Deltares

Overview of the hydromorphology of ebb-tidal deltas of the trilateral Wadden Sea

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Summary

Ebb-tidal deltas are a relatively less-well studied part of the Wadden Sea system. In this report information on the hydromorphological development of the ebb-tidal deltas of the trilateral Wadden Sea area is brought together. It is primarily meant to serve as an overview guide. The study illustrates that much can be gained from a uniform approach for data collection and sharing data for comparison between the three countries involved in the management of the Wadden Sea, a World Heritage site.

Morphologically, ebb-tidal deltas can respond relatively quickly (within a decade) and changes may continue over long periods due to human-induced or natural changes and climate change. Data strongly suggest that the morphological changes on the ebb-tidal delta may influence the backbarrier area as well as the barrier islands in terms of shelter, hydrodynamics and location or volume of sediment supply. Testing empirical relations for the seaward extension and the sediment volume of the ebb-tidal deltas against the collected data shows that these relations are qualitatively correct. However, a large scatter in the data is found, which implies that other effects play a role in the development as well, such as geology, human interventions and storm surge climate.

For the Dutch and Lower Saxonian tidal inlets, where the tidal propagation and the littoral drift are both eastward, the size of the tidal basins has an important influence on the orientation of the ebb-tidal deltas. Larger tidal basins are oriented in line with the tidal wave propagation direction, with the large part of the basin on the east side. Their main ebb-tidal delta channels are directed towards the direction where the tidal wave comes from (west). Smaller inlets are relatively more influenced by littoral drift. They have generally downdrift (east) oriented ebb-tidal delta channels, confirming the ideas of Sha. In the North Frisian area, where littoral drift can be in the opposite direction as tidal propagation, the orientation of the ebb-tidal delta channels is characterized by much more variation. Cases with symmetrical backbarrier basins and symmetrical ebb-tidal deltas occur there as well.

The barrier coast in the Wadden Sea area ranges from wave dominated to mixed energy- tide dominated according to the classification of Davis & Hayes. Similar to earlier findings, linear sand ridges perpendicular to the coast without clearly defined ebb-tidal deltas are found if the tidal range is larger than approximately 2.7 m. This implies that a further increase of tidal range in the future might change some ebb-tidal deltas into linear sand ridges, unless the barrier islands are stabilized.

The relatively fast hydromorphological responses of the ebb-tidal deltas to changes in internal and external drivers indicate that they might be sensitive to the effects of climate change, especially sea-level rise which leads to increase in backbarrier sediment demand. Historical developments of various inlet systems reveal that an increase in sediment demand from the backbarrier areas may lead to erosion of the ebb-tidal delta. It is likely that this may lead to less shelter, different channel configurations and changes in sand distribution to the coast and backbarrier area. Furthermore it is concluded that knock-on effects may occur, leading to morphological changes in a substantial part of the tidal inlet system. Also it is shown that in-

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crease in storm-surges may lead to strong erosion. It is concluded that especially the (sub-) inlets with smaller ebb-tidal deltas may respond relatively fast (within a decade or so) and relatively strong to accelerated sea-level rise and changes in storm surges.

A joint trilateral approach to data analysis and research to gain more insight in the possible consequences of (rapid) changes of ebb-tidal deltas and to develop inventories of management options is recommended. The aim should be to develop a system understanding which allows predicting inlet system development over the course of decades. It is also recommended to study the relations between the development of the ebb-tidal deltas with geology, internal and external drivers over decades to centuries.

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1 Introduction

1.1 General

The report has been written on request of the Task Group Climate, a working group under the trilateral cooperation for protection of the Wadden Sea. It gives an overview of the ebb-tidal deltas of the trilateral Wadden Sea and their possible future development under conditions of climate change. The study was made possible through financing by the Ministerie van Infrastructuur en Waterstaat (Ministry of Infrastructure and the Water Management) of the Netherlands. Furthermore, the study was supported by the Niedersächsische Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz, the Ministerium für Umwelt, Energie und Klimaschutz (Lower Saxony Agency for Water Management, Coastal Defence and Nature Conservation of the Ministery for Environment, Energy and Climate Protection), the Ministerium für Energiewende, Landwirtschaft, Umwelt, Natur und Digitalisierung of Schleswig-Holstein (Ministry of Energy, Agriculture, the Environment, Nature and Digitalization of Schleswig-Holstein; MELUND) and the Kystdirektoratet, Denmark (Danish Coastal Authority). Part of the work has been made possible through the co-financing of the project “KPP Kennisontwikkeling Morfologie Waddenzee” (KPP Knowledge Development Morphology Wadden Sea) of I&M WVL. In the program, knowledge is developed on the morphology of backbarrier areas, which is partly directly related to ebb-tidal delta developments. To support policy making and management morphological indicators will be developed. To that end a description of relevant parameters is needed, to allow comparison between tidal basins. Through an international comparison the insight in the morphological functioning of basins will increase.

The hydro- and morphodynamic development of the Wadden Sea forms the foundation for the ecological, cultural and economic development of the area. A central notion is that the trilateral Wadden Sea consists of a number of joined sediment-sharing inlet systems. Ebb-tidal deltas[1] constitute an integral element of Wadden Sea tidal inlet systems. Situated remotely along the seaward margin of the Wadden Sea ecosystem, they haven’t received much attention yet in the trilateral cooperation. Furthermore little is known about their possible development to climate change.

Over the last years attention has increased for the role ebb-tidal deltas, especially with respect to the natural resilience of the Wadden Sea (eco)system to climate change and with regard to the connectivity between the North Sea and the Wadden Sea backbarrier basins (e.g. Coastal Genesis II program). The ebb-tidal deltas consist of large amounts of sediment. The sediment may function as a natural source of sand for the barrier islands and tidal basins, which might be needed to keep pace with sea-level rise. Furthermore, the ebb-tidal deltas provide shelter to the islands and backbarrier area, thus providing the low-energetic conditions for sediment to deposit. Also, due to a wide variety in depths and energy distribution (waves, currents) over the various elements of ebb-tidal deltas, a wide range of habitats is formed, probably hosting a diversity of biota. Erosion of several ebb-tidal deltas and relatively rapid changes in orientation and height of ebb-tidal deltas have been observed in the trilateral Wadden Sea. These changes are reason for concern, as they might lead to changes in hydrodynamic conditions and sediment supply for the barrier island coasts and the backbarrier area of the inlet system in question. Thus it was decided to make a trilateral inventory study on data and on the available hydro-morphological knowledge of the Wadden Sea tidal deltas.

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[1] *An ebb-tidal delta is the bulge of sand formed at the seaward mouth of tidal inlets as a result of interaction between tidal currents and waves (USACE 2003).*

Figure 1.1.1: Main habitats in the Wadden Sea Area (source: Wadden Sea Plan, 2010).

The Trilateral Wadden Sea Cooperation has identified a Wadden Sea Cooperation Area as the geographical basis of their Cooperation. The Wadden Sea Area includes an offshore zone 3 nautical miles from the baseline as fixed nationally or where the Nature Conservation Area exceeds the 3 nautical mile, the offshore boundaries of the Nature Conservation Area (Figure 1). As from 14 March 2011, the Netherlands has redefined the delineation of the Natura 2000-area North Sea Coastal Zone to be based on the AOD -20 m depth contour, which is slightly deviating from the 3 NM boundary shown in Figure 1.1.1.

Ebb-tidal deltas are addressed in the Wadden Sea Plan (2010) in Chapter 7 “Offshore Area”. Trilateral targets have been set for the Offshore Area of which targets 7.1 and 7.2 are most relevant to the objectives of this study:

“7.1 Trilateral policies will be based on an integrated approach to coastal flood defence and protection and nature protection on the mainland coast, the islands and the offshore zone.

7.2 In view of accelerating sea-level rise, increased attention will be given to the role of the offshore zone in the total Wadden Sea sand balance. In this respect sand will only be extracted from out side the Wadden Sea Area. Exemptions for local coastal flood defence and protection measures may be granted, provided it is the Best Environmental Practice for coastal protection (e.g. taking the sand from below the wave base).”

1.2 Scattered Information

Information on the geomorphology and ecology of the Wadden Sea ebb-tidal deltas and their inlet systems lies scattered in publications and data archives. A trilateral assessment is not yet available, with an exception for the tidal basins (Kraft et al., 2011). Data relevant to the study were gathered in one comprehensive overview. Literature has been gathered on the functioning of the various ebb-tidal deltas of the Wadden Sea both from peer-reviewed scientific and grey literature (i.e. management reports and studies etc.).

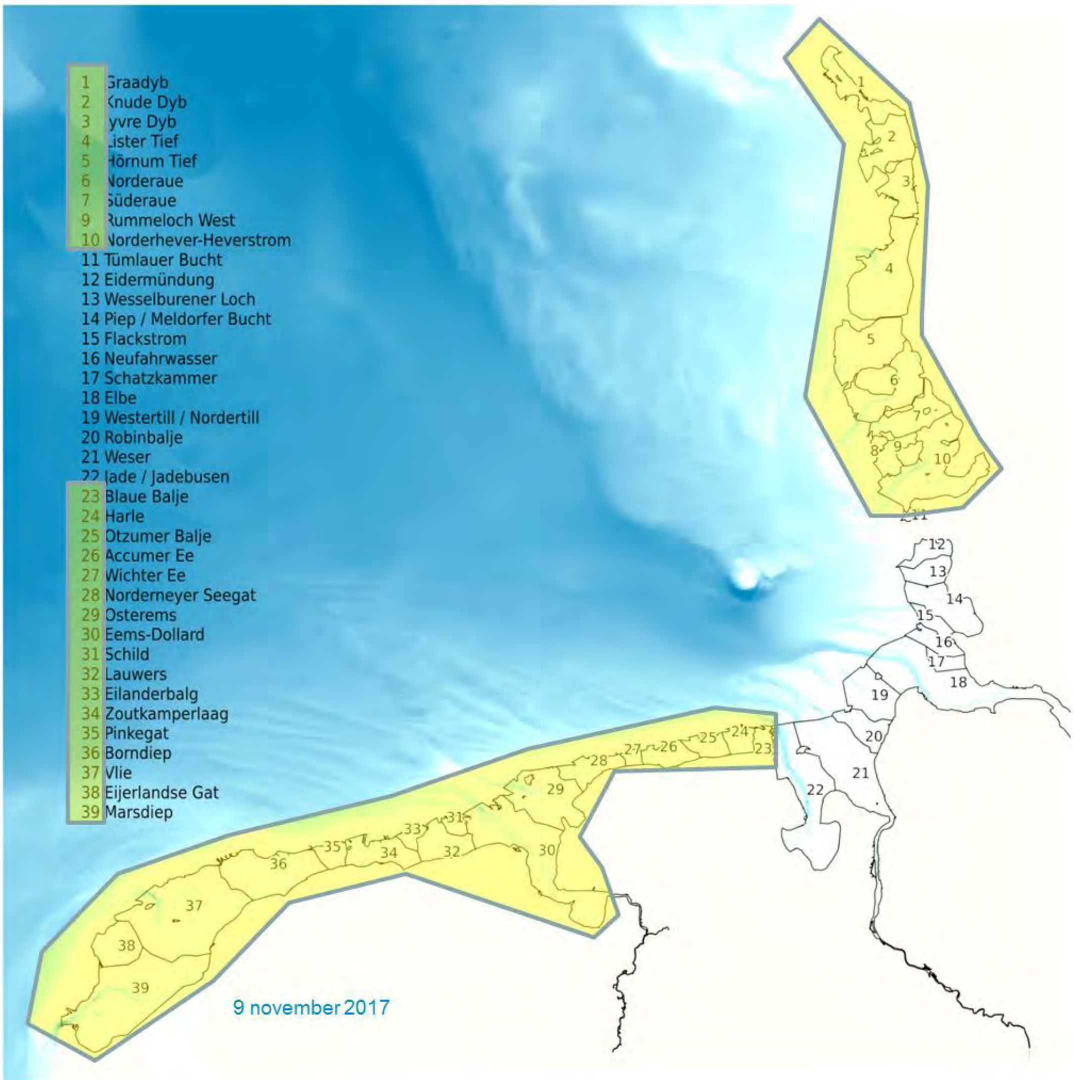


Figure 1.1.2: Inlets and ebb-tidal deltas discussed in the report given in yellow; 8 = Hooger Loch (after Kraft et al., 2011).

Clear-cut ebb-tidal deltas only exist up to a tidal range of 3 m. As a result the following 26 inlet systems were discussed: Marsdiep, Eierlandse Gat, Zeegat van het Vlie, Borndiep, Pinkegat, Zoutkamperlaag, *Eilanderbalg,* Zeegat van de Lauwers, *Schild, Westerems* (Eems), Osterems, Norderneyer Seegat, Wichter Ee, *Accumer Ee*, Otzumer Balje, Harle Seegat, Blaue Balje, Hever, Rummeloch West, *Hooger Loch*, Aue, Hörnum Tief, Lister Dyb (Lister Tief), Juvre Dyb, Knude Dyb, Grådyb, based on available information (Figure 1.1.2). Of the ones given in *italics* only a short description was given, based on deliberations within the working group.

1.3 Project aims

The aims of the project are:

- To provide an overview of the current hydromorphological knowledge and information on the Wadden Sea ebb-tidal deltas.

- To demonstrate the significance and, from available data, the functioning of the trilateral Wadden Sea ebb-tidal deltas, amongst others for the long-term stability of the trilateral Wadden Sea in times of climate change.

The report targets the hydromorphological knowledge and information and demonstrates the significance of ebb-tidal deltas in that respect. From that point of view also the hydromorphological functioning is discussed, including the possible effects of climate change on ebb-tidal deltas. The report is also intended as a quick reference guide to the ebb-tidal deltas of the Wadden Sea. The study is a supporting preparation for a brochure addressing these points in the 2018 Ministerial Conference at Leeuwarden. The brochure is intended for decision makers and non-scientists.

1.4 On the following chapters

After a short description of what ebb-tidal deltas are in chapter 2, possible classifications which can be used to analyse ebb-tidal deltas are discussed introduced in chapter 3. To make classification possible, it is necessary to collect the relevant data. Which data are collected and how the general description is made, is discussed in detail in the chapter 4. Chapter 5 to 8 describe the hydromorphologic characteristics of the ebb-tidal deltas of the Netherlands, Lower Saxony, Schleswig Holstein and Denmark. In the report the local non-translated names are used for all inlets and channels. Also, the names of embayments and islands are not translated. In chapter 9 the most recent data will be analysed and discussed with the help of the classifications introduced in chapter 3. In chapter 10 the possible effects of climate change will be discussed. Chapter 11 gives the conclusions and recommendations for management and future re-search.

1.5 Acknowledgements

The report benefitted greatly from the support of the members of the working group, who all kindly provided information in the various stages of the project: Ms Margrita Sobottka, Nationalparkverwaltung Niedersächsisches Wattenmeer; Mr Jannes Fröhlich, WWF – Wadden Sea Office; Dr Anni Lassen, Kystendirektoratet, Denmark; Drs Jacobus Hofstede, Ministerium für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein; Dr.-Ing. Andreas Wurpts, Leiter Forschungsstelle Küste / Coastal Research Station, Dezernent NLWKN-Bst. Norden-Norderney; Robert Zijlstra, Rijkswaterstaat Noord-Nederland; Willem Kattenberg, Ministerie van IenM – DGRW. Furthermore, Ralf Weisse and Elke Meyer contributed wave climate data with the kind help of Robert Zijlstra, who is also thanked for his general support and great coordination throughout the project. Furthermore, Gerold Lüerßen of the Common Wadden Sea Secretariat provided the maps of the various regions. Contributions from the colleagues at Deltares and Rijkswaterstaat via discussions are sincerely acknowledged. Many thanks go to Wang for usefull comments for this report.

2 What are ebb-tidal deltas?

2.1 Ebb-tidal deltas as part of inlet systems

Ebb-tidal deltas are part of inlet systems. The tidal inlet systems of the Wadden Sea each consist of a back-barrier tidal basin (with tidal channels (Cleveringa & Oost, 1999), sub- and intertidal flats and supratidal salt marshes), an ebb-tidal delta and barrier islands (Davis, 1994) at either side of the inlet (Figure 2.1.1). 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). Hydromorphological 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 (Oost et al., 2012; Elias et al., 2012; Wang et al., 2012). Net sediment import into the inlet system from the out side (here: North Sea) is possible. Sand is imported from the coastal zone (coast and ebb-tidal deltas), whereas mud (<63 microns) is imported in suspension from afar.

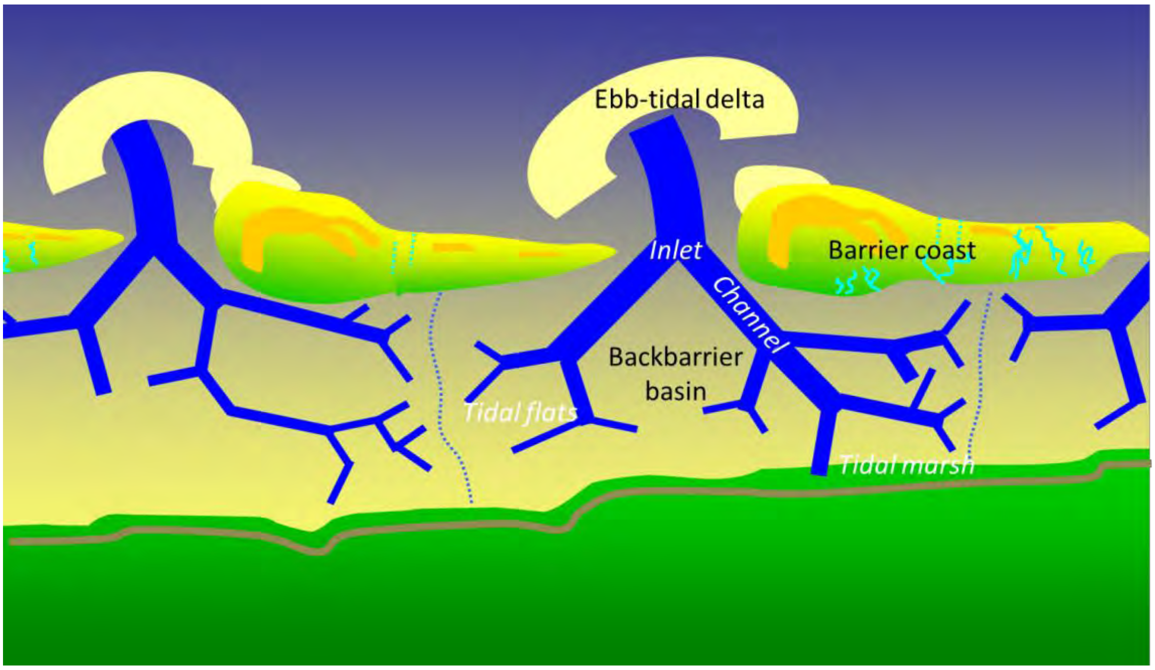


Figure 2.1.1: schematic overview giving the three main elements of the sediment sharing inlet system (black font) and some minor elements (white font).

When changes in boundary conditions/drivers are temporary (e.g. perturbations by storm surges) or limited (e.g. subsidence by local mining activities or dredging), the original 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. How fast a dynamic quasi-equilibrium can (re-)establish depends on the magnitude of the perturbation, the sediment availability and transport capacity and sets limits to the resilience of a tidal inlet system if changes are more permanent. For instance, the limits to the extent to which a backbarrier basin can keep pace with relative sea-level rise are one of the major focal points in trilateral sea-level rise research (CPSL, 2001, 2005, 2010; Oost et al., 2014). From strong disturbances (e.g. closures of the Zuiderzee and Lauwerszee in the Netherlands) it is known that the transport capacity is sufficient to import net large amounts of sediments, leading to ebb-tidal delta erosion, if the amounts cannot be replenished immediately by longshore drift (Elias et al., 2012).

2.2 Ebb-tidal delta morphological features

Ebb-tidal deltas are formed seawards from the tidal inlet, due to the interaction of tides and waves. A tidal inlet is an interruption in a barrier coast and is defined by the tidal flow between the open sea and the backbarrier basin (Figure 2.2.1; Niemeyer, 1990). Therefore, the width of the inlet itself is usually small with respect to the size of the tidal basin, as opposed to estuaries or deltas (Steijn, 1991). Seaward, in front of the inlet, a shallow sedimentary body is present known as the ebb-tidal delta. The sediment volume of ebb-tidal can be huge and sometimes comparable to the sediment volumes stored in the barrier islands (Steijn, 1991). For instance, the sediment volume of the ebb-tidal delta of Marsdiep (Figure 2.2) was $650*10^6$ m^3 in 1933 and has been reduced to $489*10^6$ m^3 in 1981 (Eysink, 1993); the latter figures being of comparable magnitude as the sediment volume of Texel, the Netherlands.

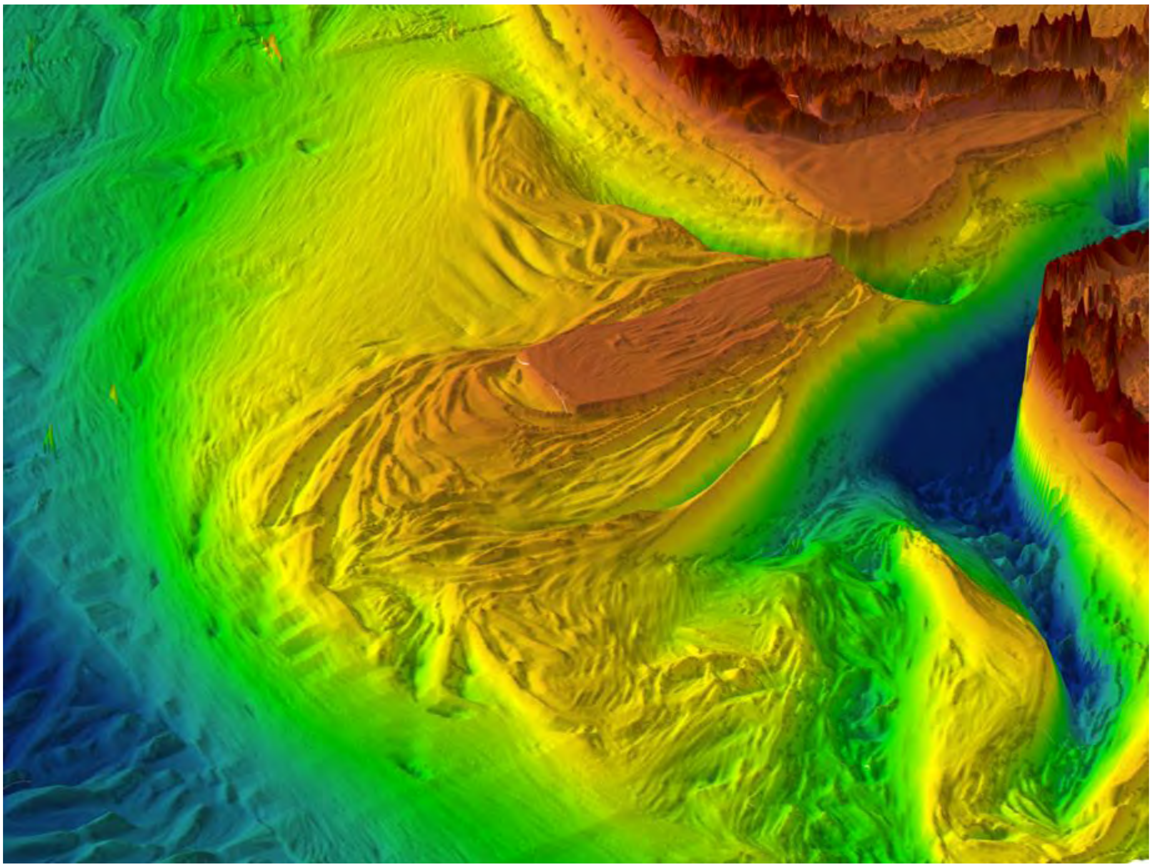


Figure 2.2.1: Oblique view of the ebb-tidal delta of Marsdiep with in blue the Marsdiep inlet (Texel Inlet) between the mainland and (top) the barrier island of Texel.

A typical ebb-tidal delta consists of a main ebb channel, marginal channels which are often dominated by flood currents, channel margin linear bars, a terminal ebb-tidal delta lobe, swash platforms and bars (Figure 2.2.1; Hayes, 1975, 1980). The occurrence of ebb- and flood dominated tidal channels on the ebb-tidal delta was explained by Van Veen (1936), Stommel & Farmer (1952) and Postma (1982). Ebb dominant currents are enhanced by tidal basins which are rather flat, with an increasing surface area with rising tide (i.e. with relatively large intertidal areas; Speer & Aubrey, 1985). Due to the size of the backbarrier basins the maximum ebb-currents often occur towards low water, when the whole flow is largely concentrated in the tidal channels and exit the inlet as a jet (Stommel & Farmer, 1952). Upon entering the North Sea the current loses its velocity and sediment is deposited at the seaward end of the ebb channel, forming the so-called terminal ebb-tidal delta lobe.

The flood currents choose the way of least resistance: along the margins of the delta (Van Veen, 1936; van der Vegt et al., 2006), although sometimes also additional marginal ebb-dominated channels may come into existence (Oost, 1995).

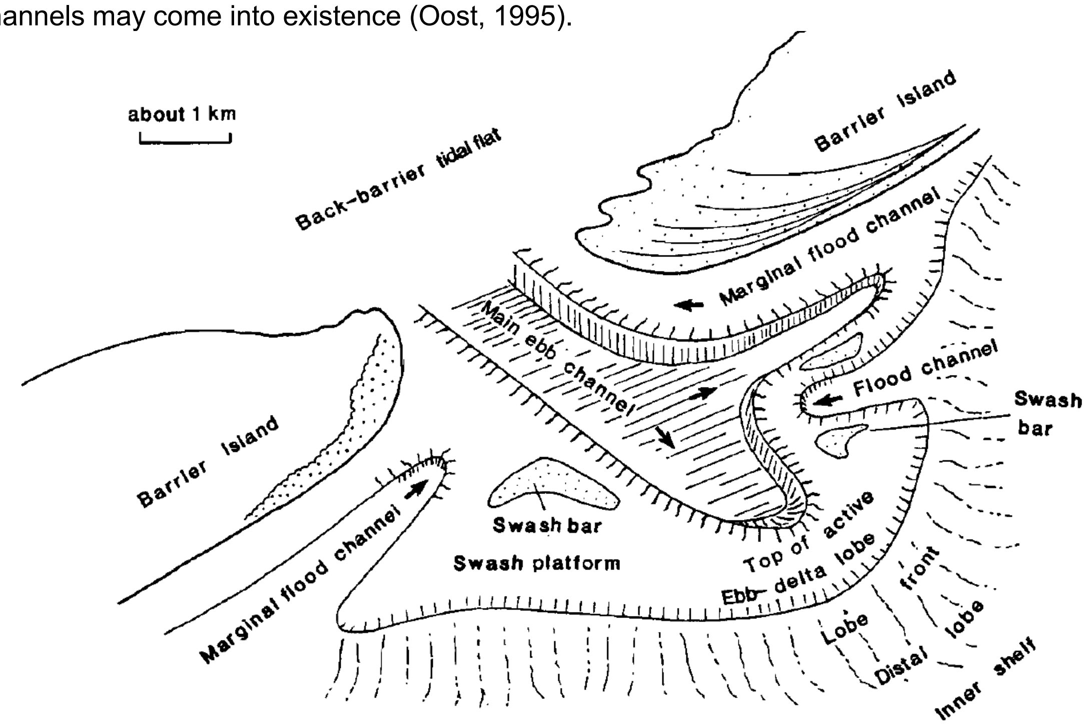


Figure 2.2.2: Overview of the general morphological features of a West Frisian Wadden Sea (the Dutch part of the Wadden Sea) ebb-tidal delta (Sha, 1990).

The channels on the delta are flanked by broad sheets of sand which typically "sit" at the height of the fair weather wave base (-5 to -6 m below MSL), forming so-called swash platforms. In the Wadden area these are mainly present at the downdrift side of the main ebb channel. On these swash platforms swash bars are often present, built up by waves.

Along the margins of ebb-tidal deltas, swash bars and larger shoals migrate towards the island coast mostly in a downdrift clockwise fashion (a.o.: Joustra, 1976; Ehlers, 1988). At the updrift side of the main channel the sediment follows an often complicated path to the N in a zigzag fashion (Oost, 1995). Already Gaye & Walther (1935), using data over the period 1888-1933, concluded that shoals from the eastern end of Juist migrated as individual bars to the E-NE up to channel Busetief, thus passing shallow flood-channels. Subsequently the sand was transported along that channel towards the N and form new small northward migrating shoals at the ebb-tidal delta lobe of the Busetief. In the process marginal channels are forced to migrate to the N, and may change character during the migration from flood marginal channel to an ebb marginal channel into a part of the main ebb channel (Oost, 1995). Also the main ebb channel may be forced to migrate downdrift if huge amounts of sediment are gathered at the west side (e.g. Otzumer Balje 1986-1989).

From this northern position sediment and swash bars migrates along the terminal lobe to the E. Upon reaching the downdrift side of the main channel the bars migrate in a clockwise manner towards the downdrift island. In the process they merge, forming bigger shoals which migrate to the downdrift island, where they merge with it and are “smeared out” along the beach forming beach ridges.

The above idea of a generally E-ward directed sediment transport, as first brought forward by Gaye & Walther (1935) would influence the ideas of sediment transport up 1981 (Lüders 1953; Homeier & Kramer, 1957; Homeier & Luck, 1971; Homeier, 1972; Bremermann & Meyer, 2012). Hanisch (1981), studying the Harle inlet, states that the sediment transport at the W side of the inlet is mainly northwards in suspension and as megaripples with the ebb currents until it reaches the ebb-tidal delta lobe, where the bars built up during fair weather conditions (Hanisch, 1981). During storm surges the sediment is eroded and transported back by wave-generated currents and the bars become lower. The net result of the changing conditions is that the sand moves in a zig-zag movement towards the northern part of the ebb-tidal delta. There the sediment is transported to the E (Hanisch, 1981).

The migration of the shoals at the east side of the inlet often deflects channels on the outer delta until a breach is formed and a hydraulically more efficient channel is formed. The old channel, depending on its position, may silt up or change in character (van Veen, 1936; Oost 1995). The terminal lobe forms the outer end to the ebb-tidal delta and is a rather steep seaward sloping body of sand.

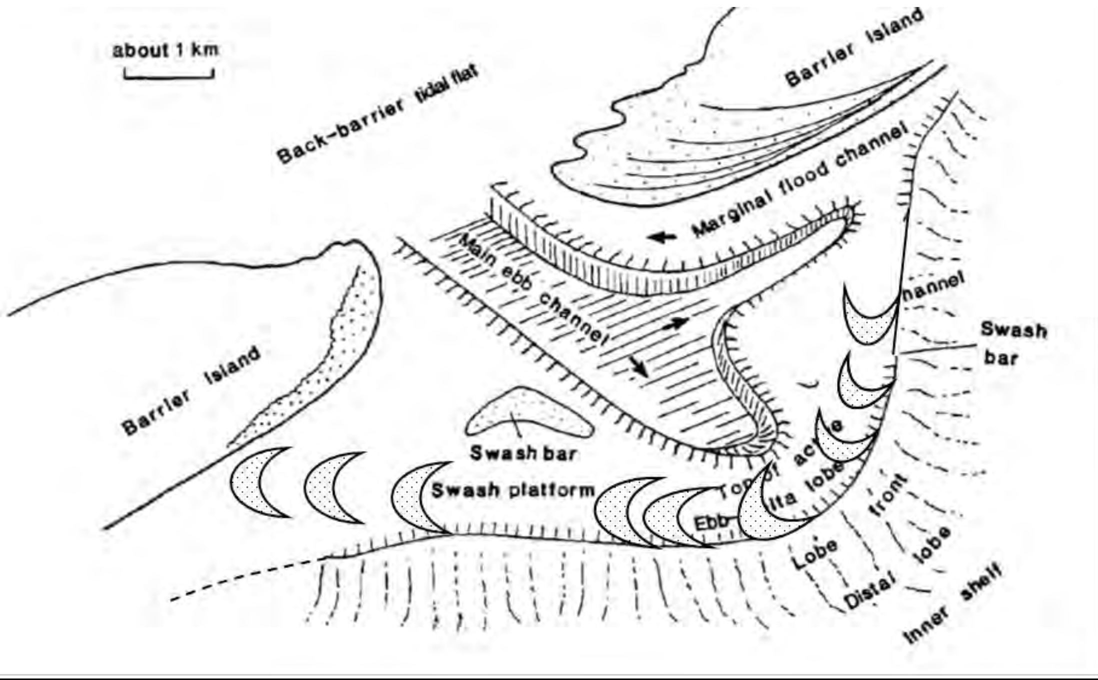


Figure 2.2.3: Overview of the general morphological features of an East Frisian Wadden Sea (the Lower Saxony part of the Wadden Sea) ebb-tidal delta (Adapted after Sha, 1990).

In the West Frisian (Dutch) area the ebb-tidal delta platforms tend to be dissected by well-defined ebb- and flood channels and a few pronounced ebb-tidal deltas are present (Figure 2.2.2). In the East Frisian (Lower Saxonian) area relatively small swash bars migrate along the outer rim of the ebb-tidal delta in close procession (this will be called a “Riffbogen” throughout the text; Figure 2.2.3; Lüders & Luck, 1976). In the North Frisian (Schleswig Holstein and Denmark) area the ebb-tidal deltas take the form of almost linear sand ridges where the tidal range approaches 3 meters. More to the N where tidal ranges are smaller forms resemble the previous two classes.

2.3 Existence of ebb-tidal deltas in relation to driving forces

Ebb-tidal deltas are influenced by the high energies exerted by coast-parallel tides and coast-perpendicular tides through the inlet and by waves and drift currents (van Veen, 1936; Edelman, 1961; Sha & van den Berg, 1984). The morphology is determined by the dynamic balance between a net offshore directed sediment transports due to the inlet currents (ebb dominance), onshore sediment transport induced by waves at open sea and coast-parallel drift transports. It should be realized that this is not the full description of how ebb-tidal deltas are formed but it gives a rough basic explanation (Steijn, 1991; see also chapter 3). Ebb-tidal deltas are characterized by strong gradients in energies which can bring about fast and relatively large-scale morphological changes. As such, ebb-tidal deltas can be expected to respond quickly (in the order of decades to a century) on natural or human induced changes in driving forces.

2.4 Importance of ebb-tidal deltas as part of the inlet system

It is often asked whether the out side influences and the resulting changes in the ebb-tidal delta and adjacent coasts determine the development of backbarrier area, or that the (biotic and abiotic developments in the) backbarrier area determine the development of the ebb-tidal delta. The answer is that both are true, but that also the adjacent inlet systems may influence the ebb-tidal delta.

The out side influences can be considered to be autonomous: they are external drivers which may both vary over various time spans (e.g. wind climate) as well as show gradual developments over time (e.g. increase in tidal amplitude during the Holocene; Franken, 1987; Van der Molen & De Swart, 2001). Driving forces (tide, wind and waves) exert a strong influence on the morphology of the ebb-tidal deltas and change during the year, as well as over decades (Sha & Van den Bergh, 1993; NLWKN, 2010; Herrling & Winter, 2014). The interaction between tide, wind and waves is a complex process. Changes in the driving forces will lead to morphological changes (Ridderinkhof, 2016), which may influence development of other parts of the system. For instance the landing point of the ebb-tidal delta shoals on the barrier island may shift. Thus, knowledge about ebb-tidal delta development under different drivers (Herrling & Winter, 2014) is essential to our understanding of the functioning of the sediment sharing inlet system.

In this respect ebb-tidal deltas play an essential role in the sedimentary development of inlet systems. They are the intermediary in the sediment exchange between the open sea, the barrier islands and the tidal basins. Their channel patterns determine currents. They dissipate the wave energy and provide shelter to parts of the islands and to the adjacent back-barrier area. Furthermore the ebb-tidal delta and inlet reflect and absorb part of the tidal wave moving into the back-barrier area, changing the predominant tidal constituents offshore towards higher harmonic components onshore (overtides; DiLorenzo, 1986; Steijn, 1991). Thus they can be considered to function as “filters” to the backbarrier allowing limited passage. Reversely they are also influenced by the influences generated at the inside, which are determined by the basin configuration and the conditions in there. For instance: the orientation of the backbarrier basin and its size will partly determine the direction and tidal volume flowing out of an inlet and exert influence on the orientation of the ebb-tidal delta. Another example is that backbarrier erosion of the island due to extreme meandering may lead to the development of new channels through the island tails, thereby changing the inlet and ebb-tidal delta configuration. In the latter case external influences (tidal gradient; Van Veen, 1936) and backbarrier influences (Oost, 1995) are together leading to such a change. Furthermore geology may influence the development (e.g. North Frisia).

Lastly it should be realized that the sediment sharing inlet systems are not closed systems. Under natural conditions, the backbarrier basin is in contact with the basins at either side of it. Depending on their sizes the bigger backbarrier basins may influence the smaller ones relatively strongly (for instance by a takeover of part of the drainage area). This in turn influences the ebb-tidal delta. Also ebb-tidal deltas may influence each other if they come into eachothers sphere of influence. A remarkable example can be found in the Eilanderbalg ebb-tidal delta, E of the barrier island of Schiermonnikoog, which is “nested” in the ebb-tidal delta of het Zeegat van de Lauwers, which is “nested” in the ebb-tidal delta of the Westerems.

The ecosystems of the Wadden Sea and the North Sea are intimately linked via the ebb-tidal deltas. The organic matter turnover in the Wadden Sea is driven by import from the North Sea (Van Beusekom et al. 2012). Shellfish may restock the Wadden Sea from populations from deep water refuges in the North Sea. Mobile animals like fish, shrimps and crabs largely leave the Wadden Sea in autumn to survive the winter in the relatively warm waters of the North Sea, after which they return to the Wadden Sea. And last but no least birds and sea mammals demonstrate both a daily and a seasonal shift in their use of the Wadden Sea and the North Sea (Garthe et al., 2009). Ebb-tidal deltas themselves are specifically rich in fish-eaters such as terns, gulls, cormorants and seals. Smelt or other sand eel species probably are key-stone species for the ecological functioning of ebb-tidal deltas. Besides these, shell-fish eating birds such as the common scoter and eider find important food stocks on the edges of the deltas (Leopold & Baptist, 2016). Also to understand the importance of ebb-tidal deltas to ecosystems, knowledge on the hydrodynamical functioning of ebb-tidal deltas is essential.

3 Introduction to classification of ebb-tidal deltas

3.1 Introduction: why classify?

Many classifications are possible which can be used to analyse ebb-tidal deltas. In this chapter various classifications will be introduced shortly. Also the need for the data which are collected is discussed (see chapter 4 for a full description). Classification of ebb-tidal deltas provides a tool to (Steijn, 1991):

- *Compare a specific ebb-tidal delta with similar ones*
  This is important, because, although many ebb-tidal deltas have been studied, for many others less information is available. Knowing the behaviour of similar ebb-tidal deltas, will give a first idea of the behaviour of a less well known delta.

- *Analyse the ebb-tidal delta and detect the parameters representative for the formative processe*s
  As it may be expected that formative processes change due to human interferences and climate change effects it may also give insight in the possible future changes in development.

Ebb-tidal deltas may be classified according to (Steijn, 1991):

- *Geometric parameters*
  These parameters are dealing with the morphology of the ebb-tidal delta. This is especially of importance where insufficient or unreliable data on wave climate and tidal regime are available or where other intrinsic mechanisms at work are less well understood (e.g. the effect of human induced disturbances or transport of water and sediment over the watersheds). A geometric classification such as size can also form an indicator of the tidal volume and possibly wave conditions, etcetera. The advantage of such a classification is that it is often relatively easy.

- *Hydraulic parameters*
  These parameters focus primarily on the shaping parameters, thus the governing physical processes and provides general information on them. The hydrodynamic parameters are not system-determined, but can be regarded as independent boundary conditions. The advantage is that it does allow for direct coupling between the observed general behaviour and the underlying physical processes. However, it should be warned that the geometry and intrinsic influences of the backbarrier and adjacent islands, as well as adjacent inlet system development may also strongly influence the development of the ebb-tidal delta and cannot be neglected in all cases.

3.2 Geometric classification

Extension of the ebb-tidal delta

Obviously the easiest geometric classification is to size. That might be the extension of the ebb-tidal delta measured perpendicular to coast starting from the inlet (Sha, 1989ba). The larger the ebb-tidal delta's extension the larger its tidal prism most likely is and the larger the influence of the ebb-tidal delta on the coast-parallel water and sand movements.

Geometry of the backbarrier

Bruun & Gerritsen (1960) developed a geometrical classification and distinguished 18 different groups, based on backbarrier basin geometry, direction of tidal wave propagation and direction of littoral drift. Niemeyer (1990) simplified this set into 6 basic cases (Figure 3.2.1):

1) Asymmetrical backbarrier basin oriented against the tidal wave propagation direction; tidal wave propagation and littoral drift going in the same direction;
2) Asymmetrical backbarrier basin oriented in line with the tidal wave propagation direction; tidal wave propagation and littoral drift going in the same direction;
3) Asymmetrical backbarrier basin oriented against the tidal wave propagation direction; tidal wave propagation and littoral drift going in opposite directions;
4) Asymmetrical backbarrier basin oriented in line with the tidal wave propagation direction; tidal wave propagation and littoral drift going in opposite directions;
5) Nearly symmetrical backbarrier basin; tidal wave propagation and littoral drift going in the same direction;
6) Nearly symmetrical backbarrier basin; tidal wave propagation and littoral drift going in opposite directions.

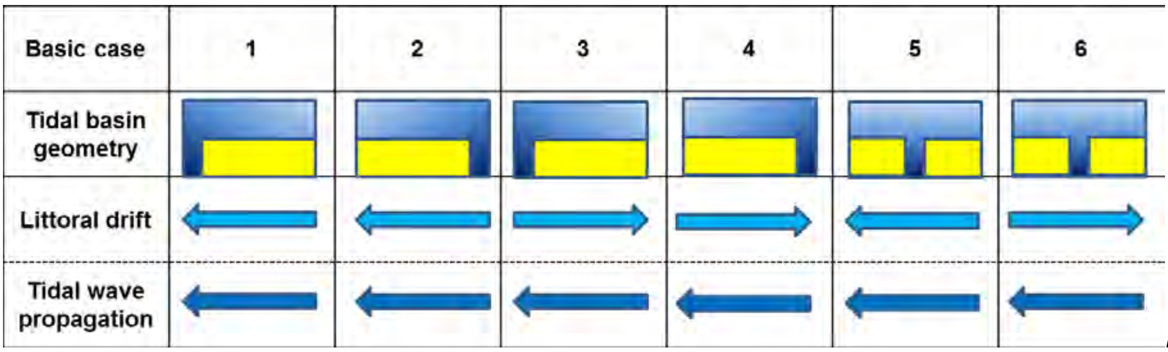


Figure 3.2.1 Geometrical classification of inlets; inlets are schematically indicated in blue shades; islands in yellow (after Niemeyer, 1990).

Niemeyer (1990) concludes that tidal basin asymmetry somehow must be related to offset geometry: an updrift basin supports updrift offset and a downdrift basin supports downdrift offset. Also, correspondence between littoral drift and tidal wave propagation seems to support downdrift offset. Steijn (1991) expresses doubt on the applicability of the classification, finding the absence of the strength of the wave climate as a parameter and proper data on the actual basin geometries a shortcoming. As we shall see in chapter 5 to 9 all basins and, to a fair extent, ebb-tidal deltas, can be classified according to the classification of Niemeyer.

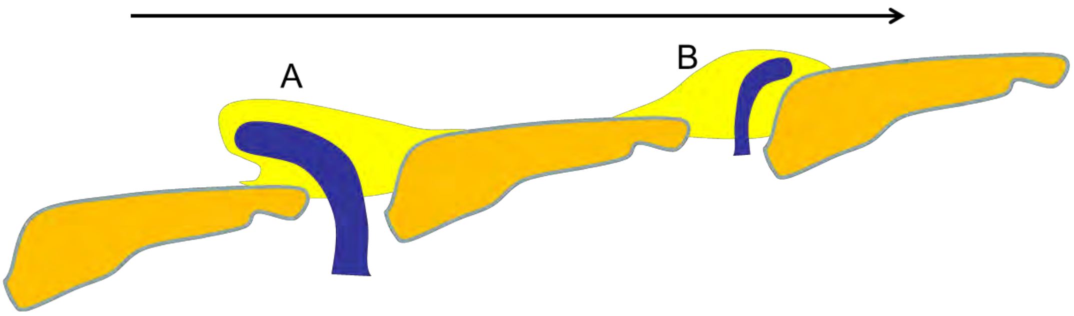


Figure 3.2.2: Various orientations of deltas in the Dutch and Lower Saxonian Wadden Sea A: Inlet oriented against the tidal wave propagation direction of which the major part of the sediment of the ebb-tidal delta platform is present at the other side; B: Inlet oriented in line with the tidal wave propagation direction and coastal drift of which the major part of the sediment of the ebb-tidal delta platform is present at the other side. Barrier islands in orange, main ebb channel in blue and ebb-tidal delta in yellow. Arrow gives direction of longshore drift and tidal propagation direction (After Sha, 1990).

Orientation ebb-tidal delta

Another classification was proposed by Sha (1990a). He divided ebb-tidal inlets into oriented against the tidal wave propagation direction (Figure 3.2.2, situation A) and in line with the tidal wave propagation direction and coastal drift (Figure 3.2.2, situation B). As we shall see below Sha (1990a) came up with a conceptual hydraulic explanation, which was later elaborated by Sha & Van den Berg (1993).

3.3 Hydrodynamic classification

The two most important acting forces which are normally used for hydrodynamic classification are waves and tides. The tidal range at open sea out side of the inlet is primarily determined by the ocean tides and the interaction with the sea bottom. Wave conditions are generated seaward of the inlet. Both can be considered as independent boundary conditions (Steijn, 1991).

Classification based on tidal range

A simple classification is according to the tidal range in an area. There are several cases which show that, in general, tidal barrier islands decrease in length with increasing tidal range (Hayes, 1975; Eliott, 1978; FitzGerald, 1988). This is also true for the Wadden Sea, although it should be noted that the “rule of thumb” does not apply in all cases (e.g. compare Vlieland and Terschelling). The possible mechanism was discussed by van der Vegt (2006), whose work suggests that islands grow coast-parallel upon perturbation of a straight coast due to interaction between the coastline position and the shore-parallel tidal currents. However, when also the influence of sediment transport due to waves is taken into account, the length scale of the perturbation which grows fastest decreases with the increasing magnitude of the shore-parallel tidal currents (= increasing tidal range). If the sediment transport due to waves increases the length scale of the fastest growing perturbation increases. The results compare well with the observed trend in the length of the islands along the Dutch and German coast.

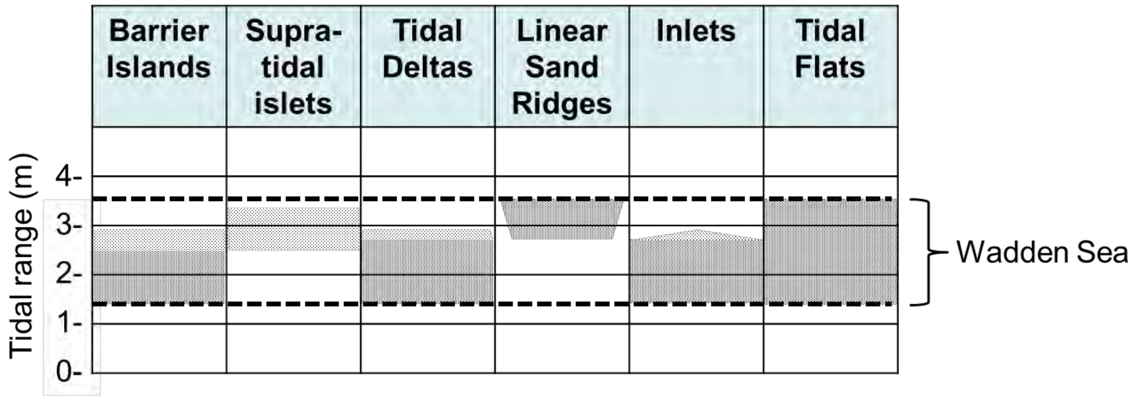


Figure 3.2.3: overview of the various morphological features in the Wadden Sea area. Dark grey = range of existence; light grey = outer range of existence (partially after Ehlers, 1988 and personal observations).

Hayes (1979) indicated that ebb-tidal deltas are present in a tidal range zone between 0 and 4.5 m, occasionally 5.5 m. Because regional conditions also play a role, ebb-tidal deltas within the Wadden Sea area only form between 1.4 and ca. 3 m tidal range and already have some difficulty to exist above 2.7 m tidal range (Figure 3.2.3; Ehlers, 1988). In the Wadden area barrier islands are absent above 3 m tidal range (Roos et al., 2013). Above that range coast-perpendicular linear sand ridges dominate. As a result clear-cut inlets are missing (e.g. inner German Bight). The resulting less concentrated outflow of the ebb water, results in a less outspoken sedimentary body seaward of the Wadden Sea. Thus, ebb-tidal deltas are missing above approximately 3 m tidal range in the Wadden Sea.

Classification based on tidal range and mean wave height
A more general classification does not only take tidal range into account but also the mean wave height. The classification of Davis Jr. & Hayes (1984) leads to five types of barrier coasts (Figure 3.2.4; Steyn, 1991):

- Wave dominated coasts, with long continuous barriers and only a few inlets and many washovers.
- Mixed energy coasts (wave dominant) are characterized by less long islands and more inlets and somewhat larger ebb-tidal deltas.
- Mixed energy coasts (tide dominant) are characterized by drumstick barrier islands many tidal inlets and larger ebb-tidal deltas.
- Tide dominated coasts (low dominance) occasionally have wave built bars.
- Tide dominated (high dominance) are characterized by tidal current ridges and have often large ebb-tidal deltas and deep inlet gorges.

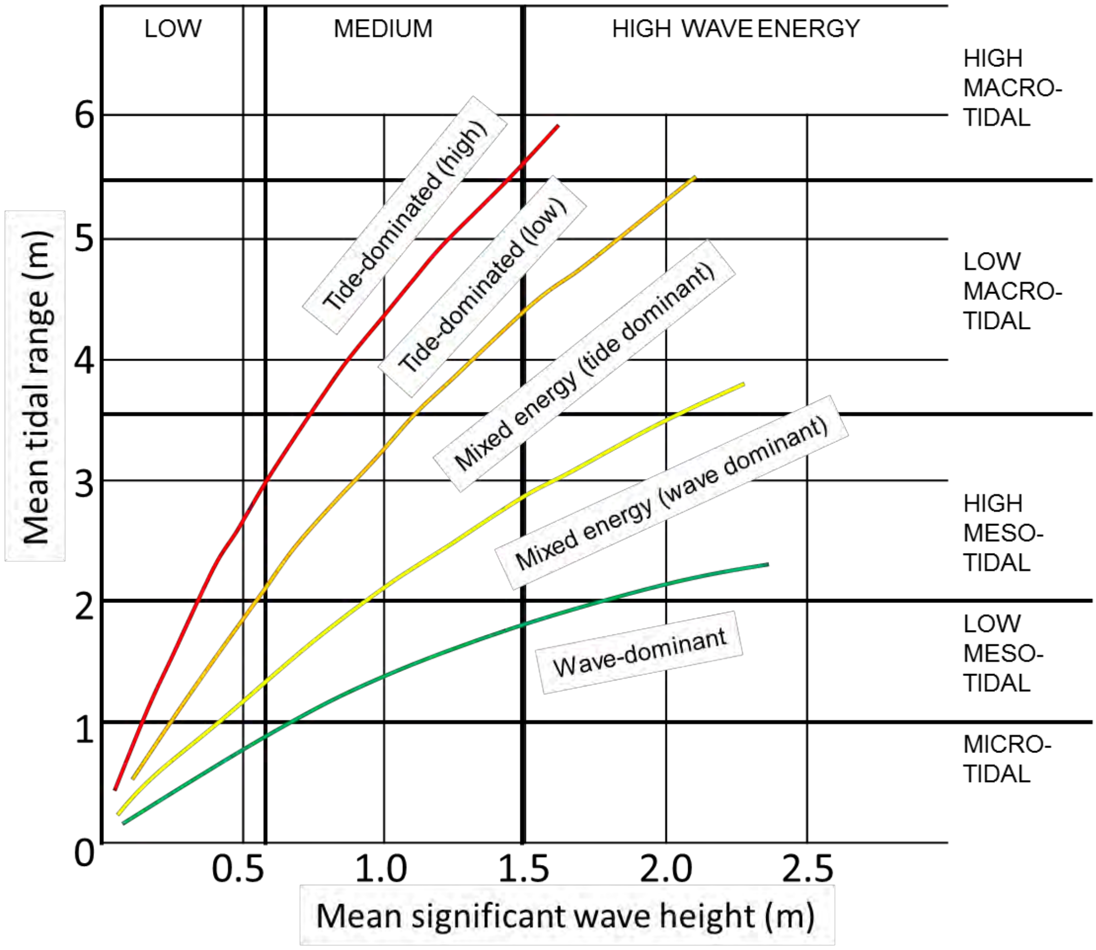


Figure 3.2.4: Tidal range versus mean significant wave height plot giving the various energy regimes redrawn after Davis Jr. & Hayes (1984; see also McBride et al., 2013). Tidal range classes are according to Davies (1964) with modifications by Hayes (1979), Hubbard (1977) and Nummedal et al. (1977).

Classification based on tidal prism and wave energy

In general, the volume of sand stored in an ebb-tidal delta increases with increasing tidal prism (Dean & Walton, 1975; Walton & Adams, 1976; Hicks & Hume, 1996; Oost, 1995; Powell et al., 2006; Fontolan et al., 2007). It has been suggested that the higher the wave energy, the smaller the ebb-tidal delta volume will be (Walton & Adams, 1976; Dean, 1988). Walton & Adams (1976) gave the following relation:

Sand volume $S = a*P^{1.23,}$

with **P** being the tidal prism at spring tide and **a** being $64.4*10^{-4}$ for somewhat exposed coasts; $53.3*10^{-4}$ (for exposed coasts) and $84.6*10^{-4}$ (for non-exposed coasts) (Walton & Adams, 1976). In the Wadden area a bigger tidal prism is generally observed to coincide with a larger sediment volume of the ebb-tidal delta (Eysink & Biegel, 1993; Niemeyer et al., 1995), although the relation seems less clear cut than suggested by Walton & Adams (1976). Many of the ebb-tidal deltas of the Wadden area have a lower sediment volume then might be anticipated based on tidal prism and the above relation (Niemeyer et al., 1995; Ladage & Stephan, 2005; Meyer, 2014) although there are also ones with a larger sediment volume such as the Juvre Dyb (Ingvarsen, 2006ba).

In general, if tidal prism decreases/increases it may be expected that the ebb current through the inlet decreases/increases and that the ebb-tidal delta becomes smaller/larger in sand volume. An example of such changes has been observed after the closure of the Lauwers-zee embayment in 1969. As a result, the tidal prism of the Zoutkamperlaag inlet decreased from ca. 305 to $200*10^6$ m^3. In response the sand volume of the ebb-tidal delta decreased with some $26*10^6$ m^3 over the period 1970 to 1987 (Oost, 1995).

Research by Niemeyer et al., (1995) indicated that a differentiation with respect to wave exposure is questionable for the ebb-tidal deltas of the Netherlands and Lower Saxony. Niemeyer (2000) states that the Walton & Adams (1976) relation is: *“at least problematic for barrier coasts with dunes and island offset”* (the downdrift island head protruding further seaward then the updrift island tail).

Classification according to littoral drift and tidal prism

The ebb-tidal delta platform in front of the inlet may form the bridge via which sediment is transported to the downdrift area. Bypassing of sediment occurs in different ways and this was found to depend on the total littoral drift M_{tot} (in m^3/y) and tidal prism P (m^3/tidal cycle) (Bruun & Gerritsen, 1960; Bruun, 1978) via $r = P/M_{tot}$:

If $r < 20$: inlets are unstable and not permanent and transport will occur due to the forming of overflow channels.
$20 < r < 50$: sediment transport takes characteristically place via bar-by-passing where bars move over the ebb delta fringe.
$50 < r < 150$: sediment transport takes characteristically place via both bar-by-passing and flow by passing. Bars near the entrance are still pronounced.
$R > 150$: sediment transport occurs predominantly by tidal flow bypassing (bars are small and there is a good flushing of the inlet).

Characterisation ebb-tidal delta asymmetry with tides and wave climate

Ebb-tidal deltas in the Wadden Sea show differing asymmetries in the morphologies. In the Lower Saxonian and the Dutch area, the main ebb-tidal delta channels are often asymmetrically oriented against the tidal wave propagation direction (to the west/south), with exception of the ebb-tidal deltas of small inlet systems such as Pinkegat and Wichter Ee, which are oriented downdrift (Sha, 1990). Along the North Frisian coast the deltas vary strongly in orientation from against or in line with the tidal wave propagation direction, or perpendicular to the coast.

Gaye & Walther (1935) showed that sand transported by the eastward littoral drift bypasses the inlets of the East Frisian Islands via bar migration along the periphery of the ebb-tidal deltas (“Riffbogen”; Walther, 1969). These ideas were modified to some extent (Homeier & Kramer, 1957; Kramer, 1960; Luck, 1966, 1976; Hanisch, 1981; Nummedal & Penland, 1981; FitzGerald et al., 1984), but the original idea of Gaye & Walther (1935) was generally accepted for the East Frisian coast. Wind-driven waves coming dominantly from the west were considered to be the main cause of the downdrift asymmetry of several of the ebb-tidal deltas of the East Frisian inlets (Sha, 1990).

Originally, the orientation of the Dutch Wadden Sea inlets was attributed to tidal forcing (Van Veen, 1936; Edelman, 1961; Bakker & Joustra, 1970). Ideas about the influence of wave refraction, leading to local longshore drift reversal at the downdrift coast of an inlet (Goldsmith et al., 1975; Hayes & Kana, 1976), and wave-current interaction at the inlet mouth (Lynch-Blosse & Kumar, 1976; Davis & Fox, 1981) were picked up by Sha (1990a). He attributed the differences in the ebb-tidal delta morphologies to the varying importance of the tidal prism and the wave-induced longshore drift for the different inlets. Inlets with a small tidal prism have small ebb-tidal deltas and they are dominated by waves. Eastward moving deep-water wave and wave-induced longshore drift drive the ebb-tidal delta main channels of small inlet systems asymmetrically downdrift.

Sha concluded that inlets with a large tidal prism are dominated by tidal currents and interaction of marine shore-parallel tidal currents with onshore-offshore inlet tidal currents, which is enhanced by the ebb-tidal delta shoals, causing the large ebb-tidal deltas and their main ebb channels to be asymmetrically directed against the tidal wave propagation direction. Sha & van den Berg (1993) extended the idea. In most inlets of the Dutch and Lower Saxonian Wadden Sea the cross-shore and alongshore tides are approximately in phase with maxima in currents at the same times. The interaction between both causes weaker and more rotary currents at the side downstream (with reference to the tidal propagation direction in open sea) of the tidal inlet and stronger tidal currents at the upstream side. Hence, the ebb-dominated channel has a tendency to be oriented to the upstream side. If tidal prism is small the waves may overrule the effect and in the Wadden Sea generate an orientation in a more downdrift direction (Sha & van den Berg, 1993). For the Vlie and Marsdiep inlets numerical models by van der Vegt et al. (2009), Dissanayake et al., (2009), Dissanayake (2011) and, to a certain extent, Ridderinkhof (2016) showed that the phase difference between the cross- and alongshore tidal currents at Texel Inlet and Vlie Inlet increased somewhat. Van der Vegt et al. (2006) showed that the asymmetry against the direction of tidal wave propagation of the larger ebb-tidal deltas increases with the increasing magnitudes of the cross-shore and large-scale alongshore tidal currents and with decreasing phase differences between both, and with decreasing width of the inlet.

However, the conceptual model of Sha (1990a) for the inlets with a bigger tidal prism could not be confirmed by numerical morphodynamic model studies for tides alone (Van Leeuwen et al., 2002; Schuttelaars et al., 2014). Schuttelaars et al. (2014) showed that forcing with only a semi-diurnal component (M2 tide) would result in a downdrift orientation of the inlet, and suggested that an added asymmetry in the residual sea surface due to M0 tide results in a orientation against the tidal wave propagation direction of the channels on the ebb-tidal delta, reminiscent of the ideas of van Veen (1936). The explanation is sought in the spatial pattern of residual vorticity, but research is on-going.

4 Data and methods

4.1 Data collection and analysis

The descriptions and parameters which have been brought together are those considered to be relevant -also given the various classifications introduced in chapter 3- to characterize the major morphodynamics of ebb-tidal deltas in the Wadden Sea area;. Here, a short overview is given on which data were brought together and how they were determined. For clarity, a list of the various abbreviations used in this and the following chapters is given in table 4.1. First some general principles are discussed and then the various parameters will shortly be discussed. For each ebb-tidal delta these data (where available) will be given in a table at the beginning of the respective chapter on that delta.

The text in the next chapters describes the various areas. This is done on a regional scale for the West Frisian or Dutch Wadden area (chapter 5), the East Frisian or Lower Saxonian Wadden area (chapter 6), and the North Frisian area, consisting of the Schleswig Holsteinian Wadden area (chapter 7) and the Danish Wadden area (chapter 8). At the beginning of each chapter a short overview is given of the general characteristics of the area at large, so that the less-familiar reader gets a first impression. Also, the geology of each region is shortly described, because the Pleistocene and Holocene geological history may influence the development of the various inlet systems and their ebb-tidal deltas.

Mainly based on existing literature (both peer-reviewed scientific and research reports) an overview is given of each inlet system of:

- ***Basic data*** giving at the minimum a map (if possible around 2012), an erosion-sedimentation map of the ebb-tidal delta over a period of ca. 30 years[2] and in a table the present-day parameters (see below) which characterize the present inlet system and ebb-tidal delta. For the extended tables giving also the historical data, the reader is referred to Appendix I.

- ***Description of the tidal inlet system*** discussing the system and its development with special attention to the recent past.

- ***Development of the ebb-tidal delta*** discussing the ebb-tidal delta and its development with special attention to the recent past.

- ***Coastal development*** discussing coastal development at either side of the ebb-tidal delta to get an impression of the influence of the (development of the) delta on coastal development and vice versa.

The parameters which have been brought together in the tables for each inlet system are primarily measurements of natural phenomena; only where really needed some relevant modelling results were added. Hardly any new data was generated in preparing the overview, except for wave climate and length of the ebb-tidal delta. When using the data for studies, it should be realized that the data and their inherent uncertainties are determined for a substantial part by the way the data are collected and the methods of calculation. As both collecting and calculating is

[2] It should be noted that the AUFMOD data, which are partly used for the ebb-tidal delta overview maps (2012 and erosion-sedimentation maps), do not have the necessary quality to perform precise morphological analyses, but they do show the general pattern of development. These data have only been used for measuring the length of the ebb-tidal delta, but not for the more precise calculations given in the tables following these overview pictures.

done by individual states and by individuals there will inevitably be differences in the outcomes. Where possible, it was tried to avoid such differences, especially for the classification purposes (see below).

Table 4.1: overview of the various abbreviations used throughout the text and tables.

