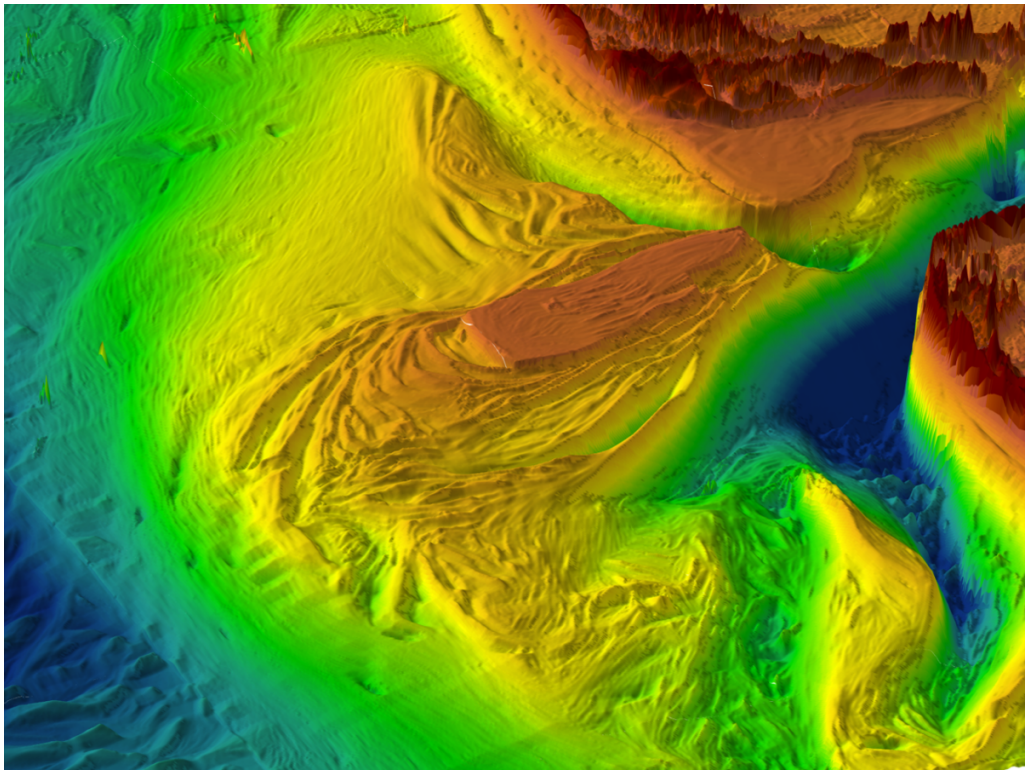


Figure 4. Oblique view of the ebb-tidal delta of Texel Inlet (Marsdiep), red scale in the inlet is 2 km, based on 2004 depth soundings; colours indicate depths (blue deepest) (source: RWS).

Ebb-tidal deltas (Figure 4) play an essential role in the sedimentary development of inlet systems. They are the intermediate in sediment exchange between the open sea, the barrier islands and the tidal basins. For the ebb-tidal deltas a semi-circular sediment transport pattern, in which the sediment is constantly being recycled is assumed (Son et al. 2011), so that sand can be transported from island to island without decreasing the sediment volume of the ebb-tidal delta. Also, they dissipate the wave energy and provide shelter to parts of the islands and to the adjacent back-barrier area. Driving forces (tide, wind and waves) exert a strong influence on the morphology of ebb-tidal deltas which are continuously changing (Sha & Van den Bergh, 1993; Herrling & Winter, 2014). Changes in the driving forces will therefore lead to morphological changes (Ridderinkhof, 2016), which may influence development of other parts of the system. Therefore, knowledge about ebb-delta development under different drivers (Herrling & Winter, 2014) is essential to our understanding of the sediment sharing inlet system. The interaction between tide, wind and waves is a complex process that needs to be unravelled for an optimal management of the coastal zones while reducing flood risks to the coastal settlements. At the moment, the observed erosion of ebb-tidal deltas as well as other form changes and the implications are reasons for concern (see inset).

Inset: Reduction of the ebb-tidal delta

Decreasing Dimensions

In general, a bigger tidal volume results in a larger sediment volume of the ebb-tidal delta (Eysink & Biegel, 1992). However, man-made changes in tidal basin volume can significantly reduce the sediment volumes and orientation of the deltas as is shown for several Dutch systems (Sha, 1990a; Oost, 1995; Elias, 2006; Elias et al., 2012; Ridderinkhof et al., 2015a&b). If the observed loss of sand of the ebb-tidal deltas also holds for situations with larger sediment demand due to accelerated sea level rise, it has to be anticipated that in future more ebb-tidal deltas may be eroding faster than at present. This may also have consequences for the barrier islands. Indeed, strong landward retreat of adjacent island coasts has been observed for West-Vlieland in the 16-17th century after landward retreat of the ebb-delta: 1 km (Abogado Rios, 2009) and SW Texel in the 19-20th century after reorientation of Marsdiep ebb-tidal delta: 1.5 km (Oost et al., 2014). If such developments would occur in the future, keeping the coasts in position with nourishments only might become problematic. In general, two issues are important when tidal delta volumes decrease, namely sediment supply and shelter for waves for both the backbarrier and the barrier islands.

