Barrier island management: Lessons from the past and directions for the future

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A B S T R A C T

The article focuses on the morphological development of the Wadden Sea barrier island system, with emphasis on West and East Frisian islands on several temporal and spatial scales. In addition, it integrates the insights for management purposes. Barrier island management is addressed with respect to morphology, sediment budgets, safety and natural values. We show that each of these issues is determined to some extent to various spatio-temporal scales and that the management of a barrier island has to be considered in terms of interactions on various spatial and temporal scales.

Morphology of some of the barrier islands is determined by the pre-existing Pleistocene relief to a fair extent, either directly due to erosion-resistant outcrops on or near the islands, or indirectly by determining the locations where inlet systems or estuaries could develop. Where this is not the case, the larger part of the sediments are locally reworked Pleistocene or Holocene deposits eroded at the North Sea coasts of the barrier chain and deposited in the back-barrier area and on the islands as a response to sea-level rise. Hardly any sand is coming in from outside the area. In order to keep up with sea-level rise sand has thus to be nourished if coastal retreat is not allowed.

During the long Holocene evolution islands and ebb-tidal deltas have been lined up during their coastward migration, forming a more or less uninterrupted barrier chain along the Frisian coasts. The present-day approach of mainly focusing on the fixation of the inhabited parts of the chain will most likely result in a de-alignment of the various parts of the chain, resulting in increasing erosion of the promontories.

An inlet system is a sediment-sharing system with a tidal inlet, the ebb-tidal delta, adjacent barrier islands and the tidal basin with channels, shoals, tidal flats and salt marshes. The sand balance of a barrier island is thus directly linked to tidal inlet system development. A natural change or an intervention in the sediment-sharing system by man may thus have repercussions for the island’s development. Sediment redistribution in the coastal zone may also depend on climate, as is illustrated by the rapid growth of the islands after the demise of the Little Ice Age.

On the barrier islands themselves many measures were taken during the past two centuries to ensure coastal safety. The successful attempts to stabilize the coasts and dunes of the barrier islands resulted in a reduction of sand transport from and along the shoreface to the beach and onto the islands. To some extent this has been restored by applying sand nourishments. However, vertical accretion of the islands is still largely impossible due to all the older coastal protection measures still present. On the long run sedimentary dynamics are essential if the island is to accrete vertically with sea-level rise, which forms a robust and sustainable strategy to guarantee safety during the next centuries. Massive stabilization also reduced the opportunities for pioneer vegetation. Dune belts and tidal marshes have experienced a fast succession resulting in a climax vegetation and the loss of the characteristic open landscape.

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1. Introduction

Barrier islands belong to the most dynamic coastal environments where rapid changes may occur in terms of coastal processes and morphological as well as ecological developments (Hayes, 1979, 1980; Davis, 1994). Coastal zone management of barrier island systems is not a trivial issue, but requires a proper understanding and appreciation of the challenges under discussion. These challenges may vary from changes in the natural system due to external forcing, to the impact of human measures on the standing and appreciation of the challenges under discussion. Major present-day challenges are related to: i) coastal safety; ii) natural resources; iii) the tourism industry and iv) the development of ecosystems and associated ecosystem services. Coastal safety is of paramount importance for those areas that are vulnerable to flooding and sea-level rise, in particular due to a lack of sediment. Coastal safety is commonly established by stimulating dune development, by building seawalls, dikes and groynes or by implementing nourishments. However, the issue of coastal safety is not limited to the barrier island “sensu stricto” but also implies the protection of adjacent wetlands and the mainland coast. In the NW European Wadden region, for example, barrier islands in combination with the Wadden Sea provide a natural buffer between the highly energetic conditions in the North Sea and the mainland coast. Likewise, barriers and barrier island systems in the abandoned parts of the Mississippi delta protect an extensive system of wetlands and lagoons (Fritz et al., 2007). Once a barrier island is eroded, an accelerated loss in wetlands is observed (Sallenger and Williams, 1989; Penland et al., 1992).

The use of mineral resources of barrier islands is another activity that requires careful management. The most important impacts are related to sand mining, gas and oil exploitation and the extraction of drinking water. All have in common that they produce a certain degree of subsidence and result in a greater accommodation space for sediment. In addition the non-sustainable extraction of drinking water may result in a reduction of the fresh water supplies on the islands and the intrusion of sea water. The increased use of local fresh water supplies is often triggered by a more demanding tourism industry that is important for the economic development of the islands. Well-known examples of tourism development are found along the West and East Coast of Florida (USA), the Algarve (Portugal) and along the West, East and North Frisian Wadden coast. Due to their highly dynamic nature, barrier islands and surrounding coastal waters also represent valuable assets in the form of ecosystems and ecosystem services. Therefore, ecosystem dynamics and development versus coastal protection and nature conservation should be important considerations in barrier island management.

Barrier island management thus involves a range of stakeholders with often conflicting interests. On top of that, environmental and societal problems are increasingly associated with global change issues such as climate change and (accelerated) sea-level rise. This can be considered as a threat, but can also be interpreted as an opportunity. Nowadays it is often tried to tackle the problems by means of an integrated coastal zone management (ICZM) approach. It “involves the comprehensive assessment, setting of objectives, planning and management of coastal systems and resources, taking into account traditional, cultural and historical perspectives and conflicting interests and uses” (WCC, 1994). The agents of change are driven by socio-economic demands, natural processes and the impacts of climate change (Misdorp, 2011). It is advocated that integrated spatial planning should not only encompass small-scale adaptations, but should also take a long-term look ahead (Baarse and Misdorp, 2011). In practice, however, the ICZM approach is mostly to react on relatively short-lived developments as far as natural processes are concerned, often without having a sufficient in-depth understanding of the causes and consequences. As a result, ICZM does seldom take into account the various temporal and spatial scales that are relevant to morphological developments. This is true for most barrier systems in the world. As an example, problems of coastal erosion on the Frisian barrier islands were tackled in the past by constructing groins and are nowadays solved by implementing nourishments. Nevertheless, in both cases measures are (were) taken without having a proper understanding of the short- and long-term causes of erosion and accretion (Wang et al., 2012). Furthermore the impact of human actions on the natural functioning of the coast, in both time and space, is often poorly understood.

In this paper we will demonstrate that barrier island management can benefit from a more comprehensive approach that is based on a careful analysis of the impact of past, present and future processes and developments on barrier island dynamics. We illustrate this approach for especially the West and East Frisian Barrier Islands and to a lesser extent the North Frisian area. To this end we address the following three questions:

- What can we learn in terms of ICZM from the natural development and behavior of the Wadden Sea barrier island system?
- What has been the impact of human measures and interventions on barrier island development in the last decades and centuries?
- Is our present-day ICZM strategy a successful, integral and sustainable approach that is able to cope with future aspects of global change or do we have to adopt our coastal policies?

We will argue that the present-day ICZM approach is in favor of short-term, local coastal safety and focuses on the maintenance of beaches and dunes. However, this approach fails to address some other fundamental issues such as long-term safety, sediment dynamics and budgets in relation to coastal resilience, ecology and biodiversity. We advocate that a more balanced approach is desirable; an approach that better acknowledges the dynamic character of the islands and involves safety, morphology and ecology. Such an approach is feasible, but also requires a trade-off between different
stakeholders, even within the community of the environmentalists if one has to deal with the dilemma of nature conservation or restoration versus spontaneous nature development due to establishment of the appropriate boundary conditions.

In our analysis the relations between different temporal and spatial scales are crucial. Our central concept is to regard morphological developments of barrier islands as the product of developments at a hierarchy of spatial scales. Our concept of scales assumes a strong coupling between the temporal and spatial scales involved; an increase in spatial scales considered automatically implies that one has to take into account developments at larger time scales (and vice versa). Developments at larger temporal and spatial scales impose boundary conditions on developments at a smaller scale. Throughout this paper, we will apply this concept of scale for different objectives.

The first and second question are addressed by analyzing the natural behavior of the Frisian barrier island system at three related scale levels, which partly correspond to three different sources of information: i) the geological record (millennia), ii) the historical record (centuries to the past millennium), and iii) the current system (years and decades to a few centuries). We distinguish the following sequence of scales (see also: Speelman et al., 2009):

- Development of the Wadden Sea barrier island system during the Holocene.

At this scale level it will be shown that the present-day configuration of the island chain is mainly the product of Holocene (marine) processes that operate(d) in conjunction with the pre-existing Pleistocene topography or relief.

- Interactions of the tidal inlet–barrier island system over the past millennium.

Each individual tidal inlet system can be considered to form a sediment-sharing system consisting of a tidal inlet, ebb- and/or flood-tidal delta(s), updrift and downdrift barrier island coasts and the tidal basin, all of which are basically in a hydro-morphodynamic equilibrium with the prevailing conditions. Changes in these equilibria will lead to morphodynamic reactions in the system until either the original equilibrium is restored or a new equilibrium is established (Dean, 1988; Eysink, 1991; Steijn, 1991; Oost, 1995; Wang et al., 1995; CPSL, 2001, 2005; Kragtjwik et al., 2004; Elias et al., 2005, 2012, acc.; Dastgeib et al., 2008).