Abbreviations	**Meaning**	**Units**	**Additional Information**
A_{cross}	Wet cross sectional area of the inlet at MSL	m^2	
A_{MHW}	Surface area covered with water at MHW in the backbarrier area	m^2	
A_{MLW}	Surface area covered with water at MLW in the backbarrier area	m^2	
AOD	Amsterdam Ordnance Datum		Approximately Mean Sea Level
$AS_{backbarrier}$	Annual sedimentation in the backbarrier	10^6 m^3/yr.	Based on the volume increase below MHW
AS_{coast}	Annual sedimentation on the coast	10^6 m^3/yr.	Based on depth sounding differences
$AS_{ebb\text{-}tidal\ delta}$	Annual sedimentation on the ebb-tidal delta	10^6 m^3/yr.	Based on depth soundings or volume calculation differences
DVR90	Dansk Vertikal Reference 1990: Benchmark at Århus cathedral referenced to mean sea level (Anonymous, 2000).		Because it was determined during 1990 at 10 tide gauges it is a slightly tilted plane: at Lister Dyb ca. 5 cm lower than NHN
Hs	Mean significant wave height	m	As calculated for a point at 20 m water depth in front of the inlet based on CoastDat hindcasts
$L_{ebb\text{-}tidal\ delta}$	Length ebb-tidal delta	km	Measured perpendicular to the coast from the inlet onwards
MHW	Mean High Water	m	
MHWR	Mean High Water Rise	mm/yr.	Taken over an as long time as possible to avoid temporary fluctuations
MLW	Mean Low Water	m	
MLWR	Mean Low Water Rise	mm/yr.	Taken over an as long time as possible to avoid temporary fluctuations
MSLR	Mean Sea-level rise	mm/yr.	Taken over an as long time as possible to avoid temporary fluctuations
MTR	Mean Tidal Range	m	
MTRI	Mean Tidal Range Increase	mm/yr.	Taken over an as long time as possible to avoid temporary fluctuations
NHN	Normalhöhennull: the reference plain for the normal height of a topographical eminence height above mean sea level used in the 1992, based on the AOD = MSL	m	
LWN	Low water neap Neap	m	
HWN	High water neap Neap	m	
Pbat	Tidal prism in the backbarrier area based on bathymetry	10^6 m^3	
Pd	Tidal prism in the backbarrier area	10^6 m^3	

	based on maximum depth		
Pdis	Tidal prim in the backbarrier area based on tidal volume measurements	10^6 m^3	
Pmod	Tidal prism in the backbarrier area based on modelling	10^6 m^3	
HWS	High water spring Spring	m	
LWS	Low water spring Spring	m	
$SV_{backbarrier}$	Sand Volume backbarrier area	10^6 m^3	As calculated between XXXX (1976)
$SV_{ebb\text{-}tidal\ delta}$	Sand Volume ebb-tidal delta	10^6 m^3	As calculated by the method of Walton & Adams (1976)
Te	Duration of ebb period	s	
Tf	Duration of flood period	s	
Tf/Te	Tidal asymmetry	-	
Tp	Mean peak period of waves	s	As calculated for a point at 20 m water depth in front of the inlet based on CoastDat hindcasts
V_{MHW}	Water volume below MHW in the backbarrier area	10^6 m^3	
V_{MLW}	Water volume below MLW in the backbarrier area	10^6 m^3	

Where needed, care was taken to make data more uniform. For instance, the wet cross-sectional area of an inlet is always given in area below MSL. To that end the calculations by Klein Wassink (1991) of cross-sectional area, which were related to MLW, were recalculated to Amsterdam Ordnance Datum (AOD: appr. MSL). As far as possible all calculations were referenced to AOD, NHN or DVR90. These levels are indicated. If alterations to make data more uniform could not be made, it was chosen to indicate the way of calculation (see below), because it was felt that several different data sets covering longer time spans (e.g. tidal prism data sets, see below) may still give valuable insights in the development of an ebb-tidal delta and its related inlet system.

Since the Wadden area is characterized by relatively fast (decade) evolving morphodynamics a leading principle was to obtain data which have a year of observation on them. During the compilation it became clear that widely used data have not always a clearly defined year and are used as fixed values. As an example: a well-known tidal prism value for the Marsdiep inlet is 1050 Mm^3 (e.g. Vroom et al., 1989), which is most likely based on RWS (1984), where a tidal prism is calculated of 1048 Mm^3. The basis for the calculation is, as far as could be reconstructed, tidal observations of 26 august 1967 and depth sounding data gathered in the period 1963-1973. If such old data were the only ones available, they were used, but then this will be clearly indicated in the texts or tables. In order to give insight in the morphodynamic developments, which may up to this day influence the morphological characteristics of an inlet system, time series of data were given where readily available.

Another guiding principle was to choose primarily data from overviews which were covering several tidal inlet systems in the same manner -and where possible by the same author- to facilitate comparison of basins. If an author uses other sources their own data were given the preference. Only where no other data were available, single inlet system studies were added.

Differences in ways of collecting the raw data, processing the data and determining the relevant parameters from them, between different research - and governmental organisations and within an organisation through time lead to differences in the data presented here. As much as possible comparable data were presented (for instance ebb-tidal delta volume is only given according to

Walton & Adams-method, 1975). Also, sometimes different approaches can be used to obtain a specific parameter. For instance, tidal prism can be calculated from bathymetry, from tidal discharge measurements, from relations between tidal prism and development of the inlet and from model studies. As far as it is known the method is mentioned. The reader is warned that even then differences in approach may occur. *To obtain more uniform results, it is advised to start comparison of the various methods for collecting and processing of data between the various Wadden countries and to harmonize the methods where possible.*

Discussions on the margin of error will be given, where these are mentioned. As a rule of thumb, the errors will most likely increase with the age of the measurements. This is only in part due to limited possibilities to make accurate observations, as the observers of centuries past did their utmost best to ensure correct and good observations (Oost, 1995). The other part is due to the fact that the original data and corrections have often gone lost and people now working with the data are not always aware of the corrections needed (such as megaripple corrections, tidal height corrections and such for depth soundings). Even nowadays, it is clear from the raw observations that systematic and random errors are present in measurements, which can only partly be filtered out. Many of the data are directly or indirectly depending on depth soundings. To get a first impression if data are significantly different it is wise, as a very rough first test, to use as a rule of thumb, an error margin of some 10% on all observations. This seems huge, but tidal variation around mean tidal amplitude (neap-spring) may be up to 20%. As we shall see some real errors may be smaller (especially tidal computations) or larger. Furthermore, errors can be reduced by taking the trend of development over time series into account.

In all cases, if the reader wants to work with the data given in the tables it is wise to go back to the original publications to check the way in which data were collected, in order to avoid erroneous use of the data.

4.2 An overview of parameters

Sea-level rise, MHW rise, MLW rise and TR increase

One of the formative factors is sea-level rise which causes a gradual heightening of the water levels in the area, and, as a result, long-term erosion and deposition patterns. From observations on the West and East Frisian North Sea coasts it is clear that over the past 5000 to 6000 years the coast has retreated in a landward direction under the influence of (trend) rising sea levels. The bulk of the eroded sediment has been deposited in the backbarrier areas. At many inlet systems this still seems to be the case (e.g. Elias et al., 2012). Determining sea-level rise is not as straightforward as it seems. Many developments can influence the observations, and have to be adjusted for, such as the 18.6 year nodal cycle, subsidence, air pressure, human influence on the tidal gauges etc. Some of the changes cannot be adjusted for. For the Dutch situation Dillingh (2013) gives a good overview. A general conclusion is that time series should be as long as possible, using all reliable data to estimate sea-level rise. For instance, for gauge Delfzijl in the Ems estuary, linear interpolation over data from 1890 to 2008 leads to a SLR of 19 cm/century, whereas using only the past 40 years results in a SLR of 25 cm/century and the past 10 years in a SLR of -15 cm/century (Dillingh et al., 2010). Where feasible, stations were used near the inlet, to give an impression of the developments in the open North Sea. This could not always be realized. For instance, the MSLR for the Hever was retrieved from station Husum, which may have been distorted by the local influence of (changes in) the backbarrier area.

Furthermore it should be realized that stations with long-term reliable tide measurements are scarce along the Wadden Sea coasts. To avoid too much bias these series are given preference above shorter time series of local stations. However, also these are mentioned in the tables where thought appropriate. Furthermore changes in HWL and LWL are also given where readily available.

As sea-level rises also the tidal movement through the North Sea basin becomes easier. Tidal amphidromes will shift and on many coasts an increase of tidal amplitude occurred (Van der Molen & Swart, 2010). However, the increase of tidal amplitude along the Wadden coast can also be enhanced by local dredging works which deepen water ways leading to tidal amplitude enhancement (e.g. Herrling et al., 2014). It is beyond the scope of this inventarisation to discuss this in detail. Tidal amplitude increases are given when known. In general, the high water levels along the coast rise stronger than the low water levels drop and, as a result, faster than average sea-level.

Wave climate
For wave climate data were calculated using hindcast data of CoastDat calculated for the point where the line perpendicular to the coast in front of the inlet would cross the -20 m MSL line. These are used for wave climate versus tidal range characterization. Furthermore the wave climate of nearby wave buoys for each ebb-delta as collected by Ridderinkhof (2016) is also given as they were used for calculating long-shore sediment transports (see below).

Sea level parameters
Mean Sea level (MSL), mean high water level (MHW), mean low water level (MLW), high water spring (HWS), low water spring (LWS), high water neap (HWN), low water neap (LWN) and mean tidal range (MTR) were taken from the available data. Preferably long-term average water levels (e.g. *slotgemiddelden 2011*) were used, in order to avoid annual bias due to air pressure and wave set-up, etcetera. For the German coast the calculations of BSH (2016) for the year 2017 are used. If feasible, stations were used near the inlet, to give an impression of the developments in the open North Sea.

Tidal asymmetry
Tidal asymmetry is given where known as the ratio of the duration of the flood period (Tf) over that of the ebb period (Te). Tidal asymmetry where Tf>Te enhances the possibility that sediment is imported into the backbarrier basin. To what extent it is resulting in a net import also depends on the ability of the backbarrier system to retain the imported sediment. For instance, abandoned channels are known to be able to trap the imported sediments quite efficiently. In turn, such a net sedimentation may lead to sediment loss of the ebb-tidal delta if replenishment by littoral drift is not sufficient. For the German coast the data were calculated as the average between two succeeding tides around mean tide on 3rd of January 2017, using the data of BSH (2016).

Seaward extension ebb-tidal delta
This is a relatively simple and direct measure which is mostly rather unambiguous as the front of an ebb-tidal delta is mostly rather steep thus reducing possible errors in length measurements. The main ebb channel length in an inlet and the related distance of seaward extension of the ebb-tidal delta generally increase with increasing tidal prism (Sha, 1989b). The extension is measured from the inlet gorge in a seaward direction perpendicular to the coast in which the furthest extension of a specific depth line was taken. In practice it turned out that the -6 m (≈ fair weather wave base) and the -10 m line could be used for the extension. In some rare cases also the -15 m line was influenced by the extension of the inlet: this line was not used.

Surge heights
Storm surge heights were taken from overviews based on long-term data sets predicting the likelihood of given storm surge. Lower Saxony does intentionally not denote occurrence probabilities for storm surges, since the resulting numbers strongly depend (by an order of magnitude and more) on the statistical assumptions used to derive them. It was chosen to mention the more frequent storms surges up to once in a 500 years. Partly this was due to the practical reason that such data were mostly available. Partly the choice was made, because more frequent storm surges are likely to happen within the time spans which are taken into account in Wadden Sea management (decades to century) and may be of influence on the development of tidal deltas and backbarrier areas. However, as is pointed out by Krögel (1995) for the Otzumerbalje, man-

agement should be aware that rare extreme storm surges such as 1976 may bring about strong morphological changes which take more than a decade to re-adjust. It should be stated that the calculation methods vary from state to state which may lead to differences in the calculated height. To obtain uniform data also the mean of the maximum annual surge was calculated over a period of ca. 50 years, from the hindcast data of CoastDat. This value is also given in the tables.

Surface areas backbarrier

The surface areas of the backbarrier area are given in water-covered area below MHW and below MLW. Such dimensions are of course depending on the total area taken into account, which is determined by the tidal watersheds and by the tidal marshes (which are in general starting somewhat below MHW). It could not always be derived from the texts of the authors to what extent the area borders of a tidal basin were flexible with respect to especially the tidal watershed positions, but for the Dutch data mostly fixed borders were used whereas the data of Lower Saxony are often based on flexible borders. Furthermore the area below MHW and MLW through time is also determined by the tidal levels used. Biegel (1993), for instance, used fixed tidal levels per basin to determine the area below MHW and MLW. Observations in the Lower Saxony area mostly took into account both changing tidal watersheds and tidal level. As far as known the way of measuring are indicated in table-descriptions.

The historic observations of Niemeyer (1995) are estimates based on reconstructions of Homeier & Luck (1969). From comparable reconstructions in the Dutch Wadden Sea, it is clear that errors in the values given can be rather large, especially due to the uncertain position of the islands (hundreds of m at the west side and ca. 1 km at the east side) and watersheds (of the order of km (Oost, 1995). Furthermore, the main channel positions may be off by as much as 0.5-1 km. The mainland dike positions are often well known. As a result the data from that period should be interpreted as semi-quantitative, giving the larger patterns over centuries.

Cross-sectional area

As many studies established a strong relation between cross sectional area below MSL of the channels with tidal prism (Eysink & Biegel, 1993, also these data were noted down for the inlet gorge. In one case, namely cross-section reconstructions at MLW-level based on old Dutch sailing maps (Klein Wassink, 1991) the data were enlarged with Width_{MLW}*-MLW-level to obtain the cross sectional areas below MSL. Care should be taken not to over-interpret these data, although in some cases they are remarkably consistent. Historic data should be interpreted as semi-quantitative, giving the larger patterns over centuries.

Water volumes backbarrier area

Water volumes are given for MHW and MLW as far as possible. The water volume is determined by the area, the tidal water levels and the sediment volumes between MLW and MHW. The first two factors can be applied as static, in which case only the third factor, the sediment volumes, determines the water volumes (e.g. Biegel, 1993). Many of the other observations take into account both fluctuating areal extent and changing MLW and MHW levels. As far as known, this is indicated in the table descriptions.

Tidal prism backbarrier area

In this report, the tidal prism of each inlet system is the volume which is landward of the tidal gorge of the inlet and is meant to represent $(V_{ebb}+V_{flood})/2$. The volume can be determined in various ways:

- Tidal prims based on tidal volume discharge measurements (Pdis): Mostly this is done by more or less sophisticated measurement of the ebb-volume and the flood-volume flowing through the inlet. Such observations need to be corrected for wave- and air pressure set up, uncertainties in the tidal cross-sectional flow patterns etcetera. In general these measurements give lower values then do the Pbat measurements.

- Tidal prism based on bathymetry (Pbat): A much used method is to distract the low water volume from the high water volume of the basin, taking into account the depth between MHW and MLW. This is noted in the tables as Pbat. Even there differences in determination may occur. For instance: Biegel (1993) uses fixed tidal levels and fluctuating watershed positions, whereas some studies for Lower Saxony take into account the variation of the water levels from year to year (e.g. Ladage & Stephan, 2004) and still other studies only use fluctuating area and fixed tides. This is indicated in the tables. Pbat generally leads to an over-estimation of the real tidal prism as part of the ebb-water may still be flowing out towards the inlet as the flood-water is already entering. Van Veen (1950) suggested the relation Pdis = 0.9*Pbat. Also, there may be a significant transport over the tidal watersheds (Duran-Matute, 2014; Herrling, 2014).

- Tidal prism based on modelling (Pmod): These use the depth sounding measurements and calculations of the tidal movements in the basin to determine the tidal prism. Nowadays these may give results which are quite comparable to the Pdis measurements (e.g. Duran-Matute, 2014; Herrling, 2014).

- Tidal prism based on maximum depth (Pd): this in only done for the Marsdiep where a large time series is available going back to 1388 (Oost et al., 2004; Elias & van der Spek, 2006). Using the work of Sha (1990a), who related depth to tidal prism, it is possible to make estimates. As the relation is not very strong (Eysink & Biegel, 1993) and old depth soundings do have relatively large error margins, the results should be interpreted as semi-quantitative, giving the larger patterns over centuries.

Sediment volumes intertidal area
In general here is meant the sediment volume between MLW and MHW. As with previous volume considerations, fixed or non-fixed borders might be applied. As far as known, fixed borders are indicated in table descriptions.

Sediment volumes ebb-tidal deltas
Here only the calculations based on the method of Walton & Adams (1976) was applied. In this an artificial surface with the coastal profile without the disturbance of the inlet and ebb-tidal delta was subtracted from the ebb-tidal delta. In this, channel incisions result in a negative sediment volume and sedimentary lobes (above the profile-plain) in positive sediment volumes. A slightly alternative method was used by Biegel (1993) who developed an average horizontal plain from the coastal profile to calculate the sediment volume, which partially avoids the problems encountered by the fact that the shoreline from the updrift island to the island downdrift of the ebb-tidal delta “jumps” seaward (Niemeyer, 1995). In general changes in ebb-tidal delta volumes thus calculated show a good correlation with calculations carried out otherwise. Also here, the calculations depend on the method applied. Originally, the idea is to subtract the contemporaneous artificial surface of the undisturbed coastal profile from the ebb-tidal delta of the same year (Walton & Adams, 1976). In practice often one coastal profile is used (e.g. Biegel, 1993; Ladage & Stephan, 2004). Where coastal profiles are very dynamic this may lead to sharply different figures (e.g. Marsdiep; see box 4.1).

Longshore drift
The longshore drift has been copied from Ridderinkhof (2016). He calculated the longshore drift based on the reverse-distance weighing of sediment transport calculated on base of long-term wave observations of various stations (see table 4.1). The data of the wave buoy at station Fino 1 were not used for the Lower Saxonian coasts, because the observed wave data was more energetic than the buoys at stations Schiermonnikoog and Elbe, which might lead to an overestimation (see also Ridderinkhof, p. 71).

Table 4.1: overview of the wave buoy stations used for determining littoral drift (for details: Ridderinkhof, 2016).

Inlet	Wave buoy stations used to calculate longshore drift
Marsdiep	IJmuiden; Eierland; K13
Eierlandse Gat,	Eierland;
Zeegat van het Vlie	Eierland; Schiermonnikoog
Borndiep	Eierland; Schiermonnikoog;
Pinkegat	Schiermonnikoog;
Zoutkamperlaag	Schiermonnikoog;
Eilanderbalg	Schiermonnikoog;
Zeegat van de Lauwers	Schiermonnikoog;
Schild	Schiermonnikoog;
Westerems	Schiermonnikoog; Elbe
Osterems	Schiermonnikoog; Elbe
Norderneyer Seegat	Schiermonnikoog; Elbe
Wichter Ee	Schiermonnikoog; Elbe
Accumer Ee	Schiermonnikoog; Elbe
Otzumer Balje	Schiermonnikoog; Elbe
Harle Seegat	Schiermonnikoog; Elbe
Blaue Balje	Schiermonnikoog; Elbe
Hever	Helgoland; Sylt;
Rummeloch West	Helgoland; Sylt;
Hooger Loch	Helgoland; Sylt;
Aue	Helgoland; Sylt;
Hörnum Tief	Helgoland; Sylt;
Lister Dyb	Sylt; Fanø Bugt
Juvre Dyb	Sylt; Fanø Bugt
Knude Dyb	Sylt; Fanø Bugt
Grådyb	Sylt; Fanø Bugt

Box 4.1: Implications technique used to calculate sedimentary development of the ebb-tidal delta

In both the Zoutkamperlaag case and the Marsdiep fixed borders were used to calculate the sediment losses. In the first case the island coast moved seaward in the observational period (1970-1987) and in the second the coast retreated (1925-1997). Applying the methodology as defined by Walton & Adams (1976; i.e. subtracting the coastal profile of that moment from the ebb-tidal delta body of the same period) would result in losses that would have been different. Walburg (2001) shows that applying fixed borders over the period 1925-1997 the ebb-tidal delta of Marsdiep would lose some $180*10^6$ m^3, whereas taking moving coasts and borders into account it would only lose some $40*10^6$ m^3 in the same period. For the ebb-tidal delta of Zoutkamperlaag, applying the Walton & Adams (1976) methodology would result in a larger sediment loss from the ebb-tidal delta as the coast prograded seaward.

Annual net sedimentation in backbarrier area

Net sedimentation in backbarrier area has been calculated by most authors as net volume changes over the same surface area. In most cases, the changes are calculated by simply subtracting two depth soundings from each other. A better way to calculate bed-level change is to make a linear interpolation through time over average bed-levels of as many depth soundings as possible. In this way, erroneous depth mappings will be less influential on the long-term observations. In all cases, depth soundings of a complete backbarrier basin may have large systematic errors (Box 4.2). From the difference the annual sedimentation was calculated over a longer period preferably from ca. 1990 to 2012. Sometimes such information was not available and older material was used or over a longer time span. This is indicated in the tables.

Annual net sedimentation ebb-tidal delta
Net sedimentation in ebb-tidal delta area is calculated by taking the same surface area into account and calculate the net surface changes. Figures given here are with reference to a fixed level. In most cases, the changes are calculated by simply subtracting two depth soundings from each other. A better way to calculate bed-level change is to make a linear interpolation through time over average bed-levels of as many depth soundings as possible. In this way, erroneous depth mappings will be less influential on the long-term observations. From the difference the annual sedimentation was calculated over a longer period preferably from ca. 1990 to 2012. Sometimes such information was not available and older material was used or over a longer time span. This is indicated in the tables.

In all cases, depth soundings of a complete ebb-tidal delta may have large systematic errors. Due to this, it is difficult to distinguish between errors and real developments on the base of such calculations only. Additional insight in the reality of a volume development of an ebb-tidal delta may be derived by looking at its morphological development.

Annual net sedimentation coast
Net sedimentation of the combined coasts at either side of the ebb-tidal delta. In methodology identical to annual net sedimentation ebb-tidal delta.

Sediment transport direction
This is not so much a quantitative parameter, but a qualitative one and indicates the main transport direction as could be observed from morphological developments, such as spit growth, island development and ebb-tidal delta shoal movements. As for the latter, it is realized that shoals might move in a certain direction without large net sediment transports.

Development island coasts
The development of island coasts is a qualitative parameter, and distinguishes between growth, stilstand and erosion. As it is clear that ebb-tidal deltas and adjacent island coasts are coupled entities which are mutually interdependent, it seems logical that island coasts and ebb-tidal deltas might be related in their developments.

Niemeyer classification
All inlet systems have been characterized based on: backbarrier basin geometry, direction of tidal wave propagation and of littoral drift in which Niemeyer classification(s) they fit. This will be done in the analysis given the data available (chapter 9).

*Box 4.2: Accuracy (*Copy from Oost, 1995 with some additions)
Depth-soundings were made with various ships applying self-registering echo-sounding, since the Forties (before that mostly sounding by hand was used). Since the Fifties the distance between depth observations decreased. For the Netherlands it was up to 100 m and changed into about 5 meters. The track-to-track distance also decreased. In the Netherlands it was usually 800 m before 1958 and 200 m thereafter. In general the observations have been made parallel to the strongest topographical gradient. All observations were made by experienced crews who applied the state-of-the-art methods of their time. It was always attempted to minimize the measurement error, both during the field observation (cross-checks of measurements, compensation of systematic errors) and during the processing (removal of unrealistic data, cross-checks, compensation of systematic errors). Even for the measurements of the Twenties a fair degree of accuracy was reached.

The depth-soundings constitute a sample of the population of the depths of the bottom. This implies that the final values always contain a sampling error. In addition, there are also the errors in the observations themselves. The causes of these errors can be subdivided into: 1) water and bottom conditions; 2) registration equipment; 3) ship movements; 4) tides, and 5) the distance between the observations; the larger the distance the larger the interpolation errors (De Looff, 1975; Van Dam, 1988).

The errors differ with the years, because of changes of instrumentation and methods. For an extensive discussion of errors, which can occur during the soundings the reader is referred to De Boer et al. (1991) and Oost & De Haas (1992, 1993). In addition to errors during sounding also errors are made during the conversion into a grid structure because of digitizing, the grid size, the bottom structure, and the interpolation method applied. Based on an extensive literature study (Anonymous, 1952, 1974; De Looff, 1975; Schaik, 1979; Hartman & Pastoor, 1985; Nanninga, 1985; Anonymous, 1991; Biegel, 1991; De Boer et al., 1991; Oost & De Haas, 1992, 1993; Navy pers. comm.) the systematic error (1 sigma) over larger areas (tens of km^2) in the Netherlands was estimated to be (Oost, 1995): in the Twenties to Forties: 30 cm, in the Fifties: 25 cm, in the Sixties: 20 cm (same value given in Denmark for Grådyb as a whole; Ingvardsen et al., 2006), since the end of the Sixties: 3 cm (5 cm given in Denmark for Grådyb as a whole; Ingvardsen et al., 2006). It is thought that errors in other states will be comparable given the use of comparable techniques. However, even for recent observations an estimated systematic mean error of 0.2 m for larger areas was thought to be realistic by Van Riesen & Winskowsky (2007), although they think that for a whole backbarrier area the errors will be neglectable. It seems prudent to use 1 sigma values for backbarrier areas of some 0.2-0.3 m up to the late sixties and some 0.05 m thereafter.

5 Ebb-tidal deltas of the Netherlands

5.1 General description of the Dutch area

Characteristics

The W to E trending Wadden area of the Netherlands has a total surface area of 4155 km² within the Bird or Habitat framework directives (Lammers, 2016; pers. comm.). The backbarrier Wadden Sea itself has a total area of some 2710 km^2 and consists of tidal marshes, supra- inter and subtidal flats and tidal channels (Figure 5.1.1).

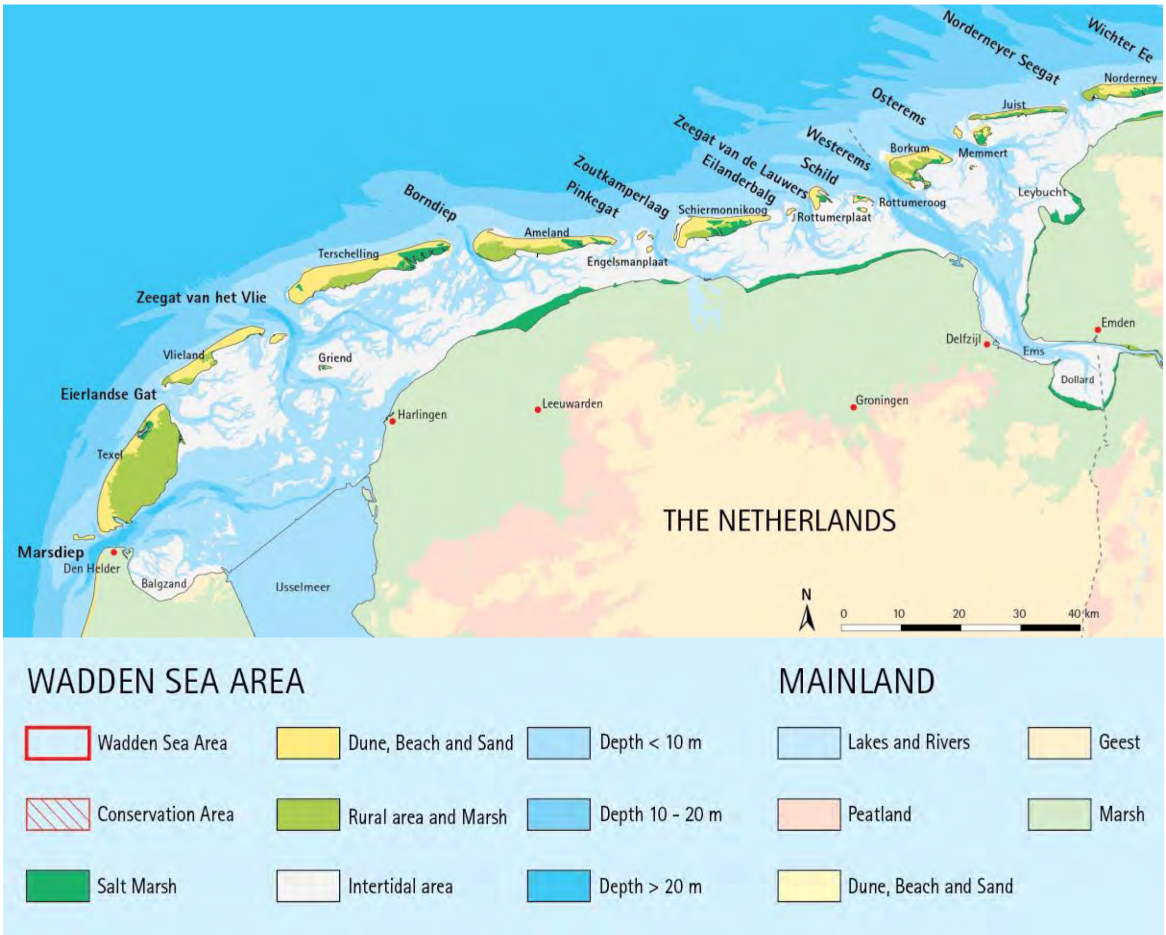


Figure 5.1.1: The inlet systems of which ebb-tidal deltas are described in the Wadden area of the Netherlands: Marsdiep to Schild (Courtesy, Wadden Sea Secretariat).

The area consists of ten inlet systems, namely, from W to E: Marsdiep, Eijerlandse Gat, Zeegat van het Vlie, Borndiep, Pinkegat, Zoutkamperlaag, Eilanderbalg, Zeegat van de Lauwers, het Schild and de Eems (Westerems; Figure 5.1.1). Several fresh water streams are entering the backbarrier, the major ones are the ones via IJsselmeer and Lauwersmeer, and the Ems. Most of the inlets have islands at either side and clearly developed ebb-tidal deltas, but Pinkegat and Eilanderbalg are bordered by an islet at their east side.

Observations over the period 1890-2008 show that MSL increase in the Dutch Wadden Sea is 1.3-1.9 mm/y (Dillingh et al., 2010). Tidal amplitude increases from W to E from 1.4 m at Marsdiep up to 2.1 m in the Westerems. Mean significant wave height is around 1,3 m (Coast Dat data). Along the North Sea coast of the Dutch Wadden Sea littoral drift is directed to the E, calculated to be 0-0.1 to 0.6*10^6 m^3/yr (Figure 5.1.2; Ridderinkhof, 2016). Windiness, storminess, wave conditions and related storm-surge conditions along the Wadden Sea have shown strong highly correlated inter-annual and inter-decadal variations during the 20th century (Alexandersson et al., 2000; Wang et al., 2009; Bakker and van den Hurk, 2012, KNMI, 2014). Windiness, storminess and wave conditions were high in the early 20^{th} century, decreased towards the mid-century and increased until the beginning of the 1990s, after which they sharply declined over the North Sea by the end of the 20th century (Flather *et al*., 1998; Langenberg *et al*., 1999; Schmidt, 2001; Weisse *et al.*, 2002, 2005, 2012; Matulla et al., 2007; Bakker and van den Hurk, 2012; KNMI, 2014). Analysis of the Dutch storm climate over the period 1962-2002 showed a marked decrease of strong wind (7 Bft along the coast), with 5-10%/10 yrs (Smits *et al.*, 2005), but trends in storms of ≥10 Bft could not be proven significantly (Smits *et al.*, 2005; Sluijter, 2008). For period 1948-2007 the share of westerly winds increased in the late winter and early spring, the number of N to NW winds is not changing (Van Oldenborgh et al., 2009).

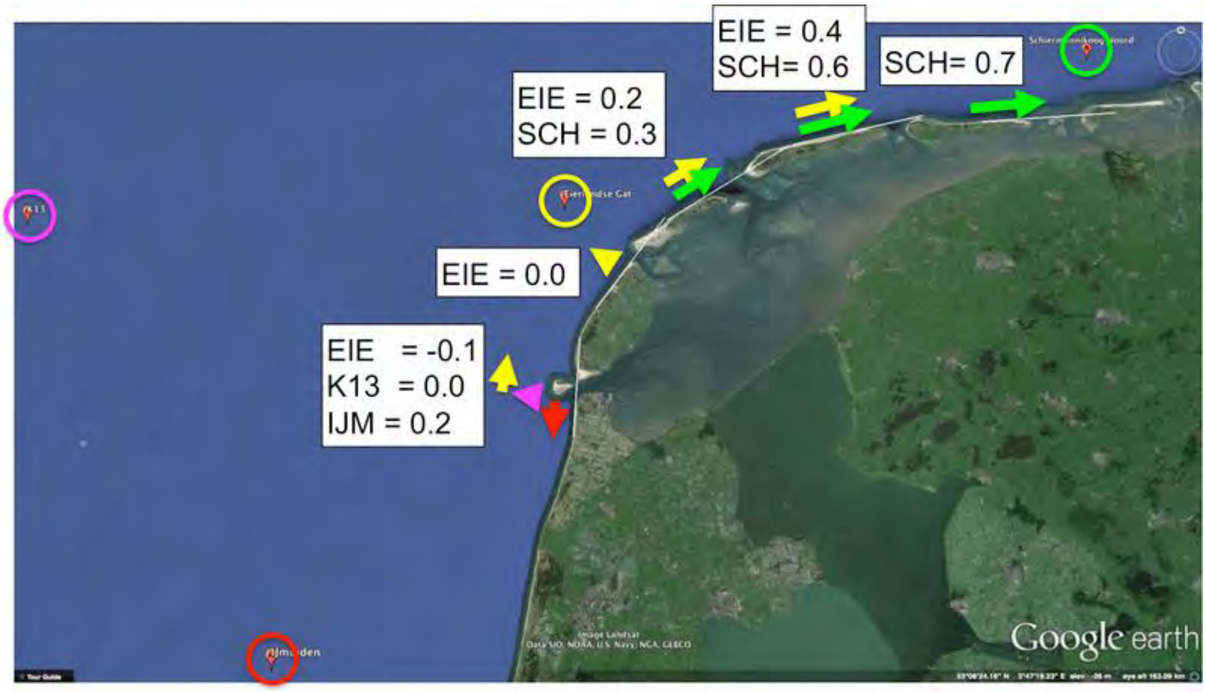


Figure 5.1.2: Littoral drift along the Dutch Wadden coast as determined on stations Ijmuiden (IJM), Eierland (EIE), K13 and Schiermonnikoog (SCH) in 10^6 m^3/yr (From: Ridderinkhof, 2016).

Several large engineering interventions have been carried out in the area. The most important are the damming of the Zuiderzee in 1932 and the Lauwersmeer in 1969. The northern tips of Den Helder and Texel, the eastern tip of Vlieland and the west side of Ameland have been protected by groynes and stonework. Also, groynes are present along the North Sea coasts of Texel and Vlieland. The mainland is diked and in front of it marsh development works have been extensive since the 1950's. On the barrier islands only the inhabited areas are surrounded by a closed chain of sand drift dikes and backbarrier dikes.

Geology

After the last Ice Age relative sea-level rise was initially rapid (over 1 m/century), but decelerated significantly after 7,500-7,000 a BP (Figure 5.1.3; 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 (Jelgersma, 1979; Franken, 1987; Van der Molen & De Swart, 2001).

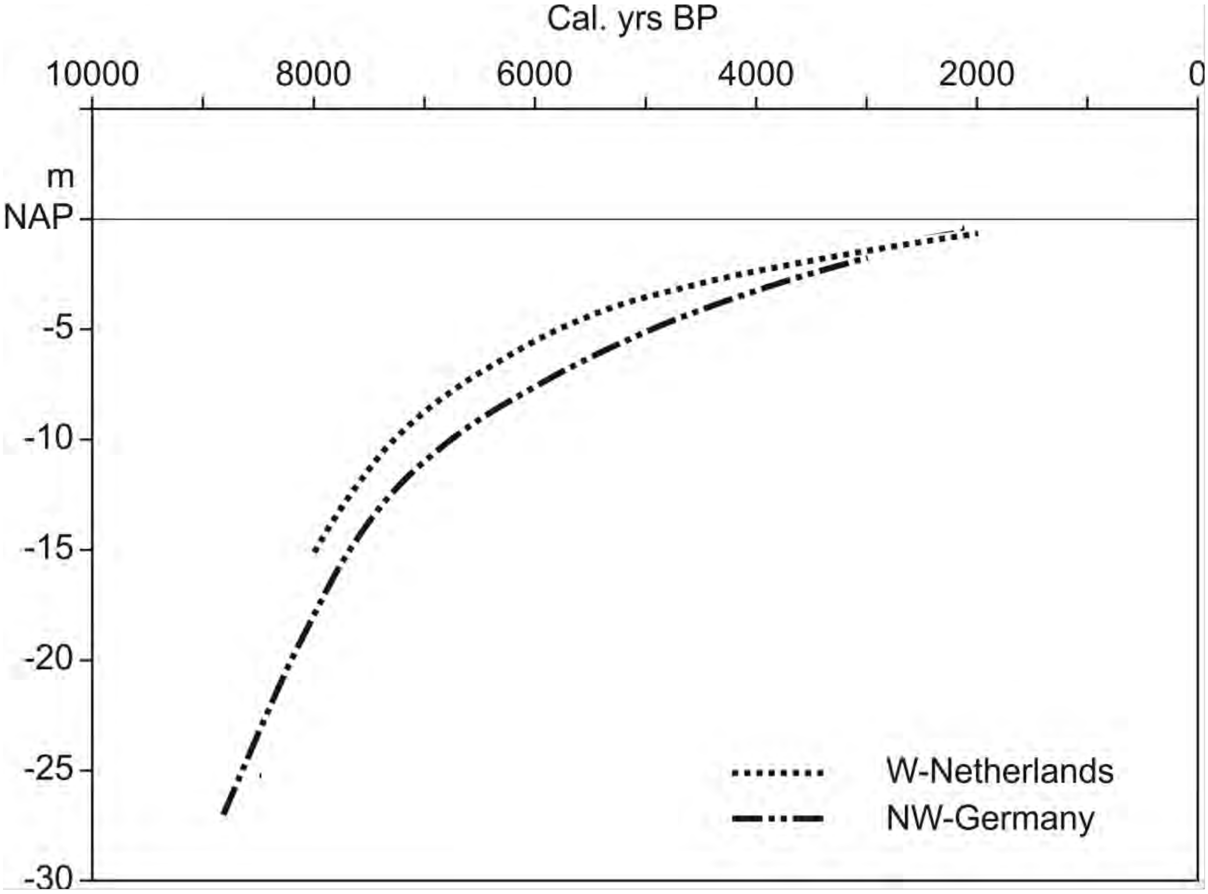


Figure 5.1.3: Differences in Holocene relative mean sea-level rise for the Dutch and NW German North Sea coast, making clear the differences on a regional scale. Sea-level rise in NW Germany has been larger than in the Western Netherlands. The differences are mainly caused by relative glacio-isostatic subsidence (Mörner, 1979). Figure modified from Kiden et al. (2008), the sea-level curves are from Van de Plassche, 1982 (W Netherlands); Denys and Baeteman, 1995 (Belgium); Kiden, 1995 and 2006 (SW Netherlands) and Vink et al., 2007 (NW Germany). The sea-level curves depicted here correspond to the mid-lines of the sea-level error bands presented in these studies (From Oost et al., 2006).

At 8000 a BP sea level was still around 20 m below its present MSL (Figure 5.1.3) and the coastline of the North Sea was much further offshore than its present position, e.g. 10 to 15 km for the central West Frisian Wadden area (Vos & Van Kesteren, 2000). The rising sea level followed and modified the mostly gentle Pleistocene relief and determined the initial position of the Wadden Sea.

The paleo-valleys incised during the Pleistocene sea-level low stand determined the location, dimensions and inland penetration of estuaries, such as the Ems-Dollard (Wiersma et al., 2009). Some of the areas were partially filled with peat and could be incised relatively easily and be converted into backbarrier embayments (e.g. Zuiderzee-, Lauwerszee-, Dollard-embayments) thereby enlarging the tidal volume of the estuaries or backbarrier basins of which they were part. In the western Wadden Sea area, the deepest river valleys were flooded around 8000 a BP

(Beets & Van der Spek, 2000). The present day tidal inlet position is in a few cases still determined by the former valleys (Wiersma et al., 2009). Locally elevated Pleistocene outcrops and headlands consisting of moraine deposits of the Saale (second-last) glaciation, and sandy meltwater deposits of the Weichselian (last) glaciation were present. The islands of Texel and Wieringen formed around such Pleistocene deposits.

The bulk of the West Frisian barrier island chain formed between 6,000-5,000 a BP. Initially sedimentation could not fill the space created by the rapidly rising sea (1 m/century), and a mainly subtidal area formed, fringed by a narrow zone of intertidal sand and mud flats and salt marshes near the mainland. At the mainland, fens gave way to raised bogs, which started to expand on the mainland of West-Frisia between 7,000-6,000 a BP (Casparie & Streefkerk, 1992; Vos et al., 2011).

At about 5,000 BP, sediment accumulation could exceed the decelerating rate of sea-level rise in the West Frisian Wadden Sea area (Figure 5.1.4) and intertidal sand flats expanded (Van Heteren & Van der Spek, 2003; Vos et al., 2011). In the following millennia bottom subsidence in the eastern part of the West Frisian Wadden Sea, was relatively large and sedimentation and despite a decelerating absolute sea-level rise sedimentation was insufficient to fill the basins everywhere (Vos et al., 2011). In some places the tidal area was extending, e.g. in the Boorne, Hunze and Fivel areas (Vos et al., 2011). In other places the Wadden Sea locally silted up and the salt marshes could advance seaward (Vos & Van Kesteren, 2000; Vos et al., 2011).

At about 5,000 a BP, the West Frisian barrier-island chain was still situated several kilometres offshore from its present position, (Ameland, 5 km and Terschelling about 9.5 km further to the north in comparison to its present position; Sha, 1990a,b; Vos et al., 2011). From 5,000 a BP until today, the chain of ebb-tidal deltas and barrier islands has been retreating landward at an average migration rate in the order of 1-2 m/year, and a large part of the sediment was deposited into the backbarrier areas (Oost, 1995).

The situation of the West Frisian Wadden area at 1,200 a BP is given in figure 5.1.4. At the mainland, tidal flats merged with tidal marshes and large brackish areas which were flanked by extensive bogs lining higher sandy areas (Esselink, 2000; Vos & Knol, 2005). Tidally influenced rivers and streams were in open connection with the Wadden Sea.

The first local dikes surrounding smaller areas to safeguard arable fields and against most winter floods, were present from around 2000 BP and became probably relatively wide spread in West-Frisia around 1,000-900 a BP (Van der Spek, 1994; Oost 1995, Ey, 2010). Since 1,000-800 a BP dikes oriented along streams were built in order to channel the outflow of waters (Ey, 2010).

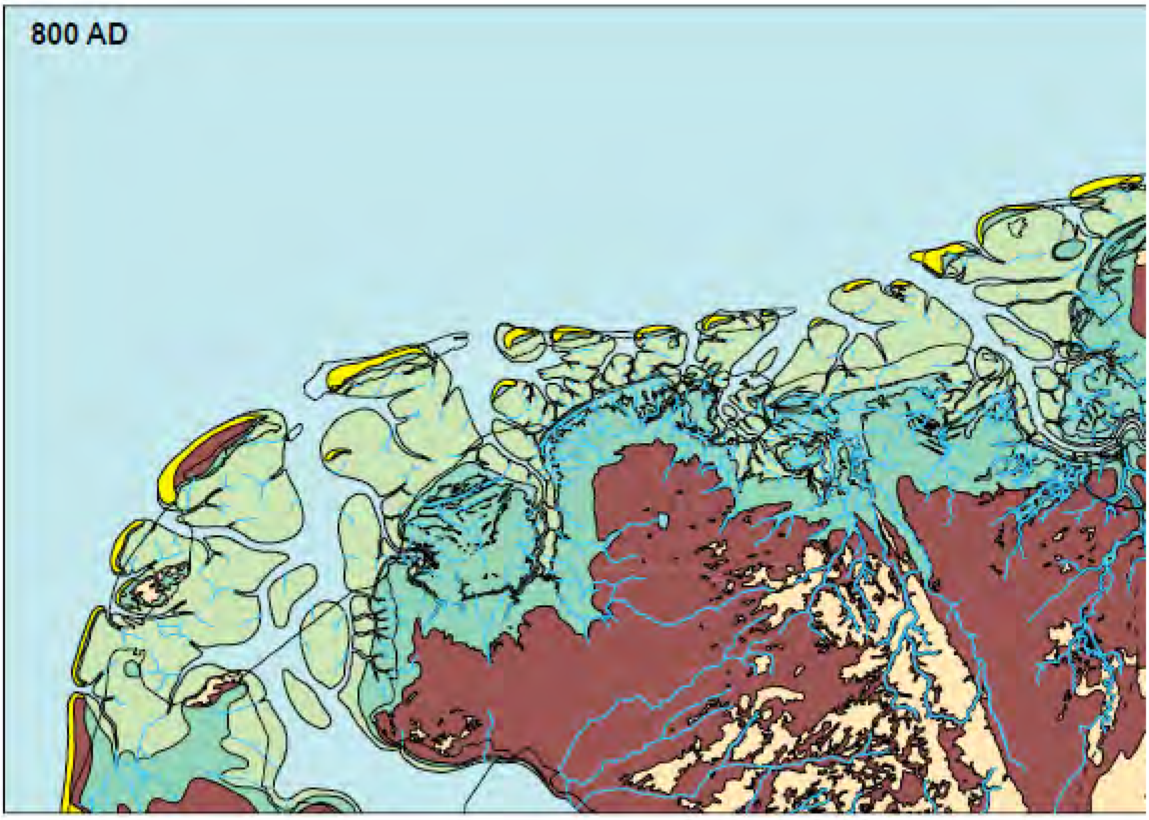


Figure 5.1.4: situation around 800 AD. Orange = higher sand grounds; brown -= peats; yellow = coastal dunes ;dark green = tidal marshes; light green = tidal flats; blue is subtidal area; contours of present day coasts are given (Oost et al., 2017).

By 800-700 a BP a continuous system of winter dikes had been constructed along the entire West Frisian Wadden Sea mainland coasts (Oost, 1995). Peat subsidence due to agriculture led to floodings and before 500 a BP many larger bays reached their maximum area. 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). Around 500 a BP and later, large parts of the salt marshes silted up so high that they could be embanked and extensive areas of land (Middelzee, Lauwerszee, Fivelboezem) had been reclaimed (van der Spek, 1994; Oost, 1995; Vollmer et al., 2001; Van Heteren & 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. Because the mainland coast was prograding seaward and the barriers were retreating landward, the tidal basins became smaller.

Since 500 yr BP large-scale attempts were made to protect dunes on the West Frisian barrier islands, but extensive livestock grazing inhibited a closed vegetation cover. Serious sand drifts were recorded on many islands, for instance Texel, Vlieland, Terschelling (van Heteren et al., 2006; Schoorl, 1999a, b, 2000a,b). In the following period, extensive sand drift dikes were built and maintained (e.g. the dike between Eijerland and Texel of 1634; Schoorl, 1999b; Oost et al., 2004). However, it should be kept in mind that existing technology at that time was largely incapable of stopping large-scale natural developments, such as channel or shoal migration. As a result, many strong especially eastward shifts of inlets and ebb-tidal deltas occurred (Oost, 1995).

The larger part of the sediments of the tidal area consists of medium sized quartz sands. The sand is mainly derived from the North Sea coastal area, which, as a result, retreated; the mud is mainly riverine or biogenetic of origin (Figure 5.1.5).

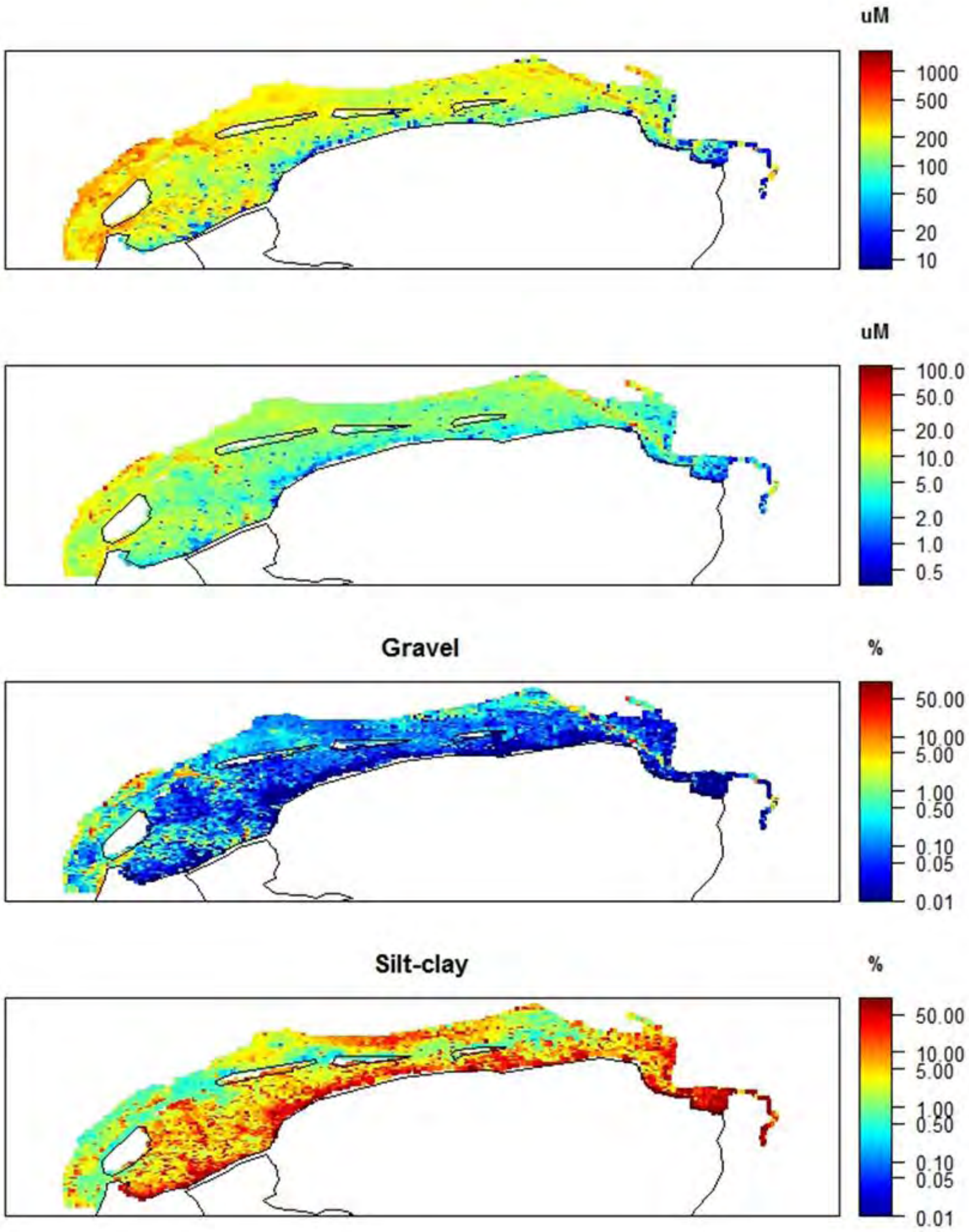


Figure 5.1.5: sediment characteristics in the Dutch Wadden Sea area. From top to bottom: median and mean grain size in micrometers, gravel content (relatively high around Texel) and mud content (high N of Ameland and near the mainland. Based on sedimentatlas Rijkswaterstaat. Data source:
http://opendap.deltares.nl/thredds/catalog/opendatap/rijkswaterstaat/sedimentatlas_waddenzee/ Karline Soetaert - using R (2013)

5.2 Marsdiep (Texel Inlet)

Basic data

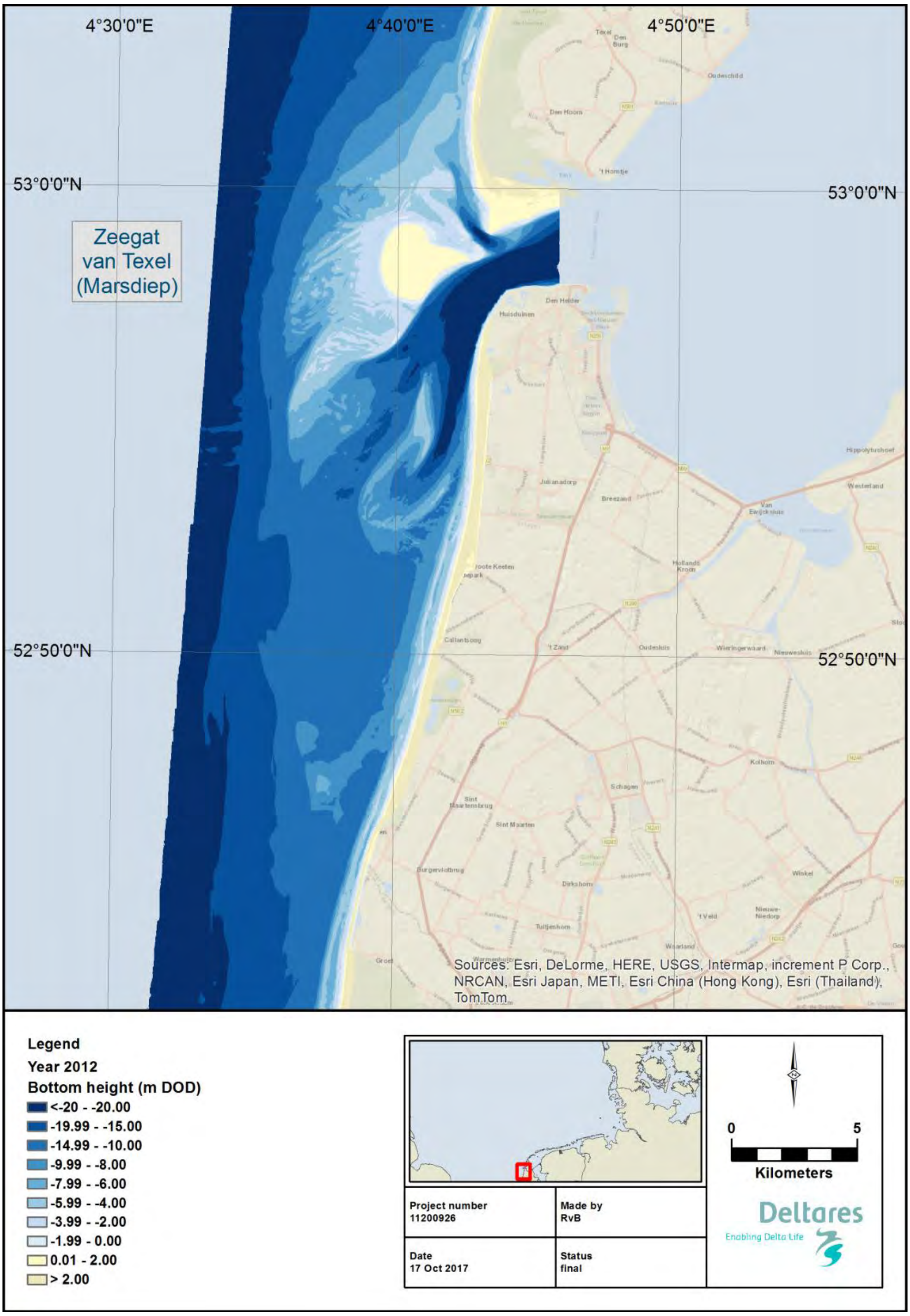


Figure 5.2.1: Overview of the ebb-tidal delta of Marsdiep.

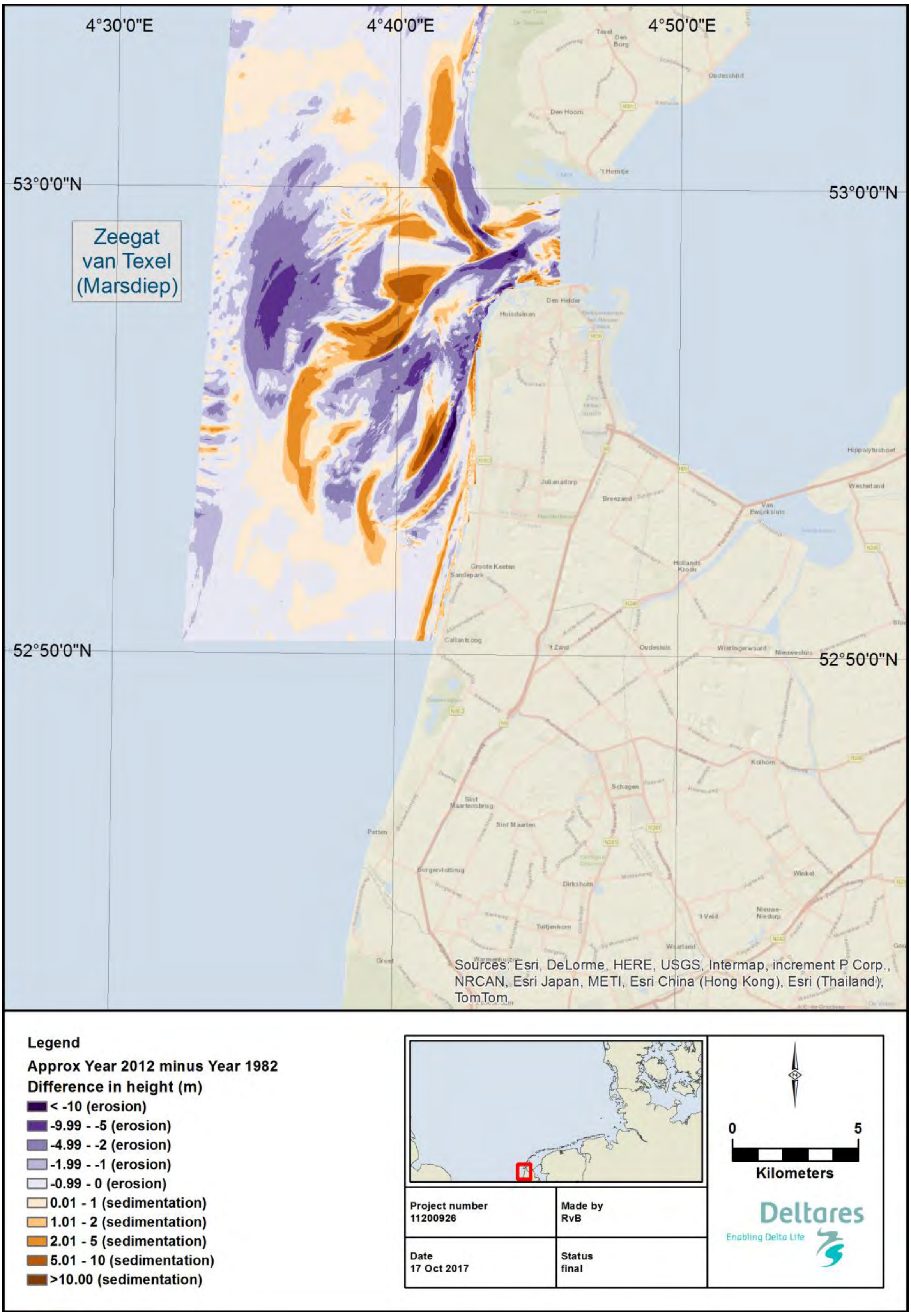


Figure 5.2.2: Overview of the ebb-tidal delta of Marsdiep showing erosion and deposition over the period 1982-2012.

Table 5.1: Facts and figures Marsdiep (see also appendix I)

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.5	1890-2008	1 (station Den Helder)						
Hs (m)	1.3		CoastDat						
Tp (s).	5.49		CoastDat						
Tf/Te	0.86	2011 Slotgemiddelde	2 (station Den Helder)						
$L_{ebb\text{-}tidal\ delta}$ (km)	8	2012	-6 m	8.1	2012	-10 m			
MHW (m AOD)	0.61	2011 slotgemiddelde	2						
MLW (m AOD)	-0.8	2011 slotgemiddelde	2						
MTR (m)	1.41 (114-155)	2011 slotgemiddelde	2	1.15	1870-1910	3			
Surge height (m to AOD)	100 y: 3.40	2011	2(station Den Helder)	200 y: 3.60	2011	2 (station Den Helder)	500 y: 3.80	2011	2 (station Den Helder)
Mean annual max surge height (m to AOD)	2.4		CoastDat						
A_{MHW} (km^2)	704	1982	4	712	~1988	5			
A_{MLW} (km^2)	567	1982	4	591	~1988	5			
A_{cross} (m^2)	49182	1980	6(map)	54994	1981	6 (map)			
V_{MHW} (10^6 m^3)	3320	1982	4						
V_{MLW} (10^6 m^3)	2240	1982	4						
P (10^6 m^3)	1036	1980	3&6 (Pd)	1070	1982	4 (Pbat)	990.5±177	2009/2010	7 (Pcom)
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)	509.1	1972	8	489.1	1981	8			
$AS_{backbarrier}$ (10^6 m^3/yr)	4.6	1935-1990	9	-1.3	1990-2005	9			
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)	-4.5	1935-1990	9	-3.6	1990-2005	9			
AS_{coast} (10^6 m^3/yr)	-0.7	1935-1990	9	-2.6	1990-2005	9			
Longshore drift (10^6 m^3/yr)	-0.2	1990-2012	10	-0.3 to +0.1	1990-2012	10 (stations Ijmuiden, K13 & Eierland)			
Sediment transport direction?	Toward inlet								
Development island coasts	Erosion at both sides of inlet								

*1 = Dillingh et al., 2010; 2 = Dillingh, 2013; 3 = Sha, 1990a; 4 = Biegel, 1992 (fixed tidal heights); 5 = Vroom et al., 1989; 6 = Klein Wassink, 1991 (Adapted for A_{cross} under AOD: by adding inlet width*0.8 before closure Zuiderzee and 0.9 after (=AOD-MLW)); 7 = Duran-Matute, 2014; 8 =Eysink, 1993; 9 = Elias et al., 2012 (incl. dredging and dumping); 10 = Ridderinkhof, 2016.*

Description of the inlet system

The Dutch inlet Marsdiep is situated between the mainland of Holland and the barrier island of Texel (Figures 5.2.1 & 5.2.2). Although a river is mentioned with the name of Maresdeop around 900 AD, the development towards an inlet probably started somewhere between 1150 and 1250 (Schoorl, 1973; Hallewas, 1984, Oost et al., 2004). Maximum inlet depth increased linearly between 1344 and 1740 (Oost et al., 2004; Elias & van der Spek, 2006) suggesting an increase in tidal prism, probably due to erosion of a supratidal peat area E of it and a take-over of a part of the Vlie Inlet area. As the tidal prism increased up to 1740, the ebb-tidal delta probably also increased in size. The ebb-tidal delta main channels changed from NW oriented to SW oriented, which is attributed to the decreasing role of the waves relative to the tides (Sha, 1990a).

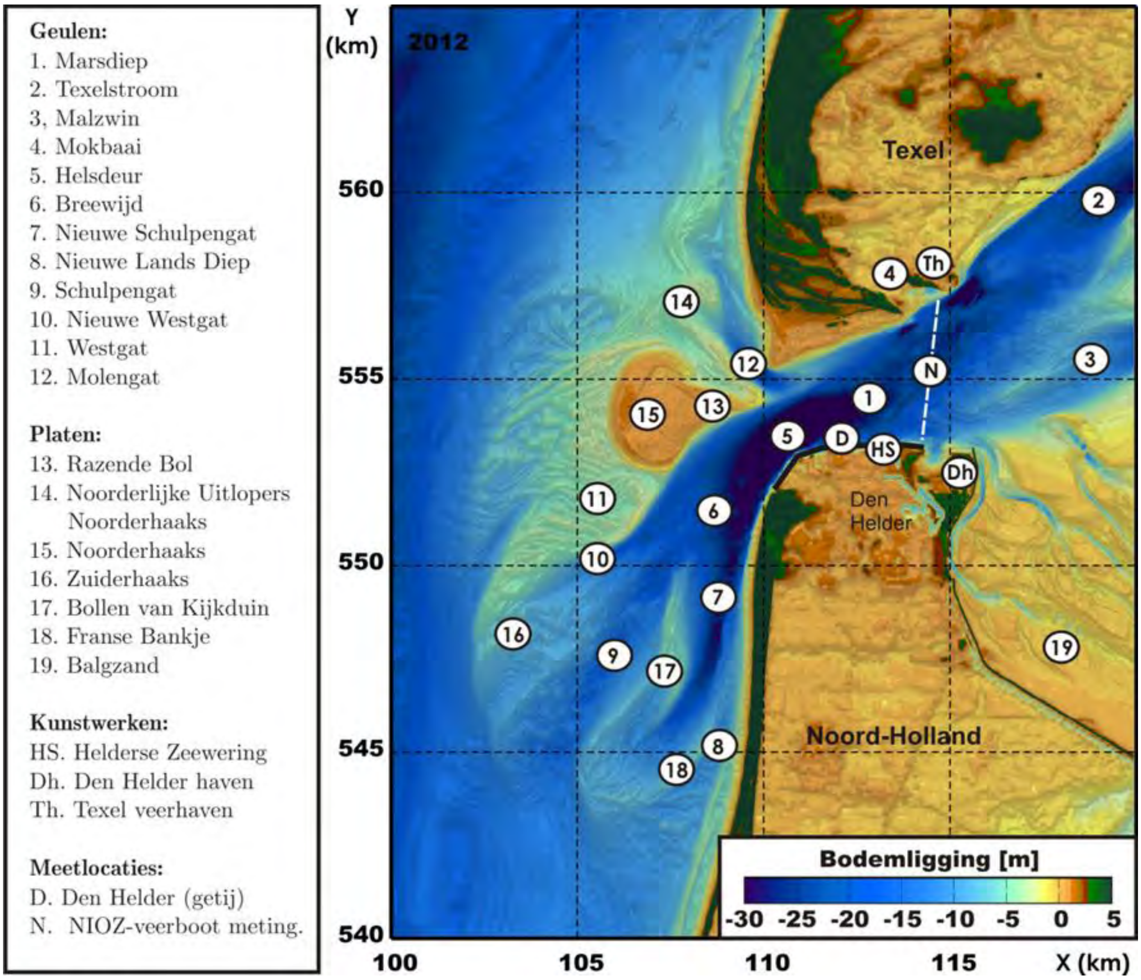


Figure 5.2.3: toponymes of the ebb-tidal delta and the throat of the tidal inlet of Texel (Elias et al., 2014).