Sediment supply

A reduction of the ebb-tidal delta volume might result in a reduction in sediment transport from the ebb-tidal delta to the down-drift island. Also, the back-barrier area would probably receive less sand. A situation of a total disappearance of the ebb-tidal delta is, however, not likely: some volume will always be there. Whether this volume can provide the down-drift coast and back-barrier area with sufficient amount of sediment is not known.

Sheltering effects

Ebb tidal shoals provide a sheltering effect by their wave breaking function offshore of the barrier islands. In general, a lowering of the ebb-tidal delta shoals will result in less shelter and waves might penetrate deeper into the back-barrier area or larger waves might reach the barrier coasts. Lowering of the ebb-delta shoals has been observed in Hörnum inlet, Schleswig Holstein (Hofstede, 1999b). A reduction in shelter for waves implies an increase in wave heights and periods. Erosion along the northern spit of the barrier island Amrum, due to increased wave power, is a likely consequence. In contrast, vertical growth of shoals has been observed in most of the Dutch ebb-tidal deltas, thus providing extra shelter. At the moment it is not possible to predict if and how

ebb-tidal deltas will change due to climate change effects (i.e., sea level rise and change of wind patterns). Therefore, effects of changes in wave spectra cannot be predicted.

In contrast to Schleswig-Holstein, Denmark is currently facing hardly any problems with its ebb-tidal deltas. There is a positive sediment budget, resulting from onshore transport from the North Sea and substantial long-shore transport from the Jutland peninsula (Nielsen & Nielsen, 2006; Madsen et al., 2010). Except for the ebb-tidal delta off the Grådyb Inlet, which is dredged, the other ebb-tidal deltas are currently stable in volume or even growing.

2.4 Barrier islands

Barrier islands play an important role in the long-term exchange of sediment, as a source or sink of sediments (mud and sand). Historical observations show that the long-term development of barrier island volumes is especially related to (Davis, 1994):

- Presence of Pleistocene core (Sylt, Texel, Amrum, Föhr);
- Shifts in position of the inlets (Dean, 1988; Sha, 1990b; Elias, 2006);
- Shifts of marginal ebb-tidal delta channels (van Veen, 1936; Joustra, 1971; Oertel, 1977; Oost, 1995; Schoorl 1999a&b; van Heteren et al., 2006);
- Sediment delivery from the ebb-tidal delta (Van Veen, 1936; Oertel, 1977; Sha, 1990b; Israel & Dunsbergen, 1999; Schoorl, 1999a&b; Van Heteren et al., 2006);
- Wind driven sediment transports (Aagaard et al., 2007; Arens, 1999; Arens et al., 2007, 2008a&b);
- Storm-surge driven sediment transport leading e.g., to wash-over formation (Ten Haaf et al., 2006; Hoekstra et al., 1999, 2009);
- Decrease in inlet cross section due to decrease in tidal basin volume (Flemming & Davis, 1994);
- Coastal erosion (Hofstede, 1994a; Elias et al., 2012a,b);
- Back-barrier erosion by barrier-ward channel migration (Oost, 1995);
- Tidal marsh sedimentation.

The development of barrier islands in timescales of decades to centuries is only partially known. Large amounts of sediment are involved (e.g., growth over 4 km of east-Schiermonnikoog since sediment release from the ebb-tidal delta upon the closure of the Lauwerszee in 1969; the strong erosion by a tidal channel of east-Terschelling over 2 km since 1990, but also a strong growth at the west side of Terschelling; see also: Schoorl, 1999ab, 2000ab; Ehlers, 1988, Winter, 2011; Oost & van Rooij, 2012; Oost et al., 2012). However, long-term sediment budget analysis in which the islands are included has not yet been made on basis of historical data. Now that Lidar data become available, this becomes feasible. A better knowledge and monitoring of the barrier islands, but also the behaviour of the channels in the inlets are essential for predicting the future development of islands (Arens et al., 2009).

On most islands, natural development (inlet and ebb-delta channel migration, dune migration and washover development) has been influenced by man, especially since

1900 (Thorenz, 2011; Oost et al., 2012). The sediment transport across the islands – from the North Sea to the southern parts of the islands has been blocked by fixating dunes and building sand-drift dikes. This will possibly have consequences for the resilience of the islands and the sediment sharing inlet systems as a whole. These consequences are, until now, poorly understood (Oost et al., 2012). A short overview of some important points is given in the inset.

Reduced resilience of barrier islands

Halting channel migration. On many of the German North Sea islands and some Dutch islands, ebb-delta channel and inlet migration is halted by massive hard sea defences, especially on the western island heads. Often the last way to maintain safety on the islands, but influencing free exchange of sediments along the coasts within the sediment sharing inlet systems. The coastal defences lead to a fixation and, from time to time, deepening of tidal channels along the island coasts, which leads to high costs in combatting coastal erosion. The influence on the functioning of the inlet system in terms of sediment exchange and natural dynamics is not well known. Some data even show that coastal defences result in faster erosion (Dr. Jan S. Ysker, unpublished data).