- Behavior of an individual barrier island on a time scale of decades to a few centuries.

At this scale level we identify different so-called morpho-ecological units, which together comprise the individual island. In our conceptual approach this island represents a prototype island since it illustrates the spatial and temporal coherence and dynamics of the morphological subunits of an island in a schematized way. This conceptual framework also appears to be extremely useful from an ecological point of view (Löffler et al., 2011).

The paper is organized as follows. In the following section we will present some main characteristics of the entire Wadden Sea region. We will then continue with discussing the processes and developments at the three different temporal and spatial scales involved and use this information to asses the impact of centuries of human intervention on barrier island development. Subsequently the pros- and cons of present-day ICZM strategies are evaluated and an alternative approach is proposed. The paper ends with a discussion and major conclusions.

2. Description of the area

The Frisian barrier island system forms the boundary between the open North Sea and the Wadden Sea and stretches for over 450 km along the coasts of the Netherlands, Germany and Denmark (Fig. 1). The system is characterized by relatively short (10–30 km in length) barrier islands.

The mixed micro- to macrotidal, semi-diurnal tidal regime (Fig. 1) is characterized by tidal ranges that initially increase from 1.4 m at Den Helder (western Wadden Sea) to 4.4 m at Bremen (central part of the Wadden Sea in the German Bight), before progressively decreasing again to 1.5 m at the Skallingen barrier-slit that marks the northern boundary of the Wadden Sea in Denmark. Mean significant (offshore) wave heights for the calm part (15 April–15 October) were calculated to be around 0.5–1 m and 1–2 m during the storm part (15 October–15 April) of the years 2002 and 2003 (Dobynin et al., 2010). In the West and East Frisian area waves and swell are predominantly incident from the west and southwest and along the North Frisian coast the major waves come from the northwest (Bartholdy and Pejrup, 1994; Beels et al., 2007). During storm surges, the maximum recorded set-up in water level is about 3.5–4 m and the offshore maximum wave height may be up to 8–11 m (data of several water management ministries).

The islands are separated by 33 adjacent tidal inlets and associated tidal basins, separated by tidal watersheds (Fig. 1; Dijkema, 1980; Hofstede, 2005). Each tidal basin is drained by a channel system, which is connected with the North Sea via the tidal inlet (Cleveringa and Oost, 1999). The inlets are generally lined by barrier islands on either side, only the first and last inlet being bordered by the headland of Den Helder in the south and the Skallingen peninsula in the North.

The modern Wadden Sea can be largely subdivided into two different regions:

1) A chain of barrier islands fronting tidal basins, which extends from the westernmost island of Texel near Den Helder in the Netherlands, up to the area between the Weser and Elbe estuary in Germany, together forming the West and East Frisian Wadden Sea (separated by the Ems estuary).

2) The area between the Weser and Elbe estuary in Germany up to the Skallingen peninsula in Denmark which forms the North Frisian Wadden Sea with a north-south trending series of islands. In the German Bight true barrier islands are absent due to the large tidal range (Hayes, 1979, 1980; Jacobsen and Madsen, 1993).

Rivers along the Wadden Sea coast did, and do, not bring in substantial amounts of sediment. A small amount of sand and a larger amount of fines is imported with the coast-parallel currents from the south along the West Frisian coast and from the north along the North Frisian coast. The bulk of the sediments within the Wadden Sea, however, consists of locally reworked Pleistocene material selected, transported and imported by marine processes into the Wadden Sea as demonstrated by the mineralogical composition of the sediment (e.g. Winkelmoelen and Veenstra, 1974, 1980; Hoselmann and Streif, 2004). The sediment needed in the back-barrier area, among others to balance sea-level rise, was and still is largely “taken” from the North Sea side of the barrier island chain (Mulder, 2000). As a result, the barrier islands and tidal basins tend to shift landward with rising sea-level rise. The strong coastward retreat of the West and East Frisian Islands over up to 10 km and the smaller retreat of the North Frisian barrier islands resulted in the reworking of sediments.
3. Barrier islands of the Wadden Sea system: evolution in time and space

3.1. Development of the Wadden Sea barrier island system during the Holocene

During the last glacial, most of the southern North Sea was land and the nearest shoreline was off the coast of Brittany (France) in the south and near the Shetland Islands in the northwest. The rivers Ems, Weser, Elbe and Eider drained northward via a broad valley (Figge, 1980). After the last Ice Age relative sea-level rise was initially rapid (over 1 m/century), but decelerated significantly after 7500–7000 a BP (Fig. 2; Kiden et al., 2002; Gehrels et al., 2006; Busschers et al., 2007; Vink et al., 2007; Kiden et al., 2008; Pedersen et al., 2009; Baeteman et al., 2011). In close association with the relative sea-level rise, the tidal range increased from initially microtidal conditions everywhere to the more differentiated ranges presently observed along the coast as the water depth in the southern North Sea basin increased (Jelgersma, 1979; Franken, 1987; Van der Molen and de Swart, 2001).

Around 8000 a BP sea level was still some 20 m below its present level (Fig. 2) and the North Sea coastline was much further offshore than its present position, e.g. 10–15 km for the central West Frisian Wadden area (Vos and Van Kesteren, 2000). The rising sea level followed (and modified) the pre-existing relief of the Pleistocene land surface and thereby constrained the initial position of the evolving Wadden Sea. Of particular importance were the following effects:

1) The initial differences in general paleorelief, with the north-south trending North Frisian area being more dominated by a steeper Pleistocene relief and lower availability of loose sediments than the east-west trending East and West Frisian area. This is, next to lower rates of sea-level rise in the North Frisian area, considered to be an important reason for the stronger retreat of the East and West Frisian area, where sea-level rise results in inundation of larger areas in the mainland direction.

2) The location and scale of paleo-valleys incised into the Pleistocene land surface during the sea-level lowstand. This paleo-channel morphology determined the location, size and inland penetration of estuaries, e.g. the Lauwerszee (Oost, 1995), the Ems-Dollard estuary, the Jadebusen, and the Weser and Elbe estuaries (Streif, 2004; Wiersma et al., 2009). Moreover: as the estuaries were deeply incised into the mainland, the sea could easily invade inland peat areas and convert them into back-barrier basins (e.g. Dollard- and Jade-embayments) thereby enlarging the tidal volume of the estuaries. The increase in tidal prism led to deeper incision of the tidal channels. In particular the flooding of the paleo-valleys of Ems, Elbe and Weser had a large impact on the coastal development, as the landscape developed into a broad estuarine landscape, which determines
The bulk of the West and East Frisian barrier island chain formed between 6000 and 5000 BP. Because sedimentation rates were insufficient to fill the accommodation space created by the initially rapidly rising sea (1 m/century), much of the inundated surface evolved into subtidal environments, fringed at the landward side by a narrow zone of intertidal sand and mud flats and salt marshes. An increase in tidal ranges resulted in higher tidal volumes, which may have generated an increased net sediment import into the tidal basins (Vos and Van Kesteren, 2000). However, it was also accompanied by further erosion and deepening of the tidal channels of which the sediments became available to the tidal flats (Hofstede, 2002) and to the ebb-tidal deltas. In this landscape, fens gave way to raised bogs. They started to expand on the mainland of West Frisia between 7000 and 6000 BP (Casparie and Streefkerk, 1994; Lips et al., 2010). The onset is attributed to a shift to wetter climate conditions, which were brought about by rising sea level in the early and mid-Holocene (Eckstein et al., 2010).

The sea reached the Pleistocene deposits of the southern part of the North Frisian area around 6500 years ago. Cliffs were formed and the material was transported along the coast. Around 6000 BP Sylt was most likely already an island (Jessel, 2001). Until recently, not much was known about the North Frisian Wadden region in the early Holocene. However, new research (Madsen et al., 2010) suggests that the formation of northern North Frisian barrier islands started some 8000 BP.

At about 5000 BP, the decelerating rate of sea-level rise along the Dutch west coast and the westernmost part of the West Frisian Wadden Sea area (Fig. 2) was exceeded by sediment accumulation rates. Thus, intertidal sand flats grew at the expense of subtidal environments (Van Heteren and Van der Spek, 2003; Vos et al., 2011). During the following millennia, sea-level rise decelerated even further, and the infilling of the available accommodation space tipped increasingly in favor of sedimentation exceeding sea-level rise. In the eastern part of the West and in the East Frisian Wadden Sea, however, subsidence of the bottom was relatively large and sedimentation was insufficient to infill the basins everywhere (Vos et al., 2011). In some places the tidal area was extending, e.g. in the Boorne, Hunzey and Fivel areas in the West Frisian Wadden Sea (Vos et al., 2011). From time to time, parts of the Wadden Sea locally silted up and the salt marshes at the landward fringe of the tidal basin could advance seaward (see Behre, 2004; Vos and Van Kesteren, 2000; Vos et al., 2011). Raised bogs spread over a larger area up to 3500 a BP. 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

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3) The occurrence of locally elevated Pleistocene (or older) outcrops and headlands consisting of moraine deposits of the Saale (second-last) glaciation, and sandy meltwater deposits of the Weichselian (last) glaciation, especially in the North Frisian Wadden area (Bartholdy and Pejrup, 1994; Lindhorst, 2007). Several of the barrier islands evolved around such Pleistocene or older cores of ice-dislocated deposits, a.o. the islands of Texel, Amrum, Sylt and Süderoog. These headlands commonly also acted as a source of sediment for the longshore drift, responsible for a re-alignment and smoothing of the often heavily indented coastline. Furthermore there are Pleistocene headlands present along the mainland coast, e.g. at Wieringen in the Netherlands and near the coast of Blåvands Huk, north of Skallingen. Furthermore the presence of sub-marine Pleistocene ridges can influence currents and wave impacts, e.g. at the southern “spit” of Sylt (Lindhorst, 2007). Smaller barrier islands, sandy shoals or sand spits were likely present in front of the mainland coast as relics of Pleistocene headlands (Flemming and Davis, 1994).