The Marsdiep (Figure 5.2.3 {1}) connects the backbarrier channels Texelstroom {2}, Malzwin {3}) and Breewijd {6} with the main channels of the ebb-tidal delta: Molengat {12}, Schulpengat {9} and Nieuwe Schulpengat {7} (Elias et al., 2014). The closure of the Zuiderzee influenced the development of the area strongly. Around 1600 AD the Marsdiep inlet reached its largest extension and drained a large part of the Zuiderzee area (4000 km^2; Oost & KleinePunte, 2004). The length of the basin was ca. 160 km, so that half a tidal wave would fit in the basin, so that tidal amplitude decreased (Dastgheib et al., 2008). Due to the closing of the Zuiderzee (1925-1932) the backbarrier basin surface was brought back to around 712 km^2 and a length of only 30 km, or 0.17 times the tidal wave length. The tidal wave transformed from a going tidal wave to a standing wave and tidal amplitude increased with about 26% (Rietveld, 1962; Dissaniyake, 2012; see also Thijsse, 1972). As a result of the amplification tidal prism increased from 700*10^6 m^3 to ca. 1000*10^6 m^3. Also, a phase shift had occurred between the tides in the open North Sea and through the inlet, which led Ridderinkhof (2016) to conclude based on theoretical models that the Marsdiep may have changed from sediment exporting to importing.

The change of the tide and tide propagation characteristics, the basin geometry and abandonment of some of the main channels resulted in strong sedimentation in the backbarrier area (Elias et al., 2012, 2014). Sedimentation in the backbarrier area amounted to 234*10^6 m^3 over the period 1935-2005 (fixed borders, adjusted for dredging and dumping; Elias et al., 2012). Big changes occurred along the Afsluitdijk, where in the closed channels the flow rate reduced to almost zero; these were rapidly filled up by a mixture of mud and sand layers (Berger et al., 1987; Oost, pers. obs.).

After the closure of the Zuiderzee a residual flow of 1-10% of the tidal prism of the Marsdiep leaves via the Vlie during ebb (Visser et al., 1986; Ridderinkhof et al., 2002; Elias et al., 2014). After the closure the morphological watershed of between both systems has shifted towards the E and, partly due to this sedimentation changed into erosion in the period 1990-2015. The position of the Texelstroom (Figure 5.2.3 {2}) retained a NE-SW orientation near Texel. This may be explained by inertia of the flood and ebb and partly due to coastal defense works on the SE of Texel (Schoorl, 1973). Additionally, erosion-resistant layers may be present (Elias et al., 2014), but so far were not encountered during studies.

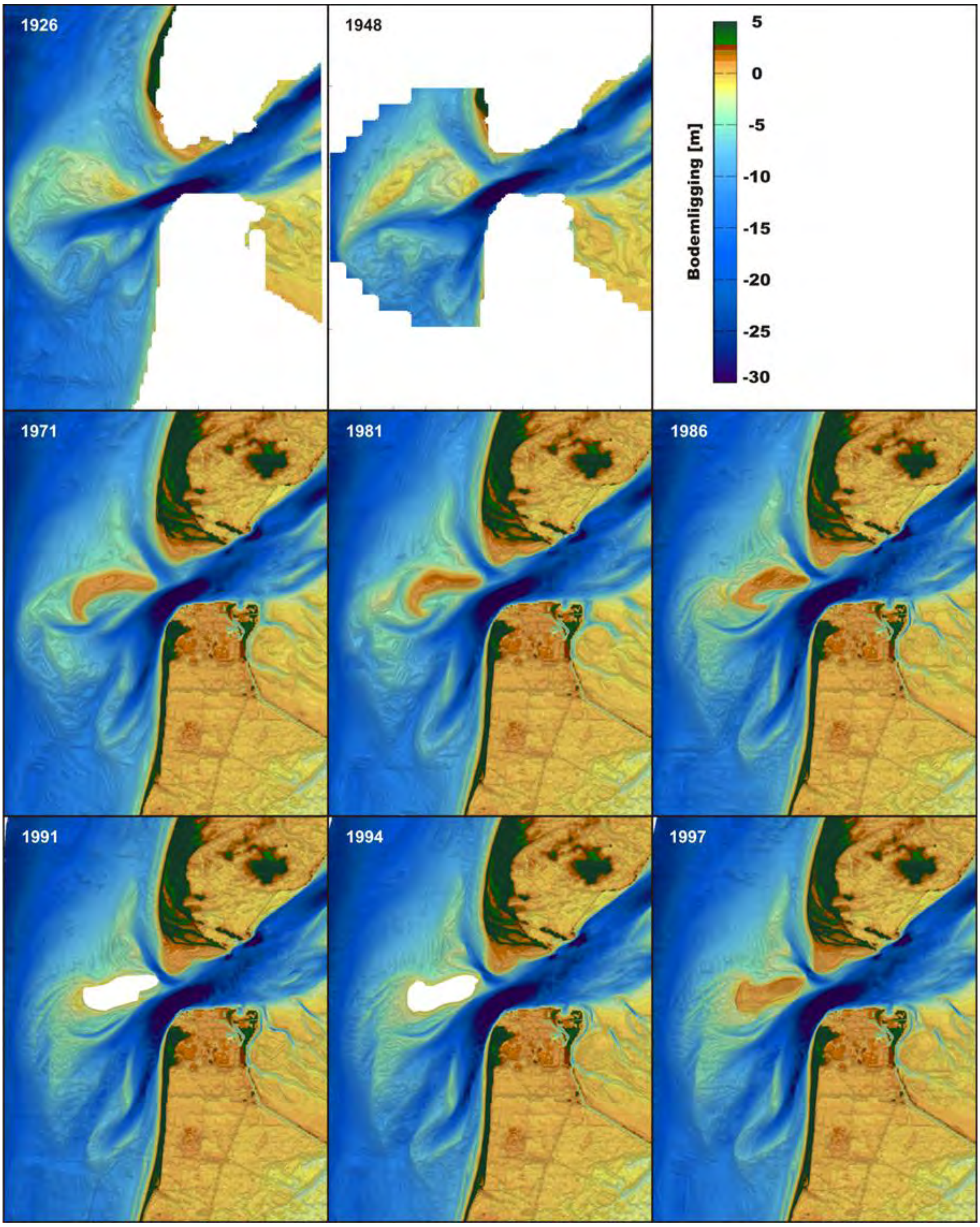
Development of the ebb-tidal delta

At present the ebb-tidal delta extends about 10 km seaward and 25 km along the coast (Figure 5.2.4). An important element in the throat is the Helderse Seawall (Figure 5.2.3 {HS}), a stone bulwark which stabilizes the south side of the inlet all the way to the bottom of the channel. This leads to accelerated flow and results in depths of more than 50 m (Helsdeur {5}; Elias et al., 2014).

In a period of 40 years after the closing of the Zuiderzee, the ebb-tidal delta adapted to the changes in hydrodynamics (Elias, 2006; Elias et al., 2012: Ridderinkhof, 2016). In the period 1935-1990 the ebb-tidal delta lost 245*10^6 m^3 of sand while the adjacent coasts lost 37*10^6 m^3 (fixed borders, adjusted for dredging and dumping; Elias et al., 2012, 2014). This has been largely deposited in the backbarrier area. Due to the changed hydrodynamic conditions southward directed channels formed and the ebb-tidal delta extended in that direction. Around 1956 the Schulpengat changed into the present-day two-channel system Schulpengat and Nieuwe Schulpengat. Their configuration was stable since 1975, but deepening was ongoing in the period 1986-2009 with Nieuwe Schulpengat eroding with 16.4*10^6 m^3 and Schulpengat with 36*10^6 m^3 (Elias et al. 2104). The Nieuwe Schulpengat, the most southern portion of the ebb-tidal delta, rotates seaward, resulting in local areas of (strong) erosion and sedimentation (Elias et al., 2014).

Erosion of, and changes on, the ebb-tidal delta continue up to this day. During the period 1986–2009 the ebb-tidal delta lost a total 88*10^6 m^3 (3.8*10^6 m^3/year), including correction for nourishments. The large part of the net losses of sand in the ebb-tidal delta were thought to have been brought about by the sediment demand in the backbarrier area (Elias et al., 2014).

The about 4 km^2 large supratidal shoal Noorderhaaks (Figure 5.2.3 {15}) is the centrum of the ebb-tidal delta. Before closing the Zuiderzee the Noorderhaaks was an area where seaward sand supply by the Westgat more or less balanced with the landward sediment transport by waves. After the closure sand transport to the Noorderhaaks reduced so that landward transport through waves became dominant and the shoal migrated inland and changed in form. Over the period 1986-present the greatest changes in the ebb-tidal delta took place on the Noorderhaaks and its northward directed spit. In the period 1986-2009 Noorderhaaks changed in form and loses 80*10^6 m^3 over the period considered at its seaward side below AOL -5m. 39*10^6 m^3 may have become stored in the Noorderhaaks and 13*10^6 m^3 in the spit (Elias et al., 2014).


1926
1948
5
0
-5
-10
-15
-20
-25
-30
Bodemligging [m]
1971
1981
1986
1991
1994
1997

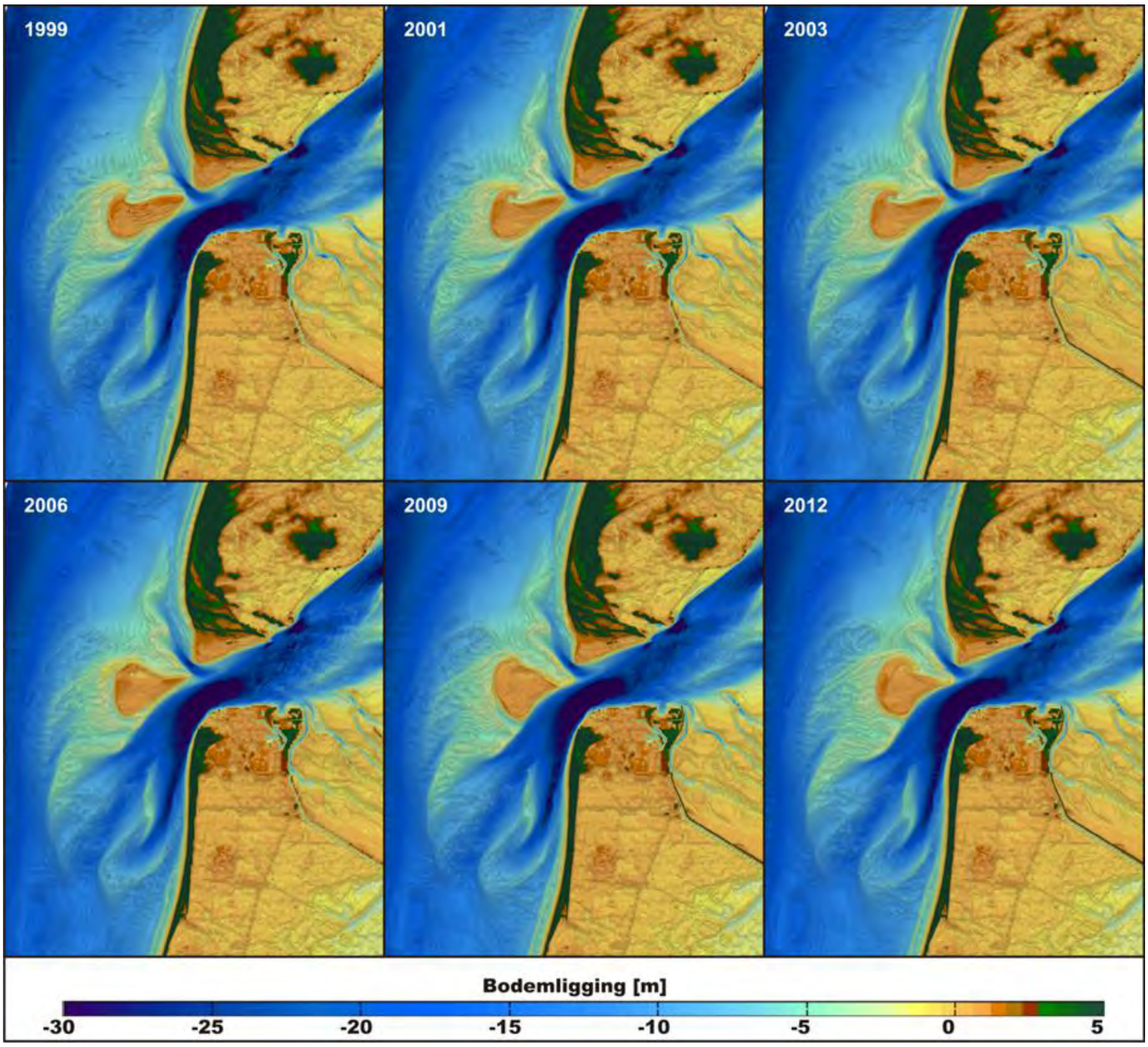


Figure 5.2.4: Development of the ebb-tidal delta of Texel for the period 1926-2012 (Elias et al., 2014).

Coastal development

Erosion in the coastal area near the inlet amounted to $76*10^6$ m^3 over the period 1935-2005 (fixed borders, adjusted for dredging and dumping; Elias et al., 2012). The formation and presence of the Nieuwe Schulpengat close along the Holland coast caused strong erosion (Elias & Cleveringa, 2003). The channel is not only important for the local sand management, but also seems to be a large influence on the larger sand balance the Dutch coast (Stive & Eysink, 1989, Elias et al., 2012, 2014). The increase in sediment volume with $15*10^6$ m^3 in the period 1986-2009 of the adjacent coast of North Holland (Figure 5.2.3 {s. 13, 14, 15}) is mainly due to sand nourishments ($17*10^6$ m^3 during this period; Elias et al., 2014).

Shoals have attached to the SW of the island Texel, on average every 127 years (ca. 1400, 1500, 1630, 1740, 1910; Oost et al., 2004), but attachments might have been more frequent during the initial phases of the inlet, when it was much smaller (Sha, 1990a). It is not known if these developments will continue, since the evolution of the ebb-tidal delta was strongly affected by the closure of the Zuiderzee basin in 1932. Sha (1989) observed a shift of the Noorderhaaks of some (67 m/yr). Ridderinkhof (2016) observed the centroid of the shoal moved with approximately 285 metres landward in the period 1985-2014 (10 m/yr). In this period the distance between the coast and the landward side of this shoal did not decrease (the shoal mainly rotated and changed in shape).

At the north side of the Noorderhaaks a spit-shaped sand bar formed. The exchange between this spit and the channel the Molengat largely determines the development of the nearby part of the coastline of Texel. The landward displacement of the spit reduced the channel, making it deeper and structurally eroding the coast of Texel (Cleveringa, 2001). During fair weather conditions, shore-parallel tidally driven transports dominate in the Molengat channel, with flood-dominated flow along the island coast and ebb-dominated flow along the spit, resulting in fairly stable positions of the Molengat and the spit. During storms landward transports dominate (Elias, 2006). Since 1994, the Molengat channel has become shallower and by 2012, the channel and spit formed a shallow platform on AOD -5m. With the development the Molengat changed from a very wide, shallow channel into a narrow deep channel. Since 2006 the latter trend was reversed: the Noorderhaaks eroded at its east side and the Molengat became shallower and wider, leading to new erosion of the Texel coast (Elias et al., 2014, pers. comm.).

5.3 Eierlandse Gat

Basic data

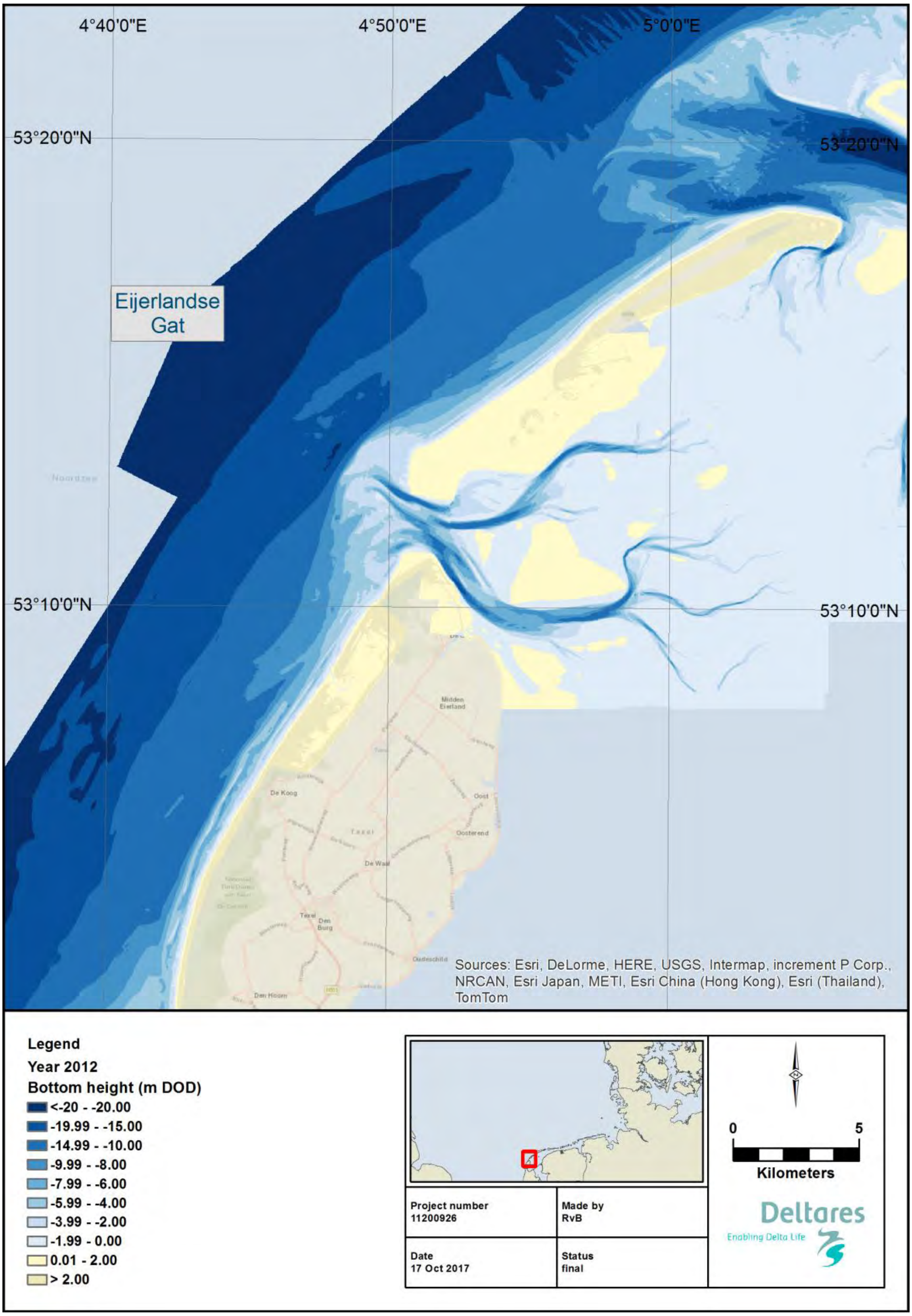


Figure 5.3.1: Overview of the ebb-tidal delta of Eierlandse Gat.

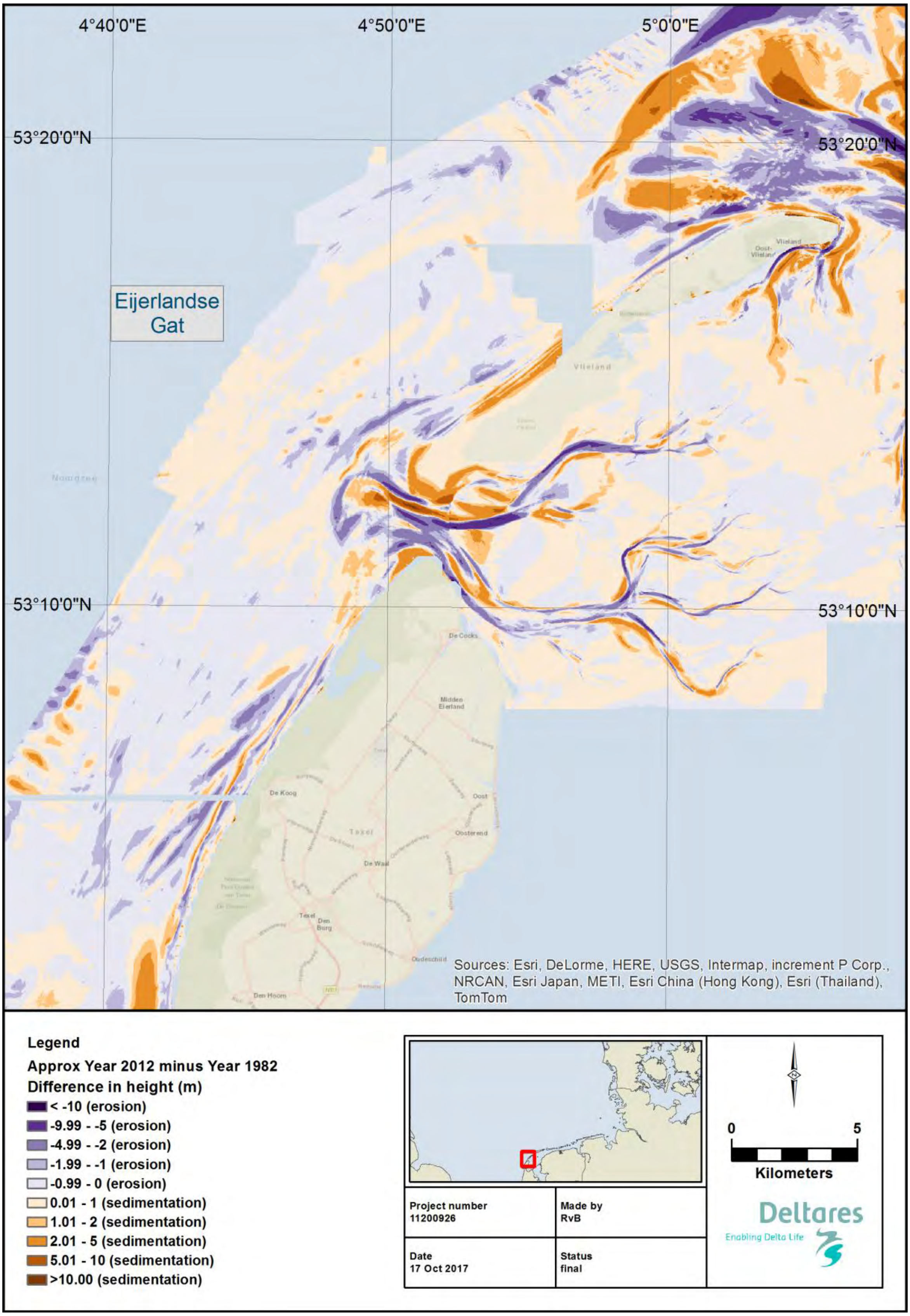


Figure 5.3.2: Overview of the ebb-tidal delta of Eierlandse Gat showing erosion and deposition over approximately the period 1982-2012.

Table 5.2: Facts and figures Eierlandse Gat (see also appendix I)

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (m)	1.5	1890-2008	1 (station Den Helder)						
Hs (m)	1.36		CoastDat						
Tp (s).	5.69		CoastDat						
Tf/Te	No data								
$L_{ebb\text{-}tidal\ delta}$ (km)	4.1	2012	-6 m	4.1	**2012**	-10 m			
MHW (m)	**0.74**	2011 Slot-gemiddelde	2, 3 (est. from station Texel Noordzee						
MLW (m)	**-0.93**	2011 Slot-gemiddelde	2, 3 (est. from station Texel Noordzee						
MTR (m)	1.67 (1.31-1.9)	2011 Slot-gemiddelde	2, 3 (est. from station Texel Noordzee						
Surge height (m to AOD)	100 y: 3.30	2017	2 (station Texel Noordzee)	200 y: 3.50	2017	2 (station Texel Noor-dzee)	500 y: 3.70	2017	2 (station Texel Noor-dzee)
Mean annual max surge height (m to AOD)	2.49		CoastDat						
A_{MHW} (km^2)	153	1982	4				153	~1988	5
A_{MLW} (km^2)	58.9	1982	4						
A_{cross} (m^2)	8293	1926	6	15650	1979	4	9721	1981	6
V_{MHW} (10^6 m^3)	306	1982	4						
V_{MLW} (10^6 m^3)	114	1982	4						
P (10^6 m^3)	205	1982	4 (Pdis)				180±41.5	2009-2010	7 (Pcom)
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)	135.1	1982	8	127.6	1987	8			
Longshore drift (10^6 m^3/yr)	-0.1	1990-2012	9						
$AS_{backbarrier}$ (10^6 m^3/yr)	-0.4	1935-1990	10	-0.2	1990-2005	10			
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)	-0.2	1935-1990	10	-0,8	1990-2005	10			
SV_{coast} (10^6 m^3/yr)	-0.4	1935-1990	10	-2.3	1990-2005	10			
Sediment transport direc-tion?	E ward								
Development island coasts	Erosion at NW-Texel up to groin; Sedimentation at W- Vlieland								

*1 = Dillingh et al., 2010; 2 = Dillingh, 2013; 3 = Vroom et al., 1989; 4 = Biegel, 1992 (fixed tidal heights); 5 = Louters & Gerritsen, 1992; 6 = Klein Wassink, 1991 (Adapted for A_{cross} under AOD: by adding inlet width*0.87 before closure Zuiderzee and 0.93 after(=AOD-MLW)); 7 = Duran-Matute et al., 2014; 8 = Eysink, 1993; 9 = Ridderinkhof, 2016; 10 = Elias et al., 2012.*

Description of the tidal inlet system

This Dutch inlet Eierlandse Gat is situated between barrier islands Texel south of it and Vlieland, northeast of it (Figures 5.3.1 to 5.3.3). The Eierlandse Gat must have been rather old, as around 800 AD a village West-Vlieland was already present near the inlet. The outlet to the sea, in the throat, consists of two more or less separate main channels: the Engelmansgat {1} and the Robbengat {2} (Figure 5.3.3). The Engelmansgat connects to the Keteldiep {3} in the W of the backbarrier area, whereas the Robbengat connects to the Vogelzwin {5} (Elias et al., 2016). The backbarrier area is completely surrounded by the larger systems of Zeegat van het Vlie and Marsdiep and is the only inlet system not connected to the mainland. Erosion in the backbarrier area amounted to $27*10^6$ m^3 over the period 1935-2005 (fixed borders, adjusted for dredging and dumping; Elias et al., 2012). Judging from sedimentation and erosion maps over this period this was mainly due to the deepening of the channels in the system. The deepening of channels suggests an increase of tidal volume which was also found by direct measurements and was probably resulting from the eastward shift of the watersheds in the area.

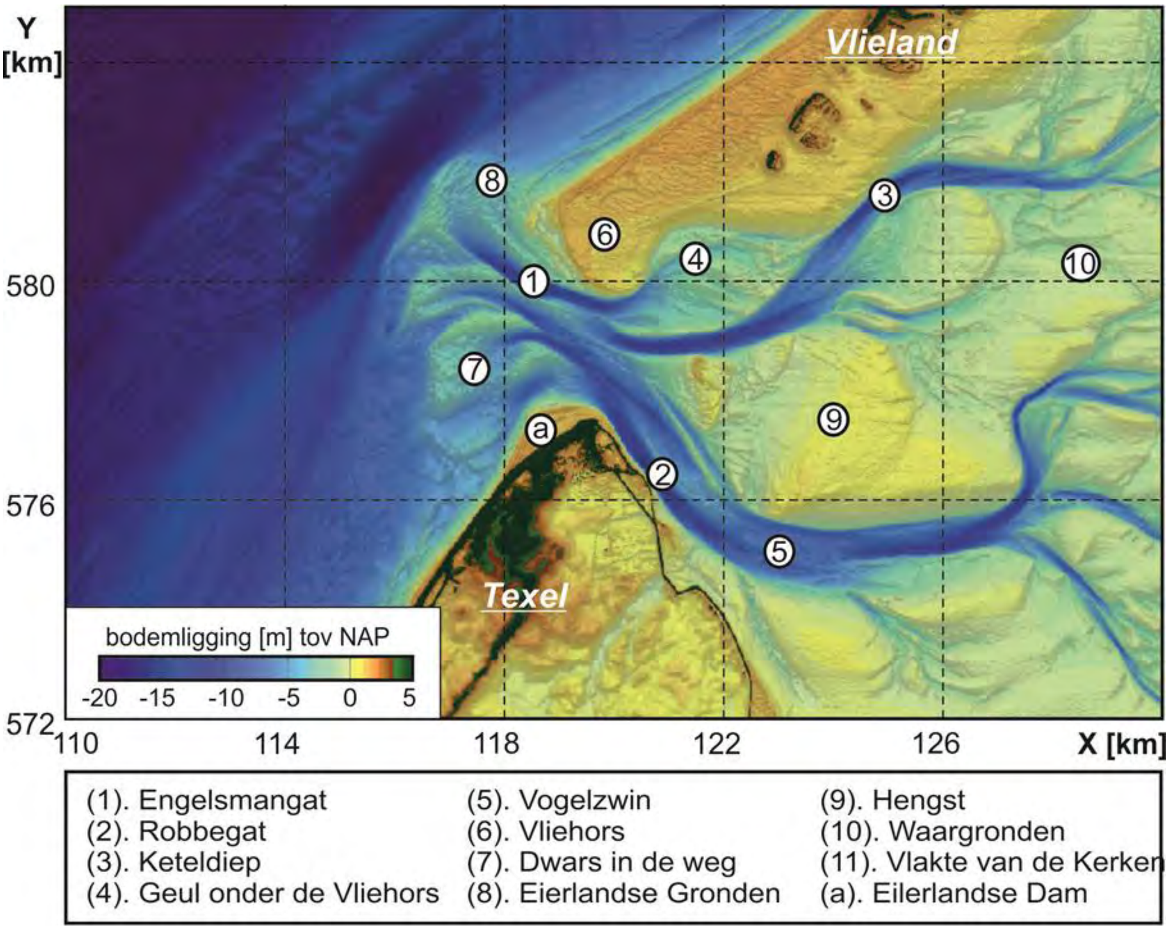


Figure 5.3.3: Toponymes of the Eierlandse Gat (Elias et al., 2016).

Development of the ebb-tidal delta

In seaward direction the channels diverges into a series of smaller channels across the southern part of the ebb-tidal delta. On the Eierlandse Gat ebb-tidal delta large scale morphological changes occurred over the past centuries. Medieval sources mention roman building traces on a shoal of the ebb-tidal delta. In the 17th and 18th century a strong landward retreat over >1 km of the barrier island at West-Vlieland occurred, which contemporaneous sources state was the result of the disappearance of the ebb-tidal delta of which the sand was carried into the backbarrier area (Abogado Rios, 2009). The coast near the inlet was losing sediments since the sand-drift dike between the Eierland (the northern part of present-day Texel) and Texel was constructed in 1629 (Schoorl, 2000). Sediment loss is attributed to the strong curvature of the coastline causing a divergence in longshore sediment transports (Rakhorst, 1999).

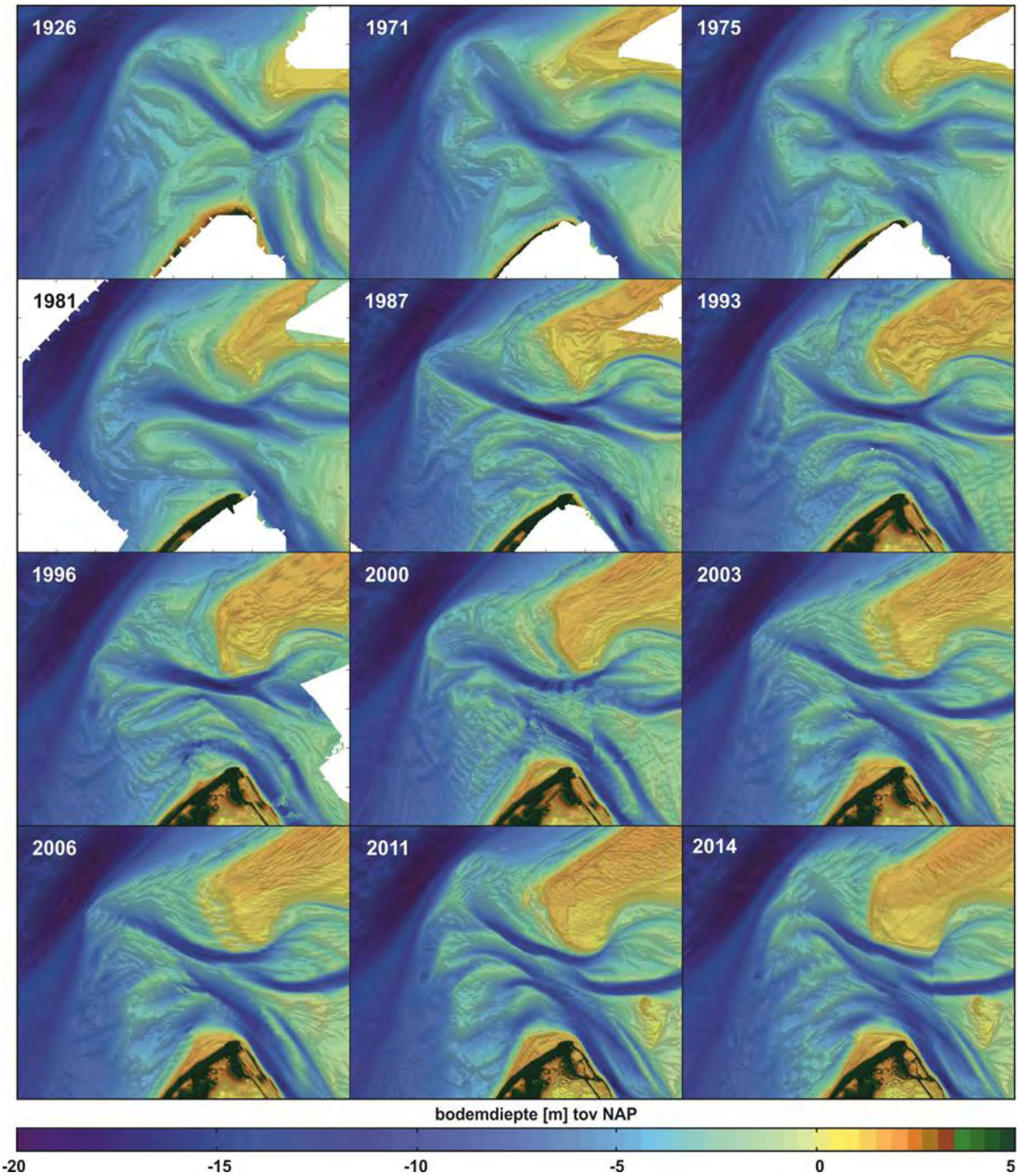


Figure 5.3.4: Development of the Eierlandse Gat 1926-2014 (Elias et al., 2016).

Before the closure of the Zuiderzee the inlet mostly consisted out of two more or less separate channels which occasionally merged into one channel (e.g. 1886). The channels seem to form or re-orient time and again towards the SW. Bars at the north side of the channels merge from time to time with the downdrift island of Vlieland (e.g. 1886). After the closure of the Zuiderzee the ebb-tidal delta clearly changed (Figure 5.3.4). Over the period 1935-2005 the ebb-tidal delta was eroded and lost $23*10^6$ m^3 of sediment (fixed borders, adjusted for dredging and dumping; Elias et al., 2012, 2016).

The NW point of Texel is protected by the bulwarks “Robbengat” (1948) and “Eierlandsgat” (1956), the Eierlandse dam (1995) and many smaller groins. The Eierlandse dam is 800 m long and oriented perpendicular to the coast (see {a} in Figure 5.3.3). Due to the many human interventions, such as connecting the Texel islands, the protection works of Texel, but also the closing of the Zuiderzee, it is difficult to say whether the observed changes are natural behaviour. Until about 1975, there was one dominant channel (Engelmansgat) on the ebb-tidal delta (Joustra, 1971; Endema, 1978) connected to the two main backbarrier channels of which the Vogelzwin was larger than the Keteldiep. After the construction of the bulwarks the Vogelzwin shifted landward and nowadays is located close to the island of Texel. Since 1975 a shoal is building up (-5 m AOD) separating the Engelsmangat (N; Figure 5.3.4) and the Robbengat. The Robbengat fans seaward along the bulwarks and the Eierlandse dam. An elongate shoal divided the Robbengat in two separate channels of which the southern channel is likely flood-dominant and the northern one ebb-dominated. In the period 1993-1996 a relatively deep channel formed along Eierland, which was initiated by dredging a sand-mining pit to build the Eierlandse dam (Elias et al., 2016).

Coastal development
Erosion in the coastal area amounted to $54*10^6$ m^3 over the period 1935-2005 (fixed borders, adjusted for dredging and dumping; Elias et al., 2012). The coast of Texel has been eroding for a long time. This was stopped by the protection works and nourishments especially since 1995 when the Eierlandse Dam was built (Elias et al., 2016).

The merger of shoals from the ebb-tidal delta at the north side of West-Vlieland led to strong sedimentation. The evolution of the mean low water line suggests that around 1942 a shoal attached to the coast of Vlieland. Based on Jarkus data it can be concluded that shoals attached to the coast of Vlieland in 1965, 1981, 1986, 1992, 1999, 2004, and 2009 (Ridderinkhof, 2016). The frequency of merger is approximately once per 6 yr based on observations in the period after 1981 (Ridderinkhof, 2016). Shoal merger sometimes leads to formation of spits at the westend to the island (1993; 2003). As a result of these mergers the head of West-Vlieland extends in the direction of Texel. At its SE-side the channel “Geul onder de Vliehors” is becoming shallower.

5.4 Zeegat van het Vlie

Basic data

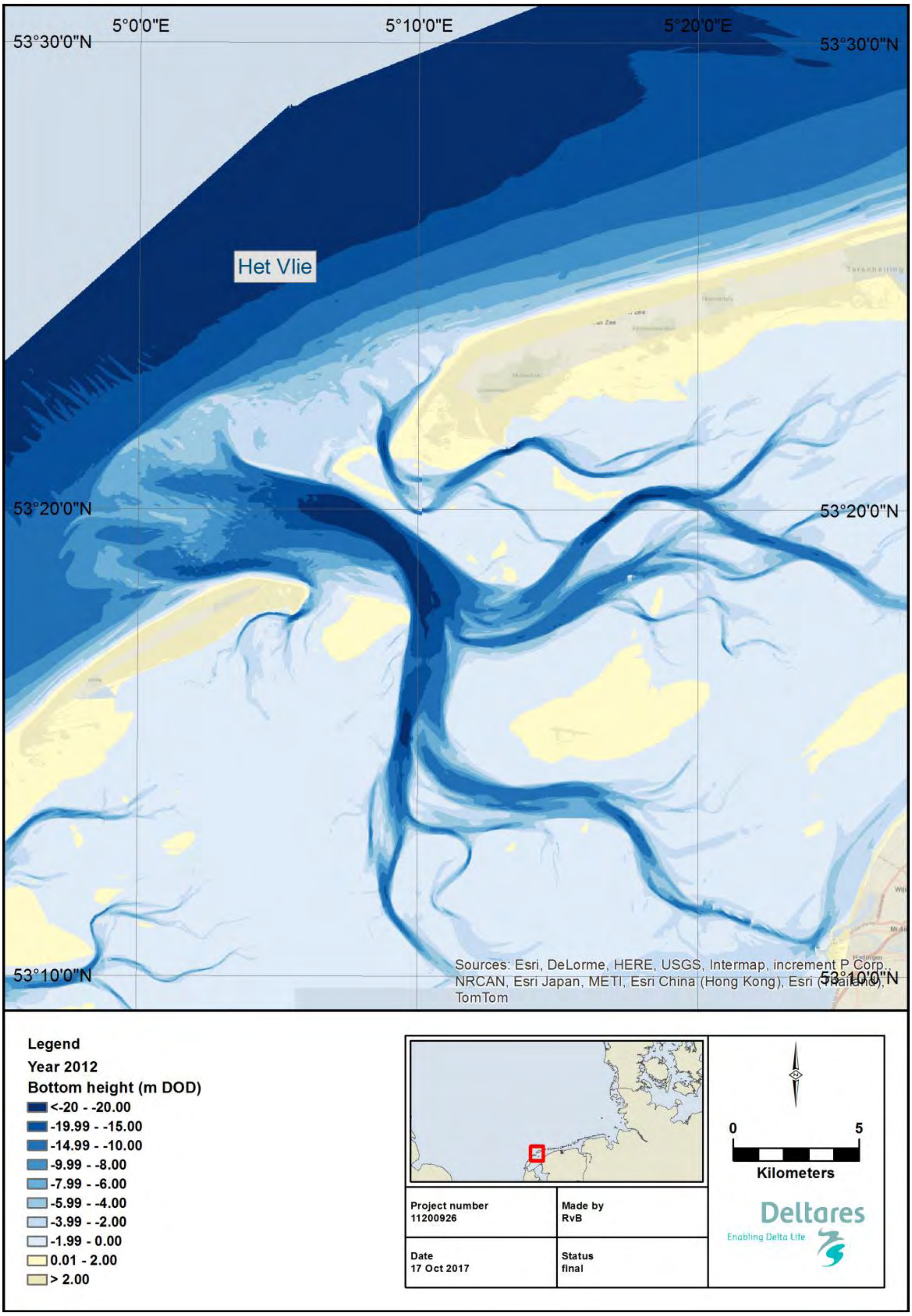


Figure 5.4.1: Overview of the ebb-tidal delta of Zeegat van het Vlie.

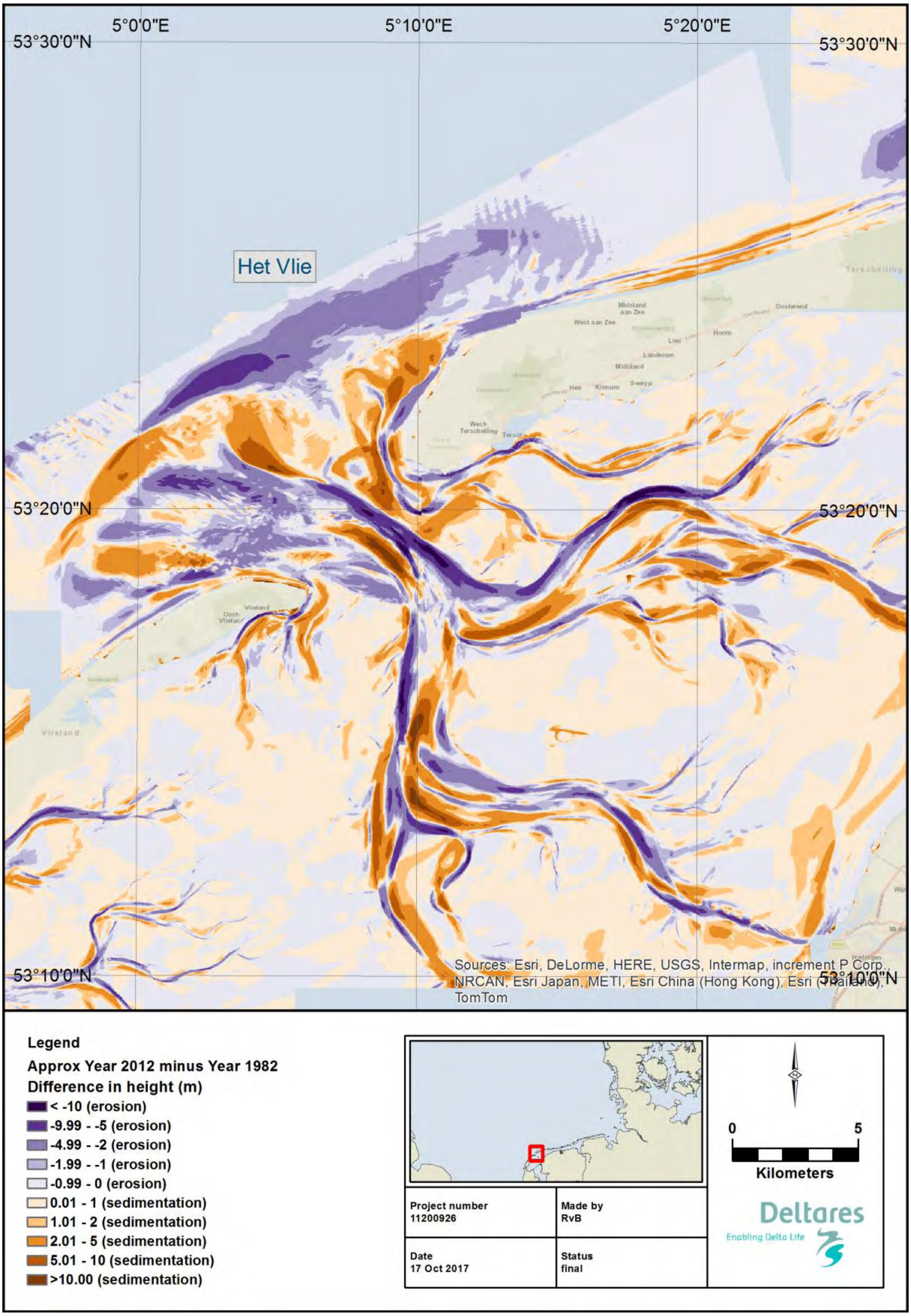


Figure 5.4.2: Overview of the ebb-tidal delta of het Zeegat van het Vlie showing erosion and deposition over approximately the period 1982-2012.

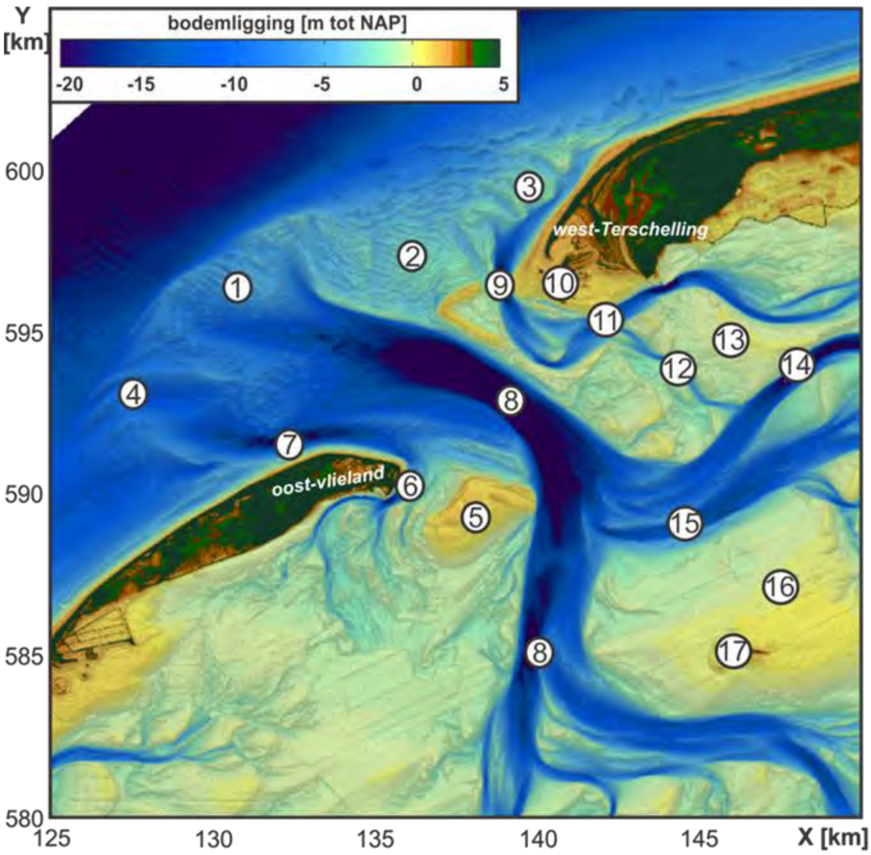
Table 5.3: Facts and figures Zeegat van het Vlie (see also appendix I)

Parameter	Observ	Year	Reference	Observ	Year	Reference	Observ.	Year	Reference
MSLR (mm/yr)	1.3	1890-2008	1 (station Harlingen)						
Hs (m)	1.34		CoastDat						
Tp (s).	5.84		CoastDat						
Tf/Te	0.89 & 0.95	2011 Slotgemiddelde	2 (stations Terschelling Noordzee & Vlieland haven)						
$L_{ebb\text{-}tidal\ delta}$ (km)	8	2012	-6 m	8	2012	-10 m			
MHW (m NHN)	0.85	2011 Slotgemiddelde	2 (station Westterschelling)						
MLW (m NHN)	-1.01	2011 Slotgemiddelde	2 (station Westterschelling)						
MTR (m)	1.86	2011 Slotgemiddelde	2 (station Westterschelling)						
Surge height (m to AOD)	100 y: 360	2011	2 (station Westterschelling)	200 y: 370	2011	2 (station Westterschelling)	500 y: 390	2011	2 (station Westterschelling)
Mean annual max surge height (m to AOD)	2.48		CoastDat						
A_{MHW} (km^2)	665	1982	3						
A_{MLW} (km^2)	394	1977	4	368	1982	3			
A_{cross} (m^2)	80550	1982	5						
V_{MHW} (10^6 m^3)	2290	1982	3						
V_{MLW} (10^6 m^3)	1190	1982	3						
P (10^6 m^3)	1100	1982	3 (Pbat)				934±169	2009 - 2010	6 (Pcom)
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)	354.8	1982	7						
$AS_{backbarrier}$ (10^6 m^3/yr)	3	1935-1990	8	3.5	1990 - 2005	8			
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)	-1.8	1935-1990	8	-1.8	1990 - 2005	8			
AS_{coast} (10^6 m^3/yr)	-0.2	1935-1990	8	-0.7	1990 - 2005	8			
Longshore drift (10^6 m^3/yr)	0.4	1990-2012	9	+0.3 to +0.5	1990 - 2012	9 (stations Eierland & Schiermonnikoog)			
Sediment transport direction?	Eastward								
Development island coasts	Erosion of East Vlieland; Sedimentation at Terschelling								

*1 = Dillingh et al., 2010; 2= Dillingh, 2013; 3 = Biegel, 1992 (fixed tidal heights); 4 = Kool et al., 1984; 5 = Klein Wassink, 1991 (Adapted for A_{cross} under AOD: by adding inlet width*1 (=AOD-MLW)); 6 = Duran-Matute et al., 2014; 7 = Eysink, 1993; 8 = Elias et al., 2012; 9 = Ridderinkhof, 2016.*

Description of the tidal inlet system

This Dutch inlet is situated between the barrier island of Vlieland in the West and the island of Terschelling in the east (Figures 5.4.1-5.4.3). As is the case with many other inlet systems several channels are present between the barrier islands: the small Zuiderstortemelk-Vlielanderbalg system in the W, the huge NW-SE oriented Vliestroom and, near the coast of Terschelling, the small Boomkensdiep-Schuitengat (Figure 5.4.3). The latter system is decaying, which is also the reason that since 1996 this is no longer the access channel to the port of Terschelling. The Zeegat van het Vlie is one of the oldest systems mentioned by name: probably already in Roman literature, but certainly in 9th century sources when het Zeegat van het Vlie formed a major estuary connecting the staple-cities inland via the entrance to the open North Sea (Oost et al., in prep.).



1. Westergronden	7. Zuiderstortemelk	12. Slenk
2. Noordwestgronden	8. Vliestroom	13. Groote Plaat
3. Noordergronden	9. Boomkensdiep	14. Noordmeep
4. Gronden van het Stortemelk	10. Noordvaarder	15. Westmeep
5. Richel	11. Schuitengat	16. Grienderwaard
6. Vliesloot / Vlielanderbalg		17. Griend

Figure 5.4.3: Toponymes of the Zeegat van het Vlie; topography of 2010/2011 (Elias et al., 2015).

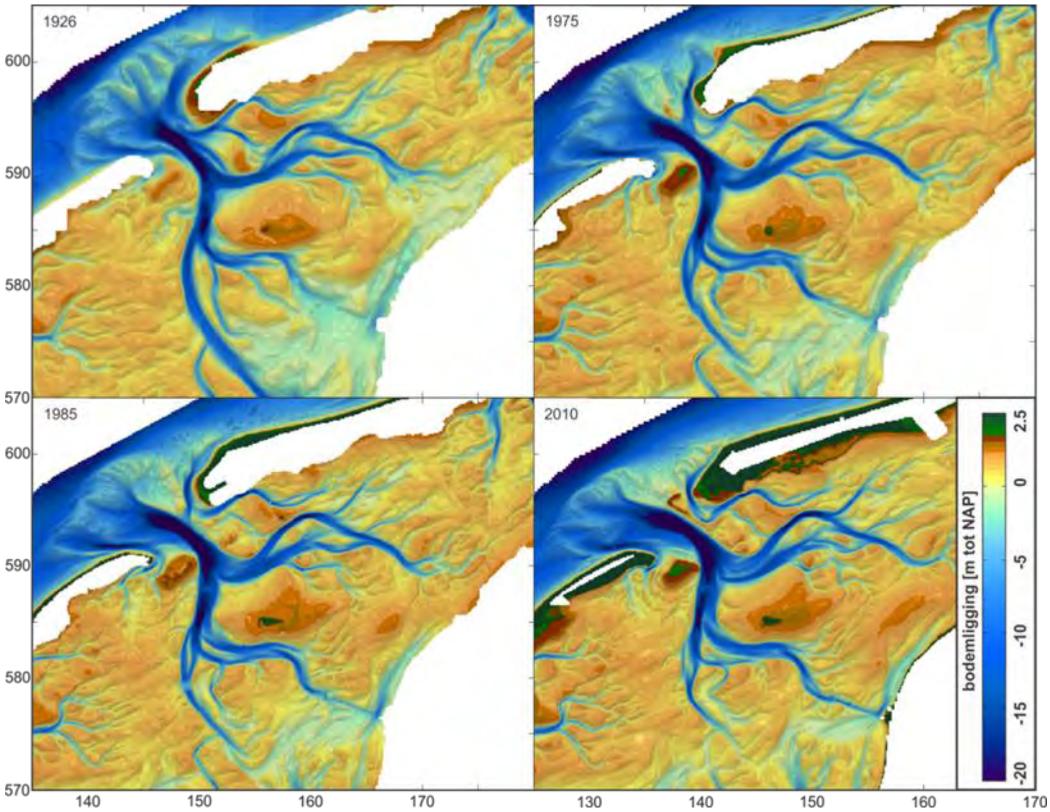


Figure 5.4.4: Large scale morphological development of the tidal inlet of the Vlie based on the depth soundings (Elias et al., 2015).

The main channel Vliestroom has shifted 2 km to the NE in the 19th century. Both West-Terschelling and East-Vlieland extended in that period, leading to a deepening of the channel Vliestroom. The developments continued in the 20th century, but at a slower pace: the main channel shifted some 0.2 km in the period 1904-1983 as the channel became some 40 m deep. It is believed that it became entrenched in the boulderclays, as the floor of the channel is covered with erratic stones (pers. obs). In the backbarrier area the Vliestroom separates into a southern branch (Vliestroom) and a northern branch (Westmeep and Noordmeep). These two channels are separated by high shoals of Griend and Grienderwaard. SE of Vlieland the shoal Richel is present.

Figure 5.4.4 gives an overview of the Zeegat van het Vlie over the period 1926-2010 (Elias et al., 2015). From 1932 onwards the closure of the Zuiderzee influenced the development of the back-barrier basin. Before the construction of the Afsluitdijk, the Zuiderzee was connected with the Vlie by the southern branch of the main channel. After closure the closed-off channels were filled in and strong sedimentation occurred along the coast of Friesland. In the period 1933-1975 the Vlielanderbalg and Vliesloot developed and became larger (Elias et al., 2015).

Elias et al. (2012) calculated that $219*10^6$ m^3 sediment was deposited in the backbarrier area of the Vlie over the period 1935-2005 (fixed borders, adjusted for dredging and dumping). A part of the sediment was supplied by the ebb-tidal delta of the Zeegat van het Vlie. It is also likely that another part of the sediment deposited in the backbarrier area was supplied through the adjacent tidal inlet system of Marsdiep, as can be judged from the eastward shift of the watershed between both systems. It might also account for the fact that coastal erosion around the ebb-tidal delta of Marsdiep was much larger than the deposition in its backbarrier area (the sediment has been transported and deposited out side of the backbarrier area considered; Elias et al., 2015).

Development of the ebb-tidal delta
The ebb-tidal delta has a size of about 8 km in seaward direction and 22 km in longitudinal direction (Elias et al., 2016). The biggest changes between the various depth maps are to be seen on the ebb-tidal delta shoals. In 1926 is the main part of the shoals were positioned NE and seaward of the Vliestroom. Nowadays, most of the shoal volume is located NW of the Vliestroom, far from the coast of Vlieland. The SW part of the ebb-tidal delta is relatively deep (Elias et al., 2016).

The ebb-tidal delta consists of smaller parallel located shoals and channels. The configuration is typical of the so-called ' shoal-bypassing ' sediment transport mechanism (Elias et al., 2016). On the ebb platform several smaller shoals are present which migrate in a NE direction. The outer side of the delta has been almost continuously eroding and a total of $125*10^6$ m^3 of sediment has been removed over the period 1935-2005 (fixed borders, adjusted for dredging and dumping; Elias et al., 2012). Despite this, the pattern of the channels and shoals over the last decades has been quite stable (Figure 5.4.5; Elias et al., 2015). The only exception is the Boomkensdiep: the channel was originally wider, shallower and was positioned further seaward on the delta.

After the closure of the Zuiderzee the mechanism of sediment bypassing probably changed as can be judged from the flattening of the shoals and channels on the ebb-tidal delta (Elias et al., 2016). Before the construction of the Afsluitdijk the orientation of the tidal inlet was in line with the direction of the tidal wave propagation direction (i.e. NE), with the Boomkensdiep as the main channel. The orientation of the outlet to the sea shifted in an upstream direction and the Zuiderstortemelk became more important (towards the SW), at the expense of the Boomkensdiep. This can be related to the change of main position of the backbarrier area, which shifted northward after the closure. The shift resulted in a more NW directed channel on the ebb-tidal delta (Figure 5.4.5). Another part of the explanation may lie in the change of the phase difference between tidal flow through the outlet to the sea and the tidal flow along coast. The construction of the Afsluitdijk created an amplificated tidal amplitude in the backbarrier basin and thus increased the tidal prism. However, sediment volume decreased on the ebb-tidal delta, probably due to the huge sediment demand of the backbarrier basin. The tidal discharges increased and the tidal flow through the inlet became more dominant with respect to the coast-parallel flow. According to the theory of Sha & Van Den Berg (1993) this would lead to an orientation against the tidal wave propagation direction, which was indeed observed (Elias et al., 2015).

During the ebb sediment is nowadays mainly deposited on the Westergronden and the Gronden van het Stortemelk (Elias et al., 2015). These two shoals now form the 'active' part of the ebb-tidal delta. The Noordwest-gronden have largely lost their function and are slowly “bulldozered” to the coast by wave action. In the process the Boomkensdiepwas gradually closed. A part of the Noordwestgronden builds a large shoal W of the channel; another part is migrating at the north side of Boomkensdiep in the form of small shoals which will likely merge with the northwest side of Terschelling (Elias et al., 2015).

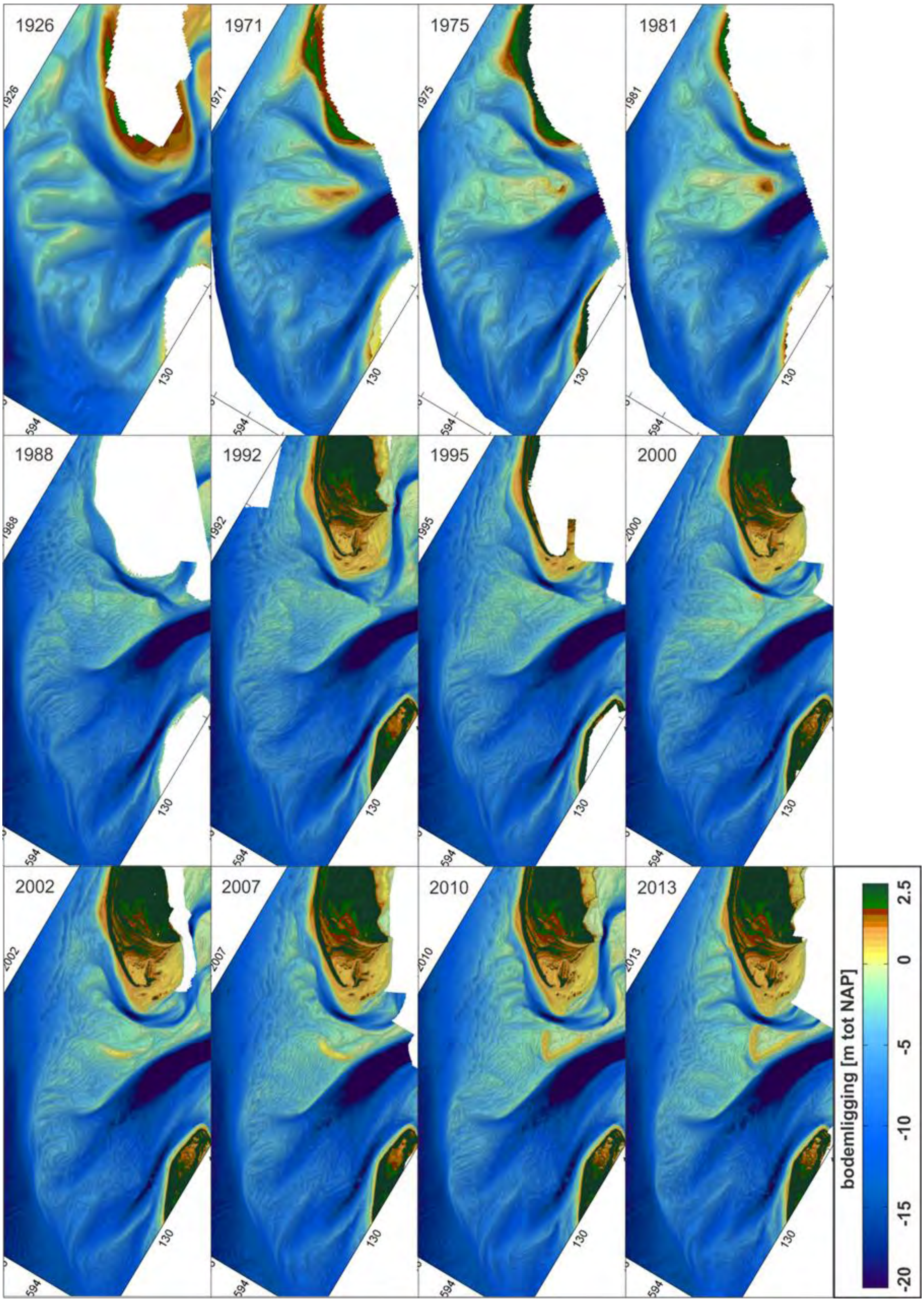


Figure 5.4.5: Development of the ebb-tidal delta of het Zeegat van het Vlie over the period 1925-2013. The islands are generated from the AHN (General Netherlands Height) file of the period 1996-2003; Elias et al., 2015).

North of the Vliestroom the ebb-tidal delta is dominated by redistribution and exchange of sand with the coast of Terschelling (Elias et al., 2015). The southern part of the ebb-tidal delta is dominated by channel development: both the Vliestroom and the Stortemelk have become larger and deeper. Seaward, in front of these channels an ebb-shield is building up to the W. The increase in volume, however, does not outweigh the losses at the Noorder- and Noordwestergronden (Elias et al., 2015).

Coastal development
Elias et al. (2012) calculated that $21*10^6$ m^3 sediment was eroded from the coasts of the islands adjacent to het Zeegat van het Vlie over the period 1935-2005 (fixed borders, adjusted for dredging and dumping). This has been attributed to the closure of the Zuiderzee and the resulting huge net sediment import into the backbarrier basin.

The development of East-Vlieland is largely determined by the interaction between the channels Vliesloot and Zuiderstortemelk. If the Vliesloot has a W-E orientation and connects to the Vliestroom there is space for island extension (e.g. period 1866-1913; Pluim & Misdorp, 1988; Elias et al., 2015). In such a configuration the Vliestroom forms the eastern boundary of the island and sediment is most likely transported to the N along this boundary. N of the island the flood-dominated Zuiderstortemelk brings in sediments to the ESE. The two sand influxes combined are apparently strong enough to allow the island tip to grow. Nevertheless, the island-tip changed from supratidal into intratidal in the period 1904-1918, where a new channel formed, connecting the Vliesloot to the Zuiderstortemelk (open sea) (Elias et al., 2015). From that moment onwards growth has more or less ceased and a series of dams was built around the eastern tip of the island, to counter landloss and slumping of the coast into the adjacent deep channel. Nowadays the entrance channel of the Vliesloot “clings” to the dams and the situation seems to be rather static. This was probably enhanced by the doubling of tidal prism flowing through the Vliesloot after the construction of the Afsluitdijk and closure of the Zuiderzee (Eysink & van Banning, 2005).