Wind-driven transport. Large-scale marram planting and the building of sand fences led to the formation of massive and often fully closed sand drift dikes along the beachfront (Arens, 1999; Van der Wal, 1999; Löffler et al., 2011). In total about 1 Mm^3/yr sand is trapped in the managed dunes at the North Sea side of the inhabited Dutch barrier islands (Arens et al., 2007). Eolian sand transport from the beach further into the interior of the barrier islands is hindered. Originally, eolian sand transport was a main mechanism to allow the barrier areas to accrete vertically (see e.g., De Jong, 1984). The lack of sediment import from the beach due to sand drift dikes and fixated dunes may ultimately result in a reduction of barrier elevation with respect to relative sea level. This is locally already observed in an area behind a sand drift dike on Ameland which is subsiding due to gas extraction and eolian transport is not sufficient to compensate to subsidence. The lack of eolian dynamics on many islands also resulted in a strong loss of ecosystem values due to fast plant succession (Löffler et al., 2011).

Overwash transport. The washover environments often consist of low areas which are topped by waves and flooded during storm surges, transporting water and sediments from the North Sea onto and over the island. Under natural conditions it is a normal phenomenon on the Wadden barrier islands. Overwash on the

Wadden Sea barrier islands is especially important for eroding and redepositing sediment of the beach and dune-face, after which eolian transport takes over (Nielsen & Nielsen, 2006, Hoekstra et al., 2009, Ten Haaf et al, 2011). The formation of sand drift dikes along the beach area blocked many of the washovers and ended their dynamics. Vegetation succession was accelerated since then and natural values of the areas are declining strongly (De Groot et al., 2015).

Sediment exchange across tidal divides. Recently, a significant mass transport across tidal divides has been assessed by a numerical modelling study of the East Frisian Wadden Sea. Volumes of up to 19 % of the respective tidal prism are exchanged through the high tidal divides between Wadden Sea basins (e.g., Herrling & Winter, 2015). At several places dams are present on the tidal divides (e.g., Sylt and Rømø): their effect on overall barrier island development is not yet understood.

Development of tidal marshes. In the lee of both natural and artificial dunes, tidal marshes develop while fine-grained sediments accumulate. Volume calculations for the Dutch islands indicate that these salt marshes are an important sink for cohesive sediment and fine sand (De Groot et al., 2013). Bartholdy et al. (2010) modelled the salt marsh growth on the backbarrier of the barrier-spit "Skallingen" in Denmark, and found that over a 100-year period, the back barrier could survive a future sea level rise of approximately 4 mm/y. On the tidal marshes of the low-diked Halligen of Schleswig-Holstein accretion rates are 1.2-2.6 mm/yr, which is insufficient to keep up with present day sea level rise (Schindler et al., 2014a & b). It is not known yet, whether the normal feedback mechanisms between sea level and salt-marsh sedimentation will be sufficient to let mature salt marshes grow with sea level rise, or if additional measures are necessary. An important matter is whether salt marshes on barrier islands exhibit the same natural cycles of horizontal growth and erosion as estuarine tidal marshes, i.e. whether lateral erosion is a long-term threat or not. Also, the hindered sediment supply from the North Sea by sand drift dikes is not compensated everywhere by extra input from fines from the Wadden Sea. This leads to relative deepening of the areas directly landward from the sand dike. It is not clear if it is possible to restore the original processes successfully, due to the massive changes in the area.

2.5 Islets

In the Wadden area, 65 small islets are present, with a total surface area of over 134 km^2. Most of them are uninhabited. They form one of the most spectacular examples of the outstanding geology, hydrology, morphology, ecology and biodiversity of the Wadden Sea (Hellwig & Stock, 2014). The islets can be divided into the following categories:

1. Remnants of former higher areas in the backbarrier area, such as Griend (Kers, 2014), possibly also Engelsmanplaat (Oost, 1995), late Jordsand (Frederiksen, 2014), the many Halligen (six of which are inhabited) and small islets between Eiderstedt and Amrum, which formed after the flooding of a peat area around 450 AD (Meier, 2006).
2. Islets forming in the outer deltas, such as Razende Bol (Sha, 1990), Rif (Oost, 1995), Rottumerplaat (Oost, 1995; van Rooijen & Oost, 2014), Noordrif (now part of Rottumeroog; Kers, 2014), Süderoogstrand (Hellwig et al., 2014) and Trischen (Stock et al., 2014; Padlat, 2014). The rate of basin-ward shifting of the islets is determined by sediment supply in conjunction with singular, mostly storm-related, events (Hofstede, 1999a).
3. Ephemeral (sandbank) islets of the meso- to macro-tidal Jade-Weser-Elbe region which do not have the potential to form larger coherent dunes (Wehrmann et al., 2014). Within the inner German Bight the islands become so small that they become unstable (Hellwig et al., 2014; Führing, 2015).
4. Islets formed in the inner deltas or inlet, such as Koffieboonplaat, Kachelotplate (Wehrmann et al., 2014), Mellum (Kleyer et al., 2014) and Memmert (Ehlers, 1988). Surveys on the Kachelot-plate revealed that high energy storm surges and related overwash and flooding are the most prominent drivers in barrier island evolution. The eroded sand heightens the sandy sedimentary base of the next generations of primary dunes, resulting in a decrease in inundation rates, leading to the development of stable dunes (Walters et al., 2014; Wehrmann et al., 2014).
5. Islands which form part of the barrier chain and are gradually eroded. An example is Buise which broke up in two parts in 1362 of which the western part disappeared in the second half of the 17th century. Rottumeroog is a barrier island which has decayed since 1500 (Oost, 1995). It is expected that Rottumeroog will continue to migrate in a southward direction. At the long-term it is unsure if the island remains stable in volume (Van Rooijen & Oost, 2014).
6. Artificial islets such as Langlütjen I & II, Nigehörn and (at least partially) islands which have been restored, such as Griend and Minsener Oldeoog.
7. Estuarine islands, situated in the brackish or fresh water tidal zone of the estuaries open to the Wadden Sea.