4) The low rate of relative sea-level rise in the northern part of the North Frisian barrier coast: Pedersen et al. (2009) gave only ~12 m over the past 8400 years. This led to a much more restricted erosion of the islands. For instance, the northern spit of Sylt was formed as early as 5000 BP (Lindhorst, 2007), whereas Rømø prograded seaward since 8000 a BP, due to abundant sediment supply (Madsen et al., 2010).
deposited on top of them (Vollmer et al., 2001; Behre, 2004; Streif, 2004).

At about 5000 a BP, the West and East Frisian barrier island chain was still situated several kilometers offshore from its present position, e.g. in the case of Terschelling about 9.5 km further to the north in comparison to its present position (Sha, 1990a,b; Vos et al., 2011). From 5000 a 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. The landward migration of the barrier islands was caused by erosion on the seaward side due to the rising sea level and transport into the back-barrier tidal basins of the Wadden Sea where the sediment deficit created by this sea-level rise more or less was compensated (Oost, 1995; Wang et al., 2012, this volume).

In the southern part of the North Frisian area (a.o. Eiderstedt), the barriers and Pleistocene outcrops in the area created an inlet-segmented coastline around at least 5000 a 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 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 several medieval times, its 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).

3.2. Interactions of tidal inlet–barrier island system over the past millennium

3.2.1. Coastal evolution between 1200 and 500 a BP (Fig. 3; after Wiersma et al., 2009)

The reconstruction of the West Frisian Wadden area at 1200 a BP (Fig. 3) shows the situation before large-scale human interference within the system developed. The situation in the West Frisian area is considered to be representative for especially the West and East Frisian Wadden Sea in this period. At that time the coastal environments from the mainland up to the Wadden islands were not yet separated from each other by dikes. Towards the mainland coast the tidal flats merged with tidal marshes and extensive brackish areas, which, in turn, were flanked by extensive peat bogs, lining higher sandy areas (Esselink, 2000). Tidally influenced rivers and streams debouched freely into the Wadden Sea. Settlements in the coastal marshes were built on dwelling mounds, which had a negligible influence on the large-scale tidal dynamics. Initially the dwelling mounds made use of the existing landscape and were built on small depositional ridges along marine/estuarine channels.

The first clear ring dikes in West and East Frisia were built around 1000–900 a BP and in North Frisia around 900–800 BP (Van der Spek, 1994; Oost, 1995; Ey, 2010), surrounding smaller areas to safeguard arable fields and against most winter floods. A second type of dikes was oriented rectangular to the main stream to channel the outflow of waters and has at least been built since 1000–800 a BP (Ey, 2010). Gradually, local ring dikes were connected and raised, and by 800–700 a BP a continuous system of winter dikes had been constructed along the entire West and East Frisian Wadden Sea coast and several parts of the North Frisian coasts (Oost, 1995; Ey, 2010). The diking was partially a response to the increasing vulnerability to flooding due to peat excavation – both inside and outside the dikes – and the development of drainage systems (e.g. Balgzand, Lauwerszee, Dollard, Jade and North Frisian area; Oost and Kleine Punte, 2004; Kühn, 2007; Wiersma et al., 2009). The vulnerability has resulted in some major “invasions” by the sea and the (re-)opening of many embayments along the Wadden Sea (Zuiderzee, Middelzee, part of the Lauwerszee, Dollard, and the Jade Busen; Pons and Wiggers, 1960). The spatial extension of the tidal basins generated a larger tidal prism and larger sediment demand. Before 500 a BP, many larger bays reached their maximum size. Partly coinciding with the onset of the Little Ice Age, successful land reclamation started, from time to time set back by severe storm surges (Oost, 1995). By 500 a BP, large parts of the salt marshes attached to the mainland which had become high enough due to natural sedimentation had been embanked and extensive areas of land bordering the inland bays

Fig. 3. Reconstructed map of the West Frisian Wadden Sea for the situation 1200 a BP (based on Vos and Kiden, 2005; Vos and Knol, 2005).
along the West (Middelzee, Lauwerszee, Fiveboezem), East (Maade Einbruch, Schwarzes Brack) and North (Bucht von Sielmönken) Frisian mainland coasts had been reclaimed (Van der Spek, 1994; Oost, 1995; Vollmer et al., 2001; Van Heteren and van der Spek, 2003). The land reclamations reduced the surface area of the tidal basins, creating smaller tidal prisms, which in turn resulted in smaller tidal inlet systems. It was coastal squeeze on a very large scale: while the mainland coast was prograding seaward and the barriers were retreating landward, the tidal basins became smaller.

Settlements on most of the islands were (semi-)permanent from at least 1000 a BP onwards. It has been documented that several of the East Frisian barrier islands were plundered around 1200 a BP (Abel, 1893; Rau, 1955). For most of the East Frisian Islands it is clear that continuous inhabitation was at least present since 800 a BP, based on written historical sources. From radiocarbon dating and pollen analysis, it appears that Ameland and Terschelling have been used for agriculture in or before 1200 a BP (De Jong, 1984, 1993; Oost, 1995). The names of the villages and excavation on some churches indicate that some settlements were founded around 1100—1000 a BP (van Oosten, 1986; Edes and Glashouwer, 1990). Management and the introduction of animals and plants on the islands initiated morphological and ecological changes. Especially dune arcs, which provided protection against flooding, were exploited. Directives protecting the marram grass and dunes date from at least as early as 650 a BP (1354 A.D.; Rottumerooog: Blok et al., 1899; Oost, 1995).

The Halligen islands in the North Frisian back-barrier area were at that time still much larger than at present, especially sea-level rise, storm surges and normal tidal and wave action during medieval times had already dramatically changed the vulnerable peaty landscape (Hofstede, 1991; Vollmer et al., 2001). From 1200 a BP onwards, dwelling mounds were once more constructed in the North Frisian region (Vollmer et al., 2001) as had been done before. Between 1000 and 900 BP, storm—flow layers were deposited on top of the earliest cultural layers, indicating increased marine influence. Flooding is also indicated by the fact that, at the same time, the peat bogs north of the Garding-Tating beach ridge system changed into a tidal marsh (Vollmer et al., 2001). Subsequently, the North Frisian marshes were protected by dikes. These required drainage, which then resulted in compaction due to dewatering of the underlying sediments and peat layers. In addition the peat started to oxidize resulting in further lowering of the sediment surfaces.

Between 700 and 600 a BP, catastrophic storm surges 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, parts of former coastal marshes changed into tidal flats. During the Middle Ages, people produced salt by burning the peat in the coastal marshlands under a cover of clay. This peat extraction made the land even more vulnerable to flooding and coastal erosion (Vollmer et al., 2001). The reconstructions around 500 a BP show that small parts of the salt marshes on several barrier islands had already been embanked. It is thought to have commenced as early as 700 BP (Oost, 1995; Schoorl, 2000a).

The high North Frisian barrier islands with a Pleistocene core, such as Amrum and Sylt were inhabited more or less uninterrupted since pre-historic times (Vollmer et al., 2001).

### 3.2.2. Changes after 500 a BP (Figs. 4–6; after Wiersma et al., 2009)

From 500 a BP onwards, successful land reclamation continued in the West (Lauwerszee, last remnants of the Middelzee) and East (Harlebucht) Frisian Wadden Sea (Van Veen, 1936; Vollmer et al., 2001). The area of embanked salt marshes gradually increased and the size of the inland bays consequently decreased.

As early as 500 a BP the first large-scale attempts were made to protect dune belts on the West and East Frisian barrier islands. However, extensive livestock grazing inhibited the intended stimulation of a closed vegetation cover. Serious sand drifts were recorded on many islands, for instance Texel, Vlieland, Terschelling, Juist and Sylt (Homeier, 1964; Schoorl, 1999a,b, 2000a,b; Jesse, 2001; Van Heteren et al., 2006). On most of the islands wind erosion must have occurred especially in the inner dunes: marram grasses benefit from drifting sands along the dune face. In this period, extensive sand drift dikes were built and maintained by placing brushwood fences, which trapped and stabilized wind-blown sand (Oost et al., 2004). As early as 370 a BP, the islands of Eierland and Texel were connected by a sand drift dike (Schoorl, 1999b). Although such measures suggest a strong influence on the sedimentary development of the area, the anthropogenic effects mainly slightly modified the impact of natural processes. Existing technology at that time was largely incapable of stopping large-scale natural developments, such as channel or shool migration.