At the north side of Boomkensdiep small shoals travel eastward and will likely merge with the northwest side of Terschelling. Elias et al. (2015) state that though this will ensure sand deliverance to the island in the near feature, it is not certain that on the long term similar masses will be brought to the island due to the strong reduction in the ebb-tidal delta volume. Furthermore, there might be indications that there has been a shift in the merging location of shoals coming from the ebb-tidal delta of het Zeegat van het Vlie through time (observations Ridderinkhof, 2016). A large merger of a megashoal (de Noordsvaarder) occurred around 1865. The evolution of the MLW line suggests that around 1890, 1905, 1925, 1940, and 1955 shoals attached at beach km 47 and 48 of Terschelling. In 1965 attachment of a shoal affected the position of the MLW-line at beach km 45-47, whereas attachments in 1976, 1996 and 2012 occurred at each km 44 and 45. The development suggests a westward shift of the location at which shoals merge with the barrier coast. This was probably brought about by 1) the decrease in sand volume and landward retreat of the ebb-tidal delta; 2) the seaward extension of the main ebb-channel to the NW; and 3) the abandonment and closure at the north side of Boomkensdiep (Figure 5.4.5; Elias et al., 2015).

5.5 Borndiep (Ameland Inlet)

Basic data

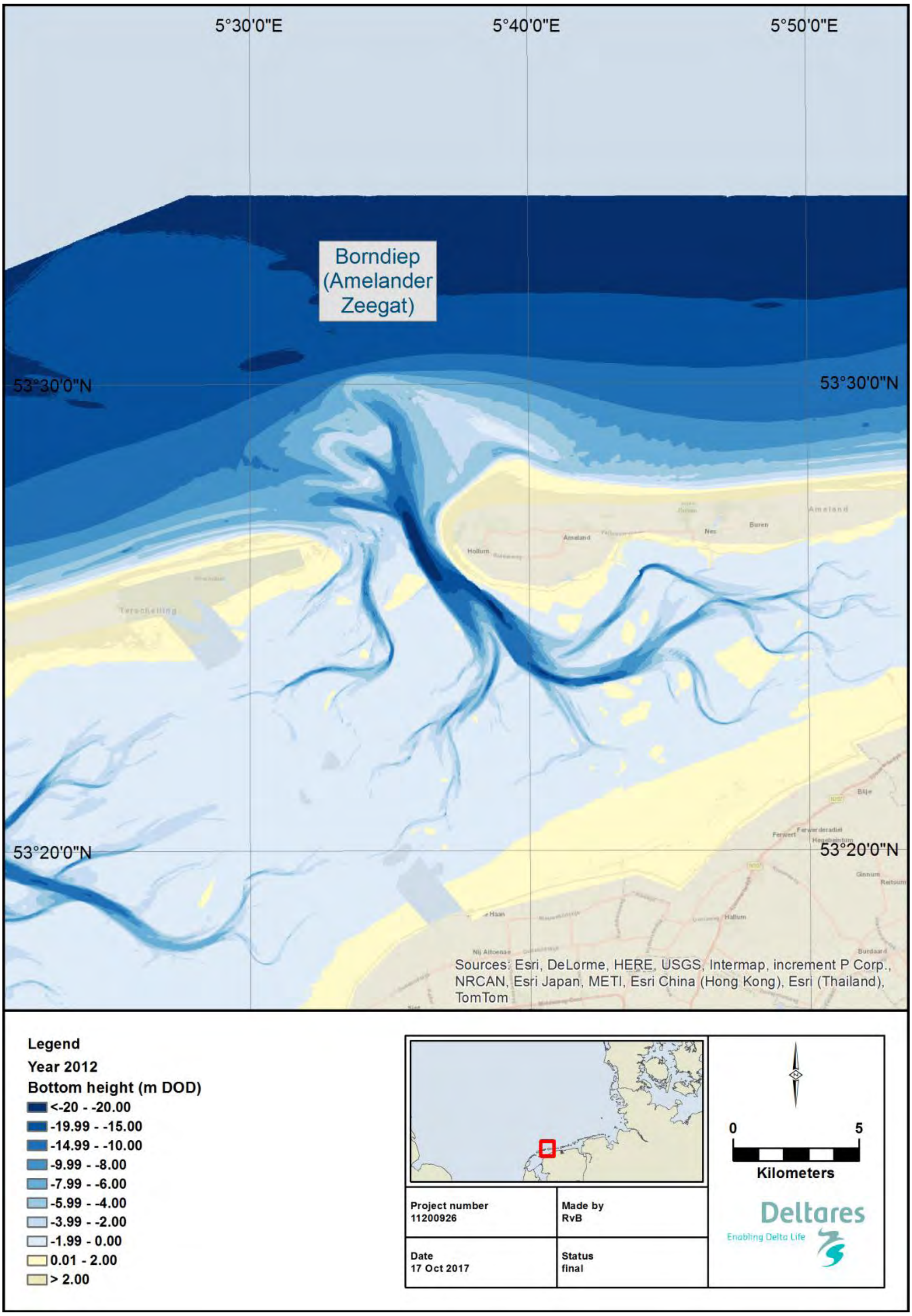


Figure 5.5.1: Overview of the ebb-tidal delta of Borndiep.

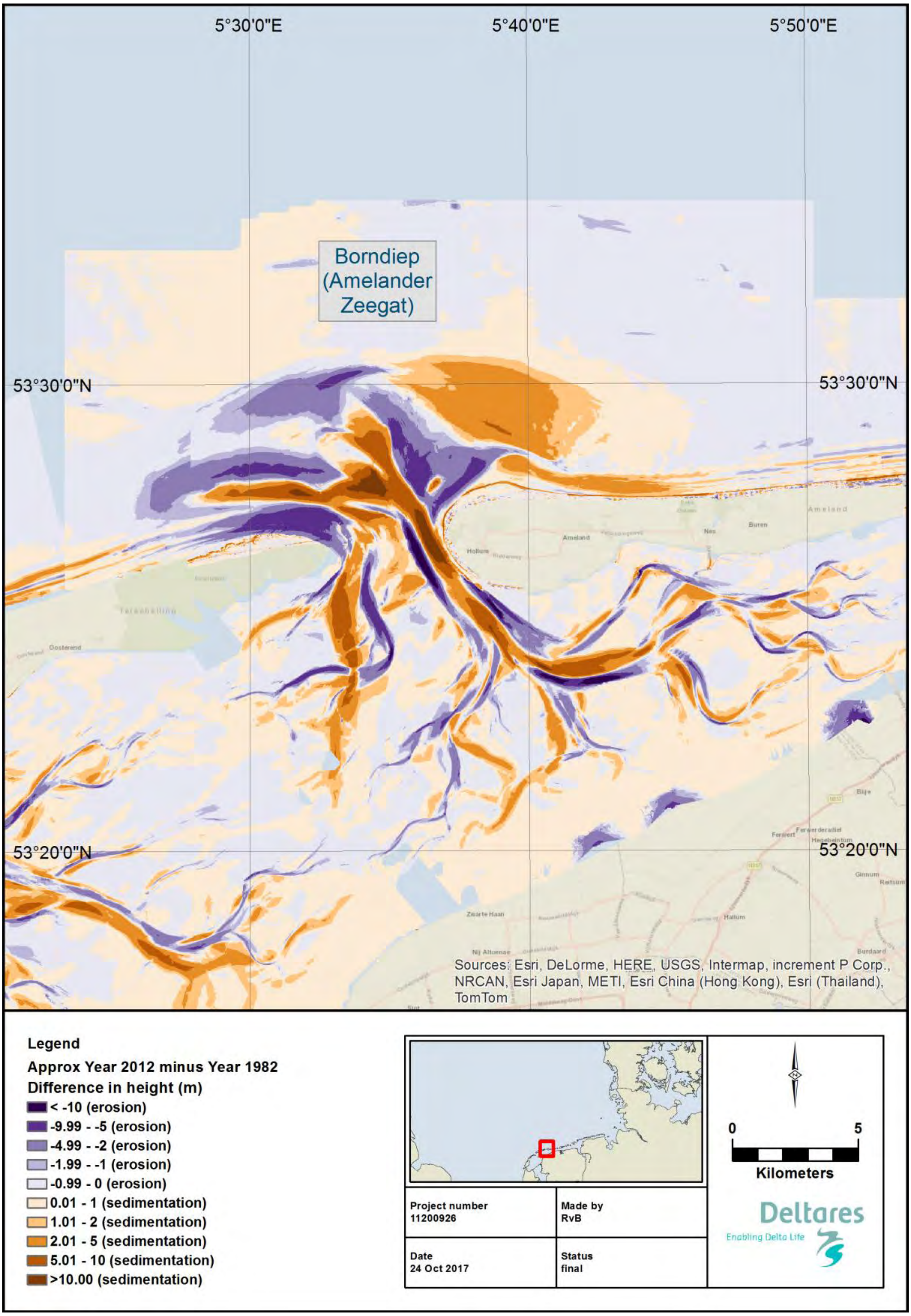


Figure 5.5.2: Overview of the ebb-tidal delta of Borndiep showing erosion and deposition over approximately the period 1982-2012.

Table 5.4: Facts and figures Borndiep (see also appendix I)

Parameter	Observ	Year	Reference	Observ	Year	Reference	Observ	Year	Reference
MSLR (mm/yr)	1.3	1890-2008	1 (station Harlingen)						
Hs (m)	1.36		CoastDat						
Tp (s)	5.89		CoastDat						
Tf/Te	0.89	2011 Slot-gemiddelde	2 (station Ter-schelling Noordzee)						
$L_{ebb-tidal\ delta}$ (km)	6.7	2012	-6 m	6.7	2012	-10m			
MHW (m AOD)	0.93	2011 slot-gemiddelde	2 (station Wierumer-gronden)						
MLW (m AOD)	-1.08	2011 slot-gemiddelde	2 (station Wierumer-gronden)						
MTR (m)	2.01 (1.61-2.28)	2011 slot-gemiddelde	2 (station Wierumer-gronden)						
Surge height (m to AOD)	100 y: 3.50	2011	2 (station Wierumer-gronden)	200 y: 3.70	2011	2 (station Wierum-er-gronden)0 (stati-on Wierumer-gronden)	500 y: 3.90	2011	2 (station Wierumer-gronden)
Mean annual max surge height (m to AOD)	2.44		CoastDat						
A_{MHW} (km^2)	284	1984	3						
A_{MLW} (km^2)	105	1984	3						
A_{cross} (m^2)	18570	1893	4	18350	1904	4	24170	1926	4
V_{MHW} (10^6 m^3)	790	1984	3						
V_{MLW} (10^6 m^3)	303	1984	3						
P (10^6 m^3)	430	1982	5	487	3	3 (Pbat)	383±74,5	2009-2010	6 (Pcom)
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebb-tidal\ delta}$ (10^6 m^3)	120.9	1982	7						
$AS_{backbarrier}$ (10^6 m^3/yr)	0.6	1935-1990	8	1.4	1990-2005	8			
$AS_{ebb-tidal\ delta}$ (10^6 m^3/yr)	0.7	1935-1990	8	-0.4	1990-2005	8			
AS_{coast} (10^6 m^3/yr)	0.9	1935-1990	8	0.7	1990-2005	8			
Longshore drift (10^6 m^3/yr)	1	1990-2012	9	+0.8 to +1.2	1990-2012	9 (Eierland & Schiermonnikoog)			
Sediment transport direction?	E-ward								
Development island coasts?	Sedimentatioin on NW-Ameland; Erosion Boschplaat Terschelling								

*1 = Dillingh et al., 2010 (lineair trend, corrected data); 2 = Dillingh, 2013; 3 = Biegel, 1992 (fixed tidal heights); 4 = Klein Wassink, 1991 (Adapted for A_{cross} under AOD: by adding inlet width*1 (=AOD-MLW)); 5 = Postma, 1982; 6 = Duran-Matute, 2014; 7= Eysink, 1993; 8 = Elias et al., 2012; 9 = Ridderinkhof, 2016.*

Description of the tidal inlet system

The Dutch inlet Borndiep is situated between the barrier island of Terschelling in the West and the island of Ameland (Figures 5.5.1-5.5.3). As many of the Wadden Sea inlet systems it consists of two separate channels. The westernmost one is the Bosgat/Blauwe Balg (or, incorrect: Koggediep, which disappeared upon the merger of the Boschplaat with the island of Terschelling). It is situated between the barrier island Terschelling and the shoal Koffiebonenplaat. To the east, between Koffiebonenplaat and the barrier island of Ameland lies the major inlet Borndiep proper. From the fact that in the 8th century the island Ameland was mentioned it can be judged that this is an old inlet. Indeed, the Borne river and the Borndiep formed a major border in Frisia, mentioned as early as the 9th century. Appearently inlets were present at approximately that position in front of the Borne river earlier, as can be concluded from 5000 year old ebb-tidal delta deposits in front of the present day ebb-tidal delta (so-called Vlakte van Ameland; Sha, 1990a, b).

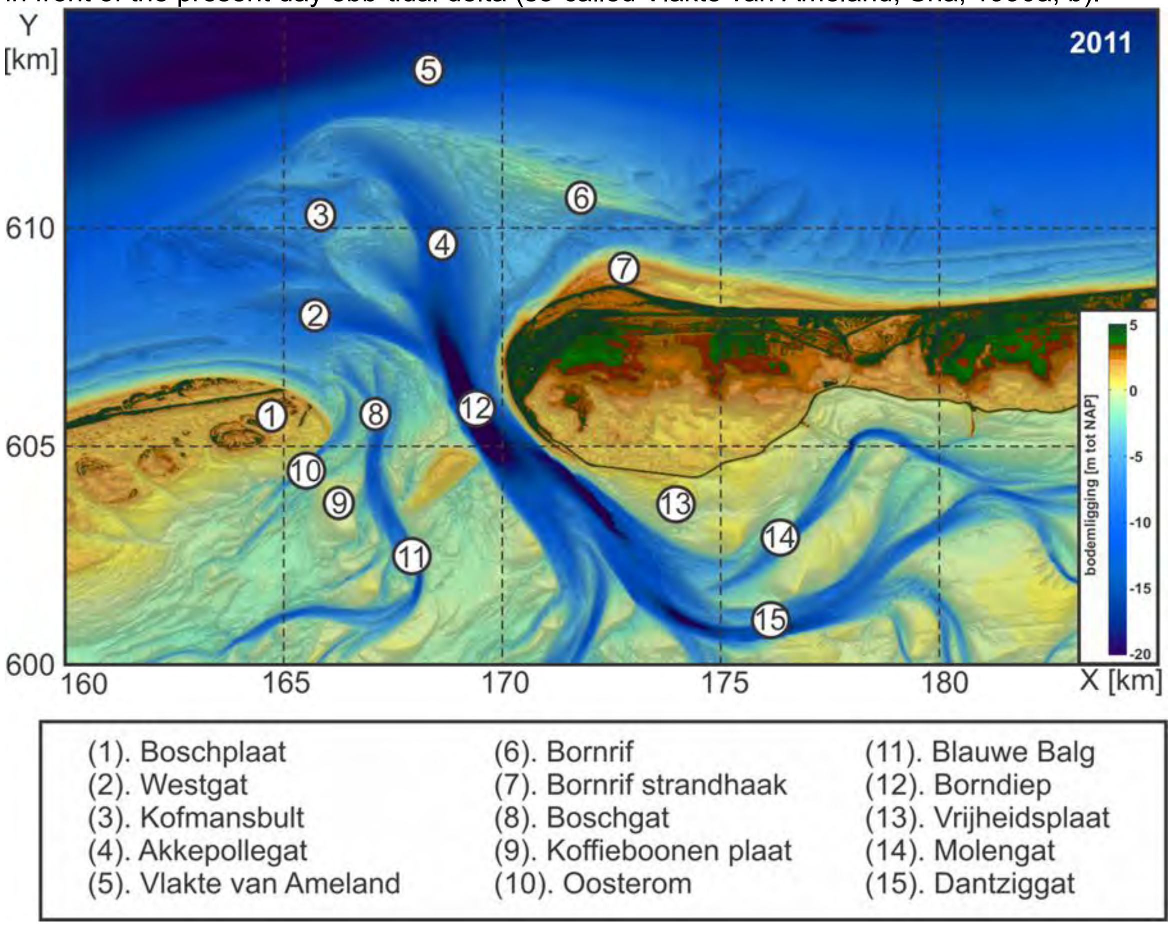


Figure 5.5.3: Toponymes of the Borndiep (Zeegat van Ameland) in 2011.

In the 10th century the 30 km long funnel-shaped embayment large inland embayment Middelzee was present (Figure 5.5.4; Van der Spek, 1994) and drained through the Ameland inlet, which, at that time, most likely consisted of two channels. Between the 10th and 13th century the Middelzee embayment had been largely filled up (Van der Spek, 1994), so that only a small bay remained around 1500 (Figure 5.5.4). The infill of the Middelzee led to a strong change in the configuration of the drainage area of Borndiep, from a N-S elongated basin to a rectangular basin, which was oriented in a W-E direction (Van der Spek, 1994). The change of basin configuration must have resulted in hydrographical changes, leading to the abandonment of the updrift channel and the eastward extension of East-Terschelling over 10.5 km. As a result the watershed S of Terschelling shifted considerably to the E. The changes occurred at a slow pace in the period 1500-1800. The drainage basin of the remaining inlet of the Ameland Inlet system was mainly positioned S of the island downdrift of it (Ameland) and the Borndiep became oriented towards that basin. A downdrift shift of the Borndiep resulted in the erosion of the western end of Ameland after 1800, mainly in the 20th century, which is thought to be also related to the closure of the Zuiderzee

(Figure 5.5.5). Erosion of SW-Ameland occurred especially during periods in which the main inlet channel was positioned to the NE (Oost, 1995). There is a striking similarity with the processes observed in the Harle and Lauwers inlets.

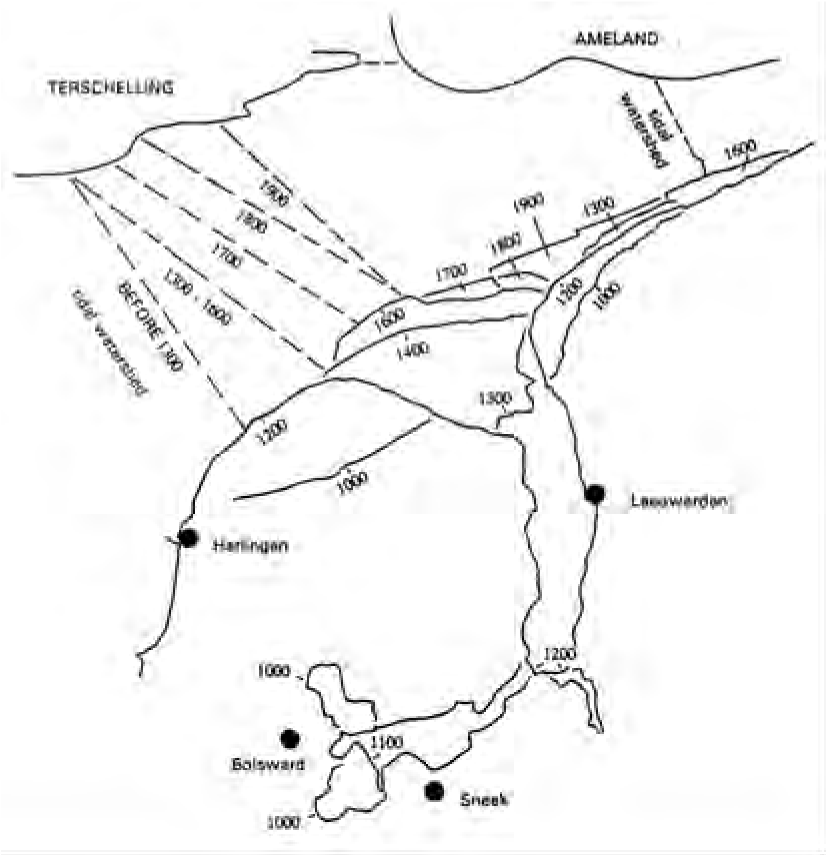


Figure 5.5.4: Poldering of the Middelzee and the shift of the watershed between het Zeegat van het Vlie en Borndiep (Van der Spek, 1994).

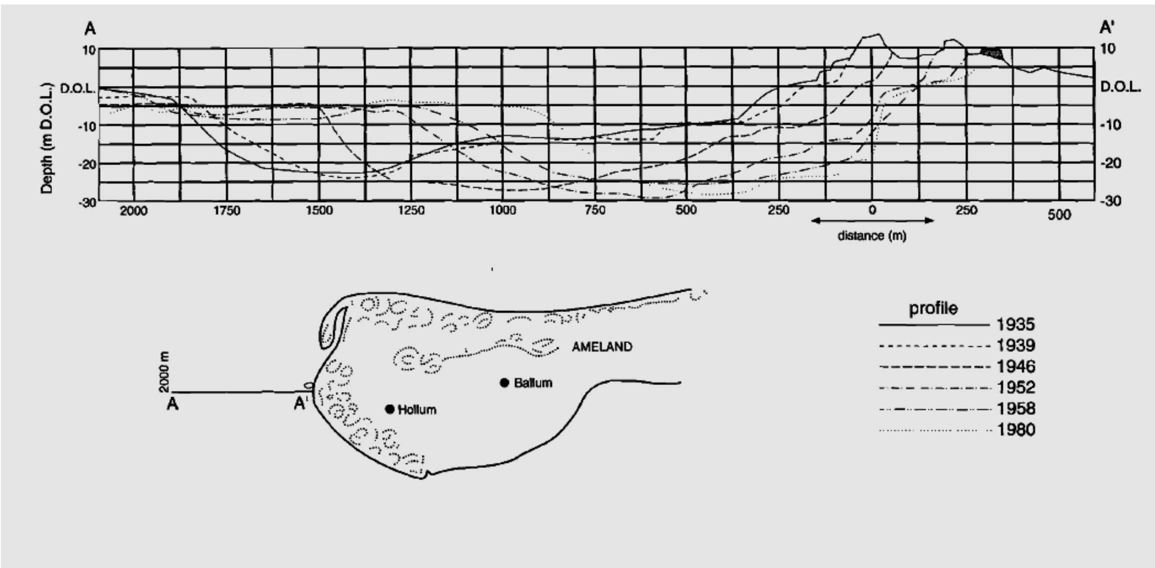


Figure 5.5.5: Shift of the gorge of Borndiep inlet (Oost, 1995).

The backbarrier area is nowadays by and large stable in position: the major channels in the Borndiep have not changed too much over the past two centuries although they have extended towards the E. Also, the sub-channels near the mainland have been silting up strongly due to decreasing tidal volumes, amongst others due to take-over by other channels and strong salt-marsh accretion at the mainland side. Elias et al. (2012) calculated that $56*10^6$ m^3 sediment was deposited in the backbarrier area over the period 1935-2005 (fixed borders, adjusted for dredging and dumping).

Development of the ebb-tidal delta

Elias et al. (2012) calculated that $34*10^6$ m^3 sediment was deposited on the ebb-tidal delta area over the period 1935-2005 (fixed borders, adjusted for dredging and dumping). Despite this and the strong shift of the inlet the ebb-tidal delta seems to have maintained a rather stable, cyclic geomorphological pattern (Elias & Bruens, 2013). Analysis of historical data for the period 1798 to 1999 suggests a cyclical behaviour, with a cycle length of 50-60 years (Van der Spek & Noorbergen, 1992; Israël, 1998; Israël & Dunsbergen, 1999; Cleveringa, 2001; Cheung et al. 2007). In it four characteristic stages can be distinguished (Figure 5.5.6; partly after Elias & Bruens, 2013):

- In phase 1 (Figure 5.5.6a), there is one dominant main channel between the islands which is connected to Westgat channel on the ebb-tidal delta and a slightly smaller sea-ward channel (Akkepollegat). The Boschplaat extends far eastward.

- In phase 2 (Figure 5.5.6b) a two-channel system starts to develops. The Boschgat migrates closer to the Boschplaat, but the Boschplaat can still extend further East.

- In phase 3 (Figure 5.5.6c) there are two channel systems. The Boschgat in the W is relatively small compared to the Borndiep. On the ebb-tidal delta the Akkepollegat becomes the main ebb-channel and orients perpendicular to the coast, while the Westgat is smaller. The Akkepollegat builds up an ebb-tidal delta lobe which becomes a hinder to the tidal flow which at a given moment shifts to the NW.

- This leads to phase 4 (Figure 5.5.6d) where the sand of the delta lobe is released and migrates to the downdrift island of Ameland. At the same time the changes in position lead to a reconnection of the Westgat which once more becomes the dominant ebb-tidal delta channel which results once more in a phase 1 situation.

Recently, Elias (2017) questioned the conceptual model as the return to phase 1 does currently not seem to occur. He concluded that it is likely that the trend of ongoing erosion of Boschplaat can be attributed to the position of the channels and shoals in the ebb-tidal delta due to which waves can influence the Boschgat more strongly than in previous situations and that this leads to loss of sediment. Model studies indicate that the sediment erodes from the eastern tip of the island and is transported via Boschgat into the Borndiep and subsequently out into the outer delta. Elias et al. (2012)

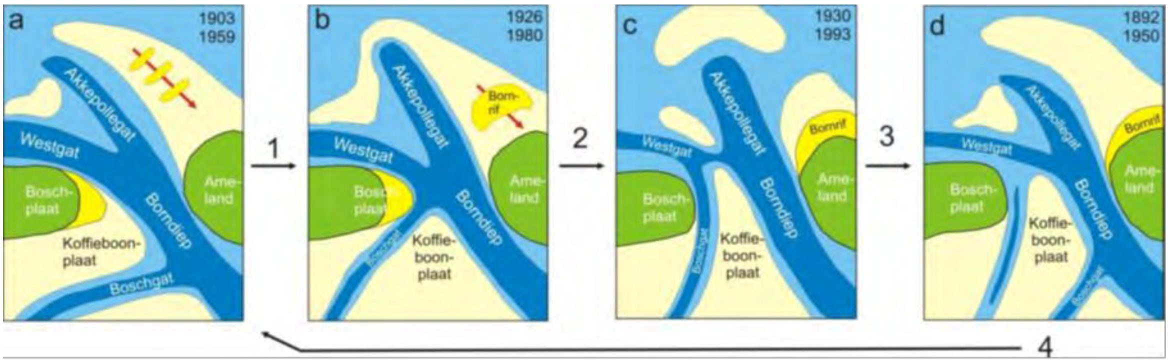


Figure 5.5.6: Cyclic development of the Borndiep tidal inlet (Israel & Dunsbergen, 1999).

In the period 1926-2011 there was a shift in the ebb-tidal delta towards the E (Figures 5.5.7 & 5.5.8)[3]. As tidal prism did not change much over this period, the explanation is not entirely clear, but might well be related to the eastward shift of the main channel.

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[3] *It should be noted that in Figure 5.5.7 a complete cycle (1926-1980) is largely missing.*

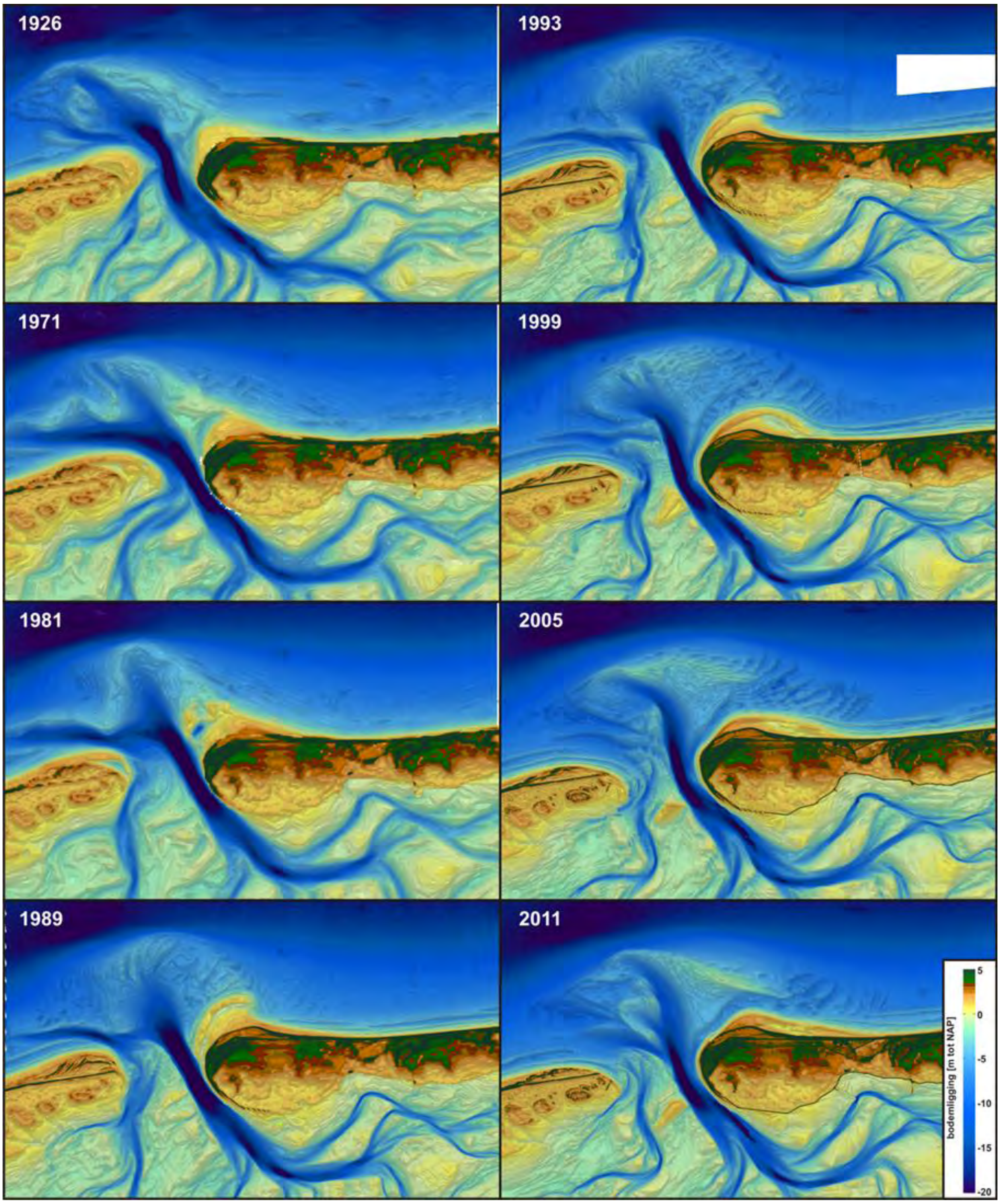


Figure 5.5.7: The morphological development of the Bornrif ebb-tidal delta over the period 1926-2011. Islands are given on basis of AHN (General Netherlands Height file with data from the period 1996-2003) (Elias & Bruens, 2013).

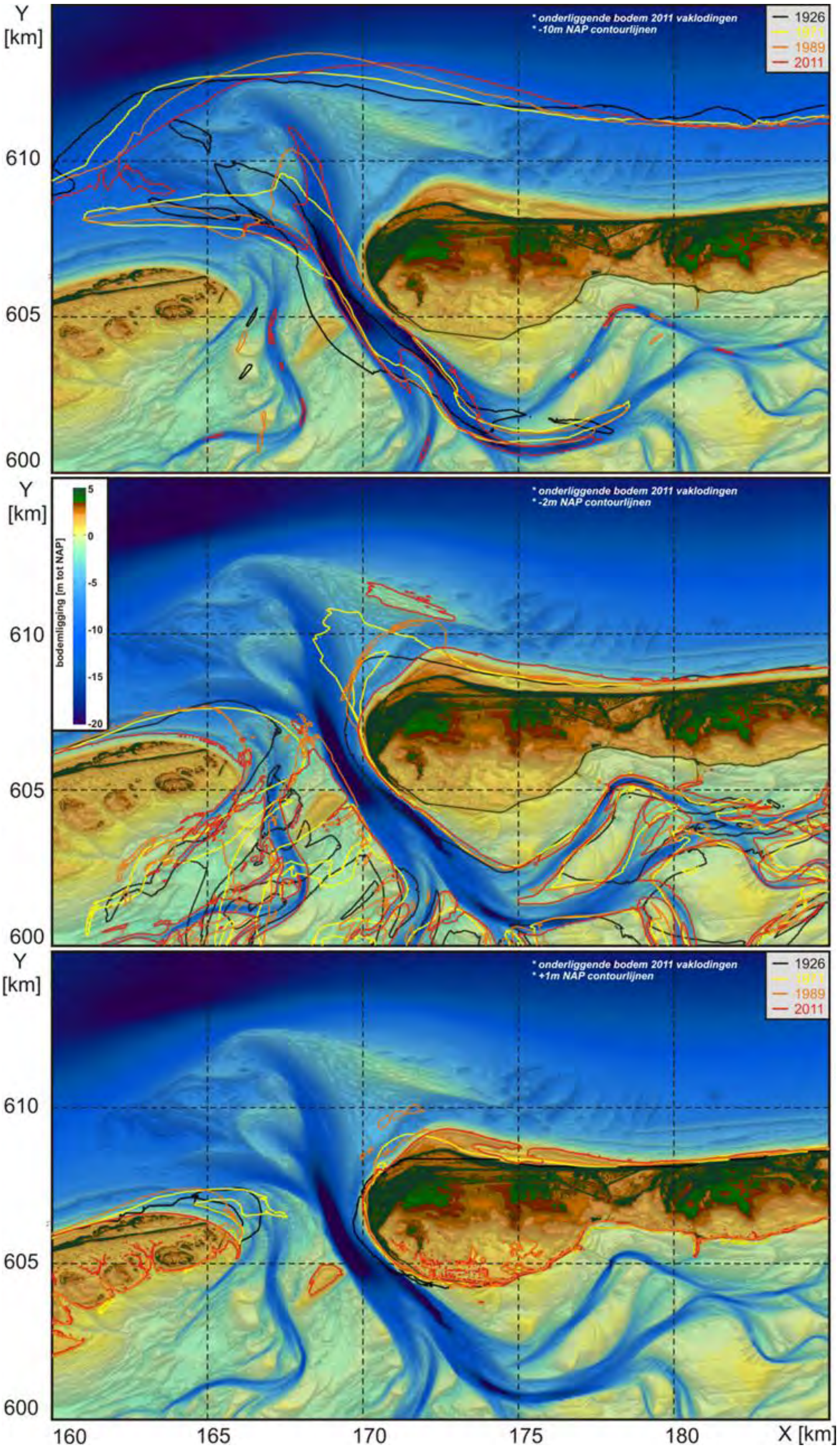


Figure 5.5.8: Morphological development of the ebb-tidal delta of Borndiep shown by selected contour lines (top to bottom): AOD -10 m AOD (representative for the main channels), AOD 2 m (just below the low-water line) and AOD + 1 m (high water mark) (Elias & Bruens, 2013).

Coastal development

The coast of Terschelling expanded far towards the east in 1965. Thereafter erosion dominated and the coast retreated over some 2 km (Figure 5.5.9). The explanation is discussed in the chapter on the inlet.

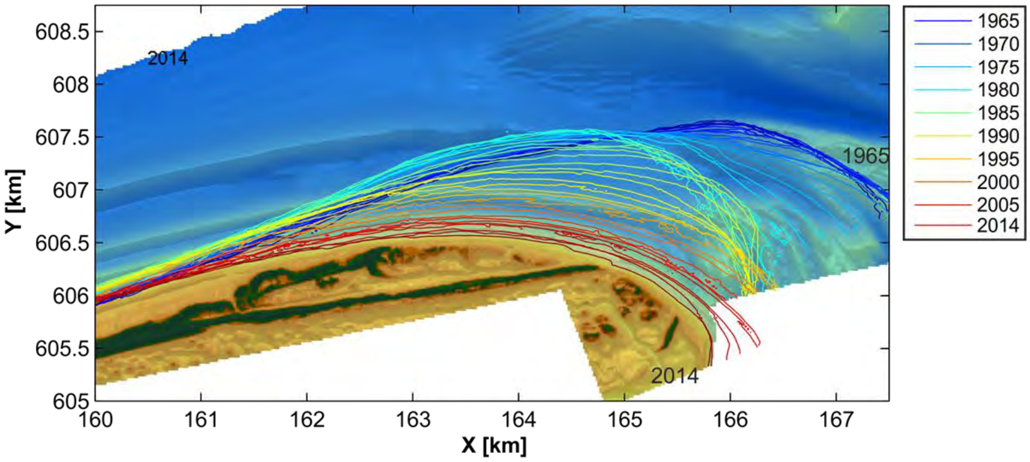


Figure 5.5.9: Retreat of MHW line of E-Terschelling (Elias & Bruens, 2013).

The largest platform area of the ebb-tidal delta is located NE of the main channel (Elias & Bruens, 2013). Periodically the landing of sand shoals leads to strong sedimentation at the coast of Ameland, which as a result builds out at its northnorthwest side (Ridderinkhof, 2016). An example of this is the formation and merger of the Bornrif shoal which influences the development of the coast already for decades. In Figure 5.5.10 the merger and deformation of the Bornrif shoal can be followed through time (Elias & Bruens, 2013). The initial landing resulted in a large, almost instantaneous, seaward expansion of the coastline (Figure 5.5.10, 1980-1985). The shoal was then smeared out in the form of a spit in the form of a hook along the coast, with a fast extension of the eastern point of the shoal to the SE (Figure 5.5.10, 1989-1995). The NW edge was eroded and moved in the direction of the coast feeding the coast which up to 1989 builds out strongly. Thereafter erosion dominated at that side as is evident from the period 1989-1995. The landed shoal developed into a semicircle in the period 1989-1998. Around 1998 the E tip of it contacted the beach and a long, drawn-out sand hook stretched along the coast over about 8 km. In between the shoal and the dunes there was a sub- to intertidal bay which was fed through a small channel. The channel paralleled (1997-1999) the coast for several km and started to meander and erode the dunes at two places (Oost, 2000a&b). After 2000 a short-circuit channel cut through the spit and the original channel becomes abandoned. The small bay has been filled by mud and washover sands. Small dunes which formed over the years were occupied by a mixture of tidal marsh and freshwater vegetation. After the strong development this part of the coast is now expected to erode gradually in the coming years to decades.

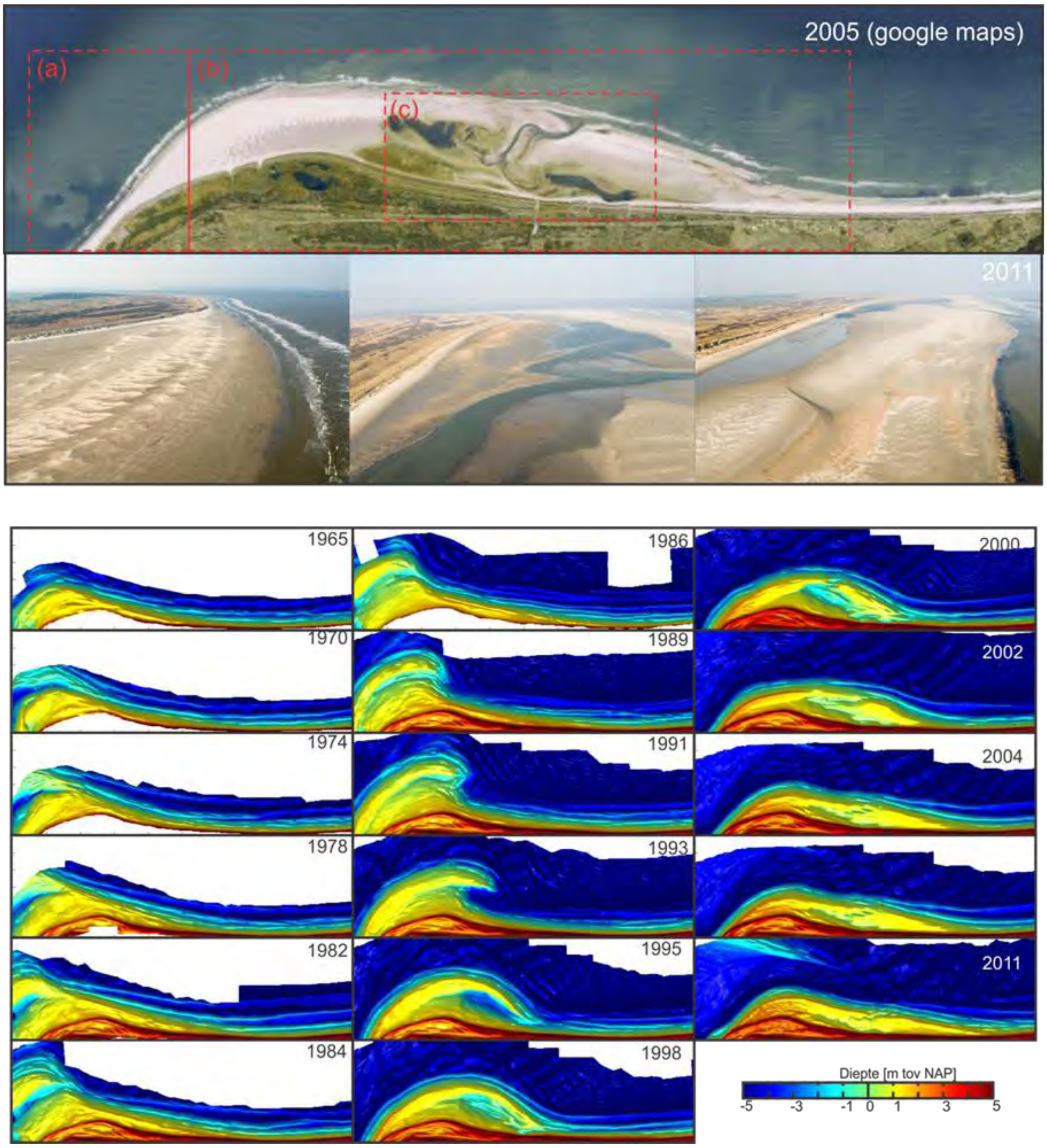


Figure 5.5.10: Bornrif sand hook: Development based on the JarKus measurements period 1965-2011 and (top) situation of 2005 (Elias & Bruens, 2013).

5.6 Het Friesche Zeegat: Pinkegat

General introduction

The inlet het Friesche Zeegat consists of two inlet systems which are separated by an early Holocene clay core of the shoal Engelsmanplaat (Figure 5.6.1; Oost, 1995): the small Pinkegat in the W and the bigger Zoutkamperlaag in the E. As the inlet is often considered to actually consist of two separate inlets, these will be discussed separately below. Before that a general overview is given of het Friesche Zeegat.

Around 1300 there was probably only one small inlet system “Scholbalg” which may have been situated W or E of Engelsmanplaat; a situation which may have existed up to the second half of the 15th century. Het Zeegat van de Lauwers, which originally drained the Lauwerszee, lost its connection to the embayment around 1550-1580 (Oost, 1995). By 1580 the inlet system of Scholbalg had taken over. Later the name of the inlet changed into Zoutkamperlaag. In the period of 1530 (or earlier) to 1600 significant land loss at the west side of Schiermonnikoog occurred. Around 1550 the position of the HW-line was still at least some 2.5 km more to the W than at present. After establishment of connection to the Lauwerszee, the HW-line at the eastern end of Schiermonnikoog migrated more than 6 km eastward in the period 1550-1975, especially after 1700 AD.

Between the island Ameland and the shoal Engelsmanplaat a small inlet system Pinkegat/Holwerderbalg can be observed on maps from the mid-16th century onwards. The ebb-tidal delta of the Pinkegat is small compared to the large ebb-tidal delta of the Schulbalg/Zoutkamperlaag, which, with exception of its west side, totally surrounds it. As a result, the two ebb-tidal deltas influence each other. During a phase that one of the main channels of the Pinkegat is oriented to the NE, sediment is delivered during the ebb into the marginal ebb-tidal delta channels of the Zoutkamperlaag, forcing them to migrate to the N. In the backbarrier area there is hardly any interaction between the two systems, due to the separation by the large Engelsmanplaat shoal and the watershed S of it. This is illustrated by the fact that after the closure of the Lauwerszee embayment in 1969, especially the Zoutkamperlaag system, which was connected to it, responded with morphological change. Sedimentary development of the Pinkegat did not change out side its observed behaviour during the past 2 centuries (see below).

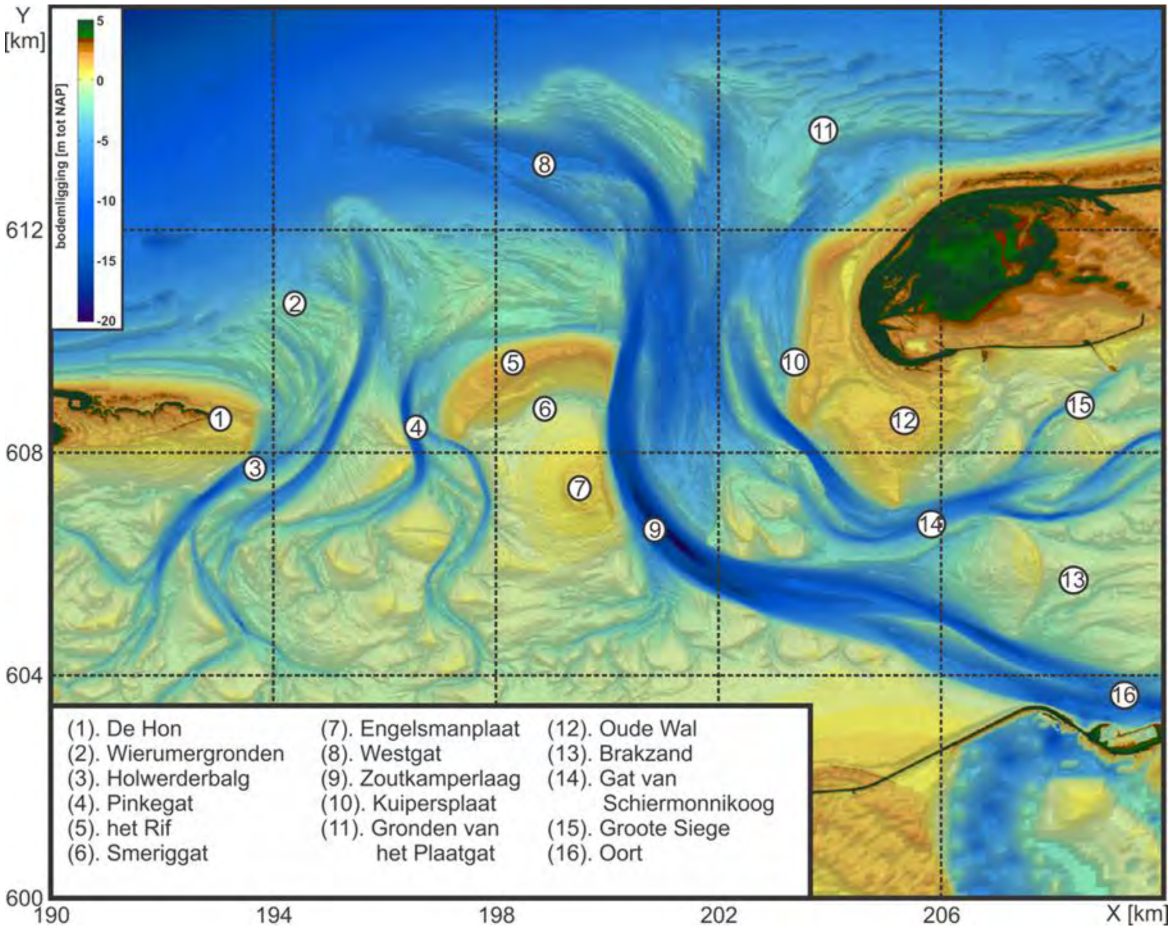


Figure 5.6.1 : Toponymes of het Friesche Zeegat (Oost & Bruens, 2013).

Basic data

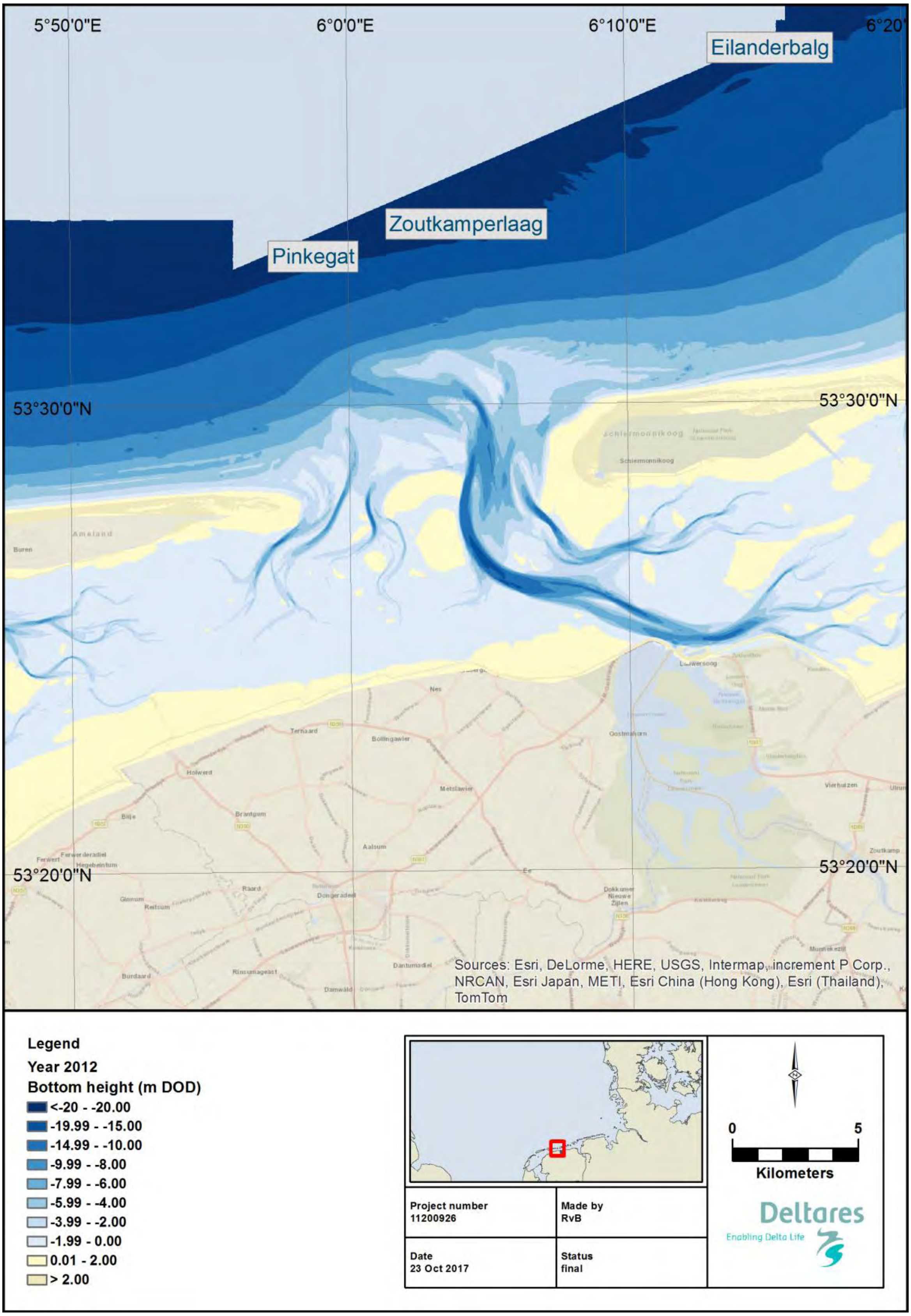


Figure 5.6.2: Overview of the ebb-tidal deltas of Pinkegat & Zoutkamperlaag

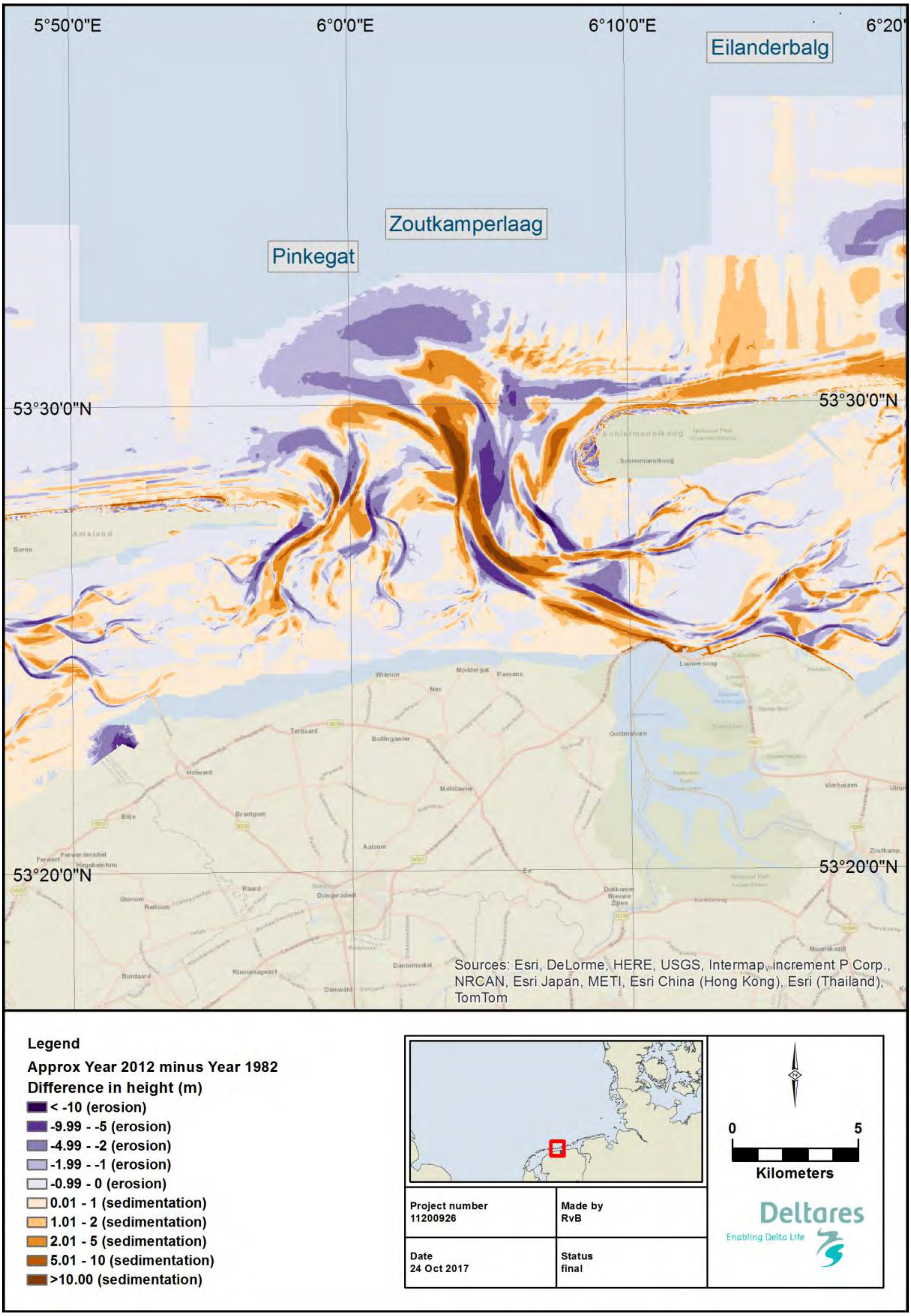


Figure 5.6.3: Overview of the ebb-tidal deltas of Pinkegat & Zoutkamperlaag showing erosion and deposition over approximately the period 1982-2012.

Table 5.5: Facts and figures Pinkegat (see also appendix I)

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)						
Hs (m)	1.25		CoastDat						
Tp (s).	5.93		CoastDat						
Tf/Te	0.93	2011 Slot-gemiddelde	1 (station Wierumer-gronden)						
$L_{ebb-tidal\ delta}$ (km)	4	2012	-6 m	4.5	2012	-10m			
MHW (m AOD)	0.93	2011 slot-gemiddelde	2 (station Wierumer-gronden)						
MLW (m AOD)	-1.08	2011 slot-gemiddelde	2 (station Wierumer-gronden)						
MTR (m)	2.01 (1.61-2.28)	2011 slot-gemiddelde	2 (station Wierumer-gronden)						
Surge height (m to AOD)	100 y: 350	2011	2 (station Wierumer-gronden)	200 y: 370	2011	2 (station Wierumer-gronden)	500 y: 390	2011	2 (station Wierumer-gronden)
Mean annual max surge height (m to AOD)	2.53		CoastDat						
A_{MHW} (km^2)	55.3	1959	3	65	Ca. 1982	4			
A_{MLW} (km^2)	16.4	1959	3	23	Ca. 1982	4			
A_{cross} (m^2)									
V_{MHW} (10^6 m^3)	116	1959	3	100	1982	4			
V_{MLW} (10^6 m^3)	24.3	1959	3	20	1982	Estimate based on 5 and 3			
P (10^6 m^3)	103	1937/1939	5 (Pbat)	91.7	1957	3 (Pbat)	100	1982	3
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebb-tidal\ delta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	-0.4	1978-1981	6	+5.5	1981-1987	6			
$AS_{ebb-tidal\ delta}$ (10^6 m^3/yr))	+0.6	1979-1982	6	-0.4	1982-1987	6			
Longshore drift (10^6 m^3/yr)	+1.4	1990-2012	(station Schiermonnikoog						
Sediment transport direc-tion?	To the E								
Development island coasts	Growth of East Ameland								

1 = Dillingh et al. 2009; 2 = Dillingh, 2013; 3 = Biegel, 1992 (Tidal heights are fixed);4 = Louters & Gerritsen, 1994; 5 = RWS, 1941; 6 = Oost, 1995 (incl. dredging and dumping; basin and ebb-tidal delta area differs before and after 1970/1971); 7 = Ridderinkhof, 2016.

Description of the tidal inlet system

The Pinkegat probably came into existence somewhere between 1480 and 1550 (see Oost, 1995). In the backbarrier area the system is draining the area between the watershed of Ameland and the watershed of Engelsmanplaat (Figures 5.6.1-5.6.3). After 1800, an eastward shift of the watershed S of Ameland occurred over some 2.8 km, which can be mainly attributed to the strong shift of the large Borndiep system, W of it. As a result, a net downdrift, eastward shift of the Pinkegat Inlet system occurred. The 1.6 km eastward shift of the watershed in the period 1923-1950 is most likely also the major explanation why the Ameland backbarrier area undergoes an erosion of $22*10^6$ m^3 in the period 1926-1950, whereas the Pinkegat backbarrier area shows a sedimentation of $24.5*10^6$ m^3 in the period 1927-1949 (fixed borders used).

Due to the cyclic behaviour of the inlet itself (see below) the channels connecting the various parts of the backbarrier area and the shifting inlet channel positions continuously shift their positions. As a result a large part of the backbarrier area is “ploughed” by the shifting channels. Due to the fact that there are several inlet channels at some times and only one major inlet at other moments, one might expect changes in the tidal volume of the backbarrier basin, due to lower, respectively higher intertidal area. Indeed in the years 1971 and 1987, when a (near) single inlet phase exists, the tidal flat area was some 5 km^2 larger than in the years 1978 and 1981 on a total basin area of 53.1 km^2.

Sedimentation in the backbarrier area amounted to some $37.8*10^6$ m^3 in the period 1927-1967 and some $10.9*10^6$ m^3 in the period 1967-1987. Averaged over the whole period 1927-1987 the sedimentation rate was some 14 mm/yr, which on first sight is much more than the average SLR (1.9 mm/yr). The large part can be attributed to shifts of the tidal watershed. Another part may be due to the sedimentation and seaward extension of the tidal marshes near the mainland.

Development of the ebb-tidal delta

The scarce data suggest that the inlet developed cyclically from a single inlet into a multiple inlet, and back again since at least 1600. Figure 5.6.4 shows a conceptual view of the cyclical development. From data since 1832 it is clear that the cycle covers a period of 20 years to, at maximum, 54 (but more likely 41) years (Oost, 1995). When the position of a single inlet becomes hydraulically less efficient, because it is positioned too far downdrift (to the E), new inlets evolve, which, during storm surges, tend to breach through the sandy shoals that form the eastern end of the updrift island Ameland (Figure 5.6.5; compare Van Veen, 1936). These new, small western inlets migrate rapidly downdrift (several 100’s m/yr) and increase in dimensions, while taking over an increasing portion of the tidal prism. As a result, the eastern inlets decrease in dimensions and migrate more slowly and finally are abandoned. By merger of channels and abandonment of others a single inlet with maximum dimensions once again forms. The process is driven by downdrift supply of sediment along Ameland, the tidal forces, and by the local wave climate (which builds up shoals). The strong curvature of the inlet, partly due to the fact that it drains a drainage basin S to SE of Ameland and the erosion in the outer bend further enhance strong lateral migration of the inlets.

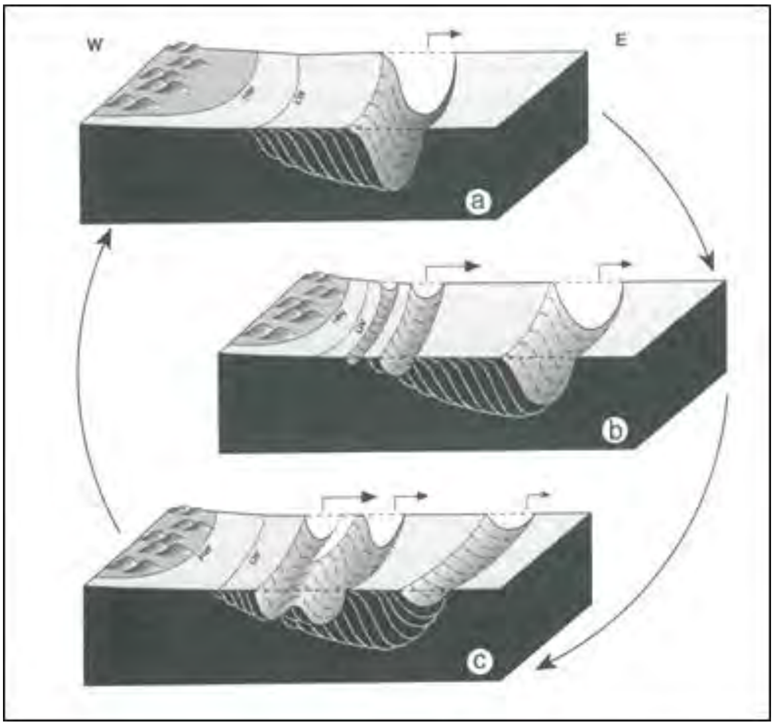


Figure 5.6.4: Conceptual model of cyclic morphological development of the Pinkegat (Oost, 1995).

On the ebb-tidal delta alternating slight erosion and sedimentation (<$1*10^6$ m^3/yr) from 1927 to 1987 led to a net sedimentation of $0.4*10^6$ m^3 in the period 1927-1970, and some $6*10^6$ m^3 in the period 1970-1987 (fixed borders, corrected for dredging and dumping). It also forms additional proof that the strong sedimentation observed in the backbarrier area cannot be attributed to transport via the inlet: given the relative small coast-parallel transports such a transport should have led to erosion of the ebb-tidal delta.

Coastal development

The cyclic extension and cut off of the eastern tip of Ameland is part of the cyclic development of the inlet of Pinkegat (Figure 5.6.4 & 5.6.5). In the process the island can extent over several km eastward before it retreats again. On top of this cyclical behaviour also a net eastward extension occurred since 1800, which was probably due to the E-ward shift of the watershed of Ameland, because the Borndiep shifted E ward, forcing the Pinkegat to shift eastward (Oost, 1995).

In the cyclic development of the ebb-tidal delta of the Pinkegat inlet shoals migrate downdrift, and accumulate seaward of the Engelsmanplaat. In the period 1967-2012 attachments of shoals were observed in 1975, 1987, 1994, and 2002; Ridderinkhof, 2016). As a result the Rif shoal could develop and increase in size. It should be noticed that such a build-up is part of a cyclic pattern (50-90 yrs), since at least 1796 (but probably during the past 5 centuries): The Engelsmanplaat increases in surface area and height as soon as a shoal in the north amalgamates with it, thereby closing the channel between them. Subsequently, the enlarged Engelsmanplaat is eroded at its north side by the forming of a channel and becomes smaller. North of the channel a new shoal is formed, and the Engelsmanplaat decreases in size, and becomes lower (see also De Haan et al., 1983).