The morpho- and ecodynamics of the 65 uninhabited islets is often locally well studied, some of them having a monitoring history of up to 120 years. Management of each of the islets has developed in reaction to the specifics of the island itself and is thus more or less tailor made. A comprehensive management philosophy which takes into account all 65 islets and deals with all aspects (ecology, safety, morphodynamics) and relations between islands (e.g., breeding birds) is missing. An inventory study and trilateral management meetings are recommended.

Table 2. Overview of all 65 islets in the trilateral Wadden Sea. Excluded are the larger inhabited barrier islands.

Islet	Description	Size (ha above MHW)	Category
Noorderhaaks	Shoal with vegetated dunes Resting place for birds and seals	500	2
Richel	Shoal with vegetated dunes Resting place for birds and seals	116	2
Engelschhoek	Inter- to supratidal shoal	10	2
Griend	Bird sanctuary, largely artificially restored	10	1, 6
Rif	Resting place for birds and seals	<10	2
Engelsmanplaat	Supra- to intertidal shoal	-	5
Rottumerplaat	Vegetated barrier islet	1000	2
Rottumeroog	Vegetated barrier islet	600	5
Zuiderduintjes	Islet with dunes	65	3
Hatzumer Sand	Ems estuary	ca. 22	7
Bingumer Sand	Ems estuary	ca. 22	7
Islet Middelstenborgum	Ems estuary	6	7
Islet near Vellage	Emsauen, Ems estuary	1	7
Islet of the Herbrum barrier	Ems estuary	ca. 10	7
Lütje Hörn	bird reserve	6.5	4
Kachelotplate	Islet with dunes and vegetation	172	4
Memmert	Islet with dunes & tidal marsh Zone 1 of Wadden Sea National Parks?	520	4
Minsener-Oldoog	Mainly artificial was formed from the Minsener Oog sandbanks and the Olde Oog sandbank	370	4
Alte Mellum	Dunes and tidal marshes Zone 1 of Wadden Sea National Parks	750	4
Langlütjen I	Artificial 19th century Navy fortification	1.6	6
Langlütjen II	Artificial 19th century Navy fortification	1.7	6
Harriersand	Weser	ca. 691	6
Rönnebeckersand	Weser near Rekum	ca. 91	7
Hoher Knechtsand	Natural bank, part of nature reserve	260	4
Hanskalbsand & Neßsand	Fauna-Flora-Habitat, Elbe Estuary	145	7
Unnamed islands near Bishorstersand	?	ca. 10	7
Bishorster Sand	Nature reserve, Elbe Estuary Haseldorfer Marsch	>60 ha	7
Pagensand	Nature reserve, Elbe Estuary Haseldorfer Marsch	460-520	7
Schwarztonnensand	Nature reserve, Elbe Estuary Schwarztonnensand	582	7
Rhinplate	Nature reserve, Elbe Estuary Rhinplate und Elbufer südlich Glückstadt	460	7
Asselersand	EU Bird- Reserve , Elbe Estuary	632	7
Scharhörn	Natural, human supported formation in the 1930's	20	2, 6
Nigehörn	Artificial island, bird sanctuary	50	6
Helmsand	Bird sanctuary	5	1
Trischen	Bird reserve barrier island, originally poldered	180	2
Blauort	Sandy shoal, Schutzzone 1 NP SH	60	3-4
Uthörn	SH WS NP bird sanctuary	13	3
Langeneß	Inhabited Hallig	956	
Hooge	Inhabited Hallig	574	
GrÖde	Inhabited Hallig	252	
Nordstrandischmoor	Inhabited Hallig	175	
Oland	Inhabited Hallig	96	
Süderoog	Inhabited Hallig	60	
Südfall	Nature reserve	46	1
St. Peter-Ording-Sand	Supratidal shoal	69	3
Westerheversand	Supratidal shoal	--	3
Süderoogsand	Supratidal shoal	1702	2
Norderoogsand	Supratidal shoal with vegetation	843	2
Japsand	Supratidal shoal	390	2
Habel	Bird sanctuary	7.4	1
Hamburger Hallig	Bird sanctuary (part of mainland)	110	1
Norderoog	Bird sanctuary	8	1
Kniepsand	Supratidal shoal	100	2
Jungnamensand	Supratidal shoal	13	2
Koresand	Sandbank, no dunes	Fluctuating part just supratidal	2
Langli	Nature reserve	80	3
Varde Ä islets	7 islets in Varde Ä estuary	ca. 2.5	7

3. Assessment

3.1 Holocene development

There are no targets for the Holocene development within the Wadden Sea Plan, but in the Joint Declaration (2010) there is the Guiding Principle “to achieve as far as possible, a natural and sustainable ecosystem in which natural processes proceed in an undisturbed way” reaffirmed during the Tønder meeting (CWSS, 2014). For that reason it is quite important to better understand the genesis of the trilateral Wadden Sea and the influence of human interferences to derive a possible future development. Also, for Landscape and Culture Identity such knowledge will help to preserve, restore and develop the elements that contribute to the character, or identity, of the landscape, which is a target in itself (see "Landscape and culture").