The Halligen area in the North Frisian Wadden Sea, which was especially vulnerable due to peat extraction for the production of salt, was struck by several catastrophic storm surges (e.g. 1634, 1717, 1825–1826) and large areas of land were lost, largely shaped in the present-day Halligen landscape (Figs. 4–6; Vollmer et al., 2001). Only a small percentage of the inundated and eroded salt marsh between Rømø and Eiderstedt could subsequently be reclaimed (Vollmer et al., 2001).

The tidal waters flowing through the inlets in combination with wave- and wind-driven currents continuously exchange enormous amounts of mainly sandy sediments between the North Sea, the islands, the ebb-tidal delta, the inlet and the back-barrier basin (Oost, 1995). Net sedimentation occurs in the back-barrier basins at the expense of the open North Sea coast, which is on average retreating in a landward direction (e.g. Juist, Texel). A closer look, however, reveals large differences from island to island, indicating that on top of the long-term regional trend in coastal behavior other processes are locally important. One of the clear examples is the western side of Vlieland during the 16th to 18th century. Due to strong sediment transport into the back-barrier area the ebb-tidal delta retreated followed by the west coast of the island. Retreat of the island was as much as 1.5 km in 150 years (Abogado Rios, 2009, unpubl. res.). Another clear example can be found on the adjacent barrier islands of Ameland and Schiermonnikoog in the West Frisian Wadden Sea. From reconstructions (Oost, 1995) it appears that after 150 a BP Ameland retreated landward. In the same period the barrier island of Schiermonnikoog, by contrast, shifted seaward, especially after a reduction of the tidal volume of Schiermonnikoog Inlet with a third in 1969 (Biegel and Hoenkstra, 1995; Oost, 1995). Also, the eastern side showed a growth of more than 6 km, whereas Ameland only grew by about 1 km towards the E (Oost, 1995).

Both developments result from the fact that the tidal inlet system is a sediment-sharing system. In the back-barrier area, roughly speaking, vertical accretion of the shoals keeps pace with sea-level rise and hence, if tidal amplitude remains constant, the tidal volume will mainly depend on the area of the back-barrier tidal basin. The volume of the back-barrier tidal channels depends directly on the tidal volume that has to be imported and exported through these channels. If this tidal volume decreases, the tidal current velocities will decrease as well and net sedimentation of sand and clays will occur in the channel until the tidal flow will establish a new equilibrium. In this morphodynamic equilibrium sedimentation in the channel is balanced by erosion and — apart from migration — the channel will maintain stable dimensions (Biegel and Hoenkstra, 1995). Something similar applies to the ebb-tidal deltas, the sediment volumes of these are also related to the...
tidal volume in the basin: the sand volume decreases with decreasing tidal volume. If the tidal volume decreases, part of the sand eroded from the ebb-tidal delta is transported into the channels and into the back-barrier area. The relationships between sand volume of the ebb-tidal delta and volume of the tidal channels though are not linearly correlated with tidal volume. This may result in a mismatch between the amount of sediment that becomes available due a reduction in size of the ebb-tidal delta in response to a reduction in tidal volume (or tidal prism) and the amount of sediment required for the morphological adaptation of the channels within the tidal basin, depending on the configuration of the basin and the infill of the back-barrier channels. If this results in a surplus of sediment, this sand will be transported along the downdrift barrier island coast, most frequently in the form of shoals. After longshore and cross-shore dispersion, this surplus of sediment will contribute to the seaward progradation or stabilization of the shoreline. Schiermonnikoog Inlet has a long history of shrinking tidal basins and decreasing tidal volumes since about 600 a BP (Oost, 1995) due to land reclamation projects in the tidal basin (mainly Lauwerszee embayment) resulting in net progradation of the barrier island in contrast to Ameland, where hardly any reclamation occurred in the back-barrier basin of Ameland Inlet.

In the past 150 years, a series of notable morphological changes occurred (Ehlers, 1988). These changes primarily concern island growth and dune development reflecting sand supply from the ebb deltas and shoreface. The islands of Wangerooge, Spiekeroog, Baltrum, Norderney, Juist, Schiermonnikoog and Ameland started to grow rapidly eastward and sometimes were eroded at their westward side. Dunes became larger on many places on the islands along the entire Frisian barrier chain. In the North Frisian Wadden area, Amrum grew and the Havsand and Juvre Sand in the inlet between Sylt and Rømø merged with Rømø. Fanø extended northwards with the formation of new dune ridges, because ebb-tidal deltas were turned southward by the littoral drift and subsequently moved landward by the waves. The Skallingen barrier-spit eroded and retreated after the 1960s (Ehlers, 1988).

3.3. Behavior of an individual barrier island on a time scale of decades to a few centuries

In recent morpho-ecological studies of the West and East Frisian barrier islands, the concept of the so-called prototype island is developed and applied (Fig. 7, Löffler et al., 2011). The prototype island illustrates and integrates most of the common morphological aspects of the natural islands of the West and East Frisian part of the sublittoral zone. It demonstrates both the temporal and spatial coherence between the large-scale morphological units, which form the island under natural conditions. The large-scale
morphological units are characterized by developments on a time scale of decades to centuries, and a spatial scale of tens of square kilometers. For that reason, this morphological concept also provides a robust conceptual framework for the ecology of the islands, because each large-scale morphological unit is characterized by a range of abiotic conditions relevant to both flora and fauna. Such abiotic conditions are expressed in terms of — for example — the exposure to waves and currents, wind and salt spray, the average bed level, the amount of relief, the role of surface water and groundwater, the availability of nutrients, and the composition of the sediment or substrate. The prototype island (Fig. 7) is characterized by five large-scale morphological units, which mutually overlap and influence each other (Hoekstra et al., 2009; Löffler et al., 2011).

1) Island heads

These encompass the updrift coast of the island adjacent to the tidal inlet. This is the area where the sandy shoals of the ebb-tidal delta merge with the island and eolian sands are mobilized on the beach plains from where they are blown into the dune belts (see: Fitzgerald et al., 1984, 1994; Cheung et al., 2007). In the long-term, processes of accretion and erosion alternate with each other (Oertel, 1977). Depending on the long-term sand surpluses or deficits in the adjacent ebb-tidal delta the downdrift coast of the island will demonstrate accretion (e.g. Schiermonnikoog) or erosion (e.g. Norderney), respectively. Within this long-term development there commonly is a shorter cycle of sedimentation due to the merger of shoals (Joustra, 1971; Oost, 1995; Israel and Dunsbergen, 1999) and (channel-driven) erosion associated with the autonomous dynamics of the ebb-tidal delta. With increasing size of the tidal volume and hence the size of the ebb-tidal delta, the duration of the cycle will increase, from decennia for tidal volumes of a few $10^6$ m$^3$ to more than a century for tidal volumes of the order of several $10^6$ m$^3$ (Oost, 1995; Schoorl, 1999a,b; Oost et al., 2004).

2) Dune arcs

This unit comprises large dune complexes that form an arc with curved and partly parallel dune ridges, encircling former beach plains with tidal marshes along the central island coast. The exact nature of the rows of dunes is still under debate, but dune belts at the accretion side of the island consist of primary dunes (Van Heteren et al., 2006), whereas those at the erosive sides of the islands consist of parabolic dunes, formed by the reworking of primary dunes. The large dune complexes have been stabilized by natural vegetation development. The dune arcs provide coastal protection to major human settlements on many of the islands.
3) Washover complexes

A (former) washover complex is normally found at the end of a dune arc with an alternation of foredunes, remnants of dunes, and local depressions. Shallow creeks form a connection between the North Sea and the Wadden Sea during storm surges. The associated supratidal plains form low depressions, separated from the beach by a beach ridge or high berm and accommodate a pioneer vegetation, tidal salt marshes and low dunes (Hoekstra et al., 2009).

However, almost all of these wide channels/openings at the end of the dune arcs have disappeared in past centuries due to the development of sand drift dikes.

4) Island tails

Downdrift tails of the islands are limited in width up to a few kilometers. Dunes alternating with (former) washover fans and channels, fringed by tidal marshes at the back-barrier side (Dijkema, 1989), form the other end of the island (Leatherman, 1976; Hoekstra et al., 2009). In general, these areas are dynamic (beach) plains where periods of accretion and erosion alternate. In addition, a “wagging” of the island tail is also possible due to the (cyclic) behavior of the tidal channels in the downdrift located inlet (Cheung et al., 2007). Here, low dunes and — in their shelter — salt marshes may also occur. If dynamics are somewhat reduced due to dune development the marshes can develop strongly and quickly (e.g. island tail of Terschelling).