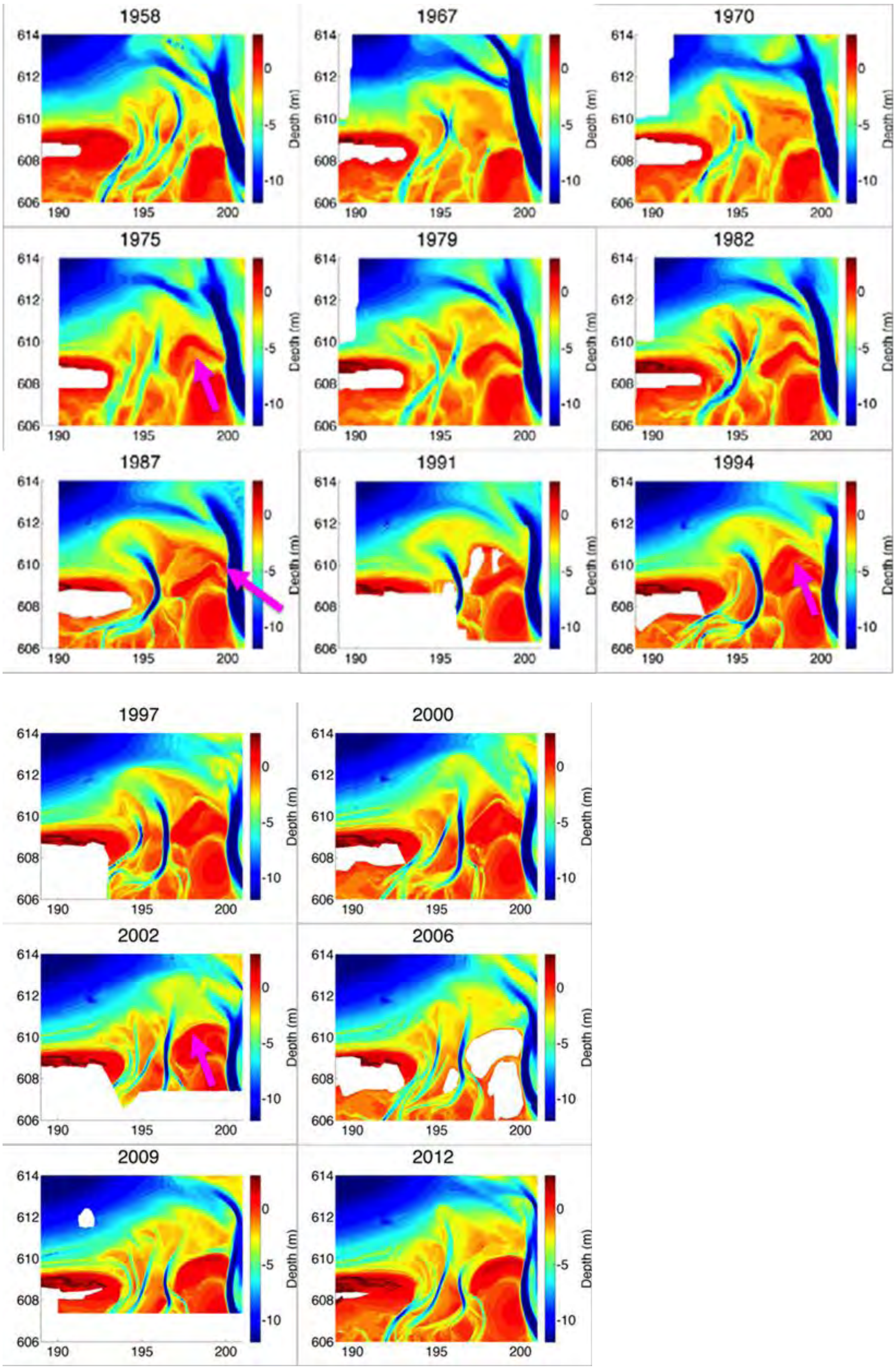


Figure 5.6.5: Development of the Pinkegat ebb-tidal delta on the basis of depth soundings. Arrows points out merger of shoals (Ridderinkhof, 2016).

5.7 Het Friesche Zeegat: De Zoutkamperlaag

Basic data

See figures 5.6.1 to 5.6.3.

Table 5.6 : Facts and figures de Zoutkamperlaag (see also appendix I)

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)						
Hs (m)	1.22		CoastDat						
Tp (s).	5.98		CoastDat						
Tf/Te	0.93	2011 Slot-gemiddelde	2 (station Wierumer-gronden)						
$L_{ebb-tidal\ delta}$ (km)	5.5	2012	-6 m	7	2012	-10m			
MHW (m AOD)	0.93	2011 slot-gemiddelde	2 (station Wierumer-gronden)						
MLW (m AOD)	-1.08	2011 slot-gemiddelde	2 (station Wierumer-gronden)						
HWS (m AOD)	1.05	2011 slot-gemiddelde	2 (station Wierumer-gronden)						
LWS (m AOD)	-1.23	2011 slot-gemiddelde	2 (station Wierumer-gronden)						
HWN (m AOD)	0.73	2011 slot-gemiddelde	2 (station Wierumer-gronden)						
LWN (m AOD)	-0.88	2011 slot-gemiddelde	2 (station Wierumer-gronden)						
MTR (m)	2.01 (1.61-2.28)	2011 slot-gemiddelde	2 (station Wierumer-gronden)	2.2	1982	1			
Surge height (m to MSL)	100 y: 350	2011	2 (station Wierumer-gronden)	200 y: 370	20117	2 (station Wierumer-gronden)	500 y: 390	2011	2 (station Wierumer-gronden)
Mean annual max surge height (m to AOD)	2.55		CoastDat						
A_{MHW} (km^2)	195	1957	3 Excl Lauwer-szee	130	Ca. 1982	4			
A_{MLW} (km^2)	61.7	1957	3 Excl Lauwer-szee	48	Ca 1982	4			
A_{cross} (m^2)	15240	1975	5	13875	1981	5			
V_{MHW} ($10^6 m^3$)	349	1981	6						
V_{MLW} ($10^6 m^3$)	156	1981	6						
P ($10^6 m^3$)	187	1975	6 (Pbat)	151	1981	5 (Pdis)	193	1981	6 (Pbat)
$SV_{backbarrier}$ ($10^6 m^3$)									
$SV_{ebb-tidal\ delta}$ ($10^6 m^3$)									
$AS_{backbarrier}$ ($10^6 m^3/yr$)	+41.4	1979-1982	7	+0.8	1982-1987	7			
$AS_{ebb-tidal\ delta}$ ($10^6 m^3/yr$)	-3.3	1979-1982	7	-1.3	1982-1987	7			
Longshore drift ($10^6 m^3/yr$)	+1.4	1990-2012	8 (station Schier-monnikoog)	+1.4	1990-2012				
Sediment transport direc-tion?	E ward								

Development island coasts	Growth and erosion of NW Schiermonnikoog							

1 = Dillingh et al. 2009; 2 = Dillingh, 2013; 3 = Biegel, 1992 (Tidal heights are fixed);4 = Louters & Gerritsen, 1994; 5 = RWS, 1986; 6 = Biegel, 1992 (tidal heights fixed); 7 = Oost, 1995 (incl. dredging and dumping; basin and ebb-tidal delta area differs before and after 1970/1971); 8 = Ridderinkhof, 2016.

Description of the tidal inlet system

The inlet Zoutkamperlaag is situated between the shoal Engelsmanplaat to the W and the barrier island of Schiermonnikoog (Figures 5.6.1 to 5.6.3). From the historical data it is inferred that around 1300 the Zoutkamperlaag Inlet system was rather small, and had no or only a limited connection to the Lauwerszee (Oost, 1995). As such it may have had a prism comparable to the Pinkegat nowadays, of the order of 100*10^6 m^3. After 1300 the Zoutkamperlaag started to take over the drainage of the Lauwerszee from the inlet Zeegat van de Lauwers, E of it. Around 1500 both inlets together provided the drainage. By 1570 the Lauwerszee was drained mainly by the Zoutkamperlaag. Around that time the inlet may have reached its greatest dimensions, with a tidal prism of the order of 400*10^6 m^3 (Figure 5.7.1; Oost, 1995; Biegel & Hoekstra, 1995).

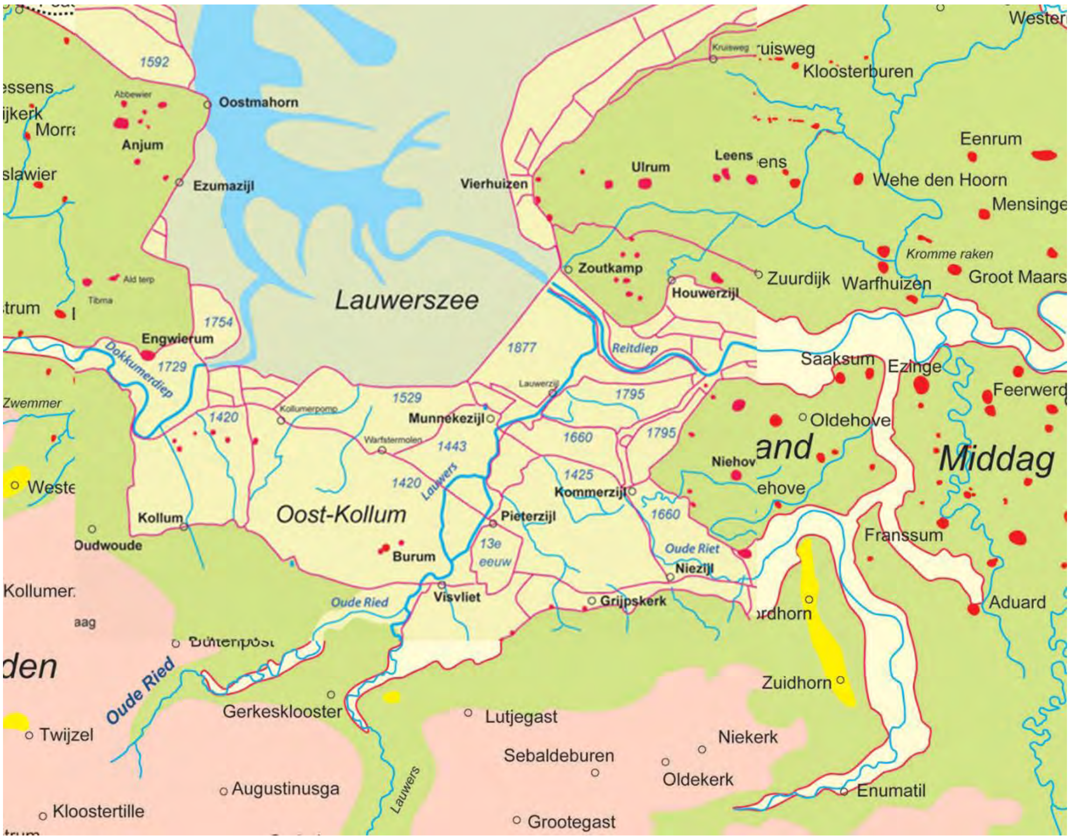


Figure 5.7.1: Overview of the diking of the Lauwerszee area, dark line gives maximum extent. After: http://landschapsgeschiedenis.nl/deelgebieden/6-Lauwersland.html

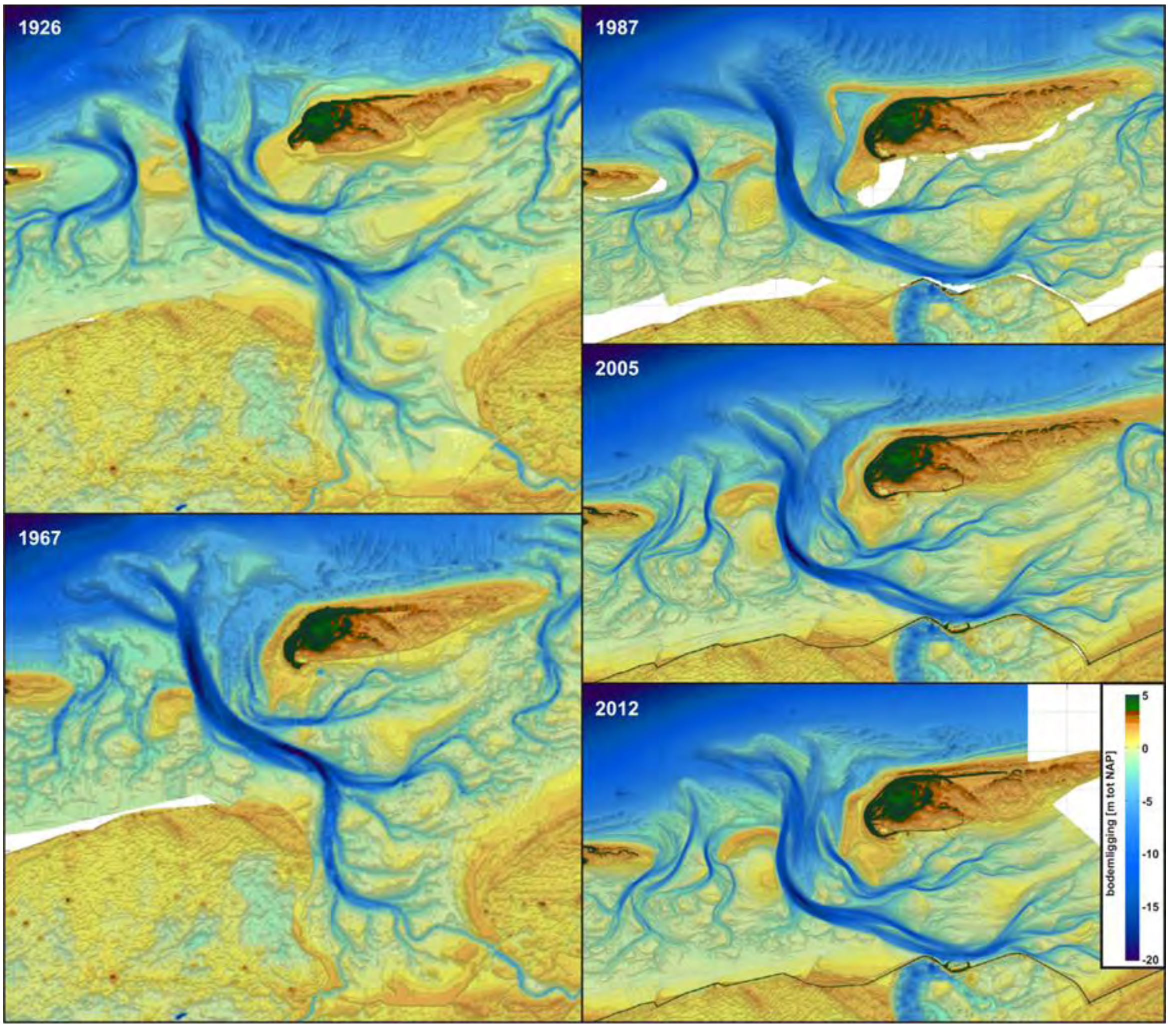


Figure 5.7.2: Large scale morphological development of het Friesche Zeegat based on depth soundings. Islands filled in with the AHN-1 (1996-2003)

When the drainage of the Lauwers Inlet was taken over by the Zoutkamperlaag, a chain-reaction set off (Oost, 1995): the Zoutkamperlaag system increased in dimensions. The western end of Schiermonnikoog was eroded by laterally migrating outer channels and backbarrier channels and perhaps the increase in inlet dimensions. At its eastern tip, Schiermonnikoog grew by lateral accretion (downdrift sediment supply) and amalgamation of shoals, such as Simenssant. Since ca. 1300, but continuing into the 20th century parts of the Lauwerszee embayment were reclaimed. The centre of the system became increasingly located S of Schiermonnikoog. It might be hypothesized that the tidal channels were probably constantly somewhat too wide for the decreasing tidal volumes due to infill of the Lauwerszee embayment. As a result, the tidal wave could travel faster to the watershed, and the watershed shifted to the east. The developments are comparable to the Otzumer Balje after the take-over of Harle Bay from the Harle Seegat. From early depth soundings it can be calculated that in the period 1927-1966/67 before the works on the closure dam of the embayment started some $15*10^6$ m^3 was deposited, almost totally in the Lauwerszee; a large part of it being mud.

The cyclic development (before the closure of the Lauwerszee embayment in 1969 in the main backbarrier channel of the Zoutkamperlaag was, to a large extent, controlled by developments in the ebb-tidal delta (see below). During short periods only one main channel drained the drainage basin. The channel split up in a flood chute at the west side and a channel bed used by both the ebb and the flood current at the east side. This happened when the outer channels and the inlet configuration concentrated part of the tidal currents along the east side of the main backbarrier channel. Successively the eastern channel became increasingly more important for the drainage of the system. Between both channels an elongated intertidal shoal was formed. Finally the most western channel became abandoned and was filled up. This again led to a single main channel configuration. The formation of new flood chutes could partly overlap with the abandonment of the old one. The stop of the cyclic developments and the change in the orientation of the channel axis after closure of the Lauwerszee suggest that this embayment, i.e., the original dimensions of the total drainage basin, was crucial for the maintenance of the cycle. Over the period 1832-1967 the morphology of the Lauwerszee changed relatively slow. A likely explanation is that the Lauwerszee forms a wind-sheltered, semi-enclosed embayment, with characteristic fine-grained sedimentation (Oost, 1995).

Strong changes occurred after closure of the Lauwerszee in 1969: also the present-day configuration of shoals and channels is strongly determined by it (Figure 5.7.2; Biegel, 1993; Biegel & Hoekstra, 1995; Oost, 1995). The closure reduced the backbarrier area with about 30%, and the tidal prism from $300*10^6$ m^3 to $206*10^6$ m^3. The large and sudden decrease in tidal prism resulted in strong deceleration of the currents through the main channel. The channel was wide and the tidal wave could travel rather fast to the watershed S of Schiermonnikoog which, as a result, shifted towards the east. In response to the lower current velocities the channel started to fill up: with mud near the Lauwerszee dam; a mixture of mud (summer half year) and sand (winter half year) halfway and sands near the inlet self (Oost, 1995). As a result of this strong sedimentation ($44*10^6$ m^3 in the period 1966-1987; a probably substantial part of it being mud deposits), the channel became shallower and current velocities increased. As of 2000 changes in the backbarrier basin in response to the closure seem to have largely ended.

Development of the ebb-tidal delta

Originally the tidal system was probably small (Oost, 1995). When the Lauwerszee was taken over by the Zoutkamperlaag the system became bigger in tidal area (Oost, 1995). Sediment may have been eroded from the backbarrier channels and ebb-tidal delta channels and been deposited in the ebb-tidal delta lobe. The reduction in tidal prism of the Lauwerszee will most likely have reduced the size of the ebb-tidal delta from 1550 onwards. Indeed, from the observations before the closure of the Lauwerszee over the period 1927-1965 it appears that some $10*10^6$ m^3 has been eroded from the ebb-tidal delta.

From observations, descriptions and detailed maps it is clear that up to the 18^{th} century large sub- to supratidal shoals were a dominant feature in the ebb-tidal delta. The sedimentary/geomorphological developments in the Zoutkamperlaag Inlet system are cyclic (Figure 5.7.3). From time to time, new flood-defined channels are formed at the western margin of the ebb-tidal delta, due to the tidal gradient and the western position of the inlet. The outer channels mainly migrate clockwise. At the west side of the main inlet, channels migrate to the N, resulting from the tendency of the main inlet channel to orient to the N, in combination with the formation of shoals and outer bend erosion of the outer channels. During migration flood-defined channels at the west side evolve into ebb-defined channels. The latter get a N-S-orientation, due to the inertia of the ebb current. East of the main inlet, the migrating sandy shoals enhance a further downdrift shift of the ebb-delta and inlet channels.

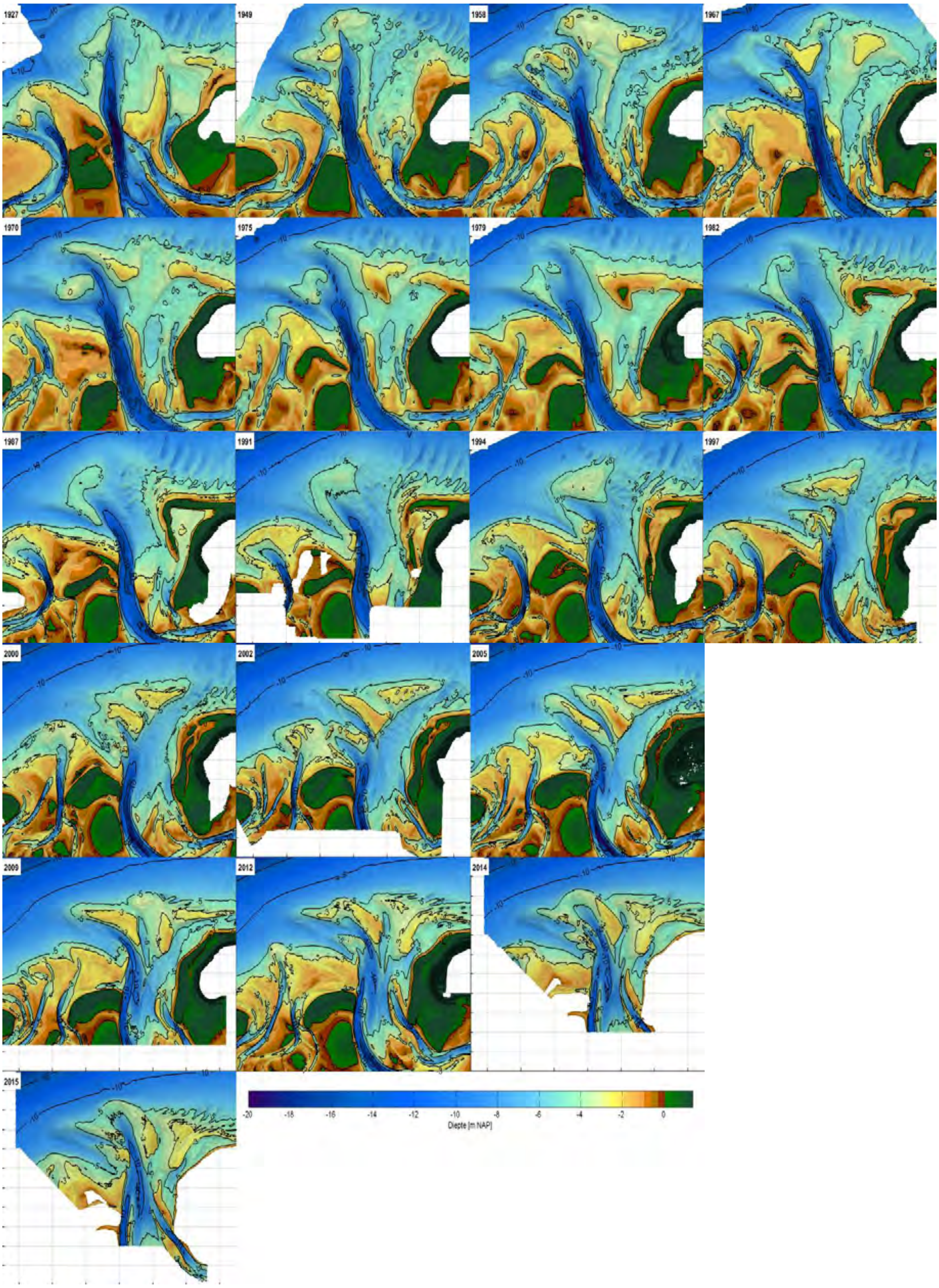


Figure 5.7.3: Overview of the development of the ebb-tidal delta over the period 1927-2015 (Oost et al., 2015).

During a further downdrift shift to a NE-SW-orientation the channels become abandoned. This facilitates the merger of shoals west of the abandoned channel with the downdrift island. New flood-defined outer channels are also formed from time to time at the east side of the ebb-tidal delta of the Zoutkamperlaag. It is inferred that these result from a mainly westward position of the other outer channels and the inlet, perhaps in combination with an eastward orientation of the Pinkegat Inlet channels.

After the closure of the Lauwerszee, the orientation of the inlet changed from WNW-ESE in 1967 to ENE-WSW in 2002, to change back to the old orientation after it (Figure 5.7.3. After the sudden reduction in tidal prism, the size and form of the original ebb-tidal delta could not be retained and the system adapted towards a new morphology (Figure 5.7.3). Wave action transported the ebb-tidal delta sands into the backbarrier. Another part was deposited onto the barrier island of Schiermonnikoog. In total some $32*10^6$ m^3 has been eroded from the ebb-tidal delta in the period 1965-1987. Over the period 1987-2007 erosion continues be it with a less clear development, resulting in an additional sand loss of $5*10^6$ m^3 (Wang & Oost, 2010). Erosion was concentrated at depths of AOD -10 m in the period 1990-2012. Possibly changes in deeper water still continue as a response to the closure of the Lauwerszee: processes are slower due to the weaker wave and current influences (Oost et al., 2015).

Coastal development

Oost (1995} described the cyclic migrating shoals from the ebb-tidal delta of Zoutkamperlaag to the coast of Schiermonnikoog since the 19th century. From the observed landing of shoals at the northwestern coast of Schiermonnikoog around 1898, 1925, 1955 and 1976 it can be inferred that shoals attach approximately every 26 years (Figure 5.7.4; Ridderinkhof, 2016). The landing and the redistributing of the sediment determines the development of the NW part of the island. A new shoal is present seaward of the island from 2005 onwards (Ridderinkhof, 2016).

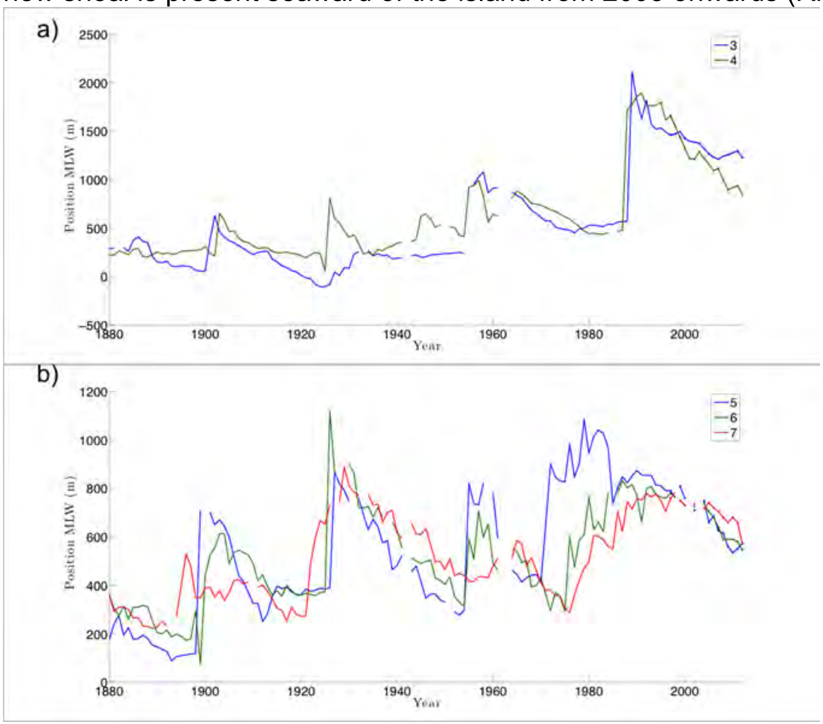


Figure 5.7.4: Evolution of the position of the mean low water line at beach poles 3 to 7 (km indication) at the northwestern tip of Schiermonnikoog. Note that the scale of the y-axis in the top and bottom panel differ (Ridderinkhof, 2016).

5.8 Eilanderbalg

Basic data

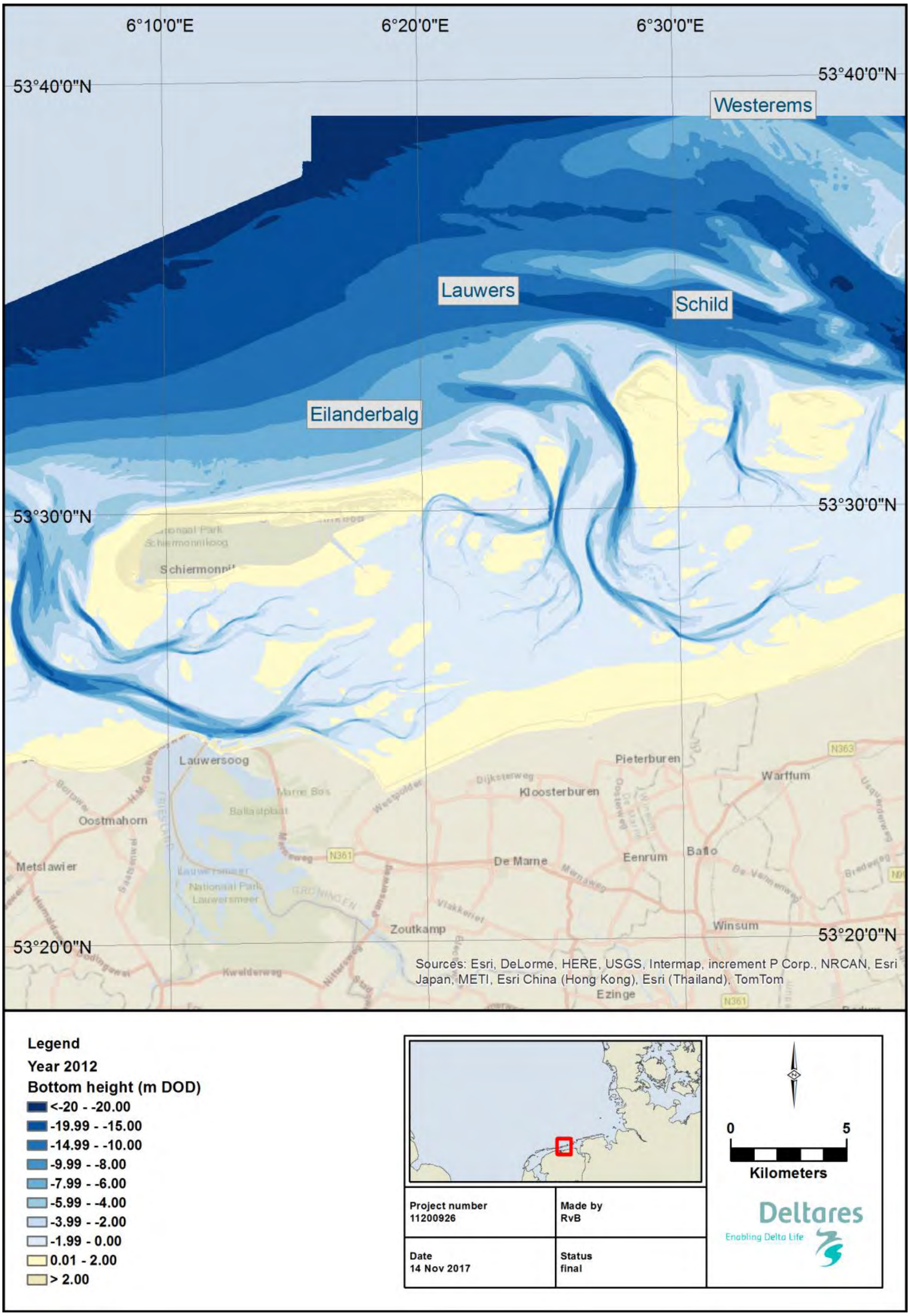


Figure 5.8.1: Overview of the ebb-tidal deltas of Eilanderbalg & Zeegat van de Lauwers.

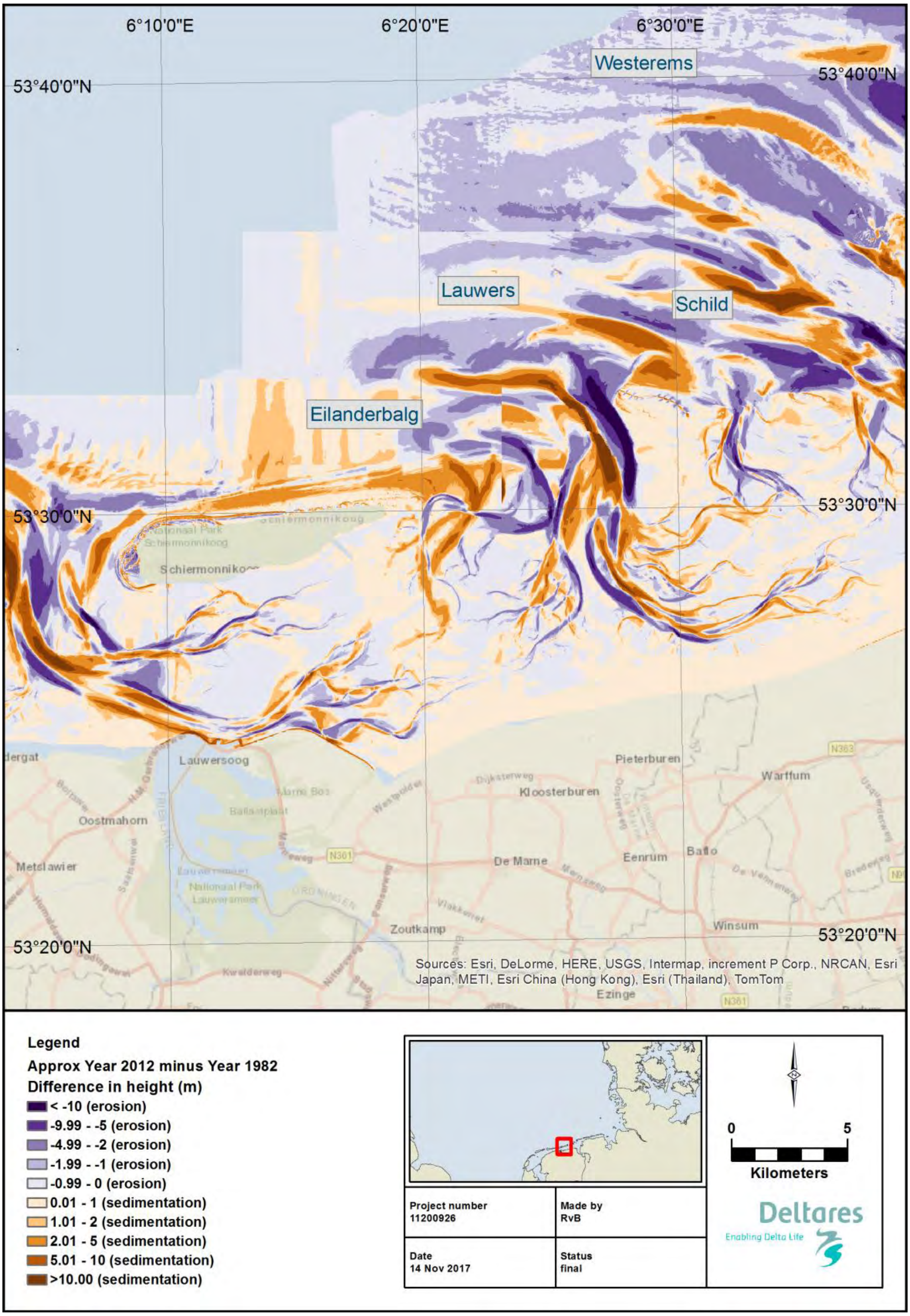


Figure 5.8.2: Overview of the ebb-tidal deltas of Eilanderbalg & Zeegat van de Lauwers showing erosion and deposition over approximately the period 1982-2012.

Table 5.7: Facts and figures Eilanderbalg (see also appendix I)

Parameter	**Obs.**	**Year**	**Reference**	**Obs.**	**Year**	**Refer-ence**	**Obs.**	**Year**	**Reference**
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)						
Hs (m)	1.32		CoastDat						
Tp (s).	5.85		CoastDat						
Tf/Te	0.94	2011 Slot-gemiddelde	2 (station Huibertgat)						
$L_{ebb\text{-}tidal\ delta}$ (km)	3.3	2012	-6 m	4	2012	-10m			
MHW (m AOD)	0.98	2011 slot-gemiddelde	2, 3 (station Huibertsgat +5 cm)						
MLW (m AOD)	-1.13	2011 slot-gemiddelde	2, 3 (station Huibertsgat -5 cm)						
MTR (m)	2.11 (1.71-2.38)	2011 slot-gemiddelde	2, 3 (station Huibertsgat +10 cm)						
Surge height (m to AOD)	100 y: 360	2011	2 (station Huibertsgat	200 y: 380	2011	2 (station Hui-bertsgat	500 y: 400	2011	2 (station Hui-bertsgat
Mean annual max surge height (m to AOD)	2.55		CoastDat						
A_{MHW} (km^2)	55	Ca. 1982	3						
A_{MLW} (km^2)	27	Ca. 1982	3						
A_{cross} (m^2)	8000	1989	4	5000	2014	4			
V_{MHW} (10^6 m^3)									
V_{MLW} (10^6 m^3)									
P (10^6 m^3)	67	1937/39	5 (Pbat)	70	1982	6			
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	0	1990-2002	7						
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	+1.3	1990-2005	Based on 8 (interpola-tion)						
Sediment transport direction?	Eastward								
Develop-ment island coasts	Eastward elongation East-Schiermonnikoog								

1 = Dillingh et al. 2009; 2 = Dillingh, 2013; 3 = Vroom et al., 1989; 4 = Van Rooyen & Oost, 2015; 5 = RWS, 1941; 6 = Postma, 1982; 7 = Cleveringa, 2008; 3 = Ridderinkhof, 2016.

Description of the tidal inlet system

The Eilanderbalg inlet is located between the barrier island Schiermonnikoog in the West and the inter- to supratidal shoal Simonszand in the east (Figure 5.8.1 & 5.8.2). Although it is a small separate inlet system it might as well be considered to be the separate small western inlet of het Zeegat van de Lauwers (between Schiermonnikoog and Rottumerplaat), comparable to Vliesloot in het Zeegat van het Vlie and Boschgat in het Amelander Zeegat. The forming of the Eilanderbalg (1708-1750) resulted in a decrease in dimensions of the western part of the drainage area of the Lauwers Inlet. In combination with an eastward shift of its gorge, the Lauwers Inlet could more than compensate the loss by increasing its drainage area to the east. Due to its large tidal prism, the Lauwers Inlet became increasingly more oriented against the tidal wave propagation direction (cf. Sha, 1989b). The westward expansion of the Lauwers Inlet, in combination with the eastward shift of the watershed S of Schiermonnikoog, will have enhanced the temporal abandonment of the Eilanderbalg (period 1811-1848). After circa 1848 the Eilanderbalg increased again in size, most likely due to the renewed downdrift shift of the Lauwers Inlet.

The above illustrates that the small dimensions of the inlet system make it sensitive to "take-overs" of tidal area by the much bigger Zoutkamperlaag system to the W and the Zeegat van het Lauwers to the E. After the closure of the Lauwerszee the watershed shift S of Schiermonnikoog resulted in a considerable loss of area of tidal flats and a reducted tidal prism of the Eilanderbalg. This happened especially in the period 1969-1979, after which the watershed shifted westward again. The Eilanderbalg has become shallower over the period 1989-1994, but increased again in depth in the period 1994-2014 (Van Rooijen & Oost, 2015).

Around 2012 the watershed of the shoal Simonsant was breached and a connection between het Zeegat van de Lauwers and the Eilanderbalg became established. With this the Lauwers once more became more or less the only inlet between Schiermonnikoog and Rottumerplaat.

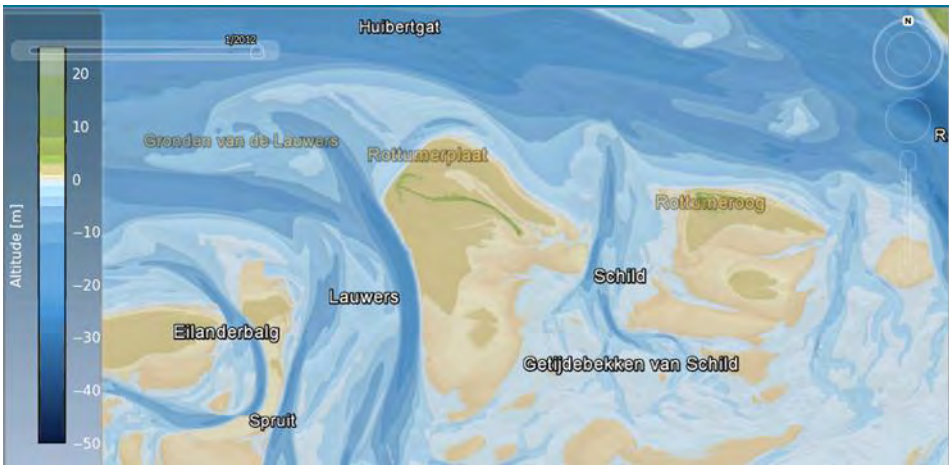


Figure 5.8.3: Toponymes of the Eilanderbalg to Schild area.

Development of the ebb-tidal delta
The development of the Eilanderbalg inlet resembles that of the Pinkegat (Figure 5.8.4). It seems to develop between a single inlet system into an inlet with several channels. Also here channels shift to the E and new channels form over the spit forming at the east tip of Schiermonnikoog. From time to time supratidal shoals formed in the mouth and migrated eastward. Sometimes the channels between Schiermonnikoog and such shoals were filled up and the island extented eastward (e.g. 1848). The difference with the Pinkegat system is that the ebb-tidal delta main channel seems to be forced into being oriented against the tidal wave propagation direction due to the presence of the larger ebbtidal delta of the Zeegat van de Lauwers which envelopes the ebb-tidal delta of the Eilanderbalg. Since 2000 it has been a system with only one distinct inlet. At the backbarrier side its main channel develops a strong meander which erodes the island tail of Schiermonnikoog. It seems feasible that the erosion might cause a break-through at that location.

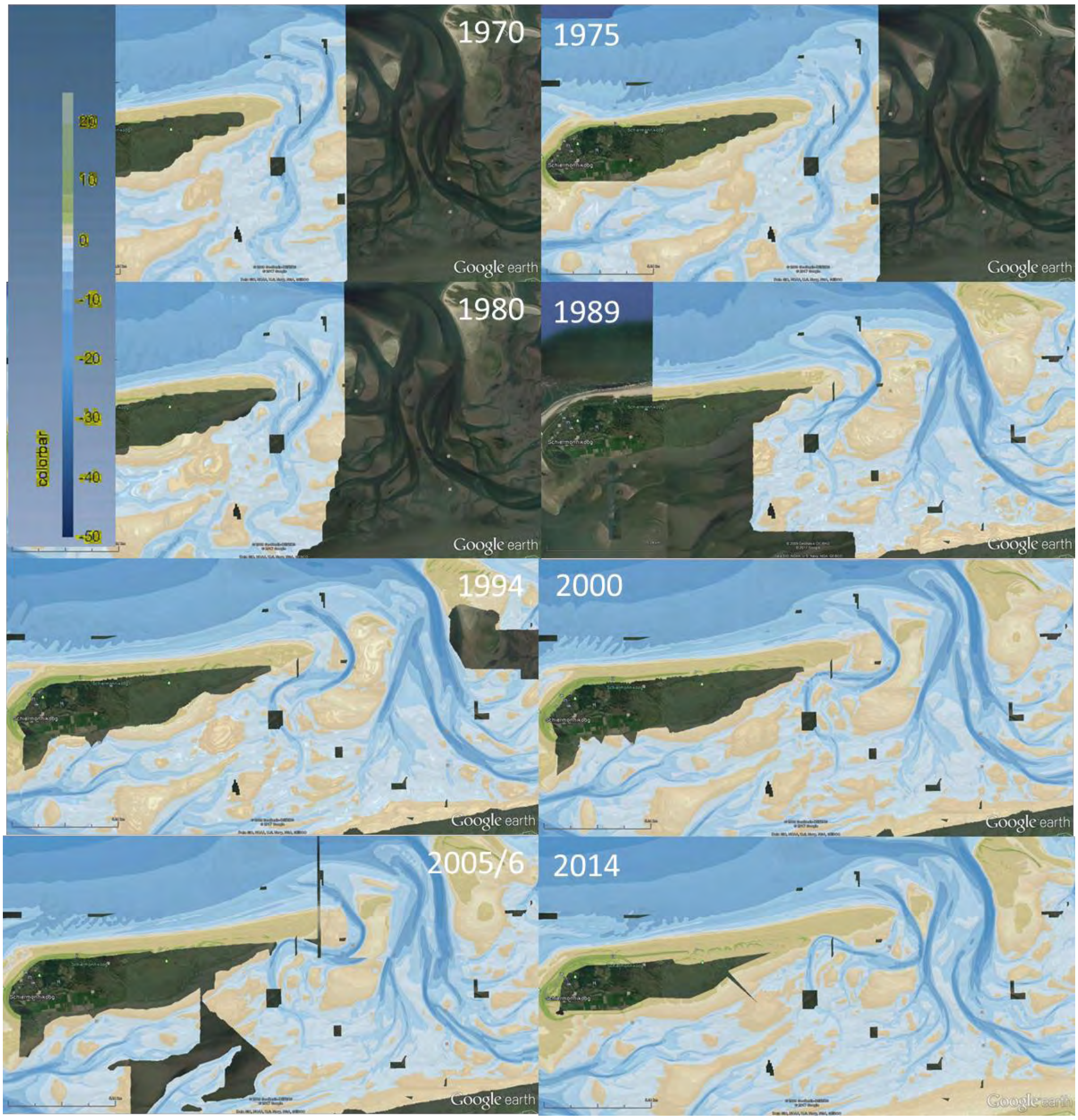


Figure 5.8.4: Overview of the development of the Eilanderbalg inlet system.

Coastal development

As a result of the changes in the watershed the eastern island tip of Schiermonnikoog extended since 1982 over 3 km. The watershed of the shoal Simonszand was breached, but recent observations (Google Earth) show that the shoal has survived this breach.

5.9 Het Zeegat van de Lauwers

Basic data

See Figures 5.8.1-5.8.3.

Table 5.8: Facts and figures Zeegat van de Lauwers (see also appendix I)

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)						
Hs (m)	1.32		CoastDat						
Tp (s).	5.85		CoastDat						
Tf/Te	0.94	2011 Slot-gemiddelde	2 (gauge Hui-bertgat)						
$L_{ebb\text{-}tidal\ delta}$ (km)	6,5	2012	-6 m	9	2012	-10m			
MHW (m AOD)	0.98	2011 slot-gemiddelde	2, 3 (station Hui-bertsgat +5 cm)						
MLW (m AOD)	-1.13	2011 slot-gemiddelde	2, 3 (station Hui-bertsgat -5 cm)						
MTR (m)	2.11 (1.71-2.38)	2011 slot-gemiddelde	2, 3 (station Hui-bertsgat + 10 cm)						
Surge height (m to MSL)	100 y: 360	2011	2 (station Hui-bertsgat	200 y: 380	2011	2 (station Huibertsgat	500 y: 400	2011	2 (station Huibertsgat
Mean annual max surge height (m to AOD)	2.55		CoastDat						
A_{MHW} (km^2)	145	Ca. 1982	4						
A_{MLW} (km^2)	36.3	1962	5	53	Ca. 1982	4			
A_{cross} (m^2)	13000	1989	6	19500	2014	6			
V_{MHW} (10^6 m^3)	303	1962	5						
V_{MLW} (10^6 m^3)	107	1962	5						
P (10^6 m^3)	160	1982	7	208	1984	8 (Pdis)			
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	1	1990-2005	4 (including Het Schild)						
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)	1.2	1990-2013	9						
Longshore drift (10^6 m^3/yr)	+1.2	1990-2005	Based on 10(interpolation)						
Sediment transport direc-tion?	??								
Development island coasts	Erosion W Rottumer-plaat; Sedimentation N Rottumerplaat								

1 = Dillingh et al. 2010; 2 = Dillingh, 2013; 3 = Vroom et al., 1989; 4 = Cleveringa, 2008;. 5 = Biegel, 1992 (tidal heights fixed); 6 = Van Rooyen & Oost, 2015; 7 = Postma, 1982; 8 = Pastoor, 1985; 9 = Vermaas & Marges, 2017; 10 = Ridderinkhof, 2016.

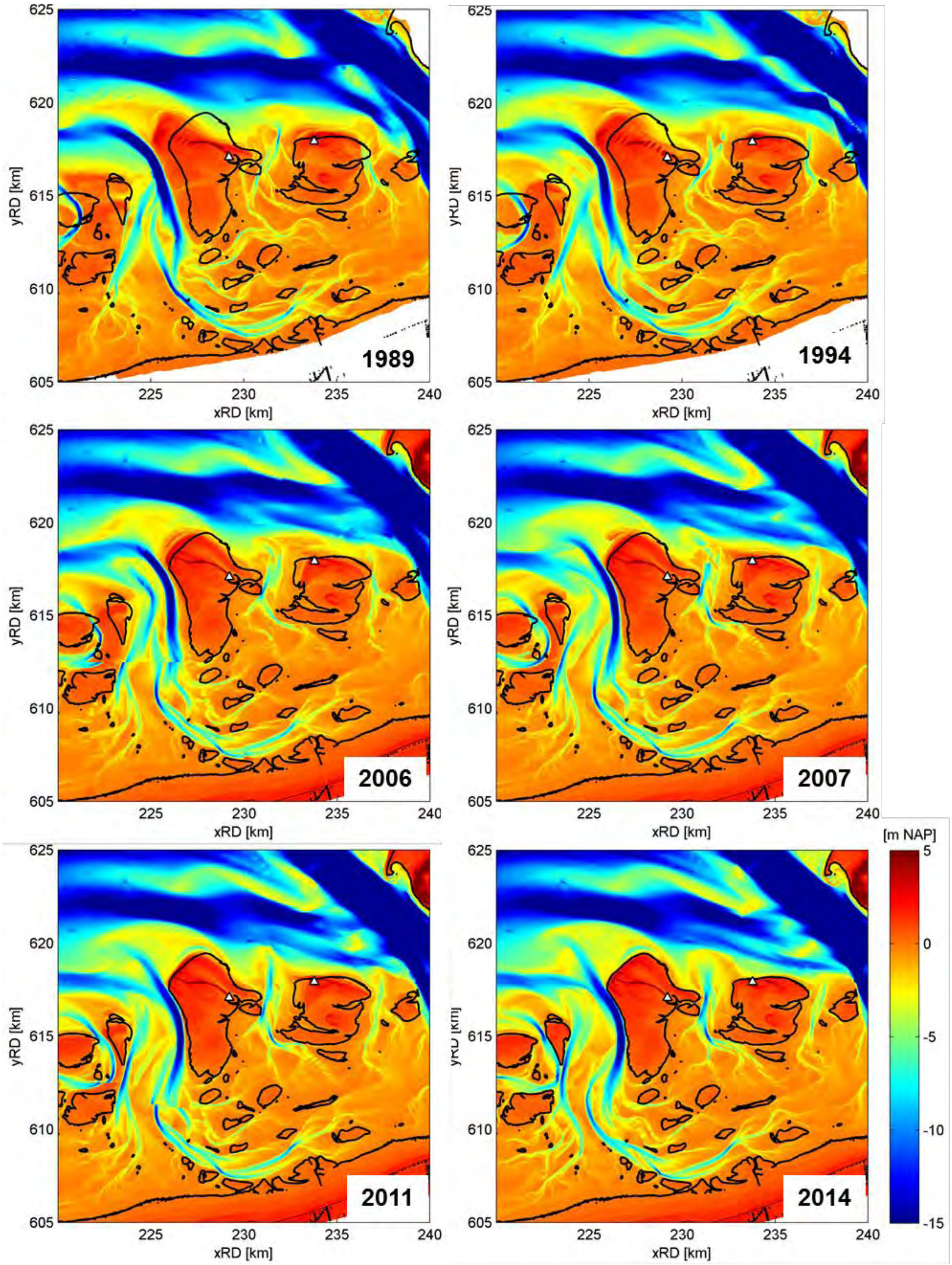


Figure 5.9.1: Development of the area of the Eilanderbalg (W, to the left), Het Zeegat van de Lauwers (the big inlet left of centre), Schild and (not mentioned in text) Sparregat, E of Rottumerplaat. All pictures are composites consisting of information of the most recent years (Van Rooijen & Oost, 2015).

Description of the tidal inlet system

Het Zeegat van de Lauwers is located between the inter- to supratidal shoal Simonszand in the West and in the east the small barrier island Rottumerplaat. From the scarce medieval sources it is inferred that around 1300 the inlet drained the Lauwerszee embayment and had a much more westerly position than at present (Oost, 1995). Changes in the period 1936/37-1982 indicate a gradual decrease in tidal prism, followed by an increase (Table 5.8). This is keeping with the changes in the backbarrier area where het Zeegat van de Lauwers has been expanding its terrain.

Development of the ebb-tidal delta
After the take-over of the drainage of the Lauwerszee by the Zoutkamperlaag Inlet system (16th century), het Zeegat van de Lauwers became gradually detached from the Lauwerszee embayment (1500-1580). It decreased in size to such an extent, that it was reported that the inlet gorge had almost totally disappeared in the first half of 17th century. Then it shifted downdrift, and its size again increased, due to expansion of its drainage area to the E. The inlet gorge shifted to the E over 10.5 km in the period 1600-1975 (Oost, 1995).

At the moment the tidal prism is around $270*10^6$ m^3 if the tidal prism of Eilanderbalg is included (or about 208, without). The inlet migrates towards the E and by doing so erodes the west-end of Rottumerplaat (Figure 5.9.1). During the period 1989-2014 the inlet decreases in depth from AOD -20 m to -15 m and has become much broader. The main inlet sometimes consists of two subchannels and sometimes of one (Van Rooijen & Oost, 2015). The large southern ebb-tidal delta channel Hubertgat of the Westerems is situated directly north of the ebb-tidal delta of the Zeegat van de Lauwers. The Hubertgat probably exerts influence on the ebb-tidal delta's development as can be concluded from its strongly westward deflected orientation. However, this has not yet been researched.

Coastal development
The west-end of Rottumerplaat is being eroded and the coastline currently retreats in a SE direction. E of this location strong sedimentation occurs. Over the ebb-tidal delta of het Zeegat van de Lauwers shoals migrate in a clockwise direction and amalgamate with the N coast of the small island Rottumerplaat. Total area and sediment volume of Rottumerplaat remain relatively stable although above MLW the area decreases slightly while the volume remains constant, but both remain constant above MHW (Van Rooijen & Oost, 2015).

5.10 Het Schild

Basic data

Table 5.9: Facts and figures het Schild (see also appendix I)

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)						
Hs (m)	1.32		CoastDat						
Tp (s).	5.85		CoastDat						
Tf/Te	0.94	2011 Slot-gemiddelde	2 (station Hui-bertgat)						
$L_{ebb\text{-}tidal\ delta}$ (km)	2.1	2012	-6 m	2	2012	-10m			
MHW (m AOD)	0.98	2011 slot-gemiddelde	2,3 (station Huibertsgat +5 cm)						
MLW (m AOD)	-1.13	2011 slot-gemiddelde	2,3 (station Huibertsgat -5 cm)						
MTR (m)	2.11 (1.71-2.38)	2011 slot-gemiddelde	2,3 (station Huibertsgat + 10 cm)						
Surge height (m to MSL)	100 y: 360	2011	2 (station Hui-bertsgat)	200 y: 380	2011	2 (station Huibertsgat)	500 y: 400	2011	2 (station Huibertsgat)
Mean annual max surge height (m to AOD)	2.55		CoastDat						
A_{MHW} (km^2)	28	1980	4 (before take over of Lauwers)	18	1980	4 (after take-over of Lau-wers)	16	1990	4
A_{MLW} (km^2)	11.6	1962	5						
A_{cross} (m^2)	5200	1989	6	6900	2014	6			
V_{MHW} ($10^6 m^3$)	78.9	1962	5						
V_{MLW} ($10^6 m^3$)	19.1	1962	5						
P ($10^6 m^3$)	36	1984	7 (Pbat)	41	1989	4 & 8 (Pdis)	32	1992	8 (Pdis)
$SV_{backbarrier}$ ($10^6 m^3$)									
$SV_{ebb\text{-}tidal\ delta}$ ($10^6 m^3$)									
$AS_{backbarrier}$ ($10^6 m^3/yr$)									
$AS_{ebb\text{-}tidal\ delta}$ ($10^6 m^3/yr$)									
Longshore drift ($10^6 m^3/yr$)	+1.2	1990-2005	Based on 9 (interpolation)						
Sediment transport direction?	To the E								
Development island coasts	Erosion of N Rottumeroog								

1 = Dillingh et al. 2010; 2 = Dillingh, 2013; 3 = Vroom et al., 1989; 4 = Huizing, 1993; 5 = Biegel, 1992 (tidal heights fixed); 6 = Van Rooijen & Oost, 2015; 7 = Brilhuis et al., 1990; 8 = Huizing & Ariaans, 1995; 9 = Ridderinkhof, 2016.

Description of the tidal inlet system

Het Schild (Figures 5.8.1 & 5.8.2) is a small inlet system between the barrier island Rottumerplaat in the West and the barrier island Rottumeroog in the east (Figure 5.8.3). In the period 1989-2014, het Schild has increased with 30-60% in wet surface area at MLW, AOD and MHW (Van Rooijen & Oost, 2015).

Development of the ebb-tidal delta

The inlet channel has become deep and narrow and ebb and flood are forced to follow the same path (Figure 5.9.1). This might be attributed to the forming of a flood chute NW of the inlet. Due to this a more direct path was opened so that tidal water can flow rapidly to the backbarrier, thus enlarging the area to the W and somewhat to the E. Also, the ebb-tidal delta seems to increase somewhat in the period 1989-2014 (Van Rooijen & Oost, 2015).

6 Ebb-tidal deltas of Lower Saxony

6.1 General description of the Lower Saxonian area

Characteristics

The W to E trending Wadden area of Lower Saxony has a total surface area of 2.777 km² within the Nationalpark Niedersächsisches Wattenmeer. The backbarrier Wadden Sea consists of tidal marshes, supra- inter and subtidal flats and tidal channels (Figure 6.1.1).

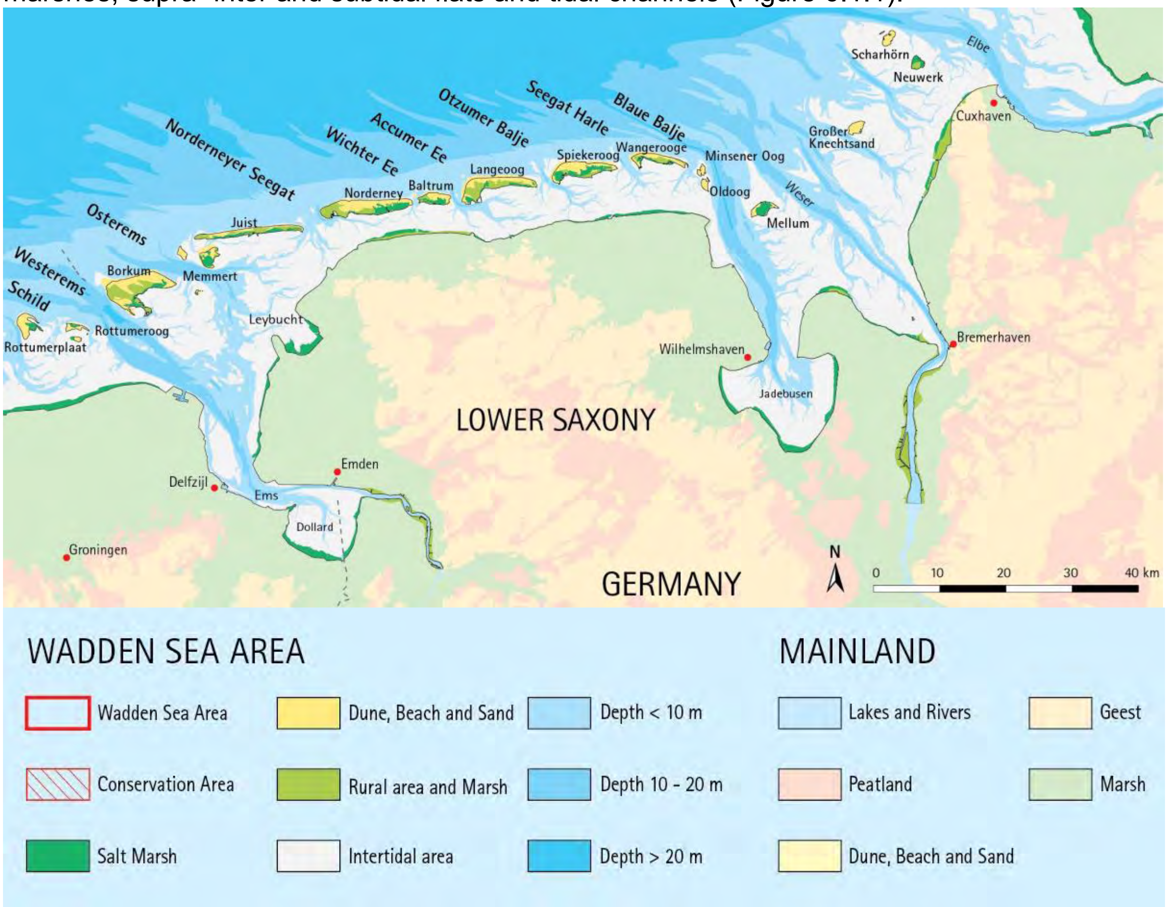


Figure 6.1.1: The inlet systems of which ebb-tidal deltas are described in the Wadden area of the Lower Saxony: Westerems to Blaue Balje (Courtesy, Wadden Sea Secretariat).

The described area consists of ten inlet systems, from W to E: Westerems (Eems), Osterems, Norderneyer Seegat, Wichter Ee, Accumer Ee, Otzumer Balje, Harle and Blaue Balje (Figure 6.1.1). In general, the described part of the Lower Saxony Wadden area resembles strongly the Dutch Wadden area, both for its appearance and the morphogenesis. Several fresh water streams are entering the backbarrier, the major one is the river Ems, whereas the eastern half is also strongly influenced by the Jade-Weser estuary. Most of the inlets have islands at either side and clearly developed ebb-tidal deltas, but Blaue Balje is bordered by an islet at its east side.

Observations over the past century show that MSL increase in the Lower Saxony Wadden Sea is around 2-2.4 mm/yr (Stations Borkum, Alte Weser, Wangerooge West and Norderney, see also: Wahl, 2010, 2011; Albrecht et al., 2011). Tidal amplitude increases from W to E from 2.3 m at station Borkum Südstrand up to 3 m in station Wangeroog-ost (BSH, 2017). Also, over time tidal amplitude has increased with some 1.2-2.2 mm/yr (Stations Borkum, Alte Weser, Wangerooge West and Norderney). The mean significant wave height decreases from 1.3 m in the Westerems to 0.9 m in the Blaue Balje (Coast Dat data). Along the North Sea coast of the littoral drift is directed to the E, calculated to be 0.3-1.9-0.6*10^6 m^3/yr (Figure 6.1.2; Ridderinkhof, 2016). Windiness, storminess, wave conditions and related storm-surge conditions along the Wadden Sea have shown strong highly correlated inter-annual and inter-decadal variations during the 20th century (Alexandersson et al., 2000). Windiness, storminess and wave conditions were high in the early 20th century, decreased towards the mid-century and increased until the beginning of the 1990s, after which they sharply declined over the North Sea by the end of the 20th century (Schmidt, 2001; Weisse *et al.*, 2002, 2005, 2012; Matulla et al., 2007).

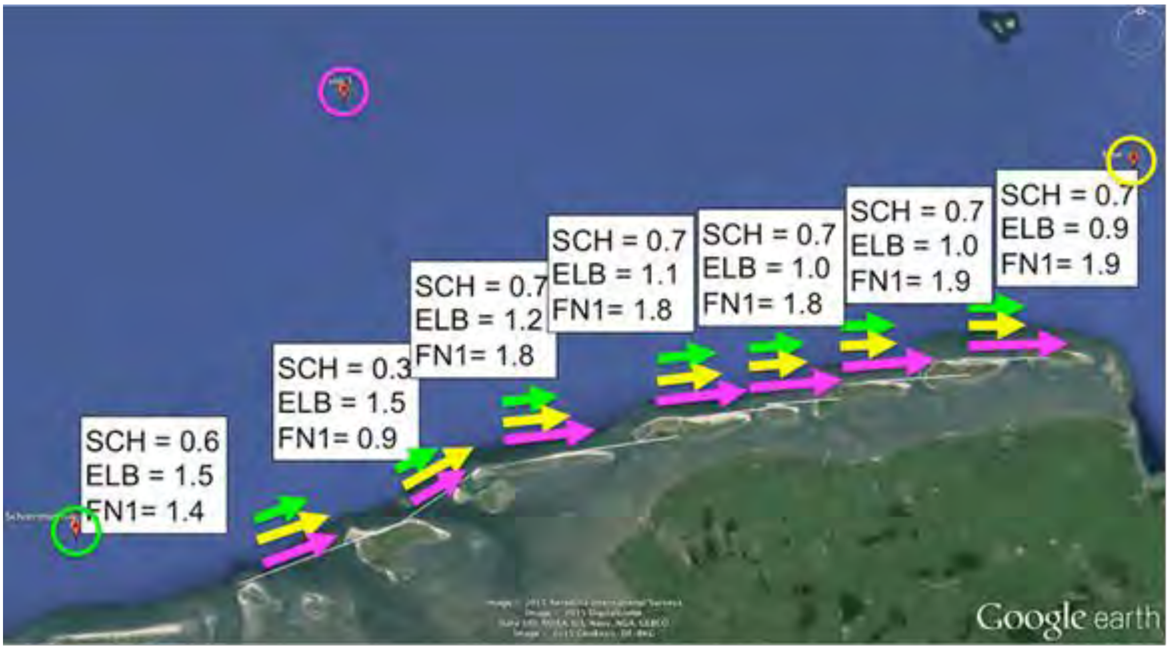


Figure 6.1.2: Littoral drift along the North Sea coast of Lower Saxony as determined on stations Schiermonnikoog (SCH), Elbe (ELB) and Fino1 (FN1) in 10^6 m^3/yr (From: Ridderinkhof, 2016).