3.2 Sediment sharing inlet system

For the backbarrier area, the following geomorphological targets have been formulated (Wadden Sea Plan 2010):

- *A natural dynamic situation in the tidal area;*
- *An increased area of geomorphologically and biologically undisturbed tidal flats and subtidal areas.*

From the point of overall geomorphological dynamics, the Wadden Sea tidal area is functioning relatively naturally. However, human impacts are influencing this natural system:

- Closure of the Zuiderzee in 1932 still influences sedimentation in the backbarrier areas and shoreface of Texel and Vlie Inlet (Elias et al., 2012a), whereas the closure of the Lauwerszee in 1969 still seems to influence the erosion of the ebb-tidal delta (Oost et al., 2015) and sedimentation around the island of Schiermonnikoog;
- The poldering of embayments and fixation of the coastline by dikes which happened in the previous centuries strongly decreased the tidal volume of the respective tidal basins, the area of muddy environments, limited connectivity and increased the turbidity of the Wadden Sea (Mai & Bartholomä, 2000; Hoselmann & Streif 2004, van Maren et al., 2016);
- In Schleswig Holstein and Denmark, dams between the mainland and the islands hinder the development of natural dynamics;
- In many estuaries (e.g., Elbe estuary) dredging of navigation channels has increased tidal amplitudes and has modified tidal phasing. These processes are known to affect the tidal asymmetry and residual sediment transport as well as the effects of storm events (e.g., Bolle et al., 2010; van Maren et al., 2015);
- Also other shipping lanes are maintained by dredging which leads to artificial sediment displacement and extra turbidity in the Wadden back barrier areas, sometimes combined with net removal of sediment;
- In large parts of the Wadden Sea bottom disturbance by fishing hinders the development of undisturbed tidal flats and subtidal flats and their related benthic communities. For the abiotic functioning of tidal flats it is concluded that trawling and bottom disturbance on the short run leads to a loss of mud content (Van Moorsel & Van Leeuwen, 2013), which may last over more than a year (Figure 5; pers. com. de Vlas; pers. obs. Oost). For the biotic part see report on fisheries;
- Developments furthering an increased area of undisturbed tidal flats and subtidal areas are closure to bottom disturbances of designated areas.



Figure 5. Traces of mechanical cockle fishing on the tidal flats at Noorpolderzijl (NL) (Photo by J. de Vlas; in: Van Moorsel & Van Leeuwen, 2013).

3.3 Shoreface area and ebb-tidal deltas

For the shoreface and ebb-tidal deltas, the following geomorphological target has been formulated (Wadden Sea Plan 1997): *An increased natural morphology of the offshore area, including the outer deltas between the islands.*

Developments hindering this target are the groins and other protection works which are already existing (The Netherlands, Schleswig Holstein) or that have been extended and improved on some barrier islands of Lower Saxony after 2009 (NLWKN, 2010). These limit the natural morphological development of the inner and other deltas by means of a fixation of (parts of) the island´s coast line. The measures are deemed crucial for coastal protection of the islands. Whether these changes exert a significant influence on natural morphology is not known. Developments furthering the natural morphology are the joining of Denmark in the World Heritage area including a large part of the North Sea shoreface area and the extra extensions into the shoreface designated by Lower Saxony in 2014. Recently an overview has been given of the ebb-tidal deltas of the trilateral Wadden Sea (Oost et al., 2017).

3.4 Barrier islands

In the Trilateral Wadden Sea Plan (1997) the following targets appear:

- *Increased natural dynamics of beaches, primary dunes, beach plains and primary dune valleys in connection with the Offshore Zone;*
- *An increased presence of a complete natural vegetation succession.*

Developments hindering the targets are: expansion, maintenance or non-removal of sand drift dikes. They decrease the natural sediment dynamics which leads to a decreased presence of a complete natural vegetation succession.

Developments furthering the targets are: Since the introduction in the Netherlands of Dynamic Coastal Maintenance in 1990 several sites have been allowed to develop in a more natural way. Examples are SW Texel, some parts of Vlieland, Terschelling at the west side and at the east side, several locations at Ameland and East-Schiermonnikoog. As a compensation measure for the building of the Statoil pipeline in 2004, the summer dike in the south of Langeoog Island was destroyed to let the salt marshes develop naturally. Also, the inclusion of many natural areas on the barrier islands as parts of the UNESCO World Heritage area furthers the targets. In 2013, the Netherlands introduced the National Vision Coast aiming at a safe, appealing and economic stronger coast. This was followed by the Coastal Policy 2015 which translates the national water safety policy for coastal areas in responsibilities and limiting conditions which determine other activities. The Coastal Policy also tries to create more possibilities for other use of the coast, resilient and sustainable multi-use practices and more natural dynamics.