5) Beaches and shorefaces

Beaches, upper and lower shoreface along the open North Sea coast of the islands form the natural link with other morpho-ecological units (Guillèn and Hoekstra, 1996; Hoekstra et al., 1999; Houwman, 2000). Often these beaches are characterized by a considerable width and a rather low gradient (1:100) (compare
hydrodynamic conditions, and over the period 1927–1997 the Wadden Sea in front of the Zuiderzee has been adapting to the new sedimentary conditions, and over the period 1927–1997 nearly 400 \( \cdot \) \( 10^6 \) m\(^3\) of sediment have accumulated in the back-barrier, especially in the abandoned tidal channels (Berger et al., 1987). A large part of the sediment was derived from the North Sea coastal zone, causing strong retreat of the ebb-tidal delta of Texel Inlet. Together with that, retreat occurred of the adjacent coasts of the barrier island of south-Texel (800 m in 50 years) and Northern Holland, where a large ebb-delta channel formed near the coast (Oost et al., 2004; Elias, 2006). From the developments, it can be judged that the effects of the Afsluitdijk will continue to influence the area for centuries (Elias, 2006; Elias et al., 2012, acc.). The process is expected to lead to serious ebb-delta erosion (Elias et al., 2012, acc.). Retreat of the ebb-tidal delta may on the long run also exert influence on the barrier coasts since shelter decreases and sand may become less easily available (Hofstede, 1999a,b).

Smaller enclosures such as part of the embayment of Schiermonnikoog Inlet in 1969 A.D. have resulted in an inflow of the main back-barrier channel connected to it and erosion of the ebb-tidal delta, all tuned to the decrease of tidal prism from 300 to 200 \( \cdot \) \( 10^6 \) m\(^3\). A substantial part of the sediment became available to the downstream delta of Schiermonnikoog. The adjustment processes took at least about 4 decades (Biegel and Hoekstra, 1995). Also in the North Frisian Wadden Sea hydrodynamical and morphological effects were produced by the construction of the dams connecting Rømø (1949 A.D.) and Sylt (1927 A.D.) to the mainland, and the construction of the Eider storm surge barrier in 1973 (Reise et al., 1996). In the case of Rømø the location of the dam did not fully coincide with the position of the tidal watershed (or drainage divide). Subsequently, the tidal prism of the areas North and South of the dam was redistributed; a process which was followed by an adjustment in local channel morphology. Furthermore, subsidence of some tidal inlet systems and a subsequent increase of sediment demand resulted from sand mining within the tidal systems (above –13 m MSL) and due to the exploitation of gas and oil. Volumes of subsidence are of the order of 0.1–10 \( \cdot \) \( 10^6 \) m\(^3\).

On the barrier islands, the increase in tourism during this period resulted in the development(672,1106),(996,997)

![Fig. 8. Population development of the barrier island Norderney (data: historical & internet sources). The boom of the population occurred after 1797 when the island became a bathing resort.](http://example.com/figure8.jpg)

response, new coastal defense structures were developed, which with the exception of nourishments, reduced the mobility of sediment and the morphological development of the islands, such as (Table 1):

- Dikes (at least since 650 a BP on Texel; Oost et al., 2004, but perhaps even 1000 a BP on some of the islands (Oost, 1995));
- Protection (since at least 650 a BP on Rottumeroog; Oost, 1995) and planting of marram grasses (since at least 350 a BP on Norderney);
- Sand drift fences and formation of sand drift dikes (since at least 370 a BP on Texel);
- (Sub)littoral stone defense works (since at least 300 a BP in the Marsdiep Inlet);
- Groynes (since about 200 a BP);
- Revetments and seawalls (since 150 a BP on Norderney; Thorenz, 2011);
- Harbor moles (since at least 150 a BP) and massive discharge sluices;
- Sand nourishments (since 60 a BP Norderney island in 1950/51; Kunz, 1990).

Substantial were the hard protection measures taken at the northwestern and western heads of the islands of Ameland, Borkum, Norderney, Baltrum, Spiekeroog and Wangerooge (Oost, 1995; Thorenz, 2011). The constructions have halted the process of tidal inlet migration (e.g. Norderney, Nummedal and Penland, 1981). In some cases, for instance Ameland and Texel inlets, this caused extreme deepening (Oost, 1995; Schoorl, 1999b). In addition to groynes and revetments, seawalls were erected to protect the barrier coast in places vulnerable to erosion (cf. Elko and Davis, 2006). The earliest were built of basalt; later, asphalt mounted with stones was used in order to increase the roughness of the surface and decelerate the waves. All these measures also influenced sediment transport along and perpendicular to the island coasts. In the same period some barrier islands have been given up for maintenance by man. For instance, in 1991 it was decided by the Dutch Ministry of Transport, Public Works and Water Management that the uninhabited barrier island Rottumeroog would no longer be managed and to let nature take its course. Due to considerable protest of several stakeholders it lasted until 2001 before the advice was really implemented and it was decided to stop all management of the dunes and let natural forces of wind and water take over.
Also, dune areas developed quite differently due to human interventions (Nordstrom et al., 2007). Whereas natural dunes are low and irregular in form (e.g. Spiekeroog) the artificial dunes or sand drift dikes are high and often strongly interconnected (e.g. Schiermonnikoog). Partially they were formed to protect the inhabited areas and partially to close off the open parts of the coast. Once formed these were often repeatedly re-enforced and grew to 5 m or more above mean sea level, especially when the first dune row could be kept, which became quite normal once nourishments became important to maintain the coastline. The dunes were also used as a reservoir for drinking water. In the Netherlands, the production has been restricted, but on the East Frisian Islands, the production is often more than the annual precipitation leading to a gradual lowering of ground water tables. Furthermore, dunes are used on many places as recreational areas. Infrastructure, holiday houses, hotels and campings have been constructed, often near the shore outside of safe zones, leading to extra demands for safety from flooding.

In recent decades, there has been a growing tendency to use sand nourishment rather than hard structures to actively protect the coast. A good example is Sylt where at Hornum, concrete tetrapod barriers were placed in 1960–1967 in cross- (jetty) and longshore direction (dune foot revetment; Sistermans and Nieuwenhuis, 2002). Also, seawalls were built in Westerland. The measures proved to be counterproductive in the long run since they contributed to disrupt longshore sediment transport, thus generating lee-erosion south of the jetty. The seawall at Westerland suffered from severe damage during storm surges as a result of foreshore lowering in front of the structure. Thereupon authorities started in the early 1970s with beach nourishments and flexible solutions such as geotextile revetments. These measures did not dispel the need for hard protection but improved their efficiency and life expectancy (Sistermans and Nieuwenhuis, 2002; http://www.ubcwheel.eu/index.php/gpdb/article/1733). An advantage of nourishments is that the beaches can maintain their dynamic states, keeping natural processes of erosion and sedimentation more intact. For many of the North Frisian barrier islands the availability of nourishment sand is limited.

Effects of nourishments are (Holzhauer, 2011; Oost, 2012) are:

1) The influence of dredging of sand

Depending on the depth on which sand for nourishment is dredged this may influence the development of the coastal zone. In the West Frisian area sand is dredged on water depths of 20 m and more, thus trying to avoid effects on the coastal development. This is different per country. This is illustrated by the erosion of the southern spit of Skallingen and the ebb-tidal delta of the Skallingen Inlet (Grådyb). The processes can partly be attributed to the dredging of the navigation channel and the associated dumping of the sand at the southern side of the inlet, which is thereby lost for the sediment circulation around the southern part of Skallingen and on the ebb-tidal delta.

2) The effects of nourishments on the morphology of the dunes at the beach

It has been shown that on the West Frisian Barrier islands an amount of sediment is blown into the dunes from the beach, which is in volume 44% of the volume of the nourishments. Depending on the management, several reactions are possible (Arens, 1999; Arens et al., 2007, 2008, 2010):

A) no dynamics in the dune face area, only minor migration of the dune foot. No sediment is transported into the dunes behind it and no primary dunes do develop.

B) Dynamics are mainly restricted to the zone in front of the dune face and the top of the dune face. Embryonic dunes develop, which may develop to new dunes. The dunes behind the dune face do not receive sands and are hence not rejuvenated.

C) Dynamics are slight to strong, and sand transported by the wind can reach the area behind the dune face. Due to the dynamics embryonic dunes can form which may develop into new dunes and older dunes are rejuvenated by the import of calcareous sands.

D) Dynamics are very strong. Depending on the beach dynamics embryonic dunes may form or not. Due to (artificial) openings in the dunes sand can reach the older dunes, which are thus developing in a natural way.

3) The effects of strange sand (Stuyfzand et al., 2010)

The sand has to be dredged somewhere else, consequently introducing sand that in terms of hydraulic or geochanical behavior may be different from the local sands, thereby affecting the habitats. Studies revealed that indeed the sand differs in grainsize and geochanical characteristics and thus may be of influence.

4) Other effects (Holzhauer, 2011)

In recent studies it could not be demonstrated that nourishments on the foreshore did influence significantly the current velocities, bottom roughness, sediment characteristics (also on the beach), infauna (also on the beach) and epifauna. Sediment nourishments did also not influence the sanderling, which is depending on the infauna of the beach.

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### Table 1

Some data on revetments, poles placed in rows perpendicular to the coast line and groynes at the North Sea coast of the West and East Frisian barrier islands (mainly after Thorenz, 2011).