Several large engineering interventions have been carried out in the area. The most important are the reclaiming of large parts of the Osterems area and the Harle embayment (see chapters 6.3 and 6.7) and the deepening of the Westerems, which led to tidal amplitude increases in a large part of that estuary. Another important feat has been the protection works on most of the barrier islands. The western tips of Borkum, Norderney, Baltrum, Spiekeroog and Wangerooge are protected by groynes and stonework (NLWKN, 2010; Thorenz, 2011). The mainland is diked and in front of it marsh development works have been developed on many places. On the barrier islands only the inhabited areas are surrounded by a closed chain of sand drift dikes and back-barrier dikes.

Geology

After the last Ice Age relative sea-level rise was initially rapid, but decreased over time (see Figure 5.1.3)

The rising sea level followed and modified the mostly gentle Pleistocene relief and determined the initial position of the Wadden Sea. The paleo-valleys incised during the Pleistocene sea-level lowstand determined the location, dimensions and inland penetration of estuaries, such as the Ems-Dollard and Weser estuaries and the Jadebusen (Streif, 2004; Wiersma et al., 2009). Some of the areas were filled with peat and could be incised relatively easily and be converted into backbarrier embayments (e.g. Dollard-, Harle- and Jade-embayments) thereby enlarging the tidal volume of the estuaries or backbarrier basins of which they were part. In the East Frisian Wadden Sea area, the deepest river valleys were flooded around 8000 a BP (Beets & Van der Spek, 2000). The present day tidal inlet position is in a few cases still determined by the former valleys (Wiersma et al., 2009). Locally elevated Pleistocene outcrops and headlands consisting of moraine deposits of the Saale (second-last) glaciation, and sandy meltwater deposits of the Weichselian (last) glaciation were present forming the present-day Geestgrunden of Lower Saxony. Smaller barrier islands, sandy shoals or sand spits may have been present in front of the mainland coast as relicts of Pleistocene headlands (Flemming & Davis, 1994).

The bulk of the East Frisian barrier island chain formed between 6,000-5,000 a BP. Initially sedimentation could not fill the space created by the rapidly rising sea (1 m/century), and a mainly subtidal area formed, fringed by a narrow zone of intertidal sand and mud flats and salt marshes near the mainland. At the mainland, fens gave way to raised bogs, which started to expand on the mainland of east Frisia between especially 7,200-5,600 a BP (Petzelberger et al., 1999; Eckstein et al., 2011).

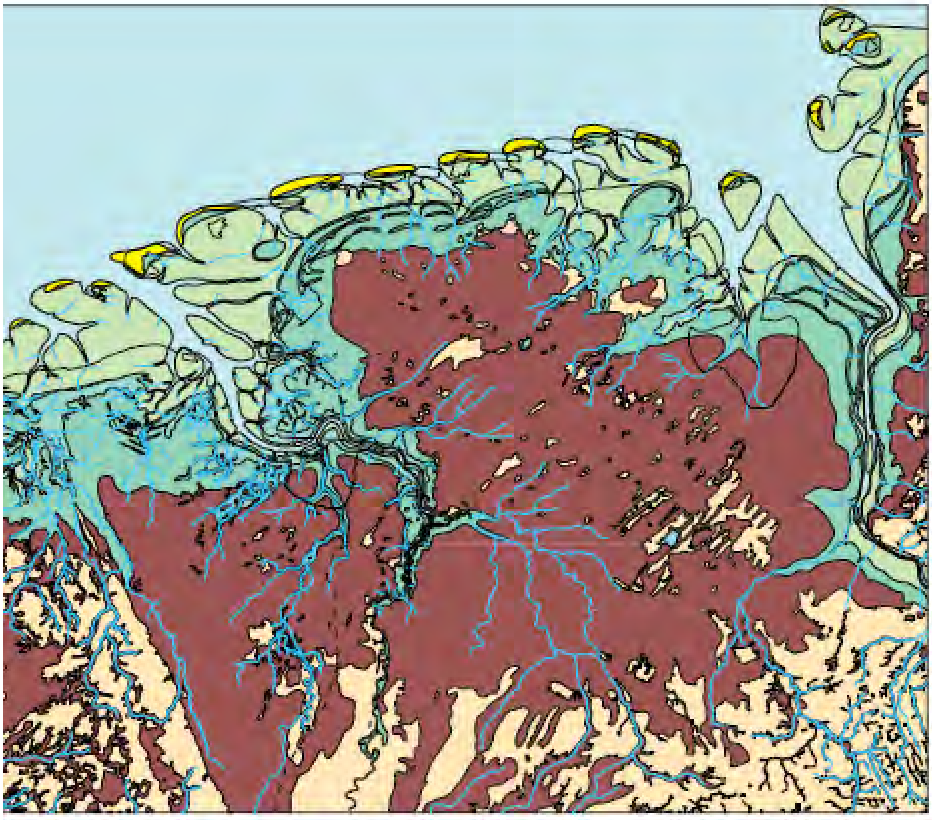


Figure 6.1.3: Situation around 800 AD. Orange = higher sand grounds; brown -= peats; yellow = coastal dunes ;dark green = tidal marshes; light green = tidal flats; blue is subtidal area; contours of present day coasts are given (Oost et al., 2017).

In the following millennia after 5000 BP subsidence of the bottom in the East Frisian Wadden Sea, was relatively large and sedimentation and despite an decelerating absolute sea-level rise sedimentation was insufficient to fill the basins everywhere (Vos et al., 2011). In some places the tidal area was extending (Vos et al., 2011). In other places the Wadden Sea locally silted up and the salt marshes could advance seaward (see Behre, 1999, 2004; Vos et al., 2011).

At about 5,000 a BP, the East Frisian barrier-island chain was still situated several kilometres offshore from its present position (Vos et al., 2011). From 5,000 a BP until today, the chain of ebb-tidal deltas and barrier islands has been retreating landward and a large part of the sediment was deposited into the backbarrier areas.

The situation of the East Frisian Wadden area at 1,200 a BP is given in figure 6.1.3. It is the period before man started to separate the various coastal environments from each other by dikes. At the mainland tidal flats merged into tidal marshes and large brackish areas which were flanked by extensive bogs lining higher sandy areas (Esselink, 2000). Tidally influenced rivers and streams were in open connection with the Wadden Sea.

The first local dikes surrounding smaller areas to safeguard arable fields and against most winter floods, were present from around 2000 BP and became probably relatively wide spread in Frisia around 1,000-900 a BP (Van der Spek, 1994; Oost 1995, Ey, 2010). Since 1,000-800 a BP dikes along streams were built in order to channel the outflow of waters (Ey, 2010). By 800-700 a BP a continuous system of winter dikes had been constructed along the entire East Frisian Wadden Sea mainland coasts (Ey, 2010). Due to peat subsidence due to agriculture areas were flooded and 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). Around 500 a BP and later, large parts of the salt marshes silted up so high that they could be embanked and extensive areas of land (Maade Einbruch, Schwarzes Brack, Harlebucht) had been reclaimed (Vollmer et al., 2001; Van Heteren & van der Spek, 2003). Land reclamations and the retreat of the barrier islands reduced the surface area of the tidal basins, creating smaller tidal prisms which in turn resulted in smaller tidal inlet systems and probably smaller ebb-tidal deltas.

Since 500 yr BP large-scale attempts were made to protect dunes on the East Frisian barrier islands, but extensive livestock grazing inhibited a closed vegetation cover. Serious sand drifts were recorded on many islands, for instance Juist (Homeier, 1964). As existing technology at that time was largely incapable of stopping large-scale natural developments, many strong eastward shifts of inlets and ebb-tidal deltas occurred (Niemeyer, 1995).

Grain sizes are mainly fine sandy, with exception of fine grained areas near the mainland coast and in the Dollart area and medium to coarse grained sediments in most of the inlets and around the islands (Figure 6.1.4).

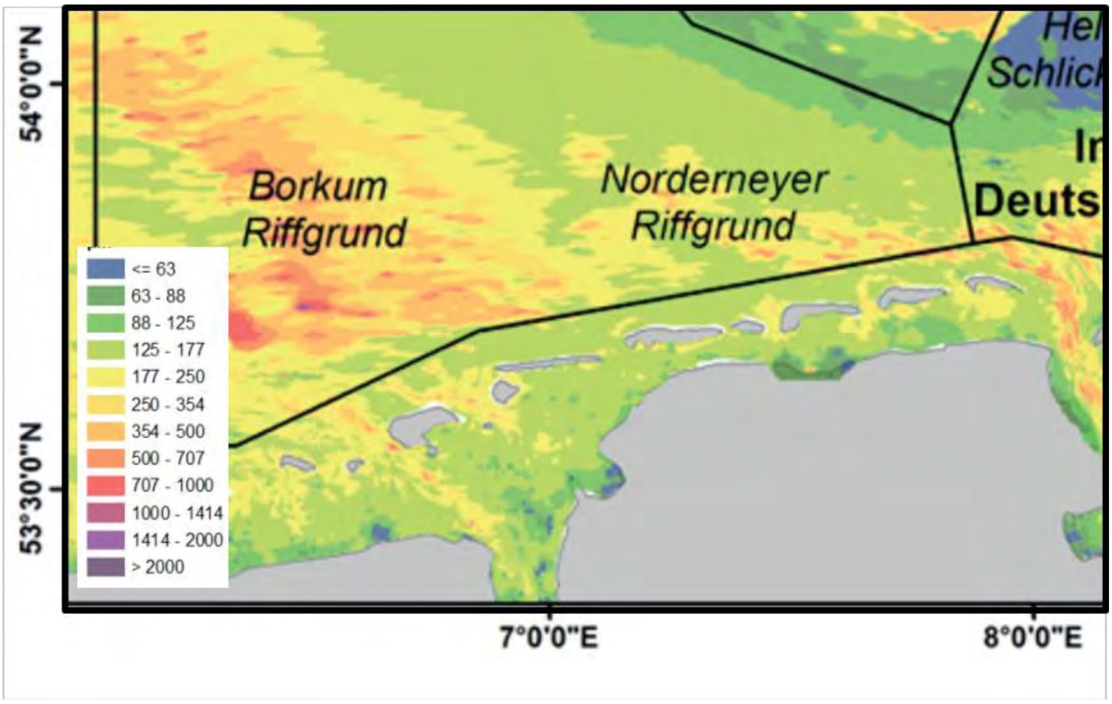


Figure 6.1.4: Median grain size distribution in micrometer-classes of the Lower Saxonian area as given in the functional bottom model (Milbradt et al. 2015).

6.2 Westerems/Eems

Basic data

Figure 6.2.1: overview of the inlet system in 2000.

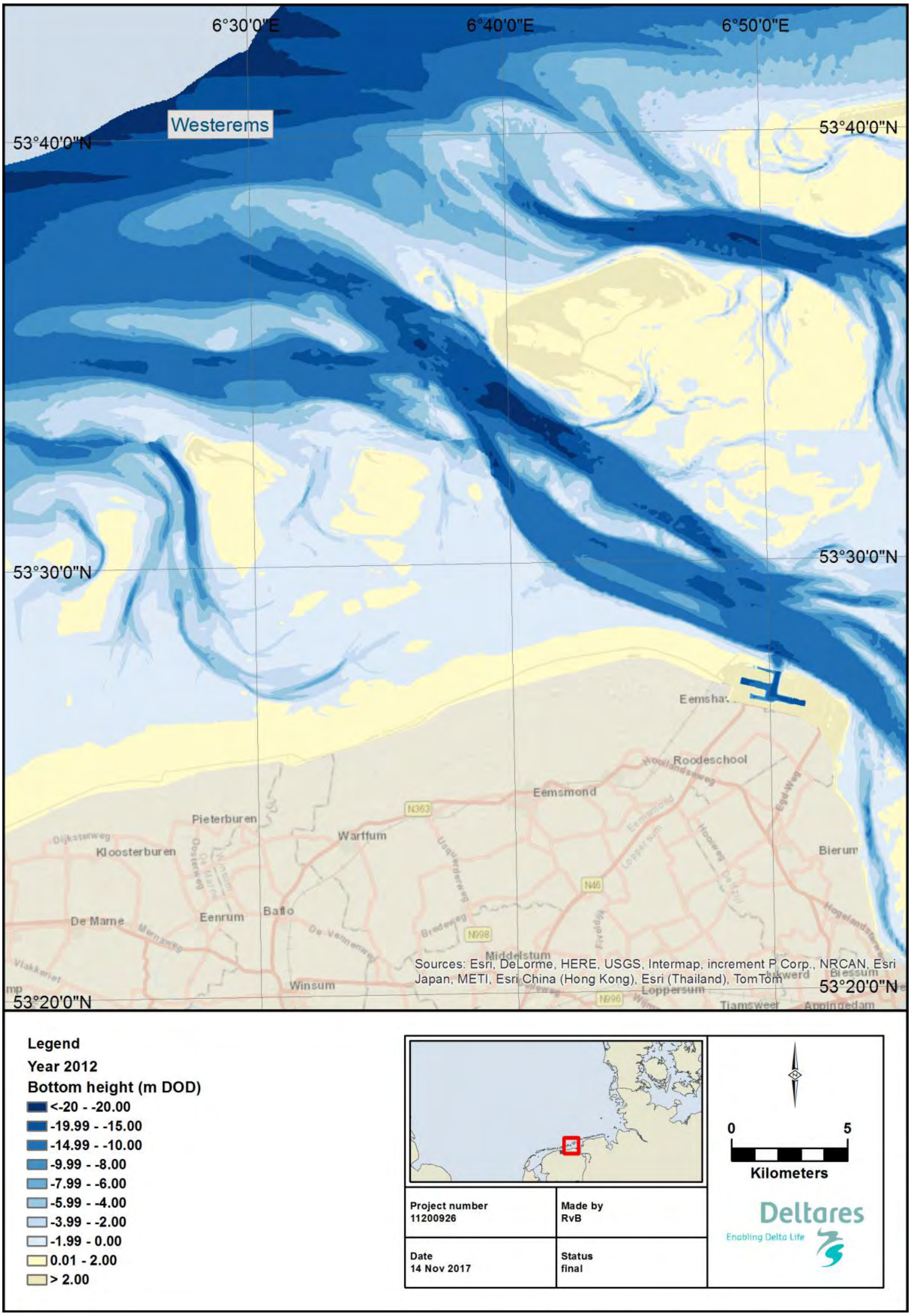


Figure 6.2.2 overview of the ebb-tidal delta of Westerems.

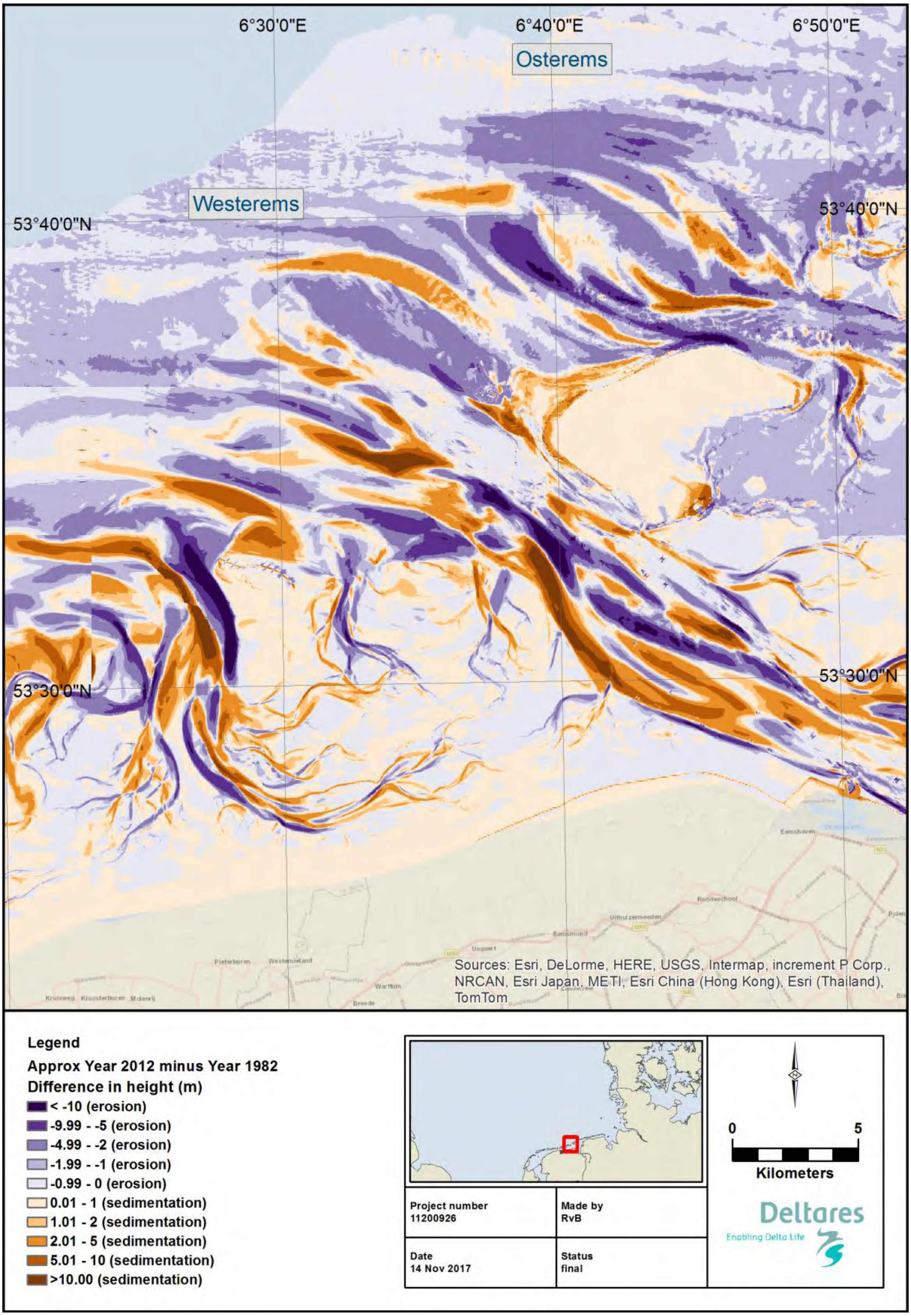


Figure 6.2.3: Westerems erosion and deposition over the period 1982-2012

Table 6.1: Facts and figures Westerems (see also appendix I)

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)	2.2	1934 - 2001	2 (station Borkum)			
Hs (m)	1.31		CoastDat						
Tp (s).	5.80		CoastDat						
Tf/Te	0.94	2011 Slot-gemiddelde	3 (station Hui-bertgat)	0.98	2017 (2 tidal cy-cles of 3 jan)	2 (station, Borkum Fischerbalje)			
$L_{ebb\text{-}tidal\ delta}$ (km)	13	2012	-6 m	14.7	2012	-10m			
MHW (m NHN)	0.98	2011 slot-gemiddelde	3, 4 (station Huibertsgat +5 cm)	1,1	2017	5 (station Borkum, Südstrand)			
MLW (m NHN)	-1.13	2011 slot-gemiddelde	3, 4 (station Huibertsgat -5 cm)	-1,2	2017	5 (station Borkum, Südstrand)			
MTR (m)	2.11 (1.71-2.38)	2011 slot-gemiddelde	3, 4 (station Huibertsgat + 10 cm)	2,3	2017	5 (station Borkum, Südstrand)			
Surge height (m to MSL)	100 y: 360	2011	3 (station Hui-bertsgat	200 y: 380	2011	3 (station Huibertsgat	500 y: 400	2011	3 (station Hui-bertsgat
Mean annu-al max surge height (m to AOD)	2.57		CoastDat						
A_{MHW} (km^2)	520	~1990	6						
A_{MLW} (km^2)	306	~1990	6						
A_{cross} (m^2)	55476	1887	7	56576	1911	7	60483	1975	8
V_{MHW} (10^6 m^3)									
V_{MLW} (10^6 m^3)									
P (10^6 m^3)	1000	1982	9						
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	4,7 (3,9-5,7)	1985-2002	10						
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)	-0,3	1990-2013	11						
Longshore drift (10^6 m^3/yr)	+1.1	1990-2012	12 (station Schiermonni-koog)	+1.1 to +1.5	1990 - 2012 & 2006 - 2009	12(stations Schiermonni-koog & Elbe)			
Sediment transport direction?	E-ward ?								
Develop-ment island coasts	Growth of NW Borkum; Erosion N side of Rottumeroog								

*1 = Dillingh et al., 2010; 2 = Jensen & Mudersbach, 2007; 3 = Dillingh, 2013; 4 = Vroom et al., 1989; 5 = BSH, 2016; 6 = Louters & Gerritsen, 1992; 7 = Klein Wassink, 1991 (Adapted for A_{cross} under AOD: by adding inlet width*1.13 (=AOD-MLW)); 8 = Biegel, 1992 (tidal heights fixed); 9 = Postma, 1982; 10 = Cleveringa, 2008; 11 = Vermaas & Marges, 2017; 12 = Ridderinkhof, 2016.*

Location: between the Netherlands, province of Groningen and Germany, Lower Saxony, between the barrier island Rottumeroog in the W and Borkum in the E (Figure 6.2.1). The ebb -tidal delta of this estuary is huge and stretches all the way up to E Schiermonnikoog (Figures 6.2.2 and 6.2.3). As this is an estuary and quite different to the other inlet systems it was decided to only give some of the basic data and not to discuss the development in detail.

6.3 Osterems

Basic data

Figure 6.3.1: overview of the inlet system in 2000.

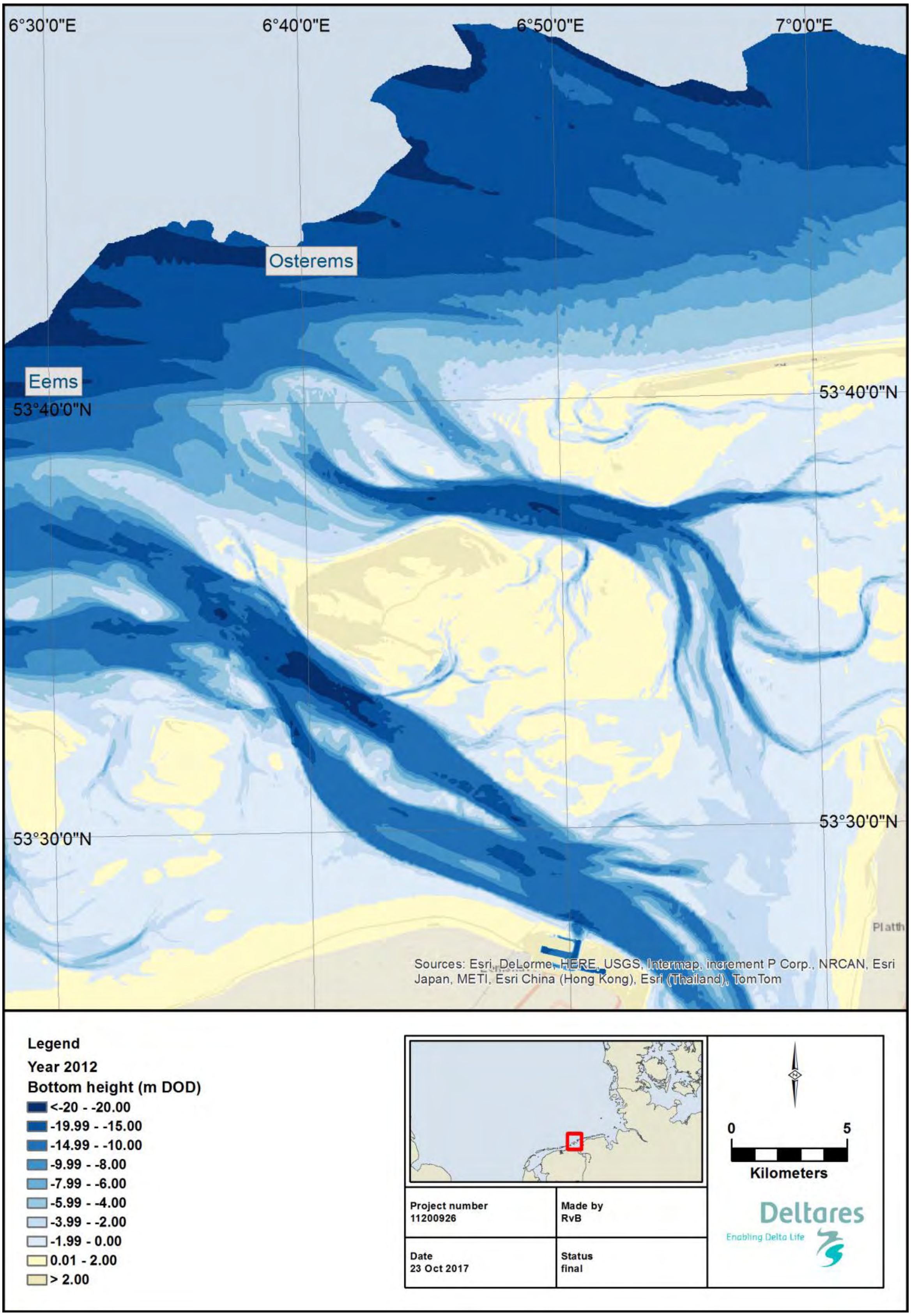


Figure 6.3.2: overview of the ebb-tidal delta of Osterems.

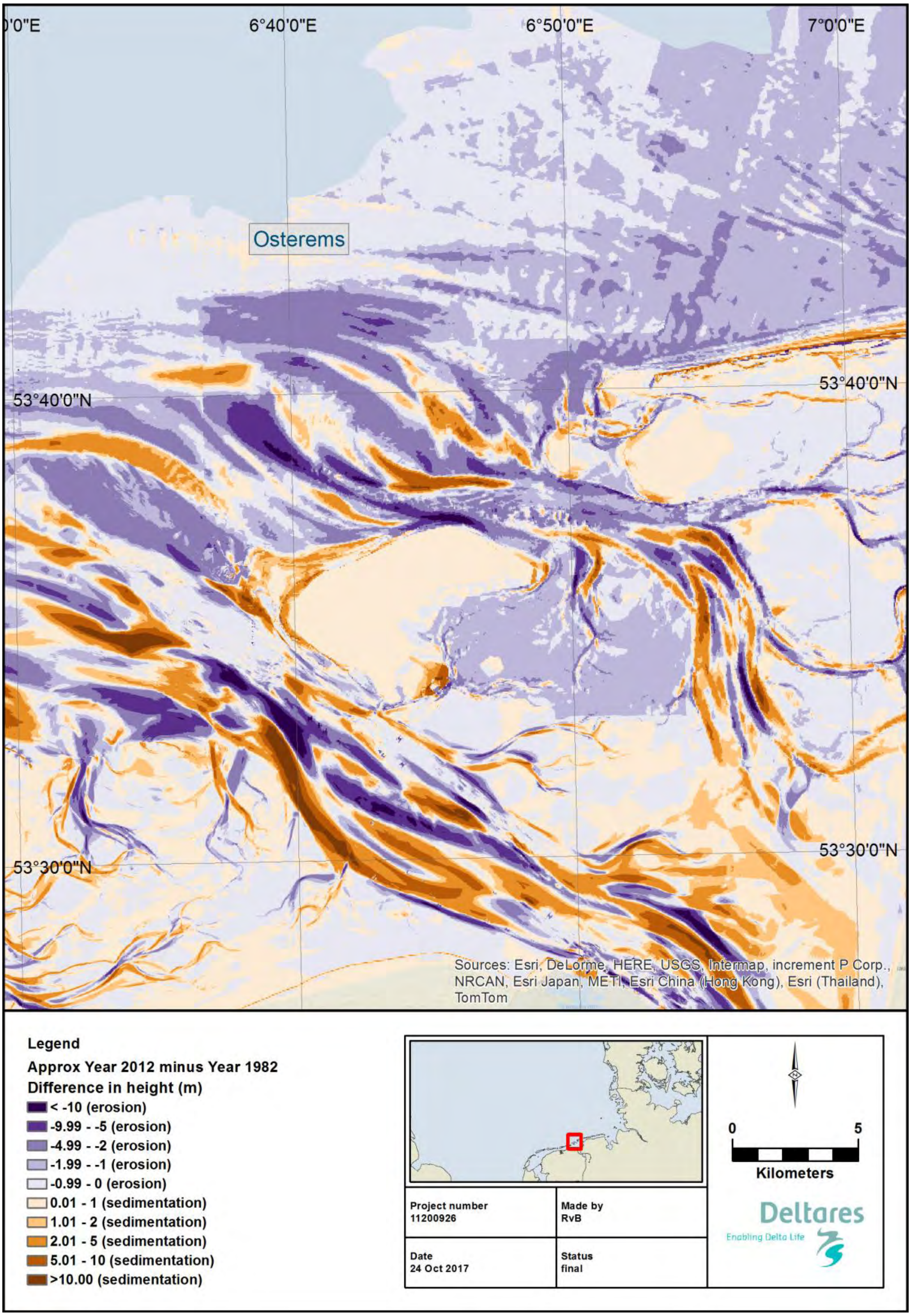


Figure 6.3.3: Osterems erosion and deposition over the period 1982-2012.

Table 6.2: Facts and figures Osterems (see also appendix I)

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)	2.2	1934-2001	2 (station Borkum)			
Hs (m)	1.26		CoastDat						
Tp (s).	5.84		CoastDat						
Tf/Te	0.99	2017 (2 tidal cycles of 3 jan)	3 (station Juist, Hafen)						
$L_{ebb\text{-}tidal\ delta}$ (km)	11	2012	-6 m	15	2012	-10m			
MHW (m NHN)	+1.2	2017	3 (station Juist, Hafen)						
MLW (m NHN)	-1.3	2017	3 (station Juist, Hafen)						
MTR (m)	2.4	1982	4	2.6	2017	3 (station Juist, Hafen)			
Surge height (m to MSL)									
Mean annual max surge height (m to AOD)	2.58		CoastDat						
A_{MHW} (km^2)	277	1975	5	296	1990	5			
A_{MLW} (km^2)	112	1975	5	139	1990	5			
A_{cross} (m^2)	46000	Ca. 2000	6						
V_{MHW} ($10^6 m^3$)									
V_{MHLW} ($10^6 m^3$)									
P ($10^6 m^3$)	525	1990	5 (Pmap)				523 (507-540)	2004-2005	7 Pcom (giving flood resp. ebb volume)
$SV_{backbarrier}$ ($10^6 m^3$)									
$SV_{ebb\text{-}tidal\ delta}$ ($10^6 m^3$)									
$AS_{backbarrier}$ ($10^6 m^3/yr$)	0	1990-2004/5	5 & 7						
$AS_{ebb\text{-}tidal\ delta}$ ($10^6 m^3/yr$)									
Longshore drift ($10^6 m^3/yr$)	+0.8	1990-2012 & 2006-2009	6	+0.5 to 1.5	1990-2012 & 2006-2009	6 (stations Schiermonnikoog & Elbe)			
Sediment transport direction?	E ward								
Development island coasts	Growth of Juist								

1 = Dillingh, 1013; 2 = Jensen & Mudersbach, 2007; 3 = BSH, 2016; 4 = Postma, 1982; 5 = Niemeyer, 1995; 6 = Ridderinkhof, 2016; 7 = Herrling, 2014;

Description of the tidal inlet system

The Lower Saxonian inlet system Osterems is situated between the barrier island of Borkum in the West and Juist east of it. SW of Juist the islet Memmertsand is situated and W of it, the Kachelotplate is present.

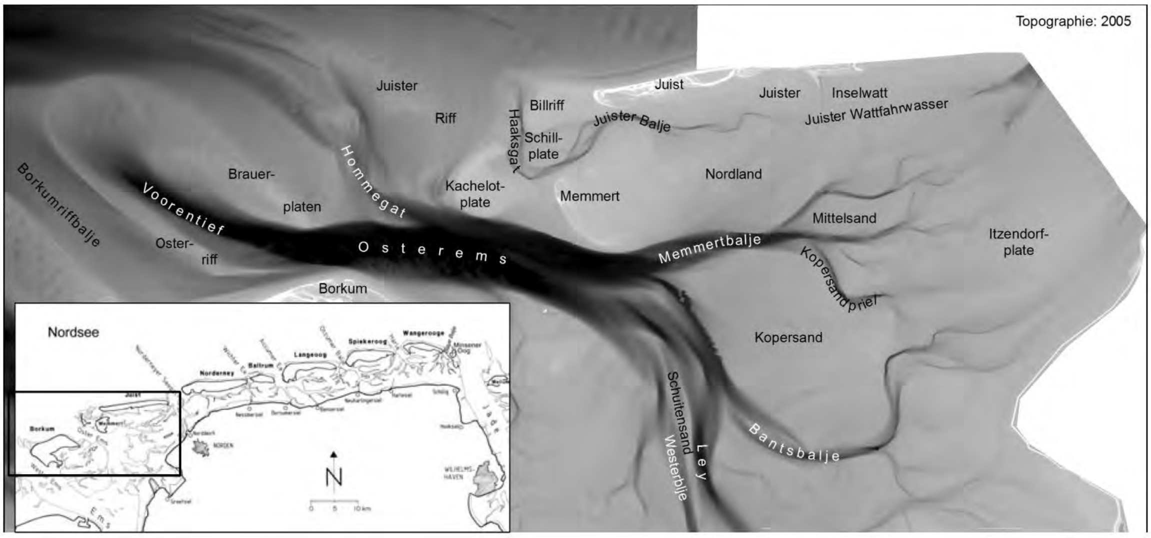
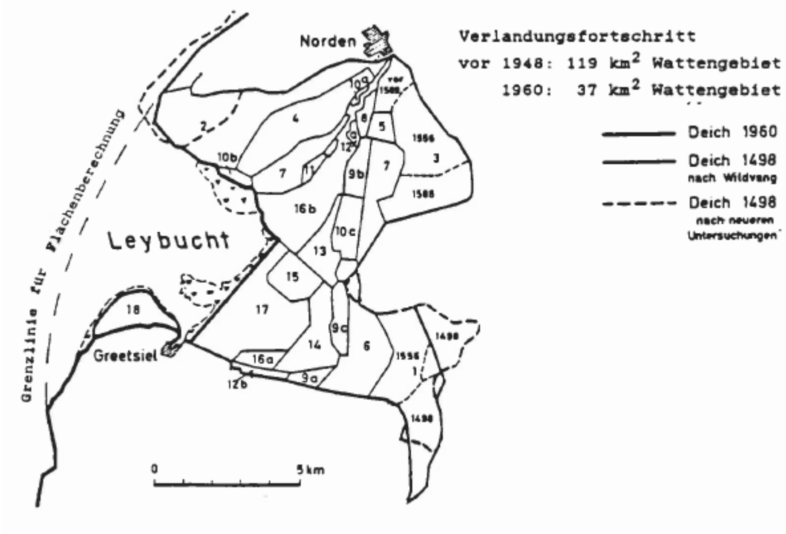


Figure 6.3.4: Toponymes of the Osterems inlet.

The Osterems can be considered a part of the Ems estuary (figure 6.3.1 to 6.3.4). Originally connections were quite strongly established, but in the 20th century the inlet became largely separated from the Westerems (the estuary). In the backbarrier area the embayment Leybucht (19 km^2) is present. It is the remnant of an embayment which formed probably as early as 838 AD (wiki; Figure 6.3.5). Medieval storm surges (1362, 1374 & 1376) enlarged the area to ca. 129 km^2 (Homeier, 1972; Abrahamse 1973). In the 15th century the embayment was reduced to 98.7 km^2, by 1650 to 59 km^2, and in 1950 it reached its present size (Abrahamse, 1973; Niemeyer, 1995). To reduce dredging and maintenance, the Leyhörn peninsula was constructed in 1984 to facilitate inland drainage and navigational access (Dissanayake et al., 2010).

Between the Leybucht and the Westerems there was the smaller Bucht von Sielmönken or Sielmönker Bucht; now on the territory of the present day municipality of Krummhörn. The bay reached its maximum dimensions between 800 to 950 A.D (Richter & Flathe, 2011). As Leybuch it silted up and was completely poldered between 1000 A.D. and the 13th century (Homeier, 1969).

The backbarrier area of the Osterems (total present-day area is 334 km^2) has been reduced with some 100 km^2 (Niemeyer, 1995) from the 14th century to 1650. Thereafter the reduction of the Leybucht was nearly compensated by eastward extension of its watershed against the backbarrier of the Norderneyer Seegat (Niemeyer, 1995). Indeed, the major part of the drainage area shifted from the Leybucht to the Memmertbalje S of Juist. It should be remarked that during the period 1935-1998 there was area loss of the Juister Balje (33%) and the northern arm of the Memmertbalje (10%), whereas the southern arm became 16% larger (Meyer & Stephan (2000). According to Niemeyer (1995) the E ward shift of the watershed cannot be explained by the direction of the littoral drift, because the tidal inlet of the Osterems migrated counter directional. However, such a development would allow a fast entrance of the flood flow coming from the West and might attribute to the eastward shift of the watershed.



Nr.	Jahr	ha	Polder
1	1498	860	Wirdumer Neuland
2	1551	1150	Westermarsch
3	1556/85	1090	Süderneuland
4	1583	550	Westermarscher Neuland
5	1593	100	Addingaster Lande
6	1603	420	Schoonorth
7	1678	610	Wester- u. Südercharlottenpolder
8	1715	70	Addingaster Polder
9a	1768		Magotspolder
9b	1769	360	Leysander Polder
9c	1770		Hagenpolder
10a	1774		Zuckerpolder
10b	1775	130	Buscherpolder
10c	1781		Schulenburger Polder
11	1789	40	Lorenz- u. Friedrichspolder
12a	1804	90	Teltingspolder
12b	1804		Angernpolder
13	1846	440	Ernst-August-Polder
14	1913	330	Schoonorther Polder
15	1924	170	Hohe-Plate-Sommerpolder
16a	1928	770	Cirksenapolder
16b	1929		Neuwesteel
17	1950	760	Leybuchtpolder
18	1956	270	Hauener-Hooge-Sommerpolder

Figure 6.3.5: Overview of the poldering of the Leybucht (Temmler, 1987).

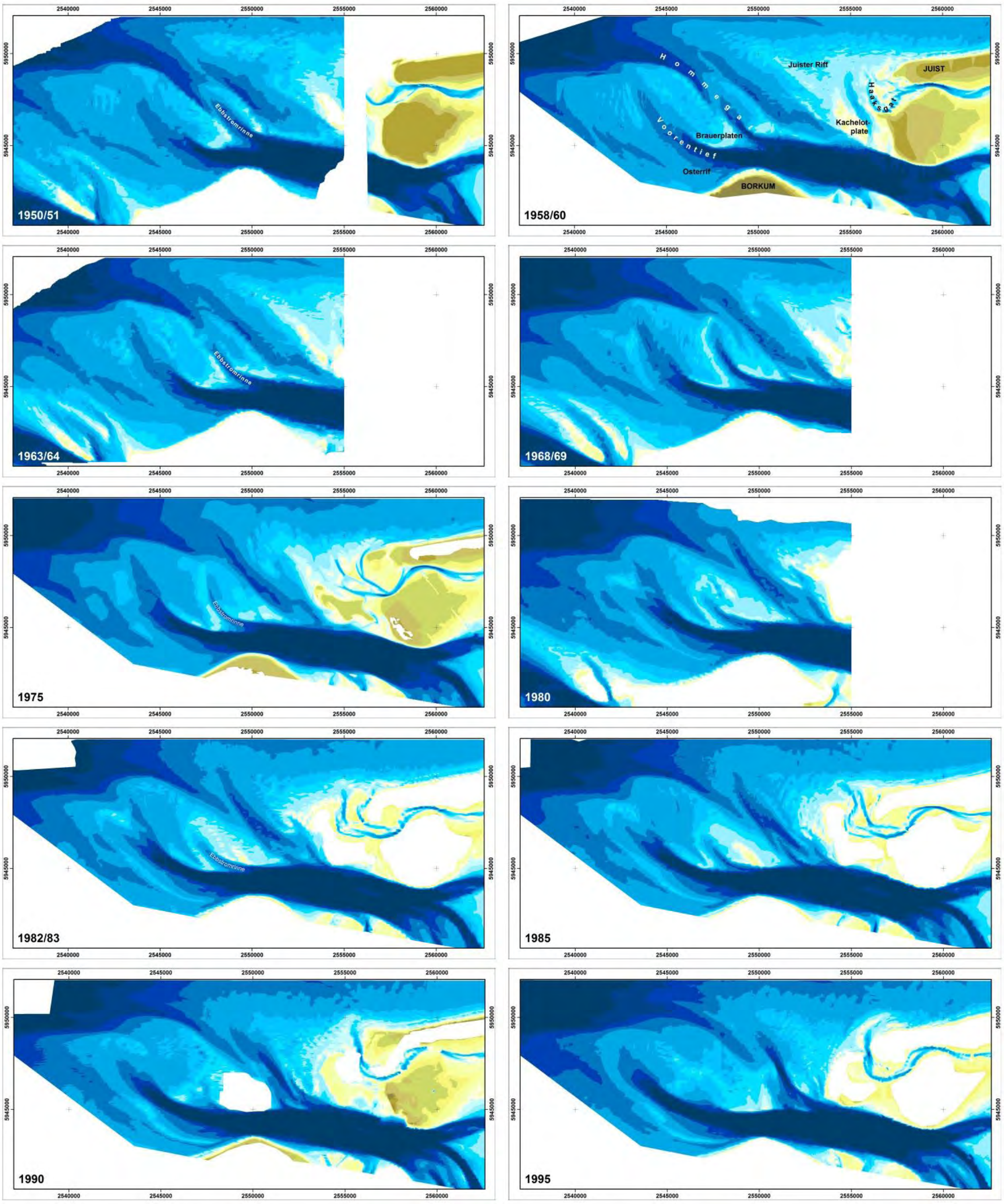
In the backbarrier also the island of Memmert is present since 1650, with a present-day area of 5.17 km^2. Tidal prism appears to have grown between 1960 and 1975 after which it decreased again. In more detail it appears that the eastern part of the backbarrier eroded up to 1990 after which sedimentation became important again (Meyer, 2013). In total the local tidal volume increased in that area with some 16%. Some parts of the area decreased some 40 cm in height over the period 1960-2010 (Meyer, 2013).

Development of the ebb-tidal delta

The main developments in the ebb-tidal delta are (Figure 6.3.6; Meyer, 2013):

1) a counter-clockwise rotating Osterems main channel around a centre of rotation SW of Memmert from a NW-SE-orientation to an almost W-E orientation, which started already in 1830;
2) An 2.5 km increase in length of the Voorentiefs ebb-tidal channel to the W between 1859-1963;
3) The Voorentiefs becoming the main channel at the expense of the more eastern Hommegat ebb-tidal delta channel.
4) Strong erosion of the Juister Riff due to erosion as a result of the reduction of the Hommegat.

As a result of the diminished role of the Hommegat and the inherent erosion and coastward retreat of the ebb-tidal delta shoal, the shoals were landing after ca. 1965 in more westward positions on the downdrift side. Figure 6.3.7 shows Landsat images of migrating shoals during the period 1984-2014. Three attached at the most westward part of the island of Juist (in 1990, 2000 and 2006). In addition, several shoals attached to a larger shoal that is located within the inlet, west of the Juister Balje, the channel closest to Juist.


1950/51
Ebbstromrinne
1958/60
Hommegat
Voorentief
Juister Riff
JUIST
Haaksgat
Kachelot-
plate
Brauerplaten
Osterrif
BORKUM
1963/64
Ebbstromrinne
1968/69
1975
Ebbstromrinne
1980
1982/83
1985
1990
1995

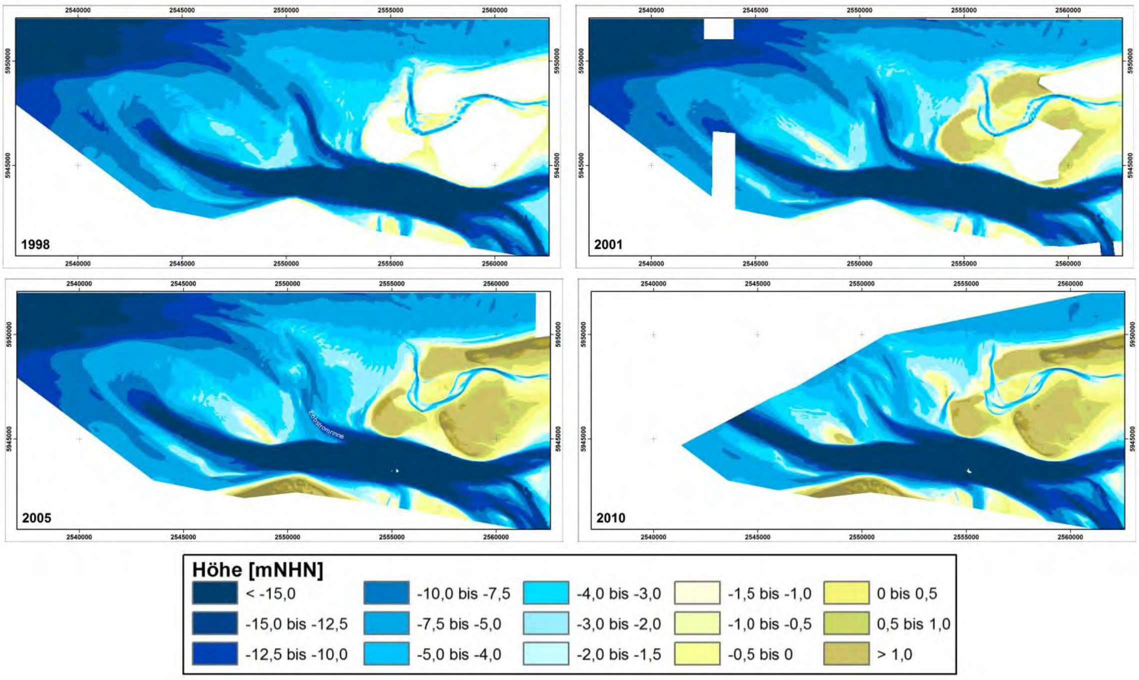


Figure 6.3.6: Morphological development of the Osterems ebb-tidal delta from 1950 – 2010 (Meyer, 2013).

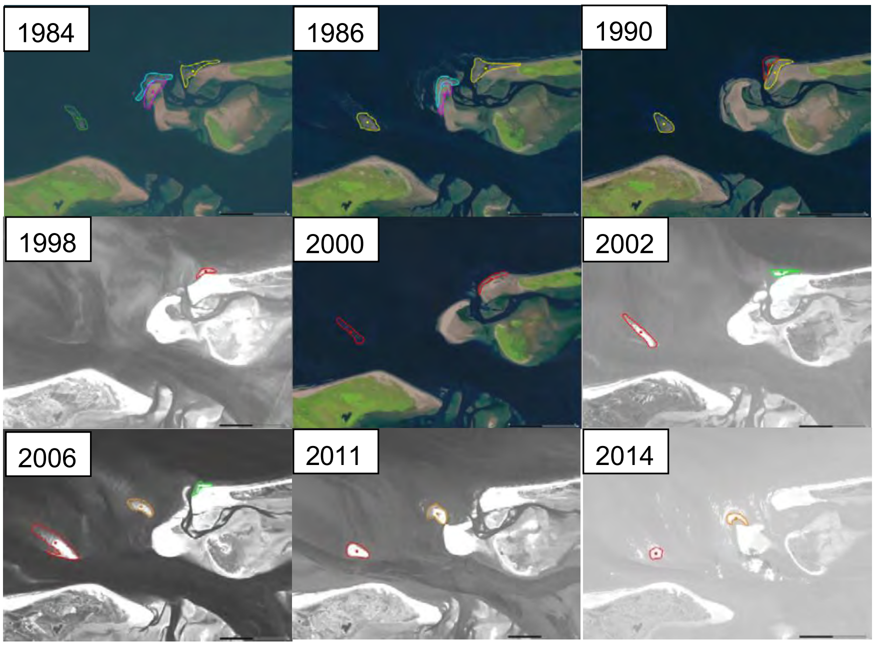


Figure 6.3.7: Landsat images of the ebb-tidal delta of the Osterems inlet in different years. Migrating shoals are marked by coloured polygons. Only a part of the migrating shoals attached to the island Juist, around 1990, 2000 and 2006 (Ridderinkhof, 2016).

Coastal development

Erosion occurs on Juist at the western part of the island (and foreshore), which was thought to be caused by structural changes in the hydro-morphological processes (Kunz, powerpoint 2009). Due to the anticlockwise shift of the main channel of the Osterems shoals of the main Riffbogen can no longer land on the island. The only sand shoals which are coming near are from the Juister Balje system, but land on the Billriff (Figure 6.3.8; Ladage & Kunz, 2002). This results in strong erosion at Juist west since 1965 (Kunz, powerpoint 2009). Indeed nourishments are needed on Juist (NLWKN, 2010).

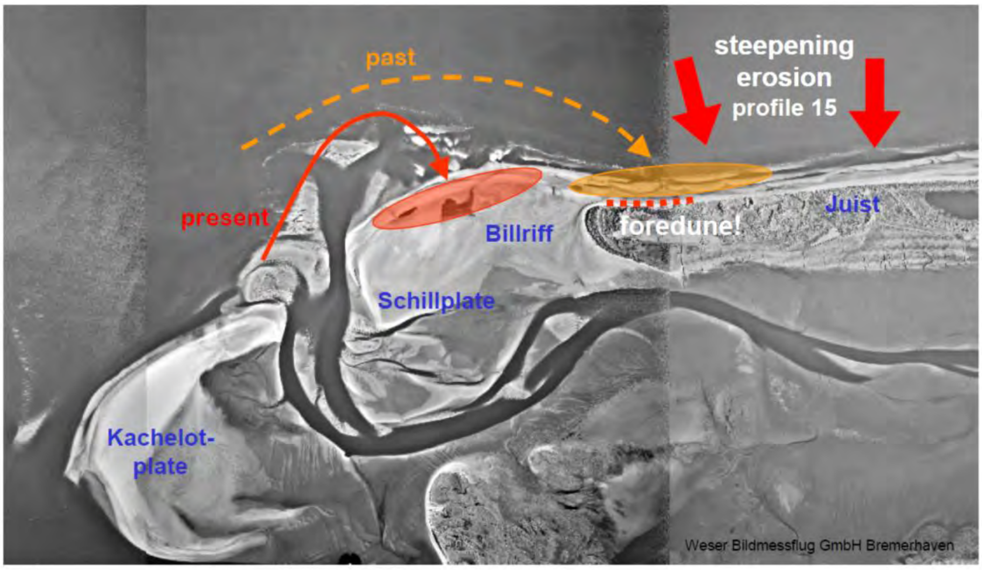


Figure 6.3.8: Course of the sediment transport via Sand Bars to Juist west (Aerial view 2001; Kunz, powerpoint 2009).

6.4 Norderneyer Seegat

Basic data

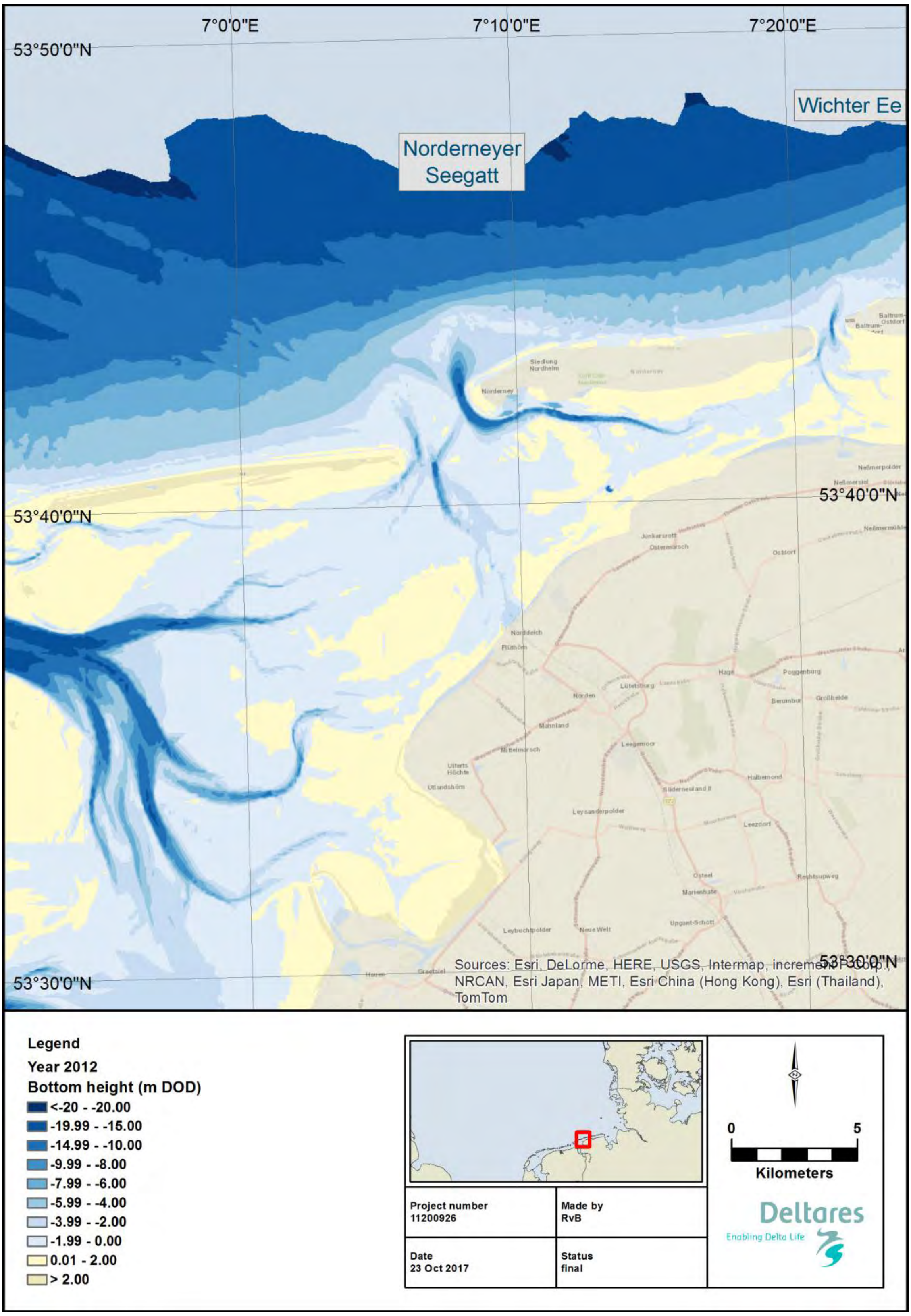


Figure 6.4.1: overview of the ebb-tidal delta of the Norderneyer Seegat.

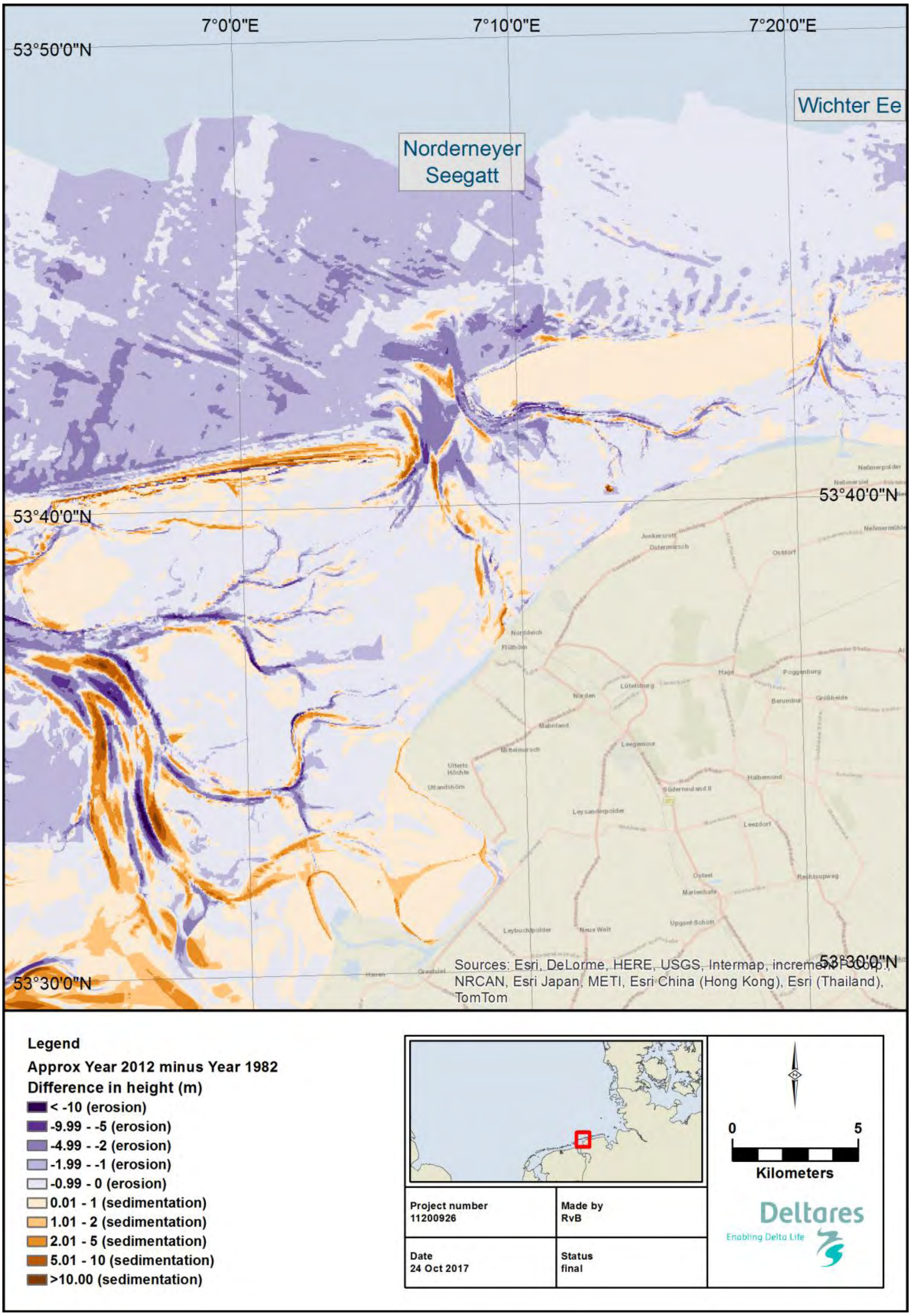


Figure 6.4.2: Norderneyer Seegatt erosion and deposition over the period ca. 1982-2012.

Table 6.3: Facts and figures Norderneyer Seegat (see also appendix I)

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2.0	1891 - 2001	1 (station Norderney)						
Hs (m)	1.28		CoastDat						
Tp (s).	5.64		CoastDat						
Tf/Te	0.97	2017 (2 tidal cycles of 3 jan)	2 (Norderney, Riffgat)						
$L_{ebb\text{-}tidal\ delta}$ (km)	3.5	2012	-6 m	4.5	2012	-10m			
MHW (m NHN)	1.2	2017	2 (station Norderney, Riffgat).						
MLW (m NHN)	-1,3	2017	2 (station Norderney, Riffgat).						
MTR (m)	2.5	2017	2 (station Norderney, Riffgat).						
Surge height (m to MSL)									
Mean annual max surge height (m to AOD)	2.73		CoastDat						
A_{MHW} (km^2)	112±2	~2000	3						
A_{MLW} (km^2)	20	1975	4	32	1990	4	28±6	~2000	3
A_{cross} (m^2)	15250	2010	5	15750	2012	5			
V_{MHW} (10^6 m^3)									
V_{MLW} (10^6 m^3)									
P (10^6 m^3)	183 (167-199)	2004-2005	6 Pcom (giving flood resp. ebb volume)	179	2005	5(Pbat, mean tidal range)	176	2012	5 (Pbat, mean tidal range)
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)	43	2007	5 (fixed refer-ence profile)	54	2008	5 (fixed reference profile)			
$AS_{backbarrier}$ (10^6 m^3/yr)									
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)	0,6	1990-2004/6	5						
Longshore drift (10^6 m^3/yr)	+1.3	1990-2012 & 2006-2009	7	+1.2 to 1.4	1990-2012 & 2006-2009	7 (stations Elbe & Schiermonnikoog)			
Sediment transport direction?	E								
Development island coasts	E Juist more or less stable; Erosion NW Nor-derney; Sedimentation more to the E								

1 = Jensen & Mudersbach, 2007; 2 = BSH, 2016; 3 = Stanev et al., 2003 (± = indicating neap and spring tide conditions); 4 = Niemeyer, 1995; 5 = Meyer, 2014; 6 = Herrling, 2014; 7 = Ridderinkhof, 2016.

Description of the tidal inlet system

The Lower Saxonian inlet system Norderneyer Seegat is situated between the barrier island of Juist in the West and Norderney east of it (Figure 6.4.1-6.4.3). Most likely, the inlet system originally consisted originally out of two inlet systems: Busetief at the west side of the, now vanished, barrier island Buise and the tidal inlet east of it. The island Buise disappeared and one ebb-tidal delta formed with wider spread swash bars. The disappearance of the shelter provided by Buise and the fact that both tidal systems Buisegat and Norderneyer Gat merged allowed for higher wave energy which likely changed part of the backbarrier into a subtidal area (Niemeyer, 1990, 1995). The wave attack led to the disappearance of a broad stretch of supratidal salt marshes in front of the mainland dikes between 1650 and 1750. After the dike breaches during the storm surge of 1717 coastal retreat became necessary (Niemeyer, 1995). In 1860 the inlets Buisegat and Norderneyer Gat had merged into the Norderneyer Seegat. This led to a situation where the ebb-tidal delta became less pronounced with swash bars and shallows spread wider. The tidal energy was funnelled leading to a relative increase of subtidal backbarrier area near the inlet (Niemeyer, 1995). Now especially the eastern part of the mainland coast started to suffer from erosion and the storm surge of 1825 flooded several polders which had to be given up. From 1860 onwards the tidal inlet was fixated by the construction of groynes across its eastern channel wall. The areal losses of the Norderneyer Seegat tidal basin have been compensated by an eastward shift of its watershed at the cost of the Wichter Ee between 1650 and 1860 (Niemeyer, 1995).