3.5 Islets

There are no specific targets for islets, but the targets for beaches and dunes seem to apply:

- *Increased natural dynamics of beaches, primary dunes, beach plains and primary dune valleys in connection with the Offshore Zone;*
- *An increased presence of a complete natural vegetation succession.*

Developments furthering the targets are that up to now much of the islands' nature is allowed to take its way, although there are exceptions such as the bird reserve Griend which is nourished from time to time. This hands-off policy seems to pay off since many natural dynamic areas and species find a place on the islets.

4. Recommendations

4.1 Recommendations for monitoring & research

4.1.1 Holocene development

Palaeolandscape reconstructions of the Wadden Sea region are useful to understand and predict morphological changes within this tidal system in the future. They may provide valuable management insights for nature policy for the next 100 years for both, interference and conservation strategies (e.g., van Maren et al., 2016). However, the existing maps only cover specific regions and are not compiled for the Holocene period. Therefore, it is recommended to compile new paleogeographical maps of the entire trilateral Wadden Sea area. To give a comprehensive overview, the most important phases of the development of the Wadden Area are: 5500 BC, 3850 BC, 2750 BC, 1500 BC, 500 BC, 100 AD, 800 AD, 1250 AD, 1500 AD, 1850 AD and the present-day landscape situation. To realise the proposed trilateral palaeo-landscape maps of the Wadden Sea an international mapping program is recommended. The new reconstructions by Vos et al. (2014) and the Wadden Sea archive-reconstructions for

the area of Norderney to Spiekeroog can form the on-set to such a trilateral enterprise.

4.1.2 Sediment sharing inlet system

A series of major knowledge gaps is identified considering the functioning of the sediment sharing tidal system. The overview is partially based on the various trilateral discussions and on recent inventory studies and overviews (Speelman et al., 2009, Oost et al., 2012, Elias et al., 2012a&b, Wang et al., 2012, Van Oeveren-Theewes et al., 2015):

With regard to water movement:

- What is the role of storms in the exchange of water and sediment between the neighbouring basins and between the Wadden Sea and the North Sea (Wang et al., 2012; Herrling & Winter, 2015)?

With regard to sediment transport:

- How is the observed sediment import/export generated and what will be the reactions to cli-mate change effects, especially sea level rise?
- What is the relative importance of the major sediment transport mechanisms in a Wadden Sea tidal inlet system and how do they contribute to the net import or export to and fro a backbarrier basin (Herrling & Winter, 2014)?
- To what extent is sediment availability a limiting process?
- How do morphological changes in the basin and on the ebb-tidal delta influence the processes and mechanisms which determine the net transports through an inlet?
- To what extent is the net transport to the backbarrier system influenced by the supply of extra sediment in the coastal zone?
- What are the consequences of various aspects of climate change (sea level rise, global warming, changing wind patterns, and changing precipitation/evaporation patterns) to the net sediment transport into the Wadden Sea?
- What determines the exchange of sediment between adjacent tidal basins?
- How much import of each sediment type occurs in each sediment-sharing tidal inlet system?
- Are there tipping points which might occur either due to changes in drivers or due to inherent evolution after which the sediment sharing inlet system can follow a different morphological development (e.g., Ridderinkhof, 2016)?
- What is the role of barrier islands as a source and sink for sediment as part of the sediment-sharing inlet system on the scale of decades to centuries?

Numerical models:

At the moment, most numerical models are aimed at the development of (parts of) inlet systems over the period of years. Although the mode and direction can be determined in this way, the exact development over a timespan of several decades cannot be calculated. Also, the uncertainties in this development (due to, for instance, stochastic processes and the uncertainties in the model-schematisation) cannot be assessed. There are several causes for this. On one hand there is insufficient theoretical knowledge leading to inherent limitations in the models. Currently, models are not capable of satisfactorily reaching a morphological equilibrium state. On the other hand, the models are also limited by a lack of accurate measurements over longer time spans (10-20 years), such as fresh-water discharges, currents and waves,

which are needed to validate the models. In addition, several uncertainties in boundary conditions and model formulations hinder successful naturalistic long term simulations. Recently, data assimilation into morphodynamic hindcast model simulations have been introduced (Chu et al., 2013). In the Dutch Coastal Genesis 2 program (Van Oeveren-Theewes et al., 2015) it is proposed to develop a suite of complementary models which should cover: 1) Short term detailed process modelling (1 year); 2) Intermediate term (5-20 years) morphodynamic process-based models and 3) aggregated modelling in which inlet systems are schematized in morphological elements to simulate the changes in volume over decades to centuries.

4.1.3 Shoreface area and ebb-tidal deltas

For the shoreface area, see report on coastal risk management. In summary, the research questions concerning ebb-tidal deltas which have to be solved are (Oost et al., 2014; van Oeveren-Theeuwes et al., 2015):

- What factors determine the size and shape of the ebb-tidal deltas?
- What changes in currents and wave conditions along the barrier coast and in the back barrier area can be brought about by changes in size and/or orientation of an ebb-tidal delta? And how will this influence the development of the barrier islands/coast, back barrier basins and shipping channels?
- What is the relative importance of the various sediment transport mechanisms on ebb-tidal deltas and how does sediment exchange between the ebb-tidal deltas and the barrier islands and backbarrier tidal basin occur?