<table>
<thead>
<tr>
<th>Island</th>
<th>Begin of building</th>
<th>Revetments (km)</th>
<th>Poles (km)</th>
<th>Begin of building</th>
<th>Number of groynes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year</td>
<td>1900</td>
<td>1997</td>
<td>1900</td>
<td>1997</td>
</tr>
<tr>
<td>Texel</td>
<td>1952–1957</td>
<td>–</td>
<td>0.6</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Vlieland</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Ameland</td>
<td>1960–1969</td>
<td>–</td>
<td>0.6</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Borkum</td>
<td>1874</td>
<td>2.8</td>
<td>6.5</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Juist</td>
<td>1913</td>
<td>–</td>
<td>1.4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Norderney</td>
<td>1857</td>
<td>2.0</td>
<td>4.7</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>Baltrum</td>
<td>1873</td>
<td>–</td>
<td>1.7</td>
<td>1.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Spiekeroog</td>
<td>1874</td>
<td>1.6</td>
<td>1.9</td>
<td>0.8</td>
<td>–</td>
</tr>
<tr>
<td>Wangerooge</td>
<td>1874</td>
<td>3.1</td>
<td>5.7</td>
<td>–</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>9.5</td>
<td>21.9</td>
<td>3.1</td>
<td>2.1</td>
<td>0.2</td>
</tr>
</tbody>
</table>

* Ten woodwork groynes were build in that year, but destroyed in 1848, stone groynes were build since 1860.

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3.4.2. The impact on morpho-ecological units of an individual island

Human interventions in the last two centuries have seriously affected the morphology and ecology of the islands. Major effects are: i) the large-scale erosion, movement and deposition of sediment around islands in relation to morphological adjustment due to closure works and large constructions; ii) the lack of mobility of sediment being fixed by constructions or “trapped” in, for example, sand drift dikes and iii) the more recent artificial supply of sand in the framework of nourishment projects to protect the coast. All measures have in common that they are related to “sediment management” within the system and that they have significantly altered the coastal dynamics of, in particular, the West Frisian barrier islands. We will now discuss the way in which these developments are visible in the landscape of the morpho-ecological units of an island.

1) Island heads

Depending on the sand surpluses (e.g. Schiermonnikoog) or deficits (e.g. Norderney) in the ebb-tidal delta the downdrift coast of the island adjacent to the tidal inlet may receive sediment or erode. As erosion is being hindered by stonework and nourishments to protect the nearby inhabited dune arcs the net effect is often an (updrift) elongation of the islands. Also, the island heads become either bulwarks or at least semi-stable areas where dune erosion is largely prevented. One has to keep in mind that dune erosion is often a source of sediment for new dune building processes. So by interrupting the natural cycle of erosion and deposition the impact of eolian processes is reduced.

2) Dune arcs

The large dune complexes that form an arc have been stabilized by coastal protection works, planting of marram grasses and forestation. It resulted in a reduction of eolian transport in the dunes. The formation of high sand drift dikes at the dune face on many of the Frisian barrier islands resulted in further reduction of eolian transport into the so-called grey dunes behind them. The characteristic vegetation of the grey dunes of grasses and lichens depends on poor nutrient conditions and a slight sand import. The reduced dynamics led to the formation of shrubbery. This is further enhanced by the increase of atmospheric nitrogen deposition and precipitation and the decrease of grazing (Van Dobben and Slim, 2011, acc.). On many parts the characteristic open landscape of the island is being replaced by a climax vegetation and a process of rejuvenation is lacking (Löfler et al., 2011). Present nature conservation strategies, such as the removal of top soils and shrubberies do not address the causes of the problem — the lack of dynamic processes — but simply are dealing with the symptoms and, consequently will not be sustainable. On the long run it will be impossible to provide the envisaged nature restoration, since the measures taken are short-lived, often have a very local character and also depend on seed banks that are becoming poorer in species (Löfler et al., 2011).

3) Washover complexes

The wide openings at the end of the dune arcs have all been closed off by sand drift dikes at the North Sea side and mostly by dikes at the Wadden side, except for the one on Spiekeroog. On the West Frisian Islands the storm surge disaster of 1953 had as a consequence that many sand drift dikes were built over the full length of the islands to link the individual dune systems and to protect the coast. This strategy was part of a major master plan to close off the entire West Frisian Wadden Sea; a plan that was later on abandoned again. Due to this, large areas of beach plain and tidal marshes have changed into polders.

4) The island tails

On the West Frisian Islands the presence of the sand drift dikes prevented the transport of water, sediment and nutrients to the interior or even Wadden coast of the islands. The sand drift dikes were also intensively maintained by planting marram grass and placing sand fences further limiting the eolian transport across the island. This lack of natural dynamics led to fast development and succession of the vegetation. After it was decided that the sand drift dikes on the uninhabited island tails would no longer be maintained new openings formed in the sand drift dikes on some locations but this has not seriously improved the situation. The contrast to the East Frisian barrier islands is huge now. Large sand drift dikes are absent there and we see a much more natural environment with highly dynamic ecosystems.

5) Beaches and shorefaces

Beaches and upper and lower shorefaces are often nourished or kept with stoneworks. In this way the natural retreat of the barrier islands thereby slowly cannibalizing themselves over the past thousands of years has come to a halt. The erosive coasts have become accretional static coasts. This implies less reworking of sediment from the dune face: sand, which is eroded from the dune face or the beach, is replenished with sand dredged from deeper waters. This sand has commonly not the same sedimentological properties as the original beach sands (compare Guillén and Hoekstra, 1996), often contains a lot of shell fragments and, as a result, is often less suitable for eolian transport.

4. Barrier island management: discussion

4.1. Introduction

In this discussion we will answer the three major questions that we addressed in the introduction of this paper.

4.2. What can we learn in terms of ICZM from the natural development and behavior of the Wadden Sea barrier island system?

An overarching theme in barrier island management is the role of coastal (morpho) dynamics in determining safety (or the opposite: creating risks), in providing the boundary conditions for the dynamics of ecosystems and in delivering ecosystem services, such as for the environment and the tourism industry. Coastal zone managers of the Wadden Sea barrier island system have to be aware of the following morphological conditions and sediment budget considerations:

1) Presence of outcrops and inherited Pleistocene topography and paleomorphology

Up to this day the Pleistocene initial topography is a dominant factor in the development of the north-south trending North Frisian Wadden area, which is characterized by a steeper Pleistocene relief and lower availability of loose sediments. On a smaller scale deeply incised river valleys, which formed during the Pleistocene lowstand, determine to a large extent the present-day positions of several major estuaries such as Elbe, Weser/Jade and Ems (Streif, 2004). Furthermore Pleistocene outcrops determine locally the formation of the coastal zone such as the southern spit of Sylt, and...
near Skallingen (Blåvands Huk). The rigid clays deposited or over-ridden by ice during the Ice Ages such as boulder clays are known to be resistant to erosion. It has been argued that the boulder clay outcrops on and in front of the southwest part of Texel Island actually form the reason why Texel forms the knick point between the N-S trending Holland coast and the W-E trending Frisian barrier coast (Schoorl, 1999a). The resistance against erosion also explains the seaward position the barrier islands of Amrum and Sylt (Fig. 1). The influence of the rigid clays on channels, which are incised into the Pleistocene sediments, and their possible influence on island dynamics may also be of importance. An example is a pipeline which was entrenched through a Pleistocene clay ridge in the Langeoog Inlet in the East Frisian Wadden Sea and which was subsequently covered with sand (Grann, 1997). Much to the surprise of the engineers the sand was quickly eroded, leaving a hanging pipeline and leading to a reorientation of the main channel via the pipeline trench. The boulder clay which had originally been present was more resistant to erosion than the underlying sand and had hindered the reorientation of the inlet channel. Currently the dredging of a deeper channel thalweg is considered through the boulder clay W of Borkum, which may have its effects on the barrier island: special attention is given to it by the state authorities.

However, the larger part of the islands coastal morphology is the result of repeated reworking of sediments and thus totally governed by the present-day natural forces and interactions between the various morphological units. In such areas morphodynamics are determined by Holocene sands and clays and not so much the Pleistocene relief. In that case the following points are of importance:

2) Holocene line-up of barrier islands and ebb-tidal deltas

During its long Holocene evolution, since 5000–6000 yrs BP the islands and ebb-tidal deltas along the North Sea side have been lined up during their Holocene coastward migration, forming a more or less uninterrupted barrier chain along the Frisian coasts. Momentarily there are management plans to push the coast locally seaward, or to keep the coast in its present position. Other parts of islands or entire islands or ebb-tidal deltas are allowed to continue to migrate towards the mainland as they have done during the large part of the Holocene. As yet, it is not clear what would be the effects of allowing such disturbances in a chain of lined-out barrier islands. If retreat of parts of the chain becomes strong it will most likely result in increasing erosion of the promontories and disturbances in the coast-parallel sand transports.