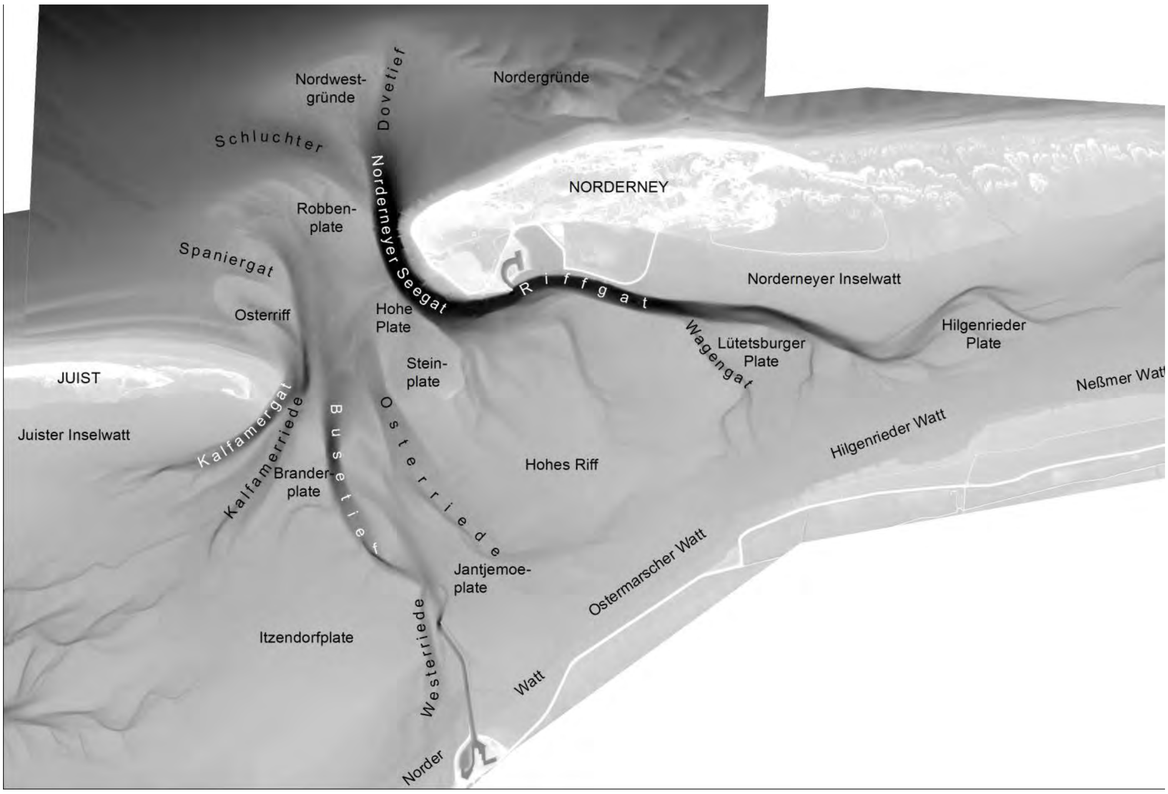
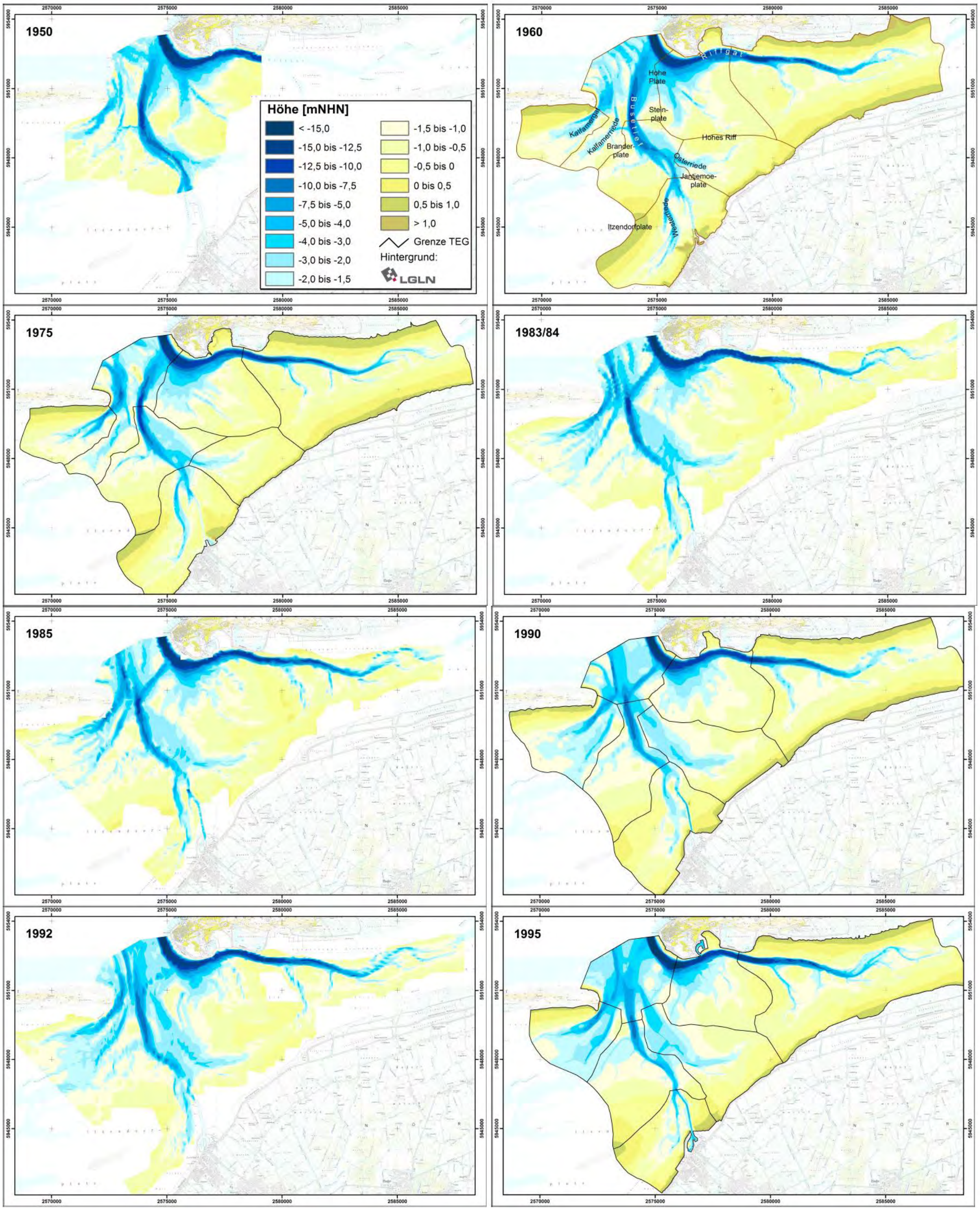


Figure 6.4.3: Toponyms of the Norderneyer Seegat (Meyer, 2014).

At the mainland in the present-day municipality Hagermarsch the small embayment *Hilgenrieder Bucht* was present. It is believed to have been formed early (4th century?) as a result of erosion at the mouth of one or more small streams. It has been filled up and by 1300 the embayment was poldered (Homeier, 1969).

Like many of the inlets in the West and East Frisian Wadden area, the Norderneyer Seegat nowadays actually exists of two more or less separated inlet systems, which may influence each other: the Kalfamergat-Busetief system at the west side and the bigger Norderneyer Seegat-Riffgat system at the east side (Figure 6.4.3). The Busetief intermittently connects to the Kalfamergat and to the NNW and to the Norderneyer Seegat-Riffgat system. Up to ca. 1975 the Norderneyer Seegat as a whole was relatively morphological stable in form and position and sedimentation dominated the backbarrier area. During the period 1975-1990 tidal volume increased from 181 to 195*10^6 m^3, after which it decreased again to 176*10^6 m^3 in 2012 (Meyer, 2014). The increase in tidal volume was especially important at the west side. Two periods (1975-1985 & 1995-1998) of general height loss (total 45 cm on average) occurred in the backbarrier area, which were not compensated by the vertical average growth in the other years (in the period 1935-1998; Meyer & Stephan, 2000). This occurs especially in the Kalfamergat-Busetief system, where intertidal shoals became subtidal shoals. The explanation can probably be found in a series of events, starting with tidal prism increase during the period 1932-1998 when the Kalfamergat enlarged its tidal area with 40% by a westward shift of the watershed S of Juist (Meyer & Stephan, 2000). Increasing depths of the inlet channels led probably to the observed deepening below MLW of tidal flats near the inlet. In the same period Busetief shifted from a connection with Norderneyer Seegat in 1970 to the Kalfamergat system by 1992 and back again in 2001, thereby causing a deepening in the mouth during some stages. An increase of wave influence on the backbarrier area due to the development of a more direct elongated passage way through the ebb-tidal delta (around 1984/85), may have further enhanced the lowering of the flood-tidal delta, as is suggested by the strong deepening E of the Busetief channel between 1975 and 1984/85.



1950
Höhe [mNHN]
< -15,0
-15,0 bis -12,5
-12,5 bis -10,0
-10,0 bis -7,5
-7,5 bis -5,0
-5,0 bis -4,0
-4,0 bis -3,0
-3,0 bis -2,0
-2,0 bis -1,5
-1,5 bis -1,0
-1,0 bis -0,5
-0,5 bis 0
0 bis 0,5
0,5 bis 1,0
> 1,0
Grenze TEG
Hintergrund:
LGLN
1960
Riffgat
Hohe Plate
Stein-plate
Busetief
Kalfamergat
Kalfamerriede
Brander-plate
Hohes Riff
Osterriede
Jantjemoe-plate
Westerriede
Itzendorfplate
1975
1983/84
1985
1990
1992
1995
2570000
2575000
2580000
2585000
5954000
5951000
5948000
5945000

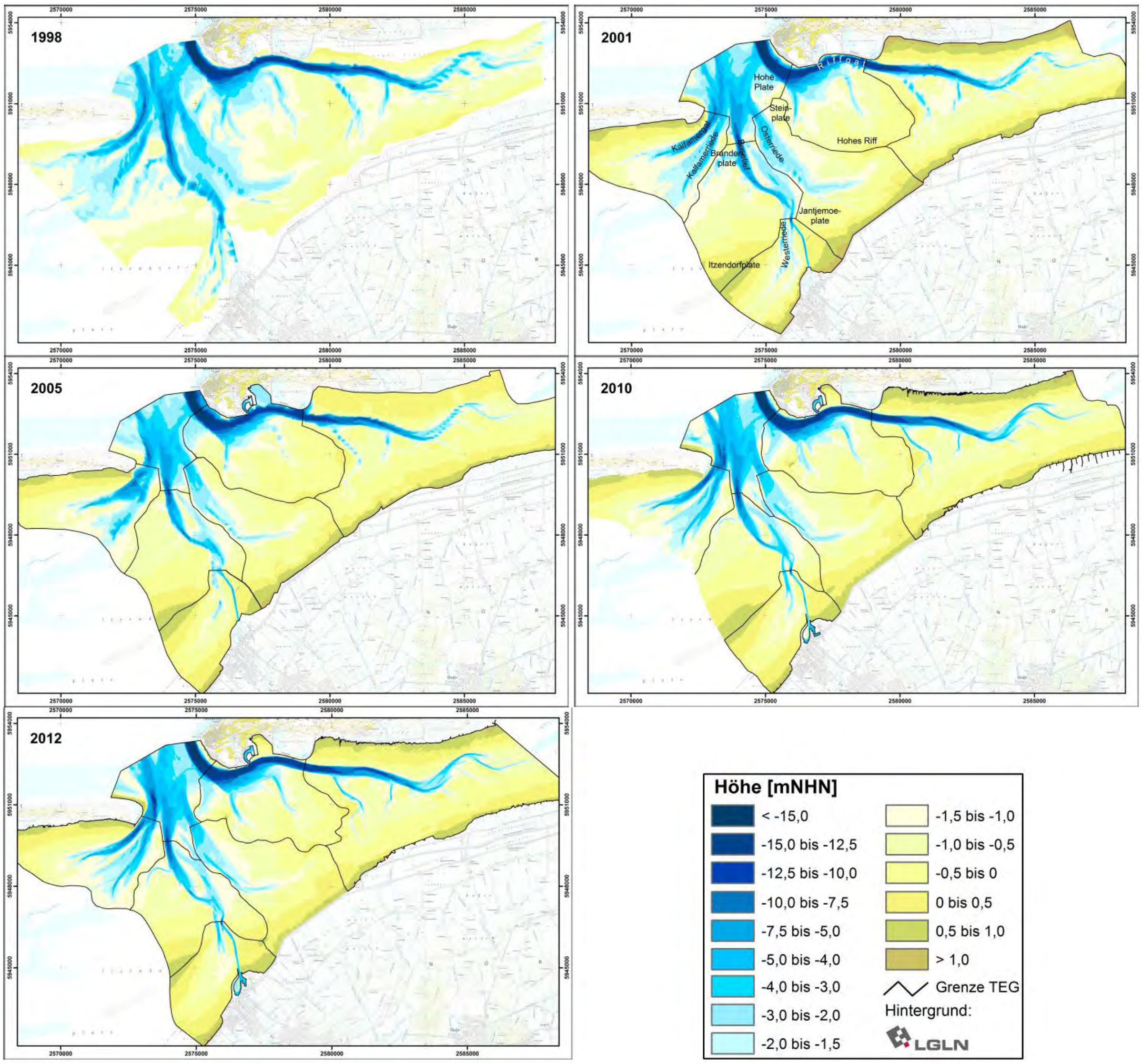


Figure 6.4.4: Overview of the backbarrier development of the Norderneyer Seegat (Meyer, 2014).

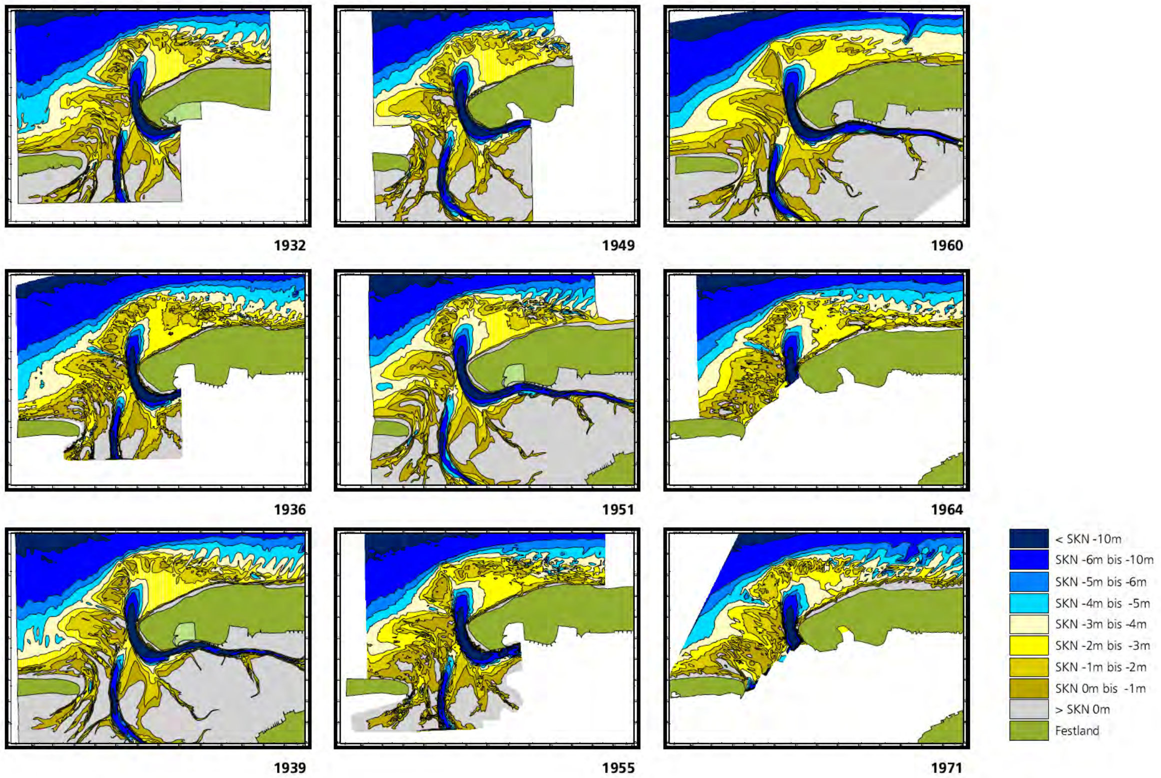
Development of the ebb-tidal delta

Up to ca. 1975 the ebb-tidal delta was compact (Figure 6.4.5 & 6.4.6). After that morphodynamic changes became more influential. The Busetief channel alternates its discharge, part of the time into the Norderneyer Seegat and part of the time towards the NW (Meyer & Stephan, 2000; Meyer, 2014). During the latter stage the Busetief discharges predominantly via the Spaniergat (Meyer, 2014). Due to the strong increase in tidal prism of the Kalfamergat it extended in a northern direction and became increasingly connected in the ebb-tidal delta with the NNW oriented Spaniergat over the period 1932-2008 (Meyer & Stephan, 2000; Meyer, 2014). In 1984/85 the Kalfamergat-Busetief-system dissected the western part of the ebb-tidal delta (Meyer, 2014) and swash bar development became less pronounced at the Riffbogen allowing the Norderneyer Seegat to orient to the NW.

In 1992 the main channel of the Norderneyer Seegat was oriented to the NW. In the period 1992-2001 the main channel shifted to the E over 50 degrees, as bars built up at its west side, after which the shoals at the west-side migrated along the terminal ebb-tidal delta lobe to the E and the channel re-established a more NW orientation up to 2007. After 2007 new shoals started to build up the west-side of the channel, leading once more to a situation which was comparable to that of 2001 (see Meyer, 2014).

Originally the inlet discharged over a broad front over the northern part of the Riffbogen, but by 1998 the outflow was concentrated into the N oriented channel which protruded far seaward. Due to this process the ebb-tidal delta lobe also got an increasingly northward position and the bars were forced to follow a more seaward positioned path around the inlet. Large amounts of sediment accumulated at the northwest side of the inlet (Bremermann & Meyer, 2012).

The migration of the bars on the Riffbogen of the Norderneyer Seegat has been studied in detail (Bremermann & Meyer, 2012). The (fluctuating) line of the Riffbogen defines the main migration direction of the shoals. It was shown that the shoals migrate with different celerities. At the west side of the ebb-tidal delta the shoals migrate with some 250-300 m/yr. While migrating northward along the west-side of the Norderneyer Seegat they accelerate from 350 m/yr (S) to 430 m/yr at the northern end. After they have reached the northeast side of the inlet they slow down and shift ESE at 250-300 m/yr (Bremermann & Meyer, 2012).



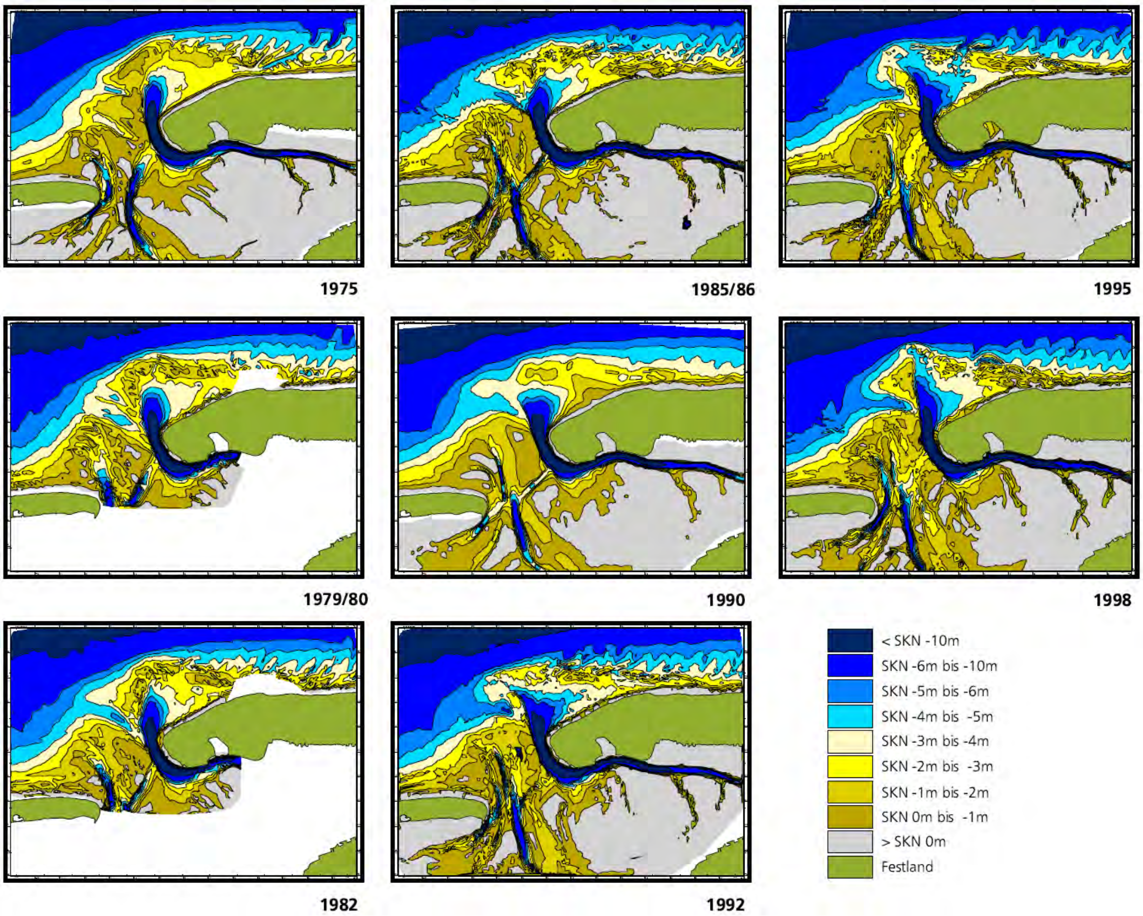


Figure 6.4.5: Overview of the development of the ebb-tidal delta of the Norderneyer Seegat over the period 1932-1992 (Meyer & Stephan, 2000).

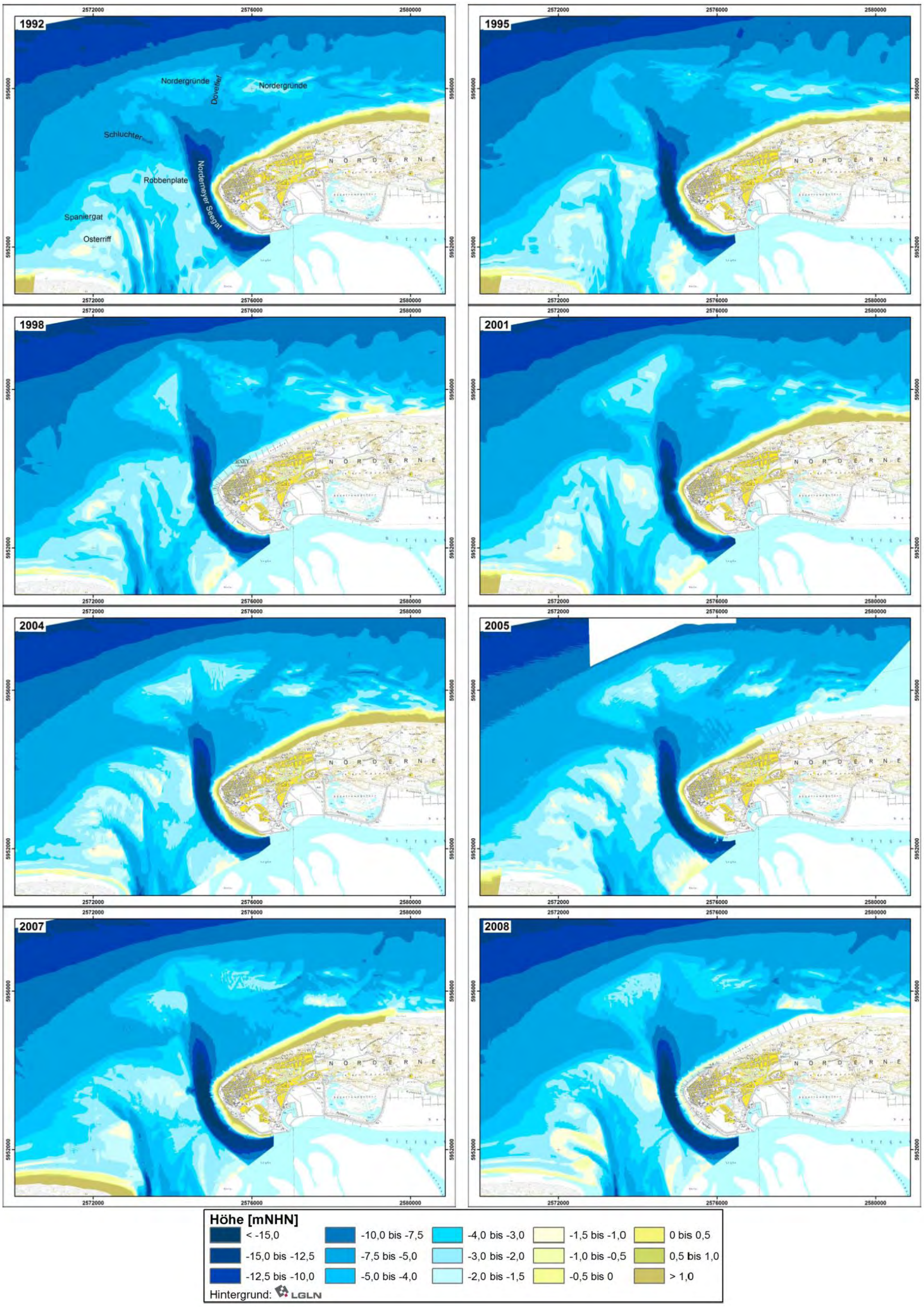


Figure 6.4.6: Overview of the development of the ebb-tidal delta of the Norderneyer Seegat over the period 1992-2008 (Meyer, 2014).

Coastal development

The growth of Norderney in an eastward direction has been attributed to the feeding of sand via the ebb-tidal delta's Riffbogen (Nummedal & Penland, 1981). Migrating, on average 37 years, over the Riffbogen many of the bars merge with the downdrift island Norderney (Figure 6.4.7; Bremermann & Meyer, 2012). Next to that there is also a substantial and fast bedload transport of sand over the ebb-tidal delta to the E.

The merger point of the swash bars with the barrier island Norderney has shifted towards the E after 1975 (Meyer & Stephan, 2000). Although the Norderneyer Seegat shifted again to the N in the period 1992-2008 the swash bar merger point remained situated more to the E then before 1975. The position of the Riffbogen has been rather stable since at least 1992 (see figure 6.4.7). This might be attributed to the elongating main channel (see Bremermann & Meyer, 2012; Meyer, 2014). Shoals land more or less on the same place at 5 km from the western tip of the island: the point where the "shoulder" of Norderney is located (Figure 6.4.8; Nummedal & Penland, 1981; Bremermann & Meyer, 2012). Over the period 1992-2005 four shoals approached the island, changed into swash bars and merged (Bremermann & Meyer, 2012). Around that area and E of it sufficient sediment is available. More to the northwest side of the island there is a deficiency of sediment and protection works and, since 1951 regular sand nourishments are needed (Kunz, 1990; powerpoint 2009; NLWKN, 2010).

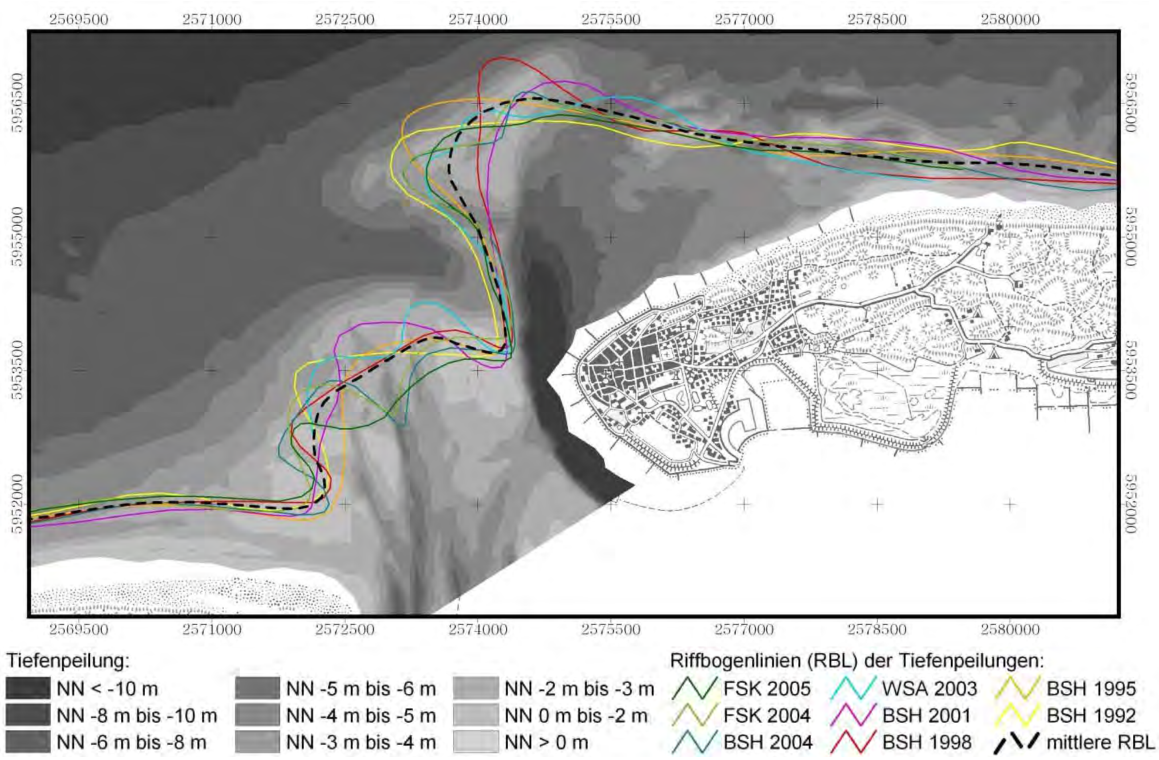


Figure 6.4.7: Overview of the average location of the highest part Riffbogen on the ebb-tidal delta (Bremermann & Meyer, 2012).

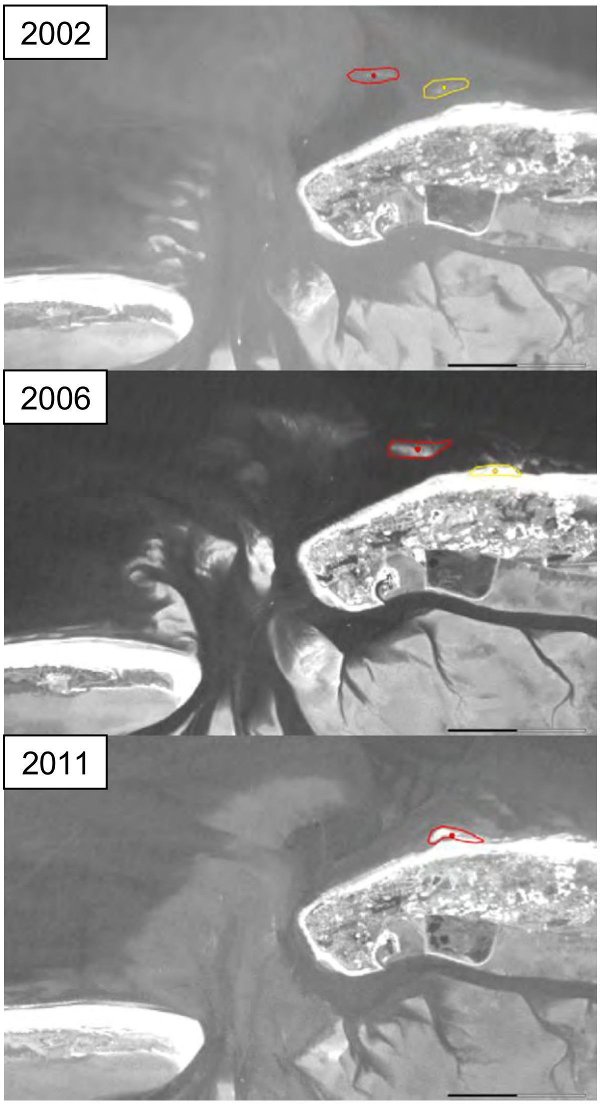


Figure 6.4.8: Landsat images of the ebb-tidal delta of Norderneyer Seegat, showing shoal attachment to the coast of Norderney in 2006 and 2011 (Ridderinkhof, 2016).

6.5 Wichter Ee

Basic data

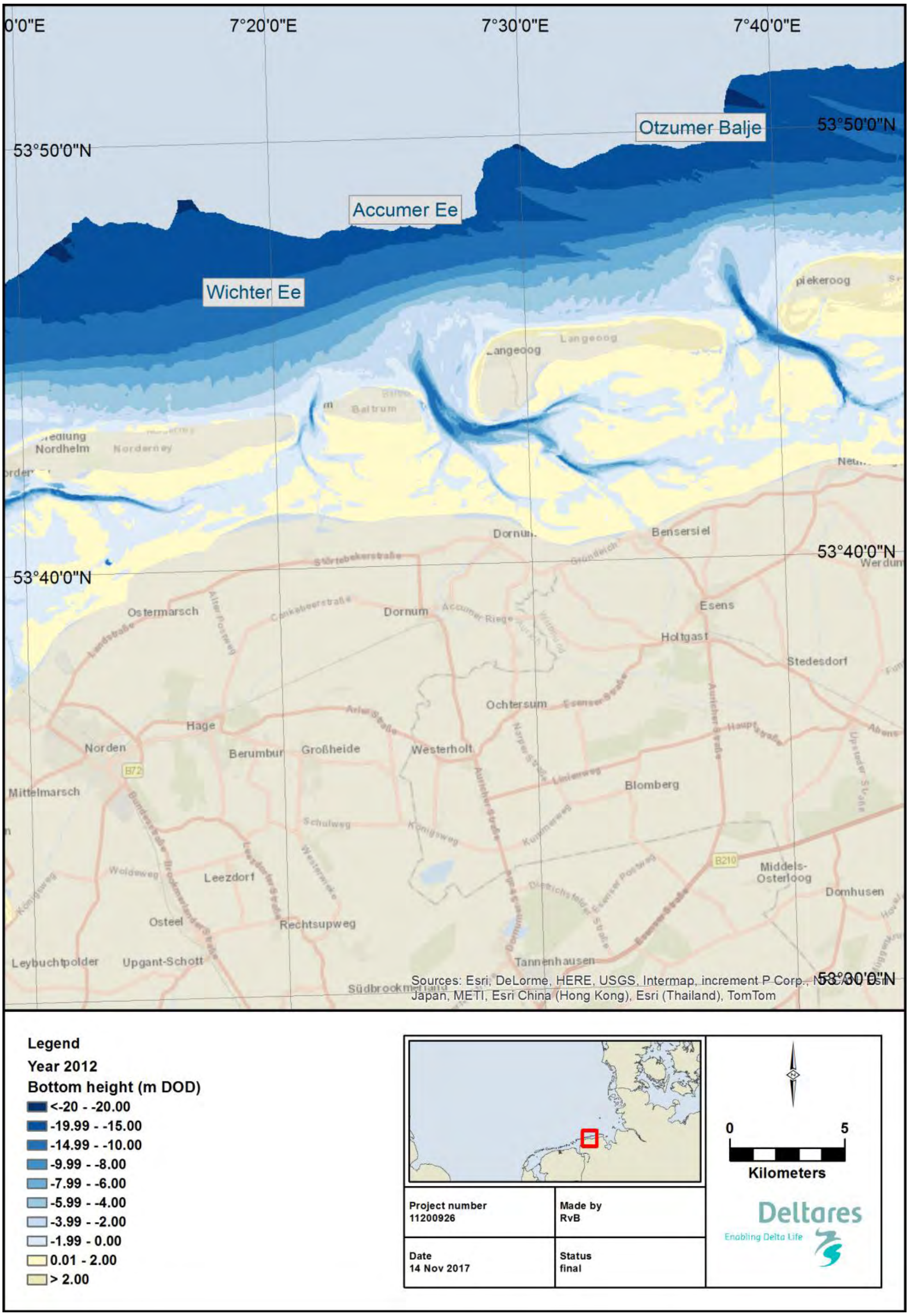


Figure 6.5.1: Overview of the ebb-tidal deltas of Wichter Ee and Accumer Ee.

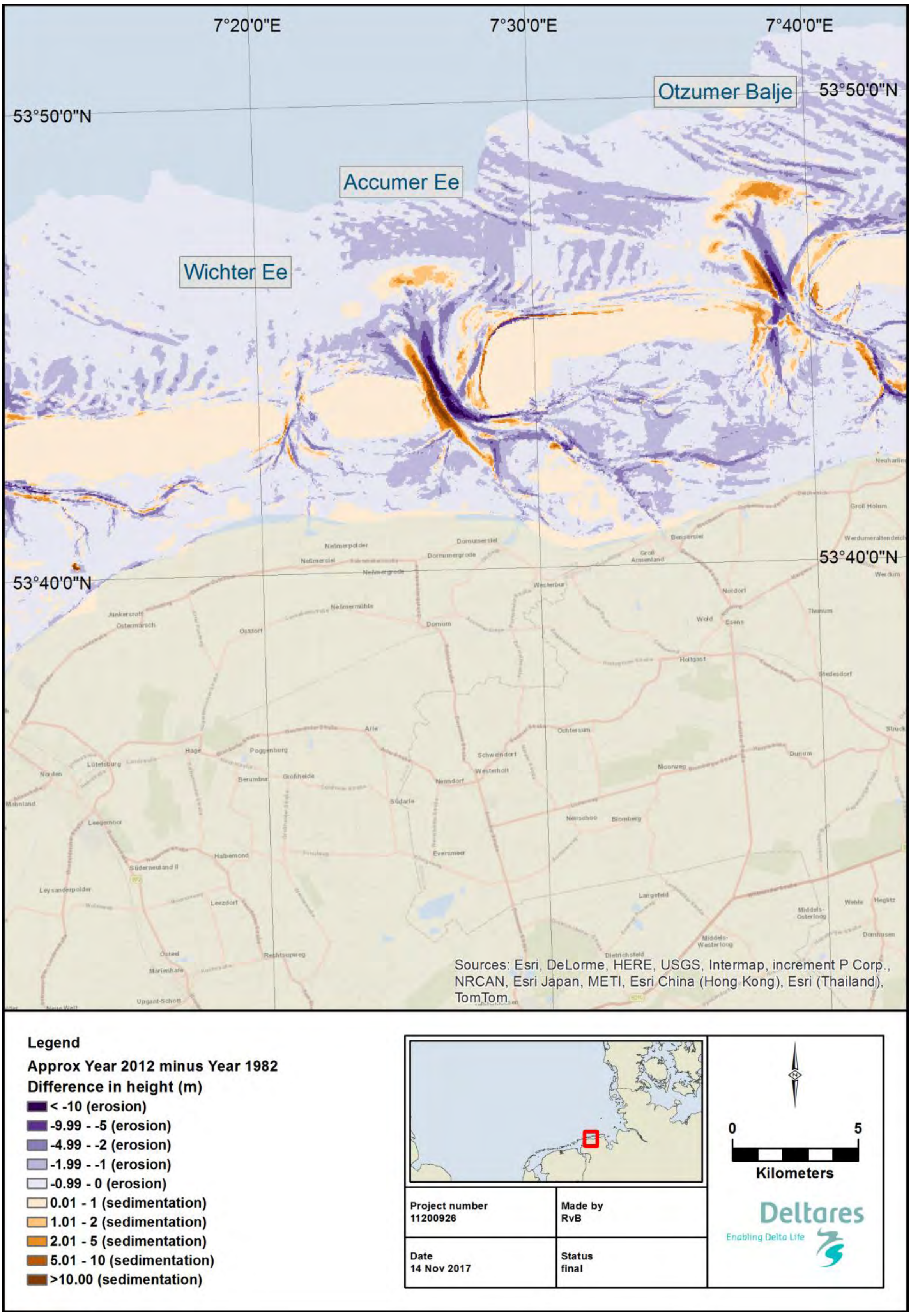


Figure 6.5.2: Wichter Ee & Accumer Ee erosion and deposition over the period 1982-2012

Table 6.4: Facts and figures Wichter Ee (see also appendix I)

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2.0	1891 - 2001	1 (station Norderney)						
Hs (m)	1.19		CoastDat						
Tp (s).	5.6		CoastDat						
Tf/Te	0.89	2017 (2 tidal cycles of 3 jan)	2 (station Baltrum, West-ende)						
$L_{ebb\text{-}tidal\ delta}$ (km)	2.5	2012	-6 m	4.5	2012	-10m	1.7	1989	3
MHW (m NHN)	1.3	2017	2 (station Baltrum, West-ende)						
MLW (m NHN)	-1.2	2017	2 (station Baltrum, West-ende)						
MTR (m)	2.4	1982	4	2.5	2017	2(station Bal-trum, Westende)			
Surge height (m to MSL)									
Mean annual max surge height (m to AOD)	2.81		CoastDat						
A_{MHW} (km^2)	26	1975	5	23	1990	5	23	1995	6
A_{MHW} (km^2)	22 ±0	~2000	7						
A_{MLW} (km^2)	2	1975	5	3	1990	5	3 ±1	~2000	7
A_{cross} (m^2)	3300	1999	8	3300	2001	8	2960	2004	8
V_{MHW} (10^6 m^3)	37±6	~2000	7						
V_{MLW} (10^6 m^3)	6±1	~2000	7						
P (10^6 m^3)	35±4	~2000	7 (Pcom)	35 (31-38)	2004-2005	8 (Pcom) (flood- resp. ebb vol-ume)			
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)	10	2004	8						
$AS_{backbarrier}$ (10^6 m^3/yr)									
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)	0,5	1988/92-2004	8						
Longshore drift (10^6 m^3/yr)	+1.2	1990-2012 & 2006-2009	9	+1 to +1.4	1990-2012 & 2006-2009	9 (stations Elbe & Schiermon-nikoog			
Sediment transport direc-tion?	E								
Development island coasts	Erosion of W Baltrum; extension of E Norderney.								

1 = Jensen & Mudersbach, 2007; 2 = BSH, 2016; 3 = Sha, 1989; 4 = Postma, 1982; 5 = Niemeyer, 1995; 6 = Ferk, 1995; 7 = Stanev et al., 2003 (± indicating neap and spring tide conditions); 8 = Herrling, 2014; 9 = Ridderinkhof, 2016.

Description of the tidal inlet system

The Lower Saxonian inlet system Wichter Ee is situated between the barrier island of Norderney in the west and Baltrum east of it (Figure 6.5.1 to 6.5.3). The watershed between the Norderneyer Seegat and the Wichter Ee shifted some 6,5 km eastward between 1650 and 1960 (Figure 6.5.4; Luck, 1975), but the eastern watershed of the Wichter Ee tidal basin shifted only with some 2.4 km. The west coast of Baltrum eroded in the period 1650-1860 and moved more than 4 km eastward, but the Baltrum watershed migrated slightly westward after the fixation of the Wichter Ee in 1873. Around 1000 A.D., the Neßmer Bucht was present on the mainland (in front of dwelling hills of Dorum and Nesse). After 1000 A.D. the embayment silted up. In the 16th century it was diked.

After protecting Norderney and the fixating the Norderneyer Seegat, migration of the watershed has decreased slowly: the channel Norderneyer Riffgat extended another 2.2 km to the E in the period 1860-1960. Next to the changes in the position of the watersheds also diking at the mainland decreased the size of the backbarrier area. As a result the backbarrier area up to MHW was reduced over the period 1650-1960 from 54 to 22 km^2 and the area up to MLW from 10 to 2 km^2 (table 6.4; Niemeyer 1995).

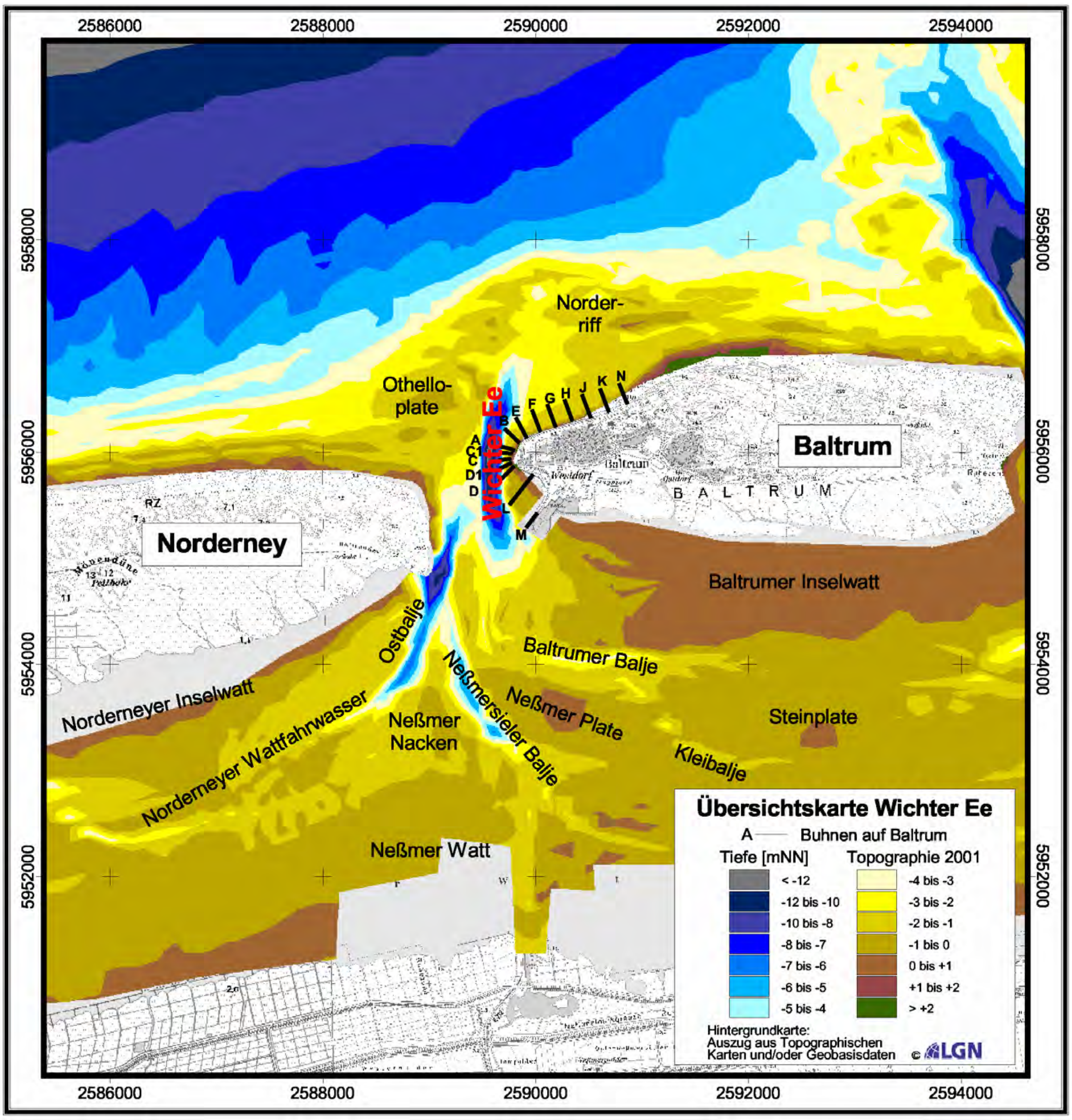


Figure 6.5.3: Toponymes of the Wichter Ee.

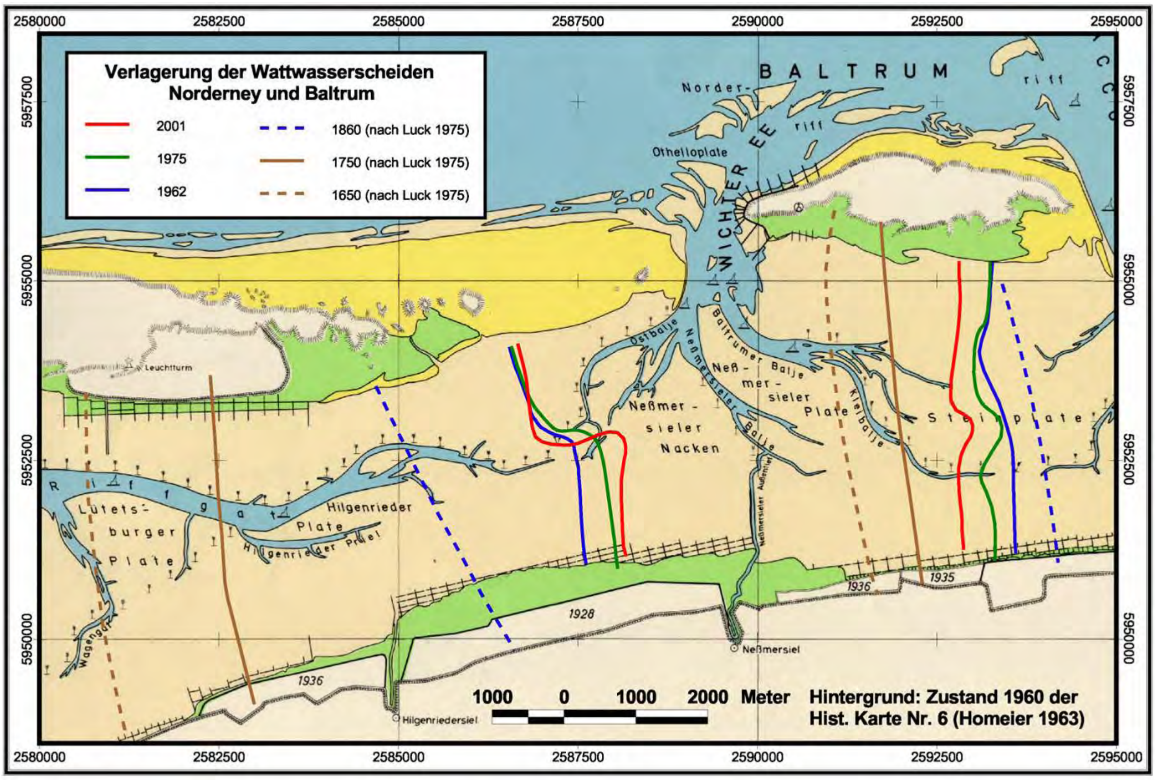
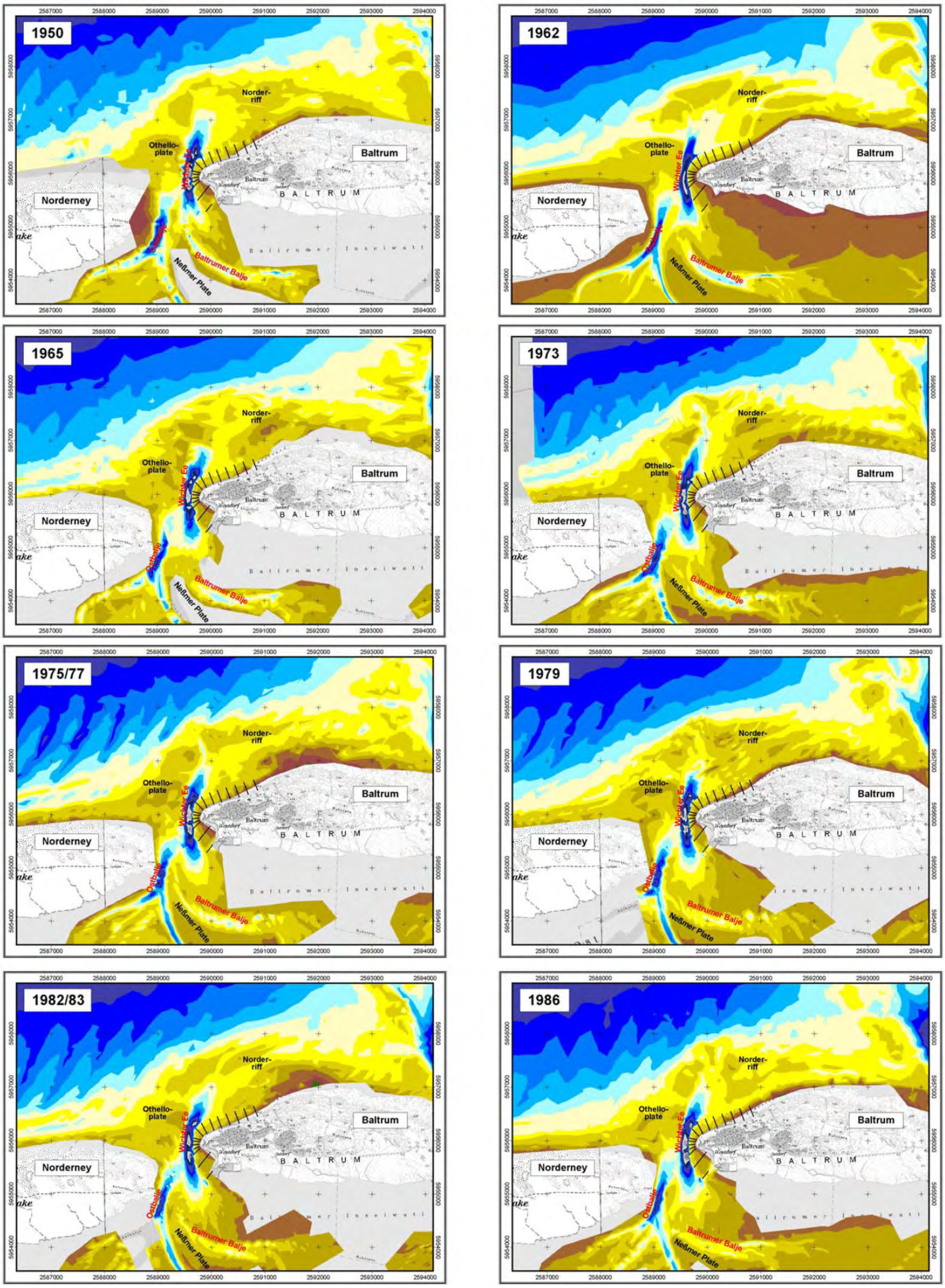


Figure 6.5.4: positions of the watersheds of the Wichter Ee inlet (Ladage & Stephan, 2005).

The observed long-term developments continued after 1960 (figure 6.5.4). The watershed of Norderney shifted at its southern part 550 to 700 m to the E in the period 1962-2001. In the same period the watershed of Baltrum shifted some 350 m W at its north side and 750 m at its south side. As a result the tidal area was reduced in the period 1962-2001 to 21.3 km^2, or with 17%, and the tidal volume was reduced with 11% (Ladage & Stephan, 2005).

Development of the ebb-tidal delta

In the Wichter Ee inlet only small changes occurred since 1950 (Figure 6.5.5). Apparently the changes in the hydrodynamic conditions are too small to cause big changes in the inlet. The northward extent of the Wichter Ee only decreased slightly in the period 1950-2004, probably due to the slightly reducting tidal volume in the same period. The inlet's cross sectional area fluctuates temporarily due to the entrance of the Ostbalje in the Wichter Ee, leading to scour holes. An analysis of the Riffbogen of the Wichter Ee showed that the eastern part has retreated landward with reference of its position before 1975, but did not change at its west side (Ladage & Stephan, 2005). The volume of the ebb-tidal delta has decreased over the period 1950-1995 and grown until 2004.


1950
1962
1965
1973
1975/77
1979
1982/83
1986
Norder-
riff
Othello-
plate
Baltrum
BALTRUM
Norderney
Wichter Ee
Ostbalje
Baltrumer Balje
Neßmer Plate
Baltrumer Inselwatt

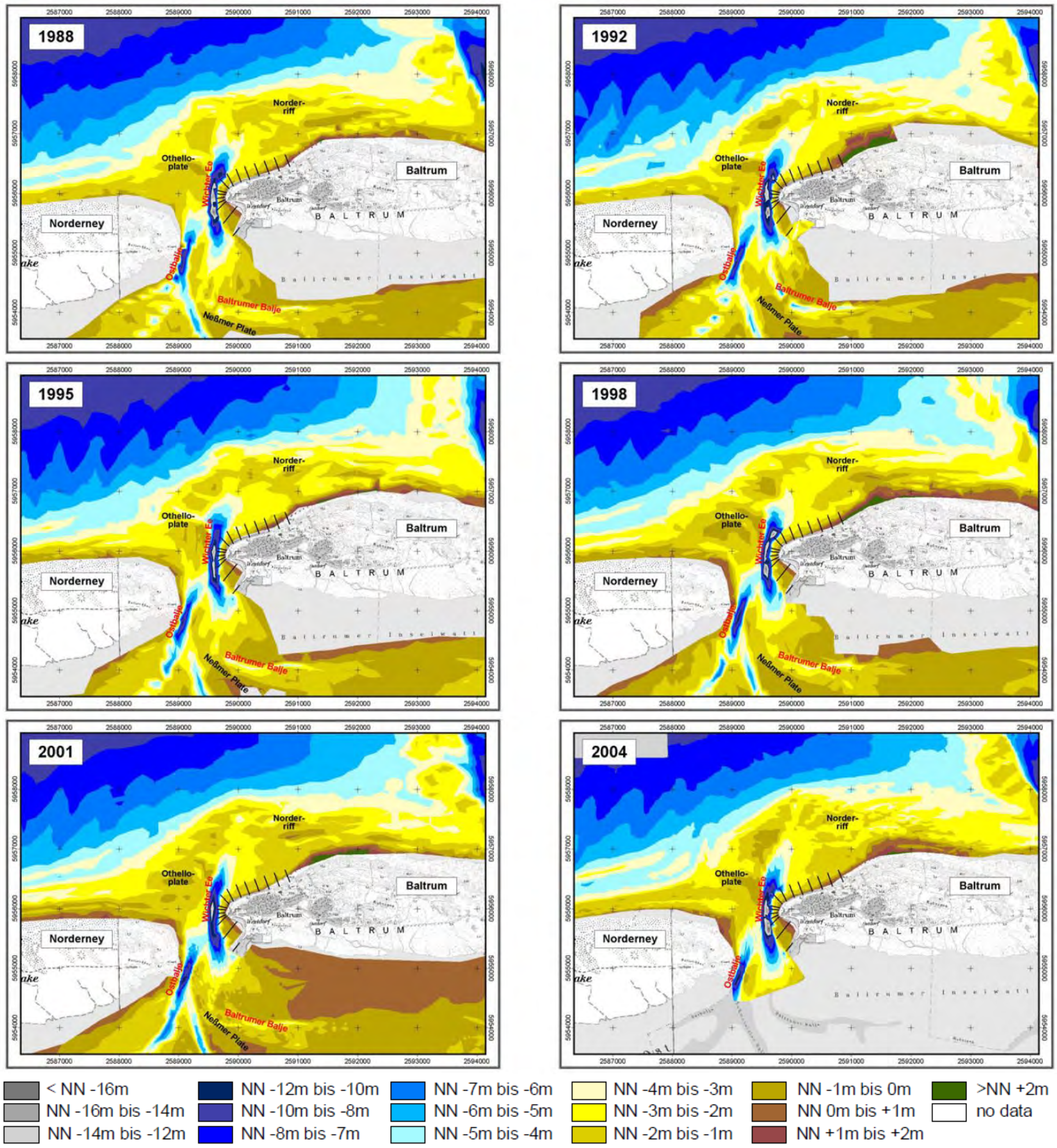


Figure 6.5.5: Overview of the development of the Wichter Ee (Ladage & Stephan, 2005).

Relation to the island coasts

The west-side of Baltrum is characterized in the period 1933-2004 by a negative sediment balance. Bars from the ebb-tidal delta's Riffbogen land at the central part of the island. Satellite images of the ebb-tidal delta of Wichter Ee show attachment of 7 shoals in the period 1986-2013; on average 1 merger/4 yrs. (Figure 6.5.6; Ridderinkhof 2016). They are smeared out to both directions. As a result this part of the island is stable (Ladage & Stephan, 2005).

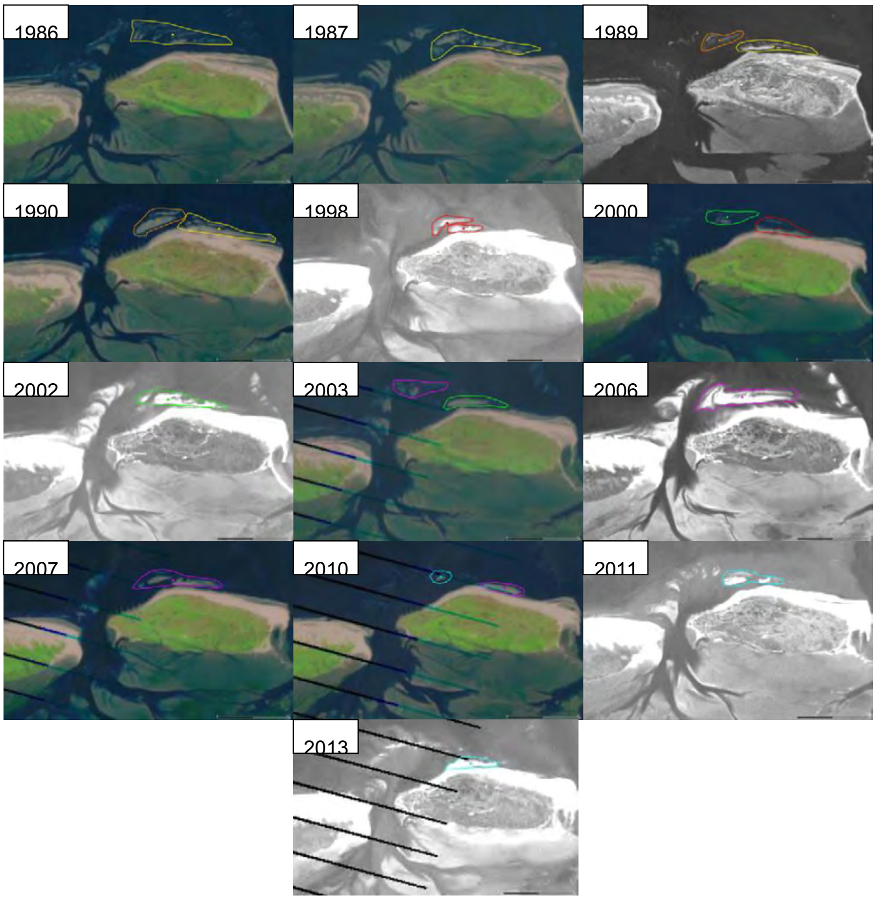


Figure 6.5.6: Landsat images of the ebb-tidal delta of Wichter Ee with shoals merging with the coast of Baltrum around 1990, 2000, 2004, 2010, and 2013 (Ridderinkhof, 2016).

6.6 Accumer Ee

Basic data (for maps see Wichter Ee)

Table 6.5: Facts and figures Accumer Ee (see also appendix I)

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2.0	1891 - 2001	1(station Norderney)						
Hs (m)	1.19		CoastDat						
Tp (s).	5.6		CoastDat						
Tf/Te	1.00	2017 (2 tidal cycles of 3 jan)	2 (station Langeoog)						
$L_{ebb-tidal\ delta}$ (km)	4.5	2012	-6 m	5.5	2012	-10m			
MHW (m NHN)	1.4	2017	2 (station Langeoog)						
MLW (m NHN)	-1.3	2017	2 (station Langeoog)						
MTR (m)	2.6	1982	3	2.7	2017	2(station Langeoog)			
Surge height (m to MSL)									
Mean annual max surge height (m to AOD)	2.83		CoastDat						
A_{MHW} (km^2)	89 ±2	~2000	4						
A_{MLW} (km^2)	20	1975	5	25	1990	5	22 ±3	~2000	4
A_{cross} (m^2)									
V_{MHW} ($10^6 m^3$)	209±23	~2000	4						
V_{MLW} ($10^6 m^3$)	62±5	~2000	4						
Sedimentation backbarrier area ($10^6 m^3$)									
P ($10^6 m^3$)	158	1975	5 (Pmap)	147±28	~2000	4 (Pcom)	175 (172-178)	2004-2005	6 (Pcom) (flood resp. ebb volume)
$SV_{backbarrier}$ ($10^6 m^3$)									
$SV_{ebb-tidal\ delta}$ ($10^6 m^3$)									
$AS_{backbarrier}$ ($10^6 m^3/yr$)									
$AS_{ebb-tidal\ delta}$ ($10^6 m^3/yr$)									
Longshore drift ($10^6 m^3/yr$)	+1.2	1990-2012 & 2006-2009	7	+1.1 to +1.4	1990-2012 & 2006-2009	7(stations Elbe & Schiermonnikoog)			
Sediment transport direc-tion?	E								
Development island coasts	Extension of E Baltrum; Sedimen-tation on Langeoog								

1 = Jensen & Mudersbach, 2007; 2 = BSH, 2016; 3 = Postma, 1982; 4 = Stanev et al., 2003 (± indi-cating neap and spring tide conditions); 5 = Niemeyer, 1995; 6 = Herrling, 2014; 7 = Ridderinkhof, 2008;

Description of the inlet system

The Lower Saxonian inlet system Accumer Ee is situated between the barrier island of Baltrum in the west and Langeoog east of it (Figures 6.5.1 to 6.5.3). Originally the Accumer Ee river (nowadays: Dornumersieler Tief) debouched freely into the Wadden Sea. It was diked and closed with a sluice during Medieval times (Heinze, 2016). During the storm surge „Marcellusflut“ of 1362 probably the NE part of the dike (now Wadden Sea area) and the original sluices were destroyed and could not be closed until 1449, which led to a considerable enlargement of the Dornumer Bucht (Wiechers, 1989; Heinze, 2016). Thereafter several dike lines were built in a progressively seaward direction (e.g. 1620 & modern dike; Heinze, 2016).

The tidal volume has remained nearly constant over the period 1650-1930. In the period 1930-2004 it increased with some 38%, whereas in the same period the tidal basin area has been increasing due to a westward shift of the watershed of Baltrum (Figure 6.5.4; see also Niemeyer, 1995). A short-lived decrease in tidal prism to 1930 values was noted around 1982, but after then it increased again (table 6.5). Part of the tidal prism increase has also been attributed to structural erosion of the tidal flats (Schroeder et al. 1994). Also, the inlet has increased in cross-sectional area especially after 1978 (see Abels et al. 1998).