4.1.4 Barrier islands

Main research questions to be resolved are (Oost et al., 2012, 2014):

- *Role of barrier islands as part of the sediment sharing inlet system*. What are the principal mechanisms of sediment exchange between the island and the other parts of the sediment sharing inlet system? What volumes are involved?
- *Dune development*. Can we reconstruct the developments of dunes on the barrier islands in the past and can we predict future developments? More specific: to what extent are these related to landward barrier retreat, ebb delta developments or to island head shifts? Furthermore, how do dune areas develop under natural conditions, i.e., when not replenished in spring after winter storm erosion?
- *Tidal marsh development*. What is the magnitude of the various sediment transporting processes which are important to accumulation on tidal marshes (i.e. washover, eolian transport and back-barrier flooding-related processes)? Do salt marshes on barrier islands exhibit the same natural cycles of lateral growth and erosion as estuarine tidal marshes, i.e. is lateral erosion a long-term threat or not? How can tidal marsh development be encouraged without using hard protection works?
- *Washover development*. How can we successfully restore washovers and migration of dunes? Which dimensions are needed? Can physical and ecological changes which occurred after the formation of sand drift dikes be successfully reversed?
- *Climate change*. What will be the future morphological development under conditions of altered drivers due to climate change?

- *Nourishments*. What are the optimal locations, frequencies and volumes for nourishments in the future in terms of morphology, ecology etc.?

4.1.5 Islets

Especially for the islets, which react fast to changes due to storms and inlet configuration, further research in relation to the impact of climate change on expected morphodynamic changes is crucial, i.e., will the islets be able to survive? Related to that is the question: what can we gain in system knowledge? For instance, how do the islets interact with changes in the ebb- and flood tidal areas? As the morphodynamic developments are fast and observations are sometimes over long periods, such data might prove very valuable. It should be noted that new non-disturbing research methods have to be developed because the islets are important breeding grounds and resting places making them off-limits during substantial parts of the year.

Helwig & Stock (2014) advised: "*To gain a better understanding of the value of natural dynamics on the level of whole islets we recommend a continuation of monitoring approaches on the dynamics of unprotected islands in an inter-disciplinary approach. The TMAP standards are a good starting point.*"

On top of that an intercomparison of all 34 islets and their morphodynamic and ecological development is advised, to better predict how these valuable natural areas will develop in the future and to obtain in depth system knowledge. Also, such an intercomparison might provide a framework for management.

4.2 Recommendations for management

4.2.1 Holocene development

Given the complex genesis of the Wadden Sea landscape, a paleo-geographical atlas of the Holocene Development including a comprehensive text is a valuable source of information for landscape management achieving or protecting natural dynamics. On the mainland, the fast development of agriculture, infrastructure, urban areas and wind farms leads to losses of the valuable Wadden Sea landscape (Frederiksen, 2006). The anticipated depopulation of many parts of the Wadden Sea Region in the future will represent a challenge in itself to maintain the landscape (Frederiksen, 2006). Other activities such as dredging, harbour development, bottom-trawling and dike building may lead to losses of the valuable landscape characteristics within the Wadden Sea and adjacent North Sea. A sound overview of the Holocene developments will provide reference framework to make optimal choices for preservation of the valuable landscape elements as well as its archaeological record.

4.2.2 Sediment sharing inlet system

The Ministerial Council Declaration of 2014 recognised that the morphological development under conditions of sea level rise is a critical element of the natural resilience of the Wadden Sea and that trilateral cooperation on exchange of knowledge on this subject is essential. They welcomed and supported continuation of a trilateral study on sedimentary behaviour in different tidal basins, acknowledging the

importance of exchange of knowledge and expertise between institutions and agencies in the Wadden Sea countries. However, after 2014 trilateral knowledge exchange became less intensive, as the Delta Program became less intensive. An initiative from the trilateral management side to revive the research with a focus on preserving and improving a natural and sustainable ecosystem in which natural processes proceed in an undisturbed way is recommended. Development of morphological models for long-term prediction of morphological changes including changes to climate, sea level rise, etc. are a first step.

Furthermore, a more integral approach on how to deal with measures for coastal protection is recommended, both, in the trilateral context and in the context of the interdependency of the various parts of the sediment sharing system. As a first step, the trilateral coastal safety managing institutes could inter-compare the approaches of Denmark, Schleswig Holstein, Hamburg, Bremen, Lower Saxony and the Netherlands on a regular basis. Also, fishing practices of the various countries and the effects on the tidal flats could be inter-compared and optimized to reduce sediment disturbance.

4.2.3 Shoreface area and ebb-tidal deltas

At the moment, there are no clear indicators by which to assess a "*natural morphology of the off-shore area, including the outer deltas*". This seriously hampers the possibility to objectively measure progress for the target. It is therefore recommended to trilaterally inter-compare the management of ebb-deltas and to come to a set of indicators which can be used to this end.