3) Balance between sea-level rise and sedimentation

The observation that around 5000 a BP sediment accumulation rates locally exceeded the rate of sea-level rise, whereas in other places areas drowned, indicates that the balance between sea-level rise and sedimentation is rather subtle (Flemming, 2002). It implies that the availability of sediment from the North Sea side and the possibility to settle in the back-barrier area both play an important role. The availability is partly determined by the variation in tidal volume and wave climate (Van Goor et al., 2003; Grunnet et al., 2005), and for the other part by changes in the North Sea facing cross-shore coastal profile. The potential for sediment to settle depends on the hydrodynamic conditions in the back-barrier basin. During the sedimentary infill and shrinking of the back-barrier basin towards the present day, the energy gradient between the mainland coast and the inlet became steeper, thus making it more difficult for especially finer-grained sediments to deposit and accumulate (Flemming and Nyandwi, 1994). If the idea is correct, it may have consequences for the demand of sediment when sea-level rise accelerates. As long as sedimentation can keep up with sea-level rise within the back-barrier basin, the sediment demand from the North Sea coast (and thus erosion) will increase linearly with the rate of sea-level rise. However, if sedimentation cannot keep up with sea-level rise, which is expected to occur at lower rates of sea-level rise for larger basins than for smaller (Oost et al., 1998), wave and tidal energy within the basin increase leading to enlargement of the tidal channels and even more difficult conditions for sedimentation on the shoals (Flemming and Barholomä, 1997; Van Ledden, 2003; CPSL, 2010). A tidal basin might then start to function as a source of sediment instead of a sink. Depending on the original dimensions of the tidal system the changing demand for sediment in the back-barrier area may thus have different implications for the management of the North Sea coasts of the barrier islands.

4) Climate change

As discussed, the striking coincidence of so many positive shoreline changes after 150 BP makes it very likely that some common processes were responsible. Since the period after 150 a BP marks the end of the Little Ice Age (A.D. ~1450—1850), a change in circulation following this period has been suggested as a driving mechanism for the observed changes (Ehlers, 1988). Partially it will, of course, also be the resultant of human induced poldering of mainland areas resulting in a reduction of tidal volume in inlets and surpluses of sand, which became available to the islands. Furthermore, the decrease of dynamics on inhabited islands and the furthering of the development of vegetation will have enhanced local dune development, especially since AD 1960. However, given the fact that also uninhabited islands show a different development from the period before 150 BP, the hypothesis of the Little Ice Age aftermath might well be correct. In that case the adaptation will not continue indefinitely: wide-spread coastal aggradation might give way to wide-spread erosion once again just as in the past (e.g. Lindhorst, 2007). Coastal managers then will be facing larger net erosion in the future. In this light it might be wise to store as much sand as possible on the islands by allowing natural processes.

5) Reactions of the sediment-sharing system

An inlet system is, as discussed in chapter 3, primarily a water and sediment-sharing system with a tidal inlet, the ebb-tidal delta, adjacent barrier islands and the tidal basin with channels, shoals, tidal flats and salt marshes. Barrier island development is thus directly linked to tidal inlet system development. A natural change or an intervention by man may have repercussions for other parts of the system. The initial increase and subsequent decrease of the tidal volumes of inlet systems due to sedimentation and digging must have influenced the development of the North Sea coasts of the barrier islands strongly, by initiating coastal erosion when sediment was needed and sedimentation when surplus sediments became available. This is illustrated by the differences in coastal development of the barrier islands of Ameland and Schiermonnikoog. It should be realized that thus caused accretionary or erosional tendencies on the islands will eventually come to an end, when the sediment-sharing system is moving towards equilibrium in the long run (decades to centuries).

Sometimes, however, a closure triggers a strong increase in sediment demand in the back-barrier basins and thus results in coastal erosion of – in the first onset – the ebb-tidal deltas, as is the case with Texel inlet. The effects are often ignored, as management is often focused on the immobilization of the island and the
6) Dynamics on the barrier island between the larger morpho-ecological units
The larger morpho-ecological units on a barrier island are in close interaction with each other. In this the beach and foreshore play an important role as conveyor belt of sediment between the other units in a coast-parallel direction. Next to that natural dynamics will allow for coast-perpendicular wind and waterflow driven transports of sediments, thus allowing the island to move in a back-barrier direction or to accrete vertically.

4.3. What has been the impact of human measures and interventions on barrier island development in the last decades and centuries?

Human measures and interventions have strongly influenced the development of the barrier islands, in terms of sediment deliverance to the island (see above), safety from flooding and natural development of the island itself. Originally safety was found on natural relief of the dunes and dwelling hills. After that closed dune--dike rings were maintained, of which the dune vegetation was somewhat protected. Gaps between the dune arcs were left open allowing eolian transport and inundation transport so that parts of the island could accrete in a natural way.

From the 17th century onwards sand drift dikes were formed at the dune face on the West Frisian islands and parts of the East and North Frisian islands. Also, marram grasses and trees shrubs stabilized the dunes. Before that vegetation density was mostly lower and there was ample possibility for sediment transport by wind or water on many locations, resulting in a more dynamic landscape. Due to plantation the vegetation trapped the transported sand more effectively and erosion was avoided better. Where needed the coast was protected by stoneworks, forming a bulwark at the western side of many islands. The fixation of inlets and sandy coasts limits the possibility of inlet migration and longshore barrier island dynamics (compare Elko and Davis, 2006). Due to all the anthropogenic attempts to stabilize the islands, also sand transport from the shoreface to the beach and onto the islands has been reduced.

The later beach and shoreface nourishments allowed for sand transport along and perpendicular to the island coasts and into the back-barrier and to the ebb-tidal delta. Thus the integrity of the sediment-sharing system was to some extent restored. However, the approach was mainly derived from the rather reactive coastal protection policies aiming at restoration of erosion and maintaining the sand drift dikes. Only locally eolian (Terschelling beach pole 10–15) or inundation transport (Spiekeroog Leegde) of sediments onto the islands is allowed. Sufficient sediment import is, however, on the long run essential everywhere outside of the dike-dune ring if the island is to accrete vertically and to keep up with rising sea levels. As such allowing sediment import onto the island has to be part of a robust and sustainable strategy to guarantee safety in the centuries to come.

The massive stabilization also reduced the opportunities for pioneer vegetation. Dune belts and tidal marshes have experienced a fast succession (Löffler et al., 2011) resulting in a climax vegetation and the loss of the characteristic open landscape. It was recommended in earlier studies (Williams et al., 2009; Feagin et al., 2010), that a more sustainable strategy of barrier island management and nature development should be based on a natural degree of substrate mobility. To that end the focus for managing barrier islands should be on maintaining the integrity of ecosystem services, their functioning and natural process development. In 2005 the United Nations Millenium Ecosystem Assessment (MEA) divided the ecosystem services in four categories: production, such as the production of food and water; regulating, such as the control of climate and disease; cultural, such as spiritual and recreational benefits and supporting, such as nutrient cycles and crop pollination (DeFries et al., 2005). Traditionally, coastal management mainly focused on strengthening especially one or more of the production-, regulating- or cultural services –, paying little attention to the supporting services (e.g. Morton, 2008). As a result, many examples of traditional coastal management projects show a negative impact on supporting services, undermining sustainability of the system. This is also the case on most of the Wadden barrier islands.

4.4. Is our present-day ICZM strategy a successful, integral and sustainable approach that is able to cope with future aspects of global change or do we have to adopt our coastal policies?

There is a clear connection between the various spatial scales considered which are strongly coupled to the temporal scales over which the characteristic developments take place. This applies as well to the regional development during the Holocene of the barrier island chain, as to the interconnectedness of the barrier island with the adjacent tidal inlet systems, as to the local large-scale morphological units, which together compose the barrier island. But it also applies to relations between the various spatial scales: larger scales to a large extent set the stage where smaller scale developments can take place. This interconnectedness implies that the management of a barrier island cannot be seen in isolation but has to be considered in terms of interactions on various spatial and temporal scales. Until now it is not taken strongly into consideration in the ICZM approach that morphodynamics of a barrier island is also connected to the developments which take place on larger spatio-temporal scales and the relative strong influence by man on these in the past two centuries. This may lead to surprises like for instance accelerated coastal erosion due to changes in the net sediment supply to the coast, or fast retreat of an ebb-tidal delta, leading to changes in wave attack on the barrier island. We advocate to take into account the bigger picture of relevant developments on larger spatio-temporal scales and to make this a consciously considered part of barrier island management. The list given in the above discussion (4.2) indicates that exact outcomes of such developments may differ from island to island. In general, a hierarchical order of influences should be considered (Fig. 9):

1) Is the Pleistocene paleomorphology important to the island?

If the answer is yes it should be taken into account in terms of less free morphological development than in the situation of only Holocene sediments (predominantly sand and some gravel, shells and clay) influencing the development. In the latter case the integrity of the barrier-ebb-delta chain should be considered. Although the effects of forming seaward bulwarks while at the same time allowing other parts of the chain to retreat coastward are yet not fully understood it is clear from experience that this may well lead to unwanted accelerations in local erosion. It thus may become more cost-efficient (also in terms of ecosystem services) to nourish those other retreatting parts of the barrier chain, for
instance in the form of ebb-delta nourishments in channels which are threatening to erode a barrier island.

2) Is the inlet system not in dynamic equilibrium?

If the answer is yes the net sand deliverance to an island might be either showing a long-term (decennia to centuries) surplus or deficit, which is temporary. Such insights may influence the coastal nourishment and development schemes of barrier islands. Nourishments will be necessary even when the inlet is in equilibrium if the coast is to be maintained on its position.

3) Is human influence on morpho-ecological units strong?

Often the answer will be yes as the supporting ecosystem services of many units are restricted due to all coastal protection measures and adverse effects of nourishments, especially with respect to dune development. Moreover, the increasing tourism on the islands is based on use of production, regulating and cultural ecosystem services, taking a gradual increase of demands for granted. This situation is not sustainable on the long run. We will expand on this below.

In the past decade the United States National Park Service (NPS) called for natural processes to be maintained and for human-altered systems to be restored on barrier islands to allow natural processes to function and natural landforms to develop and evolve. For Fire Island it is stated that: “Storms and associated processes such as waves, tides, currents and relative sea-level change are critical elements for the formation and evolution of [some] barrier islands, sand dunes, back-barrier sand flats and lagoons and vegetated wetlands. Processes such as wave run-up, overwash and barrier breaching, which occur during elevated storm surges, are all necessary processes in enabling the efficient transfer of sediments, nutrients and marine water from the Atlantic Ocean across the barriers…” (Williams and Foley, 2007). In order to restore nature sufficient space should be available to allow natural processes to develop and to create robust ecosystems. The same applies to the factor time: the system will need time to tune and adjust to changing external conditions (in the order of several decades up to centuries). Furthermore, it should be realized that developments may not always occur on the exact same place as original (before human intervention). Therefore, instead of focusing on nature conservation a paradigm shift is needed in barrier island management towards stimulating the development of nature dynamics. Stopping management of Rottermoor, allowing natural forces to take over, leading to a strong morpho-ecological development of the area is an example of this ‘working with nature’. To our opinion the best solution is to allow the geo-biological processes to take their natural course as much as possible. Only where this is not feasible other management practices should be applied. As a rule: soft and with respect for morphodynamical integrity where possible, hard where really needed. It is our expectation that this — to a certain extent — will also regulate the booming use by tourism of the barrier islands. Examples are the development of the National Park Schiermonnikoog and the barrier island of Spiekeroog, where large parts of the islands are naturally developing. But even there morphodynamics is often unnecessarily reduced due to earlier restrictive measures.

As stated above, many barrier islands originally consisted of five major morpho-ecological units, which mutually overlap and influence each other. Each of these units is characterized by its own dynamics, morphology and ecology. The interconnectedness and the morphological development of the various units are to a large extent governed by the (possibility of) transport of fresh and salt water, wind, sediments, nutrients and salts. All of these factors or processes are vital to nature development. Many barrier islands, or parts of them, have changed and are used so strongly by man that restoration of natural conditions is near to impossible. Nevertheless, in many places there are alternatives for the present-day management, which envisage a more integrated approach (Löffler et al., 2011). Restoring interconnection between the various units

Fig. 9. Scheme to evaluate ICZM-policies for the West and East Frisian Barrier Islands.
and allowing natural developments to once more take their course will be beneficial for barrier island safety, maintenance and nature development. All will benefit by the resulting increase of resilience, which is reached by increasing the ability of (part of) the islands to exchange nutrients, waters and sediments by natural forces. The development of such new approaches is nowadays without risk to safety, since today it is technically feasible to take rapid, corrective measures such as sand nourishments, stopping of eolian processes, closing openings etc.

The following alternative barrier island management options are available (see also Löfler et al., 2011):

1) Island heads

At many island heads where sandy ebb-delta shoals merge with the island, erosion and sedimentation alternate over many decades often with an overarching longer term deficit or surplus of sediments and sometimes the possibility of Pleistocene paleorelief influences (see above discussion). Taking this into account, reactivation of dunes, perhaps in combination with removing the top soils of the valleys, is thought to have the following effects: i) rejuvenation of lime-rich soil; ii) increase in the dynamics of the area; iii) increase in the ability for the more inland area to build up vertically with sea-level rise (increasing resilience); and iv) improving the conditions for the establishment of dry pioneer plant species of the xeroseris and for the wetter hygrosersies. Where net erosion dominates, larger sand nourishments and new dune formation may provide the desired level of safety (see Arens and Mulder, 2008).

2) Dune arcs

The dune arcs offer safety to man (Roelvink et al., 2009, in press). If there are many rows of dunes between the beach and the inhabited area, this offers locally possibilities for eolian sand transport. The transport can easily be stopped at a sufficient distance from the inhabited areas. In this way: i) sedimentation in the (inland) dunes is stimulated again, allowing vertical aggradation; ii) pioneer species have more possibilities to survive; and iii) larger dune massifs may come into existence, providing larger fresh water buffers and supplying the dune valleys with groundwater rich in dissolved carbonates. Any sediment losses thus caused on the beach have to be compensated by nourishments if the beach position is to be maintained. As illustrated by Landry (2007) and Costanza and Farley (2007), it is possible to optimize nourishment schemes by taking the value of houses, recreation and nature into account. In this way a coupling between dune arcs and beaches would be restored. Also, dune arcs may be allowed to form again where they were once present, either by actively assisting in the first steps of the process (e.g. West Vlieland) or by bringing back the washover complexes and removing sand drift dikes (see below).

New dune arcs such as the one currently forming in the eastern part of Spiekeroog which are not enclosed by dikes on the Wadden Sea side also provide ample conditions for tidal marsh development with gradients from high to low, salt to fresh, sandy to clayey.

3) Washover complexes

Many of the islands once had one or more washover complexes, which were mostly closed by sand drift dikes. A good surviving example is the so-called Spiekeroog Leegde. Restoration of such washover complexes is only possible if it does not form a threat to human safety. Restoration will often consist of the removal of a sufficient length of sand drift dikes and removing part of the top soils, preferably in places where the washovers were originally present. If washover complexes are restored then: i) pioneer species will re-occur; and ii) additional sand is deposited on the barrier islands from the North Sea side, resulting in a higher resilience of these natural plains with respect to sea-level rise (Van Dongeren and Van Ormondt, 2007) and iii) the washover complexes will act as a gateway for eolian transport across the island, further stimulating aggradation.

4) Island tails

Often the island tails are among the more natural parts of the West and East Frisian barrier islands and need little maintenance or restoration. Locally on the West Frisian Islands sand drift dikes are present which are relatively easy to reactivate, for instance by opening up these dunes, so that: i) small flooding openings form (Ten Haaf and Buïjs, 2008); ii) eolian sand drift may increase the topographical level in the area; and iii) tidal marshes may form. Also, a more natural development of the island tail leads to more natural and ecologically diverse dune system (De Jong et al., 2011).

That such an approach may also form a partial answer to accelerated relative sea-level rise is illustrated by the developments on Skallingen in the North Frisian Wadden Sea. At the Skallingen peninsula coastal protection was abandoned some 20 years ago. This has allowed the dune ridges to be breached during severe storm surges leading to the deposition of large washover fans. It has been shown that this process results in local gain of sediment and washover fans, which subsequently built up to new dune ridges perpendicular to the coast (Christiansen et al., 2004; Nielsen and Nielsen, 2006).

5) Beach and shoreface

One of the characteristics of a natural barrier island is the seasonal and decadal alternation of sedimentation and erosion phases of the beach. The present-day state of technology is such that the beach’s position can be safeguarded. This can be done by means of hard coastal engineering works, which obstruct or prevent natural beach morphodynamics and sediment dynamics in general. However, given the strong interconnectedness of the islands with the back-barrier and ebb-tidal deltas, and the strong connection between the beach and the rest of the island, the better solution seems to be nourishments (Hoekstra et al., 1994, 1999; see also Williams and Foley, 2007). Thus far nourishments have been carried out to primarily maintain the coastline. However, the present-day state of technology make it possible to steer nourishments in terms of location, frequency, volumes and form, so that not only safety is maintained but also nature is furthered and partially restored (see also Van der Wal, 1999). Large volumes of beach or ebb-delta nourishments may, for instance, lead to the (temporal) formation of new dunes and habitats, but hinder the development of older more landinward dunes (Arens, pers. com.). Such approaches are especially interesting on the NW parts of the island coasts where through natural developments strong sedimentation and erosion patterns occur on a decadal scale. It should be realized however, that under natural conditions sand supply at many other coastal locations is periodic but very limited. Nourishing large amounts of sand may severely disturb the more natural processes of sand transport and coastal development in such places.

For the West and East Frisian islands a simple scheme can be deduced from the various scales when addressing coastal zone management (Fig. 9). If questions are answered with a “yes” than the influence should be considered in barrier island management. The outcome however is always similar: on the long run barrier
developments on several spatio-temporal scales. In this way large parts the islands can accrete to cope with sea-level rise, safety will be maximized and pioneer conditions will not disappear on the islands.

**Ethical statement**

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

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This paper is partly based on a previous document or position paper (in Dutch) initiated by the Wadden Academy (part of the Royal Dutch Academy of Arts and Sciences) to discuss relevant geoscientific issues of the Wadden Sea (see Speelman et al., 2009). The position paper addresses three major subjects: the geological development and structure of the region (including the presence and development of mineral/natural resources), the Holocene coastal evolution and “present-day” coastal morphodynamics. The position paper was almost entirely based on data from the Dutch part of the Wadden system. Our present paper focusing on barrier islands is based on an extended and strongly edited version of the position paper on the Holocene evolution updated with our study on the Holocene evolution of the trilateral Wadden Sea on request of the Common Wadden Sea Secretariat (CWSS; see Wiersma et al., 2009) and our insights on barrier island management (see Löffler et al., 2011).

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