Currently, there seem to be no insurmounTable problems along the Wadden coasts due to changes in ebb-tidal deltas, although some may have gone unnoticed. However, if sediment demand increases in other sediment sharing inlet systems, it is plausible that ebb-tidal deltas may retreat faster or that the ebb-tidal deltas reorient. This may affect the barrier island coasts and result in more management measures to maintain the coasts. To tackle future problems and advise cost-effective solutions to prevent coastline retreat of the Wadden islands, locations for and volumes of sand nourishments may have to be reconsidered (van Oeveren-Theeuwes et al., 2015). North Sea coast nourishments are nowadays usually put on the shallow foreshore, but perhaps they could be partially shifted towards the ebb-tidal deltas, or should be given a different shape (Elias et al, 2012b, de Ronde & van Oeveren-Theeuwes, 2013). However, it is concluded that the present knowledge is insufficient to carry out such pilots without risks. Particularly knowledge on system behaviour over the medium term (1-25 years) is insufficient. Predictive models for this would greatly benefit from datasets for validation, including data on discharge, currents and waves (Van Oeveren-Theeuwes et al., 2015). For that reason, a trilateral overview of the available hydromorphological and ecological data and the current insights, especially in the light of climate change, has been started in 2016 by the Task Group Climate of the Trilateral Wadden Sea Board.

4.2.4 Barrier islands

Management of the barrier islands is highly zoned parallel to the beach, dunes and dikes. However, as the islands were originally one morphodynamic system and an integral part of tidal inlet systems, the zoned situation by (former) management is probably not always the most optimal form. For instance, nature development could

gain considerably from (restoring) natural dynamics and connectivity between the various parts of the island instead of targeting on conservation of species and environments, where this is possible without endangering the safety to the inhabited areas (Löffler et al., 2011). In this approach, natural morphodynamics form a series of sub-environments which each will be characterised by their own biota. Through time, species will shift and may locally disappear, but in a dynamic landscape there will be always sub-environments available for the species to survive, which is probably a more sustainable way of management (Oost et al., 2012; Lammerts & van Haperen, 2015). The new Dutch Coastal Policy Document (Deltaprogramma, Kust, 2013) is a good example of a more sustainable approach.

4.2.5 Islets

Development of a comprehensive management philosophy which takes into account all 65 islets and deals with aspects such as ecology, safety, geomorphology, and relations between islands (for instance, for breeding birds) is needed. Furthermore, understanding the development of the islets is thought to drastically improve the so much needed system knowledge. A first step would be the establishment of a trilateral working group of islets managers and specialists who can contribute to such an inventory.

5. Summary

With respect to natural morphodynamics, the Wadden Sea area is considered to be one of the most dynamic and valuable areas in the world. Overall many parts seem to function relatively naturally albeit within the boundaries set by humans and the influences which they exerted on the developments during the past and present.

On a geological time scale the area is relatively young and mainly developed during the Holocene. The development through time shows a wealth of different reactions to ever changing drivers especially related to climate change and human interference. Thus, a comprehensive overview is worthwhile to help understand the implications of future management decisions and to make optimal choices to preserve the valuable landscape elements.

Especially after 2006 it was trilaterally recognised that the concept of the sediment sharing inlet systems is in itself a valuable approach to help understanding the functioning of the system. The amount of sediment transport through an inlet itself stands central to understand the development of both, the backbarrier area and the North Sea coasts. The Ministerial Council Declaration of 2014 recognised that the morphological development under sea level rise is a critical element of the natural resilience of the Wadden Sea and that trilateral cooperation on exchange of knowledge on this subject is essential. Unfortunately, the related trilateral meetings on the subject seem largely to have stopped.

Overall, management practices have furthered reaching Wadden Sea Plan targets: most parts of the sediment sharing inlet systems work nowadays in a fairly natural way. But there are still concerns:

- For some of the ebb-tidal deltas some major concerns exist because of their changes in volume and shape. Moreover, it is not well known what the implications are. Also it is uncertain how to compensate or mitigate the possible

future problems. In the Netherlands, the research program Coastal Genesis 2 is currently being developed, which will pay attention to these issues. Also, in 2016 the Task Group Climate of the Trilateral Wadden Sea Board has taken the initiative to gather information on the development of all ebb-tidal deltas;

- Together with the mainland coastline, the barrier islands are parts of the Wadden Sea system where the anthropogenic influence is strong. On most islands, natural development (inlet and ebb-delta channel migration, dune migration and washover development) has been influenced by man by halting channel migration, fixation of dunes, blocking overwash transport and developing and protecting tidal marshes. In many locations the only remaining way forward is the continuation of the earlier approach due to the far-reaching consequences of a change of management. However, in some areas the choice has been made to allow nature to take its course or even encourage natural development. The measures which further the connectivity and the natural development of the area are still in a testing phase and many scientific and management questions remain. Some of the answers might be found by studying the morphodynamics of the 65 uninhabited islets; some of them having a monitoring history of up to 120 years which give valuable insights into the principal processes of barrier island formation and decay. These valuable morphological and ecological jewels of the Wadden Sea also deserve more attention from an integrated management point of view as they provide important sub-environments for many Wadden Sea species;
- At the moment, we have insufficient understanding of the relative importance of the major sediment transport processes and as a consequence we are still ill prepared for the reactions of the Wadden Sea system on short term events and effects of long term climate change. The first step is a trilateral compilation and inter-comparison of data on coastal morphodynamics, scientific insights and management practices and to optimize these where it concerns morphodynamics.

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