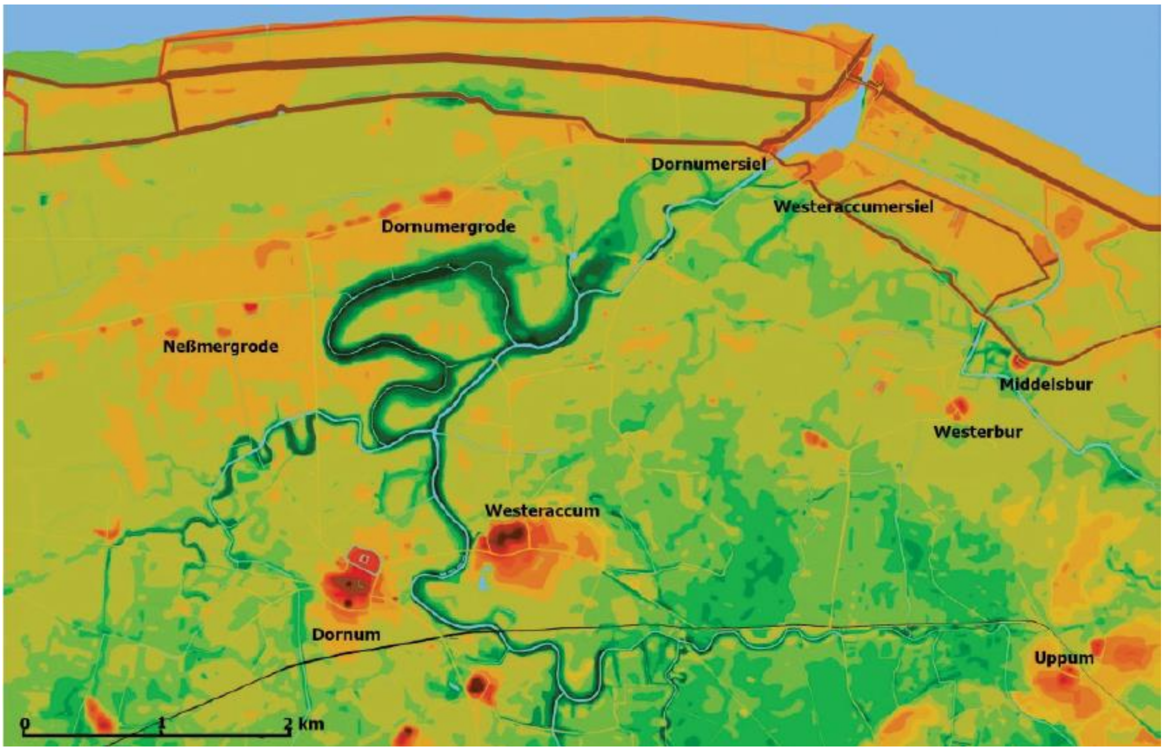


Figure 6.6.1: Remnants of the Dornumerbucht (Heinze, 2016).

Development of the ebb-tidal delta

The ebb-tidal delta of the Accumer Ee inlet is well documented over a period of more than 100 years (Homeier, 1956; Homeier & Luck, 1971; Ehlers, 1988). Studying topographical maps from the period 1866-1995, Abels et al. (1998) found that the ebb delta bar system maintained a similar compact shape with a Riffbogen which surrounded the whole ebb-tidal delta, only separated by small channels (Figure 6.6.2).

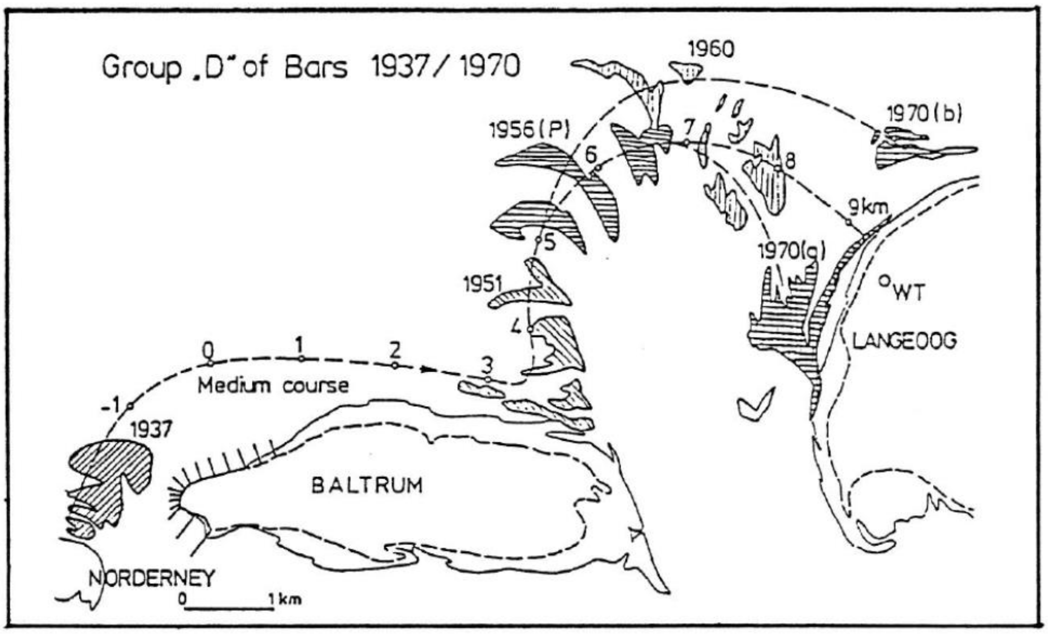


Figure 6.6.2: A still compact Riffbogen of the ebb-tidal delta of the Accumer Ee, showing different points of merger of sediment on the island (Kunz, powerpoint 2009).

The main stream channel of Accumer Ee shifted during the period from 1975 to 1995 strongly to the E, leading to a shift from a N - to a NW-orientation of the main ebb-tidal delta channel (Ladage, 2002). It was also extending in that direction, especially in the period 1975-1988 (770 m based on NHN-8 m). At the same time the channel volume more than doubled (< NN-8 m) compared to 1975, and the channel deepened to NHN-25 m. The cause for the transformations of the Accumer Ee are probably, among other things, the E ward shift of the watershed S of Langeoog, in combination with concurrent erosion of mudflats, resulting in an increase of in tidal volume in the Eastern catchment. The associated change in the flow apparently favored the channel shift between Baltrum and Langeoog (Ladage, 2002).

The shift of the Accumer Ee ebb-tidal delta channel changed the shape and location of the Riffbogen since the late 70ies. The extended part of the Riffbogen was moving NW, while the northern slope had a tendency to shift S. Resulting in the period 1975-1985 in a reinforced sand accumulation in the area of Flinthörnplate (increase of approximately $1*10^6$ m^3 above sea level-4 m) as well as on the Western beach of Langeoog.

In the early 90ies this was followed by an unusually wide and deep breakthrough through the apex of the Riffbogen, resulting in a decrease in the volume of sediment in the reef to 40% between 1985 and 1995 (above NHN -3 m; Figure 6.6.3). These are probably not structural changes, but represent a temporary extreme situation in the development of Riffbogen (Ladage, 2002). The area at Seekartennull (SKN) -2 m had decreased by about 30%. Abels et al., (1998) connect this to masses of sand which accumulate at E Baltrum (1866-1908 & around 1970), moving over the Riffbogen (maximum sediment accumulation in the period 1935-1960 and ca. 1977-1984) to finally merge with the west shore of the barrier island of Langeoog (1970 & 1985). Notice that minima in sediment on the Riffbogen approximately coincide with maxima in tidal prism. On top of that also the trajectories of the swash bars on the Riffbogen changed due to the changes in the orientation of the main ebb channel (Figure 6.6.4).

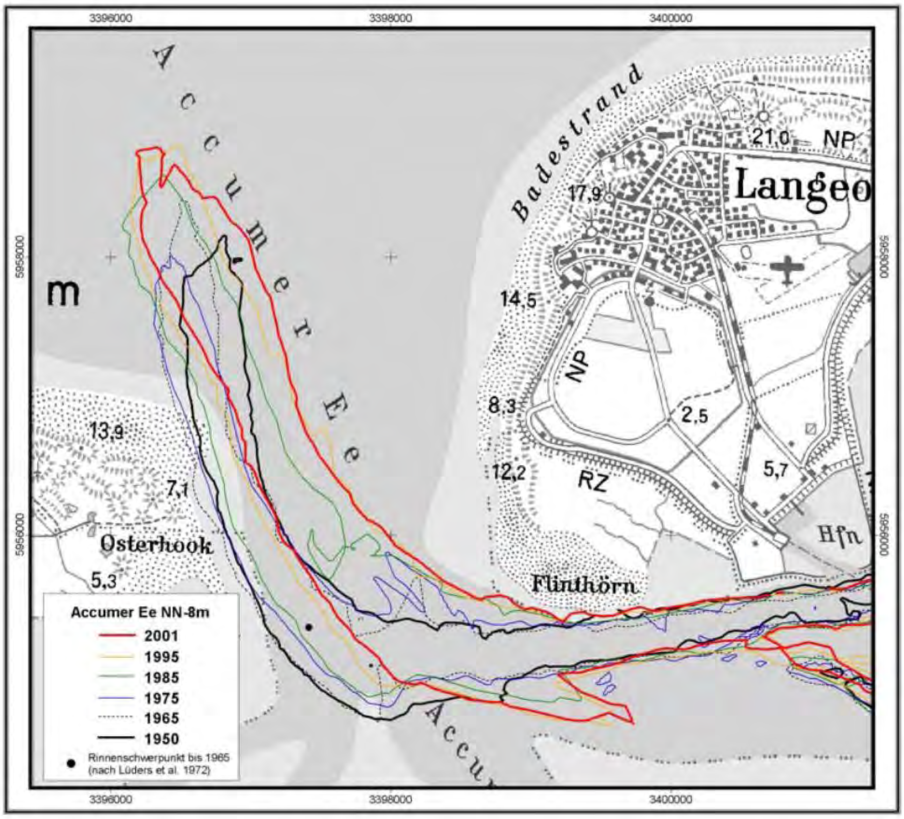


Figure 6.6.3: NN -8 m line showing the displacement and widening of the main channel (source unknown)

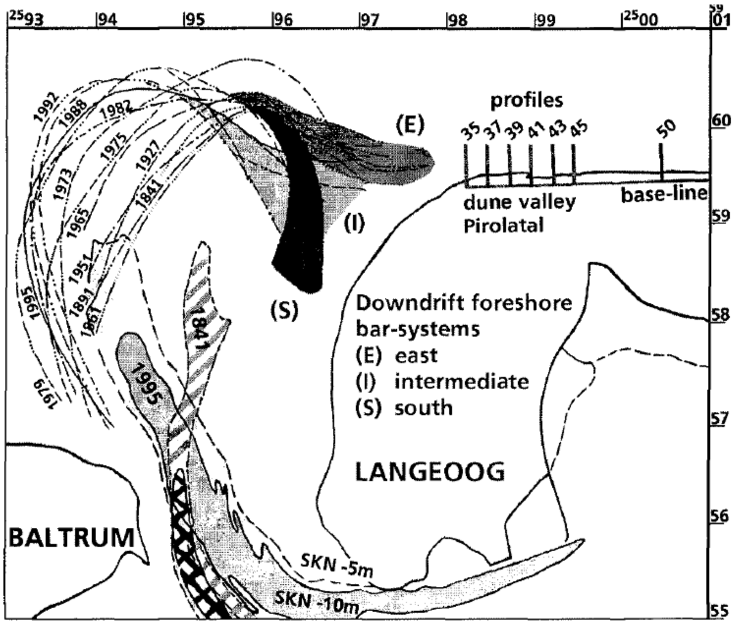


Figure 6.6.4: Different trajectories of the shoals over the ebb-tidal delta. Bars now merge in the grey zone (Abels et al., 1998).

Relation to the island coasts

The coast of Langeoog is nourished in a natural way by merger of bars from the ebb-tidal delta and has, as the only East Frisian island only a dune coast to protect it from flooding (NLWKN, 2010). As the coast of Langeoog is not receiving much sand at the moment nourishments are needed regularly since 1972 (Kunz, powerpoint 2009). Since 1984 10 shoals were identified that migrate towards the island Langeoog in the periods 1984-1990 and 1998-2014 and, on average, one shoal merged with the island every 4 years (Figure 6.6.5; Ridderinkhof, 2016). The velocity of approach is high: 304 m/yr (std: 103 m/yr; Ridderinhof, 2016). Especially since 2002 many shoals merged and, as a result a strand hook formed along the west coast, which became a dominant feature around 2011.

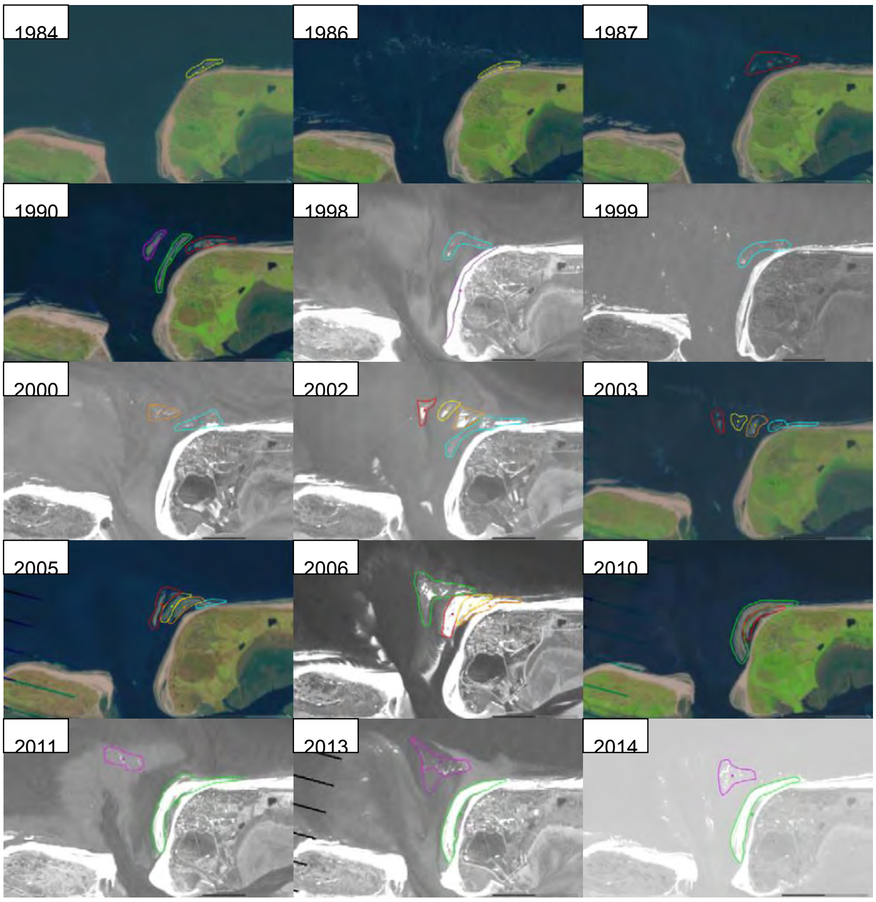


Figure 6.6.5: Landsat images of the ebb-tidal delta of Accumer Ee showing migrating shoals in the period 1984-2014 (Ridderinkhof, 2016).

6.7 Otzumer Balje

Basic data

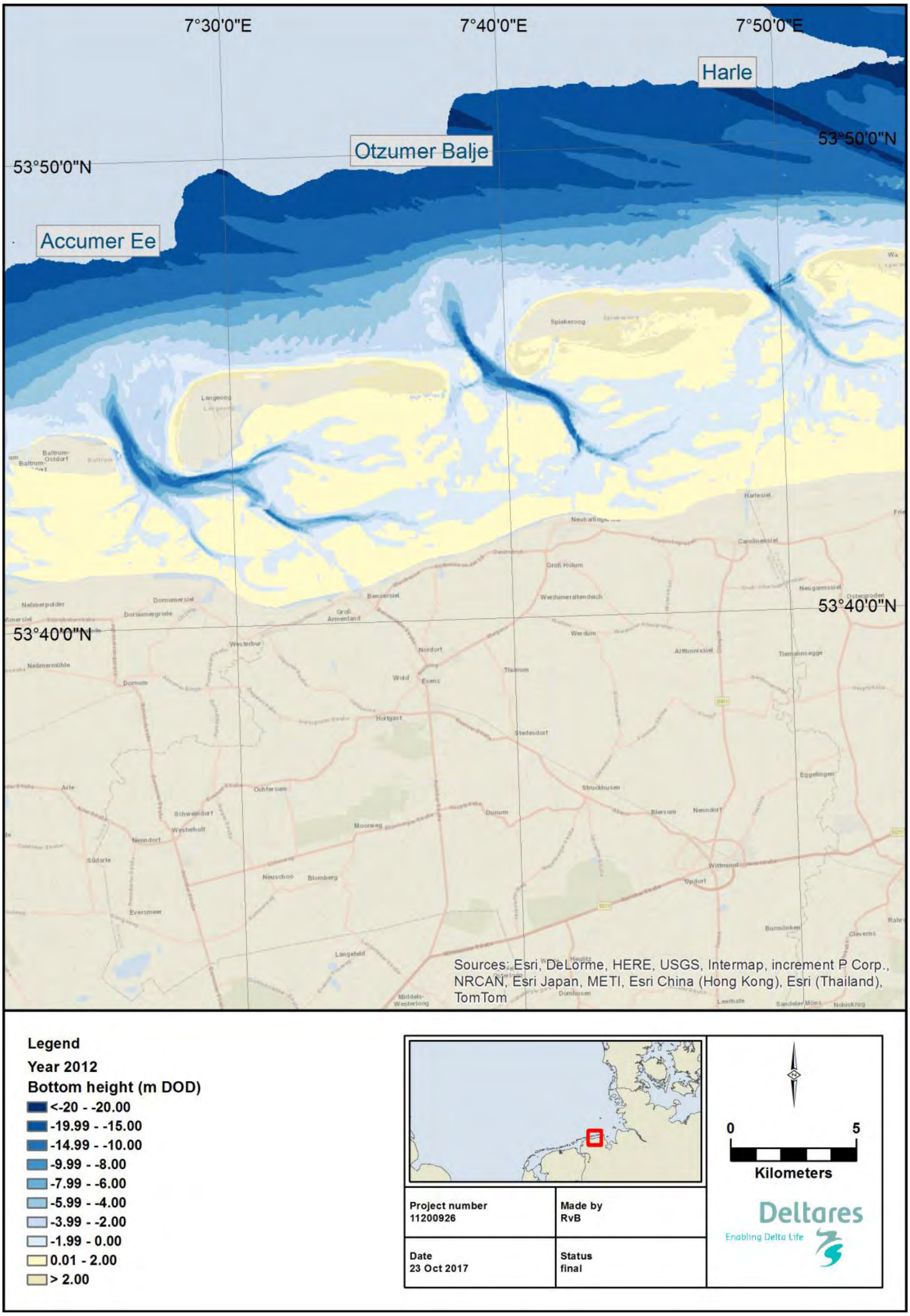


Figure 6.7.1: overview of the ebb-tidal delta of Otzumer Balje

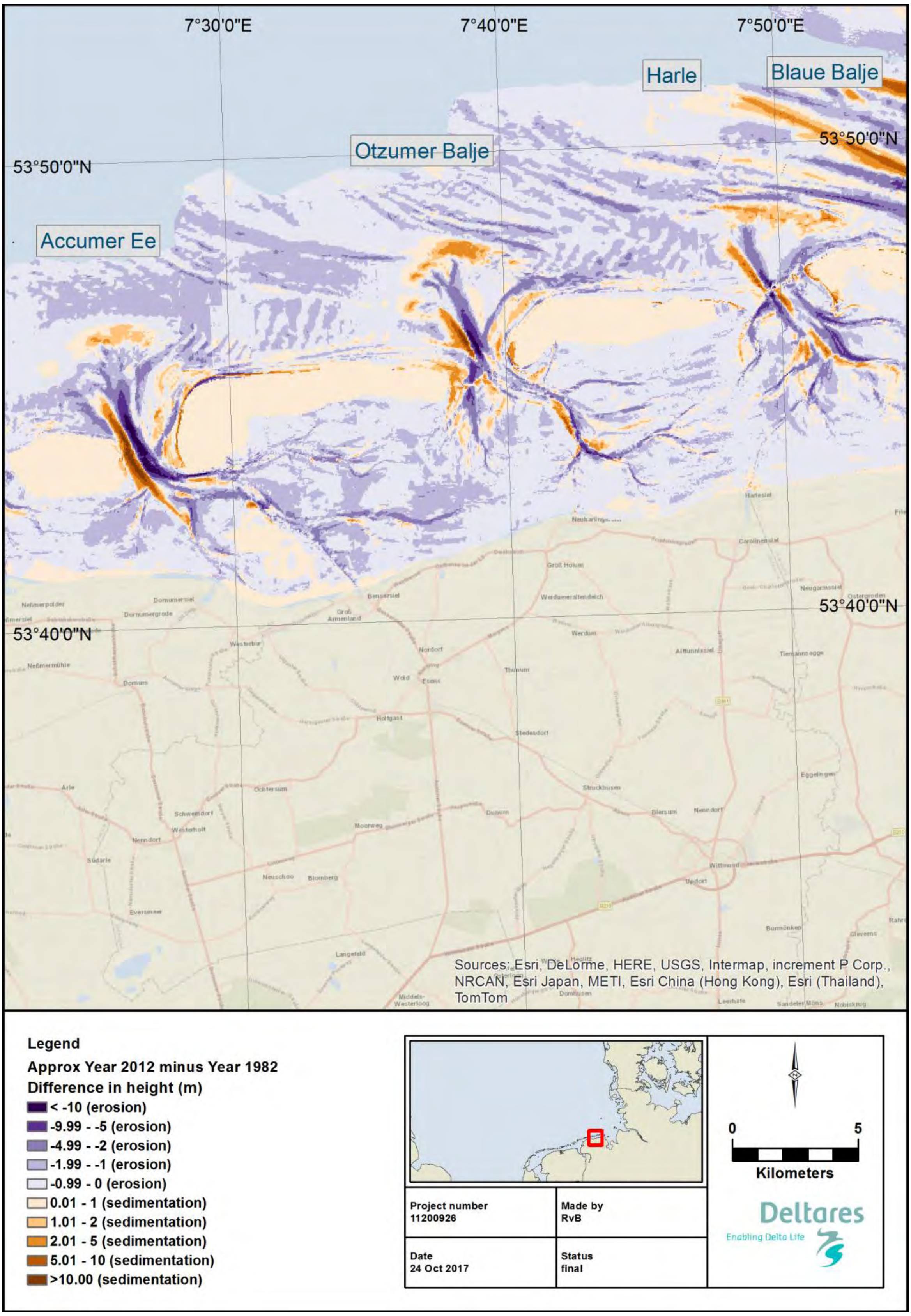


Figure 6.7.2: Otzumer Balje erosion and deposition over the period 1982-2012

Table 6.6: Facts and figures Otzumer Balje (see also appendix I)

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2.0	1891 - 2001	1 (station Norderney)	0.3	1903 - 2001	1 (station Alte Weser)			
Hs (m)	1.19		CoastDat						
Tp (s).	5.44		CoastDat						
Tf/Te	0.96	2017 (2 tidal cycles of 3 jan)	2 (station Spiekeroog)						
$L_{ebb\text{-}tidal\ delta}$ (km)	4.2	2012	-6 m	5	2012	-10m			
MHW (m NHN)	1.4	2017	2 (station Spiekeroog)						
MLW (m NHN)	-1.3	2017	2 (station Spiekeroog)						
MTR (m)	2.68	1982	3	2.71	2000-2004	4	2.7	2017	2 (station Spiekeroog)
Surge height (m to MSL)									
Mean annual max surge height (m to AOD)	2.89		CoastDat						
A_{MHW} (km^2)	74	1990	5	74	1995?	6	70 ±2	~2000	7
A_{MLW} (km^2)	16	1975	5	27	1990	5	17 ±3	~2000	7
A_{cross} (m^2)	12151	2001	4	12066	2004	4			
V_{MHW} (10^6 m^3)	167±17	~2000	7						
V_{MLW} (10^6 m^3)	43±4	~2000	7						
P (10^6 m^3)	141	2001	4 (Pbat)	151	2005	4 (Pbat)	158 (156-160)	2004-2005	8 (Pcom) (flood resp. ebb volumes)
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)	37	2001	4	38	2004	4			
$AS_{backbarrier}$ (10^6 m^3/yr)	ca. 0.1	1989-2005	4						
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)	1.1	1988/92-2004	4						
Longshore drift (10^6 m^3/yr)	+1.1	1990-2012 & 2006-2009	9	+1.1 to +1.4	1990-2012 & 2006-2009	9 (stations Elbe & Schiermonnikoog)			
Sediment transport direction?	E								
Development island coasts	Growth E side Langeoog; Growth W side Spieker-oog								

1 = Jensen & Mudersbach, 2007; 2 = BSH, 2016; 3 = Postma, 1982; 4 = Ladage et al., 2006; with reference to MTR of the year; 5 = Niemeyer, 1995; 6 = Ferk, 1995; 7 = Stanev et al., 2003; 8 = Herrling, 2014; 9 = Ridderinkhof et al., 2016.

Description of the tidal inlet system

The Lower Saxonian inlet system Otzumer Balje is situated between the barrier island of Langeoog in the west and Spiekeroog east of it (Figures 6.7.1 to 6.7.3). The backbarrier area is some 70 km^2. The backbarrier area is mainly drained via the Otzumer Balje, which in the ebb-tidal delta is oriented to the NNW. There is a small Hullbalje west of it, which is, at the moment, not clearly separated from the Otzumer Balje (Figure 6.7.3) and drains the western part of the backbarrier area.

Over the period 1650-1960 the Otzumer Balje has increased from 57 to 75 km^2, mainly due to the fast eastward extension of Spiekeroog which led to an eastward shift of the watershed of the island over some 6 km and the relative modest shift of the watershed of Langeoog (Figure 6.7.4; Niemeyer, 1995; Ladage et al., 2006). Since the 19th century the poldering of the Harlebucht (see discussion of the Harle system) has led to some loss of tidal area near the mainland (Niemeyer, 1995). In general, the Otzumer Balje backbarrier has mainly developed due to the strong SE extension of the Schillbalje, clearly related to the shift of the watershed (Ladage et al., 2006).

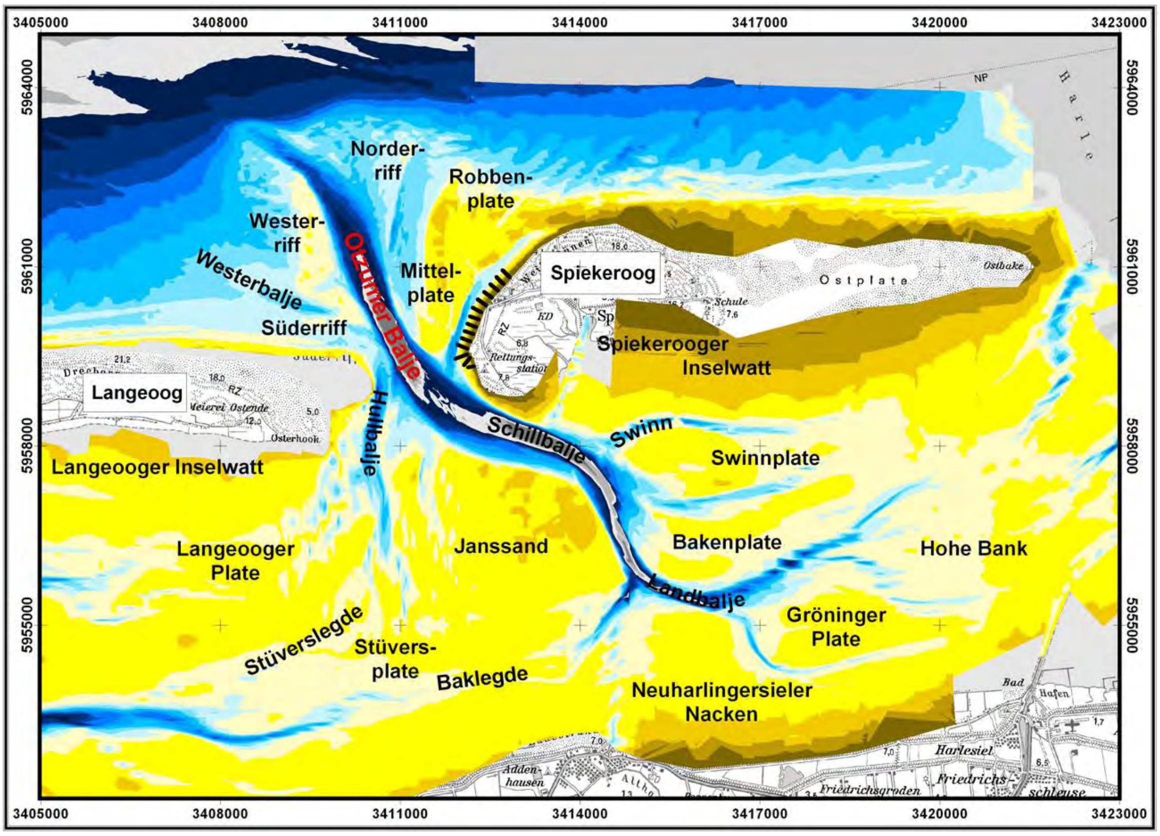


Figure 6.7.3: Toponymes of the Otzumer Balje (Ladage et al., 2006).

Over the period 1960-2005 the eastward shifts of the both watersheds of Langeooge (strong) and Spiekeroog (less strong) have led to a strong reduction of the Hullbalje (west) and an expansion Schillbalje (eastern part of the system) and hence a slightly reducting backbarrier area from ca. 75 km^2 to 71 km^2 (Figure 6.7.4; Ladage et al., 2006). Over the same period the height in the backbarrier was reduced with almost 30 cm in height on average while, on top of that, tidal range had increased with some 9 cm, resulting in an increase in tidal volume from 138 to 151*10^6 m^3 (Ladage et al., 2006). As the quality of the data are probably comparable with the Dutch data, the accuracy (1 sigma) may be around 3 cm for depth soundings after ca. 1970 (Oost, 1995), resulting in a 3 sigma error for comparing two subsequent depths of almost 13 cm. The 1970 sounding gives a tidal volume of ca. 140*10^6 m^3. Thus the reduction in height is very likely significant and reality. Indeed, the map reveals a strong deepening, widening and expansion of the tidal channels of the Schillbalje and more eastward located channels, which will add considerably to the increase in depth. Also, the mainland coast becomes lower which might be a result of the expanding channel and wave-related erosion (e.g. Janssen-Stelder, 2004).

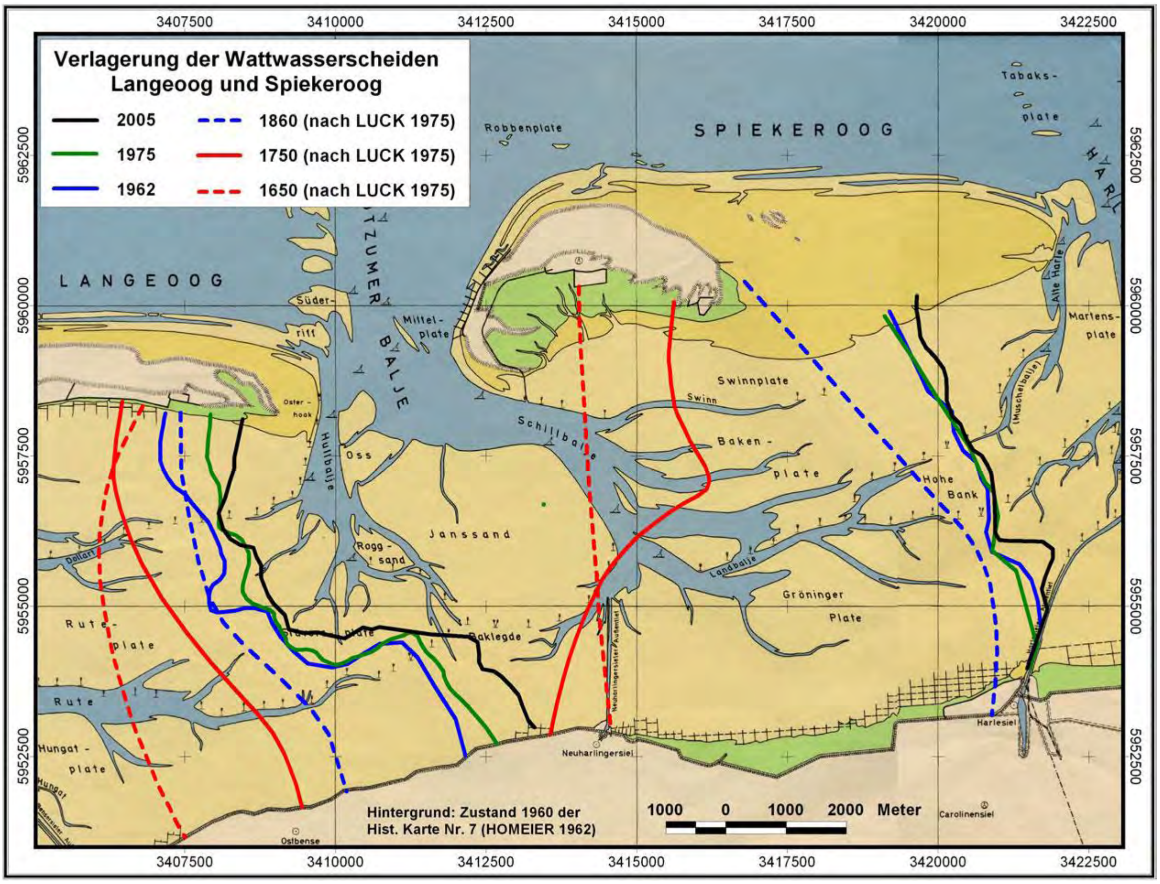


Figure 6.7.4: Overview of the watershed development over the period 1650-2005 (Ladage, 2006).

Development of the ebb-tidal delta

Originally (see above) the inlet and the west side of the barrier island Spiekeroog shifted eastward. The erosion and retreat at the west side of the island was halted by the protection works which started in 1832, culminating in groins along the whole western coast in the period 1873-1912 (Ladage et al., 2006).

In the period 1950-1960 the main channel of the Otzumer Balje migrates in a clockwise pattern downdrift. In the period 1960-1992 the channel starts to orient increasingly towards the NW with its main axis and extents seaward. Two likely reasons are (Ladage et al., 2006; Figure 6.7.5):

1) the increase in tidal prism of the system over that period, and
2) The forming of one smooth direct channel from the eastern backbarrier area to the ebb-tidal delta (situation 1992) out of a separated ebb channel (Schillbalje) and flood channel (Otzumer Balje; situation 1960).

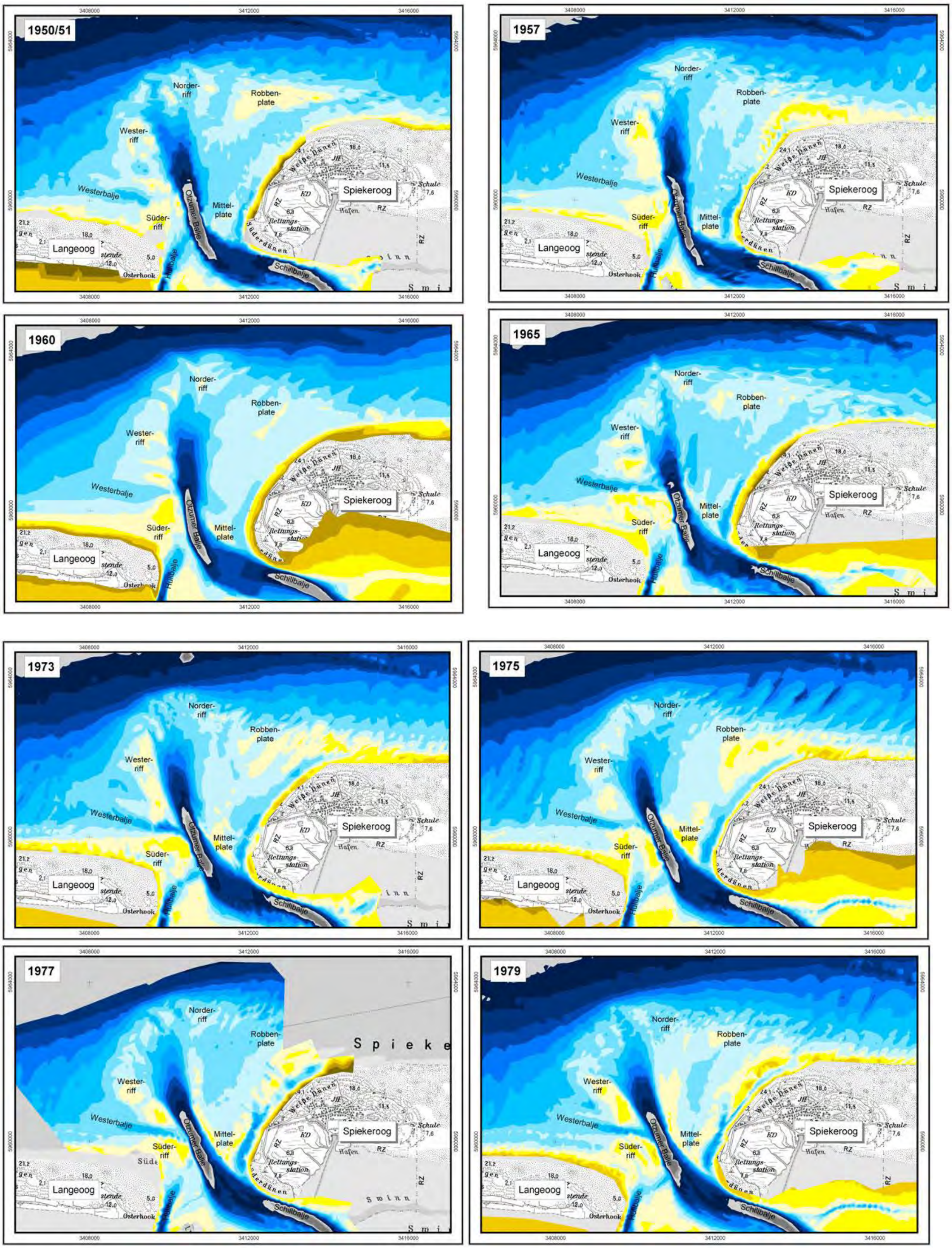
Thereafter, large shoals formed W of the channel and the channel axis was gradually rotating in a clockwise direction (Ladage et al., 2006). In this development the seaward end of the inlet maintained a WNW to NW orientation. The extension of the ebb-tidal delta in a seaward direction changed from ca. 4400 m in 1951 to 5100 m in 2005 (Ladage et al., 2006). Not only the extension but also the overall contours changed: the ebb-tidal delta protrudes around the main ebb-channel(s) and at the downdrift side it provides shelter to the ebb-tidal delta plateau. The more westward, the less the shelter will be available and the more landward the ebb-tidal delta contours will be positioned (figure 6.7.6). It should be remarked that the seaward extension of the inlet was reduced markedly after the storm surge of 1962 and infill occurred after the storm surge of 1976. This has been attributed to the erosion of the Riffbogen and sediment deposition in the inlet. Only extremely heavy storm surges are able to generate such big changes. The re-establishment of the situation before the change may have taken up to ca. 11 years (Krögel, 1995). It is unclear if the landward retreat of the ebb-tidal delta outer rim and the forming of sand banks observed in 1995 might be related to the majorstorm surge of January 1994.

The increase in tidal volume over the period 1960-2005 did not lead to an increase in cross-sectional area of the inlet gorge which remained ca. 12000 m2. Dips of 1957 and 1987 can be attributed to short-lived developments in channel form and position (Ladage et al., 2006). The general constancy might be due to development of one single channel out of an ebb channel and a flood channel; the latter resulting in a larger cross-sectional area than a single channel. In the period 1951-2004, the volume of the ebb-tidal delta had net increased, with ca. $9.3*10^6$ m^3 (above NHN –6m) of which $9*10^6$ m^3 above NHN -3 m. Following the method of Walton & Adams (1976) the increase was only $3.4*10^6$ m^3 (Ladage et al., 2006). The difference implies that erosion by channels below NHN –6 m was substantial. The net development in volume was brought about by: a fast growth in the period 1951-1957, a static period between 1957 and 1975, a gradual decline over the period 1975-1995 and a fast increase in volume after 1995, especially up to 2001 with several 10^7 m^3 (Ladage et al., 2006).

Development of the coast

The development of the beach of Spiekeroog is influenced by the regular merger of Riffbogen bars on the coast (Figures 6.7.6 & 6.7.7; Ladage et al., 2006). The merger of bars has been studied by Ridderinkhof (2016) who concluded that the shoals migrate with a velocity of 186 m yr^{-1} (STD: 100 m yr^{-1}; see also Soo Son et al., 2011) and that velocity decreases when they get closer to the shore.

On the southern and northern part of the NW coast bars merge, which are subsequently smeared out along the coast. As a result the NW coast is on the long run having a positive sediment budget, or is at least stable (Ladage et al., 2006). Since 1980 the SW part of the island is eroding, especially the dry and wet beach. The erosion is attributed to the shift of the re-orienting Otzumer Balje in the period 1980-1990 and the decreased shelter of the Mittelplatte.


1950/51
1957
1960
1965
1973
1975
1977
1979
Norder-riff
Robben-plate
Wester-riff
Westerbalje
Süder-riff
Mittel-plate
Otzumer Balje
Schillbalje
Spiekeroog
Langeoog
Osterhook
Weiße Dünen
Rettungs-station
Hafen
Schule

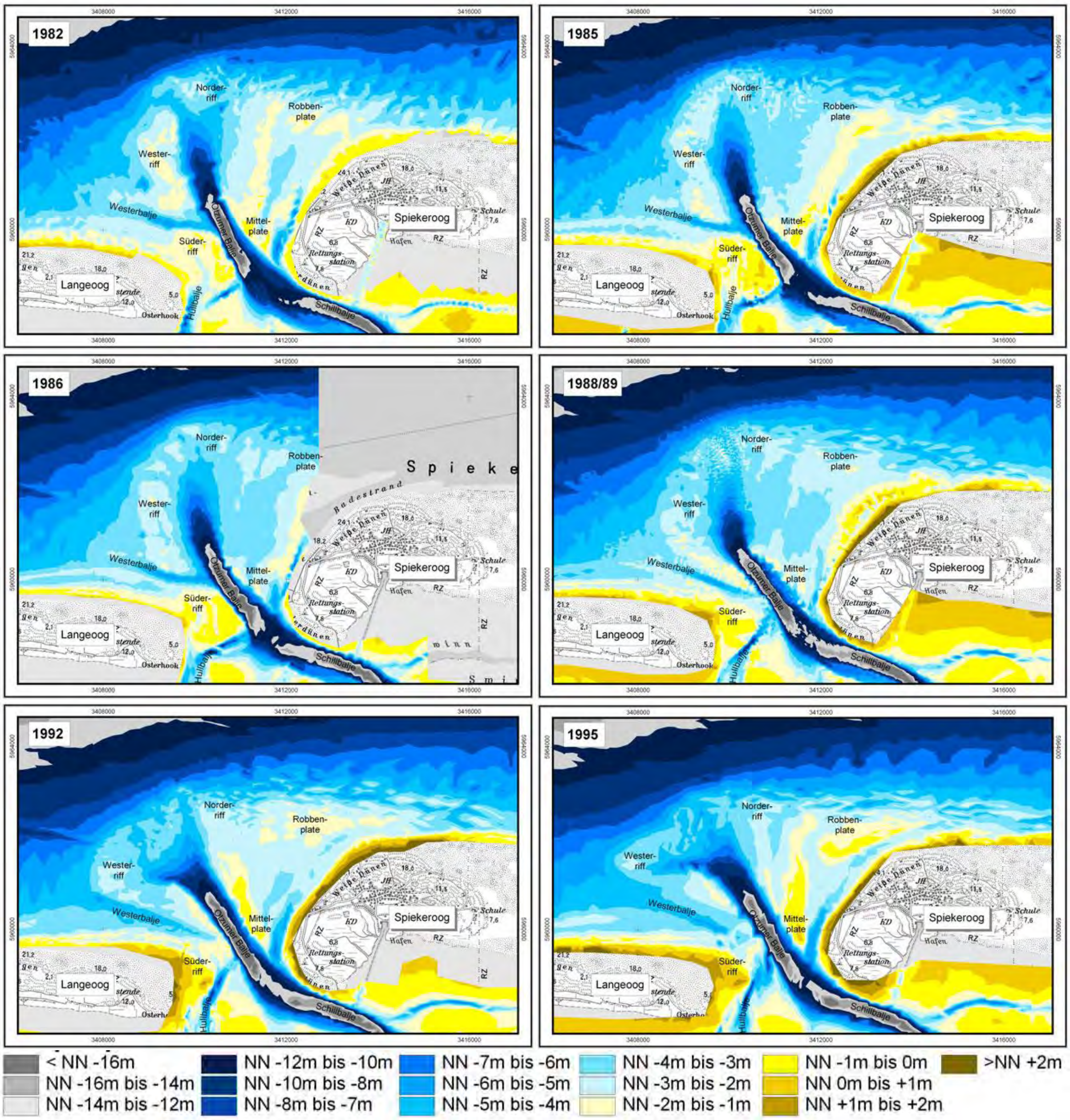


Figure 6.7.5: overview of the development of the ebb-tidal delta of the Otzumer Balje over the period 1950/51-2005 (Ladage et al., 2006).

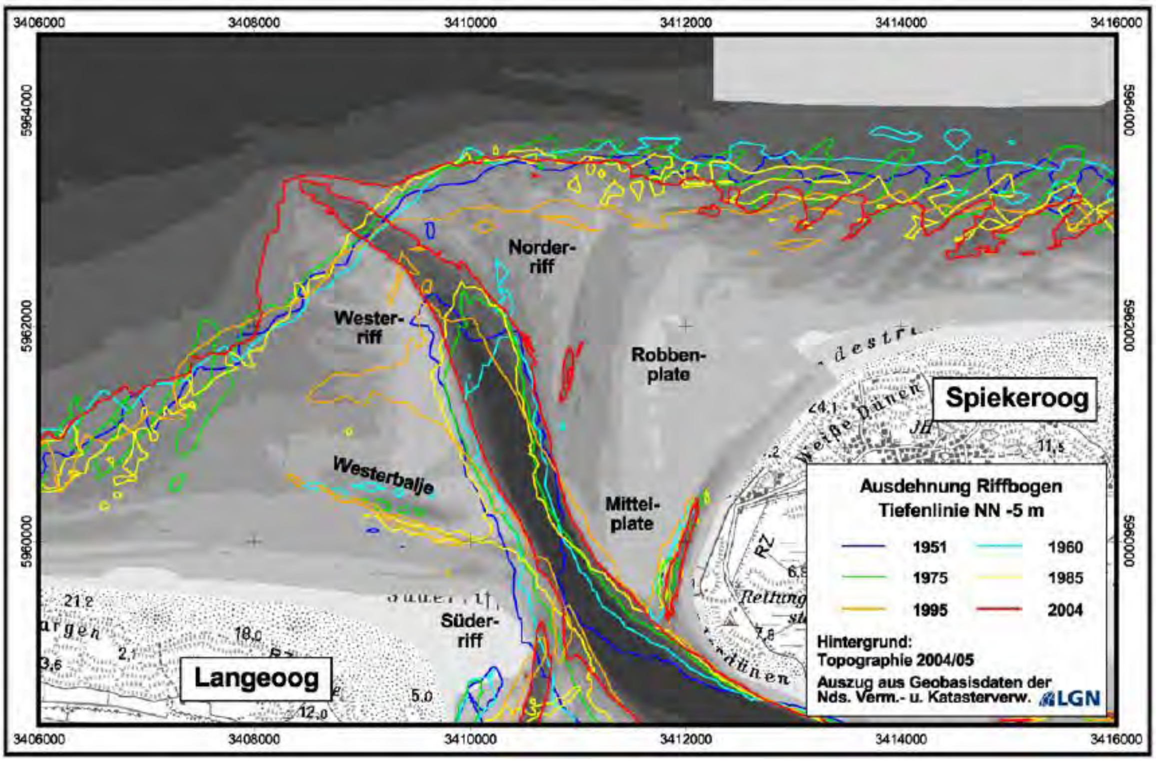


Figure 6.7.6: Overview of the position of the NHN -5 m line for various years (Ladage et al., 2006).

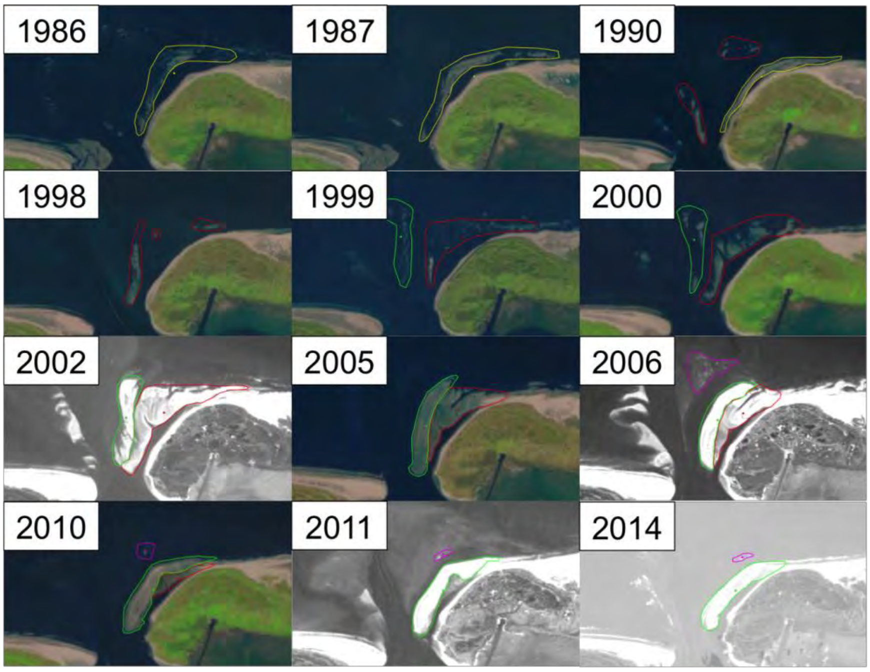


Figure 6.7.7: Landsat images of the ebb-tidal delta of Otzumer Balje showing migrating shoals that attach to the coast of Spiekeroog in the period 1986-2014 (Ridderinkhof, 2016).

6.8 Seegat Harle

Basic data

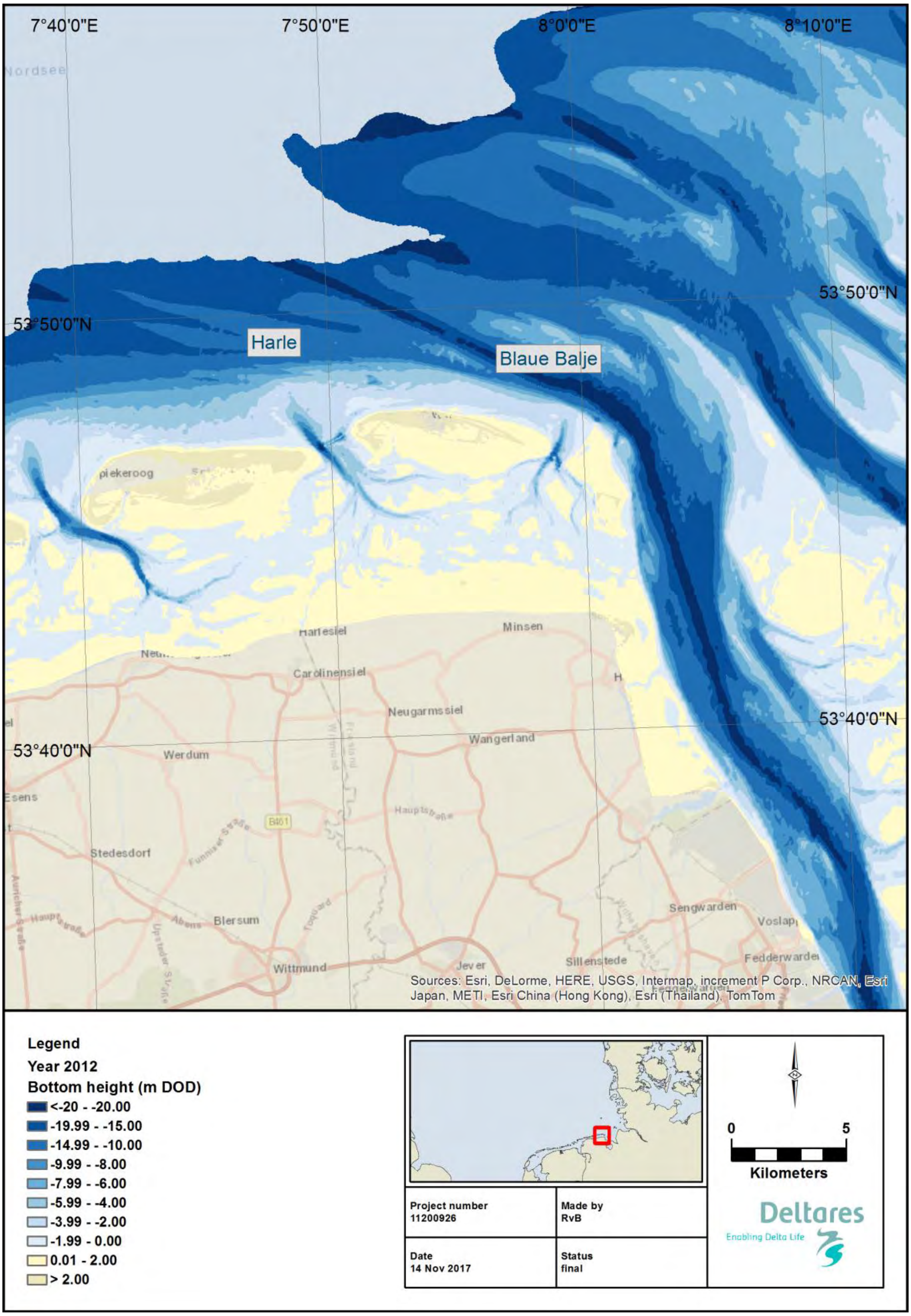


Figure 6.8.1: overview of the ebb-tidal deltas of Seegat Harle & Blaue Balje.

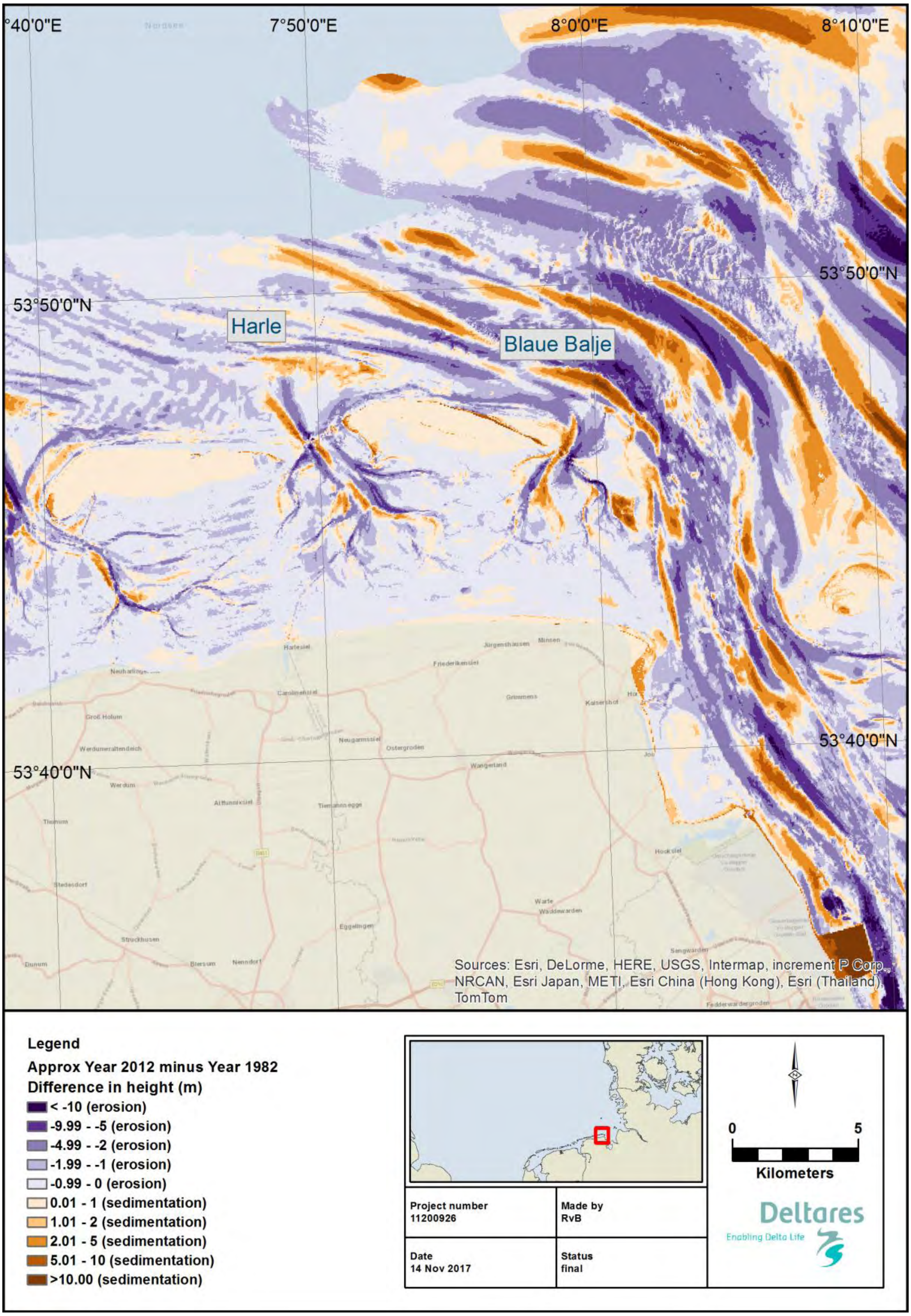


Figure 6.8.2: Seegat Harle & Blaue Balje, erosion and deposition over the period 1982-2012.

Table 6.7: Facts and figures Seegat Harle (see also appendix I)

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2.0	1891 - 2001	1 (station Norderney)	0.3	1903 - 2001	1 (station Alte Weser)	2.4	1960-2003	2 (= (MWHR + MLWR)/2
Hs (m)	1.14		CoastDat						
Tp (s).	5.32		CoastDat						
Tf/Te	0.92	2017 (2 tidal cycles of 3 jan)	3 (station Wangerooge West)						
$L_{ebb\text{-}tidal\ delta}$ (km)	3.1	2012	-6 m	4	2012	-10m			
MHW (m NHN)	+1.45	2000 (long-term average)	2 (station Wangerooge West)	1.5	2017	3 (station Wangerooge West)			
MLW (m NHN)	-1.42	2000 (long-term average)	2 (station Wangerooge West)	-1.5	2017	3 (station Wangerooge West)			
MTR (m)	2.9	2017	3 (station Wangerooge West)						
Surge height (m to MSL)									
Mean annual max surge height (m to AOD)	2.95		CoastDat						
A_{MHW} (km^2)	68	1990	4	65	1995?	5	65 ±1	~2000	6
A_{MLW} (km^2)	13	1975	4	15	1990	3	13±3	~2000	6
A_{cross} (m^2)	10500	1950	2	9300	1975	2	11800	2002/03	2
V_{MHW} ($10^6 m^3$)	126±16	~2000	6						
V_{MLW} ($10^6 m^3$)	23±4	~2000	6						
P ($10^6 m^3$)	114	1990	4 (Pmap)	104±29	~2000	6 (Pcom)	124 (118-129	2004-2005	7 (Pcom) (flood resp. ebb vol-ume)
$SV_{backbarrier}$ ($10^6 m^3$)									
$SV_{ebb\text{-}tidal\ delta}$ ($10^6 m^3$)	23	2001	2 (fixed reference profile)						
$AS_{backbarrier}$ ($10^6 m^3$/yr)									
$AS_{ebb\text{-}tidal\ delta}$ ($10^6 m^3$/yr)	-0.7	1964-2001	2						
Longshore drift ($10^6 m^3$/yr)	+1.0	1990-2012 & 2006-2009	7	+1.1 to +1.4	1990-2012 & 2006-2009	7 (stations Elbe & Schiermonnikoog)			
Sediment transport direction?	E								
Development island coasts	Growth & erosion E Spiekeroog; NW Wangerooge stable								

1 = Jensen & Mudersbach, 2007; 2 = Ladage & Stephan, 2004; 3 = BSH, 2016; 4 = Niemeyer, 1995, from reconstructions; 5 = Ferk, 1995; 6 = Stanev et al., 2003 (± indicating neap and spring tide conditions); 7 = Herrling, 2014; 8 = Ridderinkhof, 2016.

Description of the tidal inlet system

The Lower Saxonian inlet system of the Seegat Harle is situated between the barrier island of Spiekeroog in the West and Wangerooge east of it (Figures 6.8.1 to 6.8.3). The backbarrier area is some 65 km^2. The area is drained via the Seegat Harle, which in the ebb-tidal delta is oriented to the NW. The maximum depth of the inlet is NHN -35 m, which is mainly brought about by the dam Buhne H, which reduces the width of the inlet and blocks the Dove Harle channel of which the tidal waters are also forced to flow through the Harle inlet (Lüders, 1952; Ladage & Stephan, 2004).

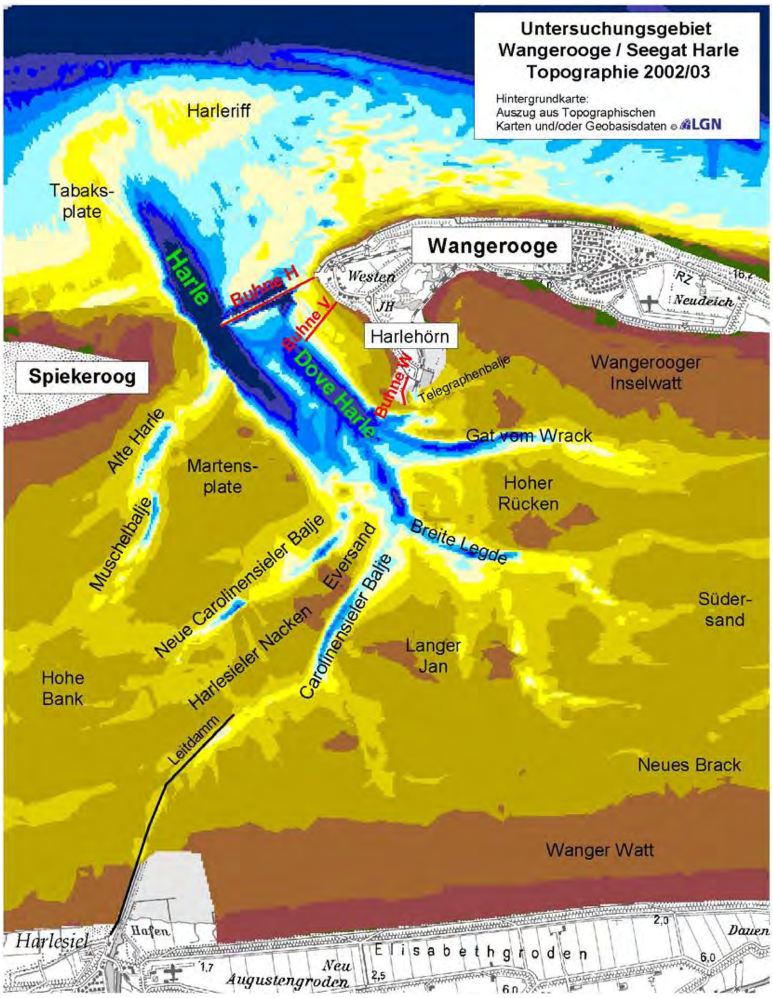


Figure 6.8.3: Toponymes of the Harle

Due to the strong eastward expansion of the barrier island Spiekeroog the watershed S of the island also shifted over to the east (Figure 6.8.4). Especially in the period 1750-1860 the watershed shifted over 2 km at its north side and 7 km near the mainland. In the period 1860-2001 the watersheds shifts roughly 2 km to the E at its north side and ca. 1 km near the mainland. In the period 1650-2001 the southern part of the watershed of Wangerooge has shifted ca. 1 km to the W, while the N part has shifted ca. 2 km to the E (Ladage & Stephan, 2004).

South of the backbarrier basin, the silting up and poldering of the Harle Bay has led to a considerable loss of backbarrier area. The Harle Bay, which existed before dike construction began, is known to have been poldered between the 12th and 19th century (Figure 6.8.5; Homeier, 1969, 1979a), with an interruption during the middle of the 14th century (Niemeyer, 1995). Up to 1362 some 30 km^2 were poldered, but the storm surge of that year led to even greater land losses. In the period 1362-1500 some 56.6 km^2 were reclaimed, in the period 1500-1895 another 88.5 km^2, of this area some 45 km^2 was intertidal. Thereafter the southern border remains more or less on the same place (Ladage & Stephan, 2004).

All in all, in the period 1650-1960 the changes of the watersheds and the diking of the Harle reduced the tidal area from 154 to 63 km^2 (Ladage & Stephan, 2004). Tidal prism has been estimated to be reduced during that period from ca. 229 to 111*10^6 m^3 (Niemeyer, 1995). In the period 1960-2003 the backbarrier area grew to ca. 65 km^2 (Ladage & Stephan, 2004). The development of the tidal volume over the period 1950-2003 followed a similar trend, increasing from ca. 120*10^6 m^3 to ca. 127*10^6 m^3 (Ladage & Stephan, 2004).

The main change in the backbarrier over the period 1950-2003, but especially after 1984, was that the backbarrier area drained by the Dove Harle increased sevenfold, while the Harle drained only a third of its original area. The tidal volumes of the two channels followed a similar pattern (Ladage & Stephan, 2004). The changes have been attributed to the shift of the watershed of Wangerooge. The increase of importance of the Dove Harle at the east side and the reduction of the Harle enabled sedimentation in the western part of the drainage area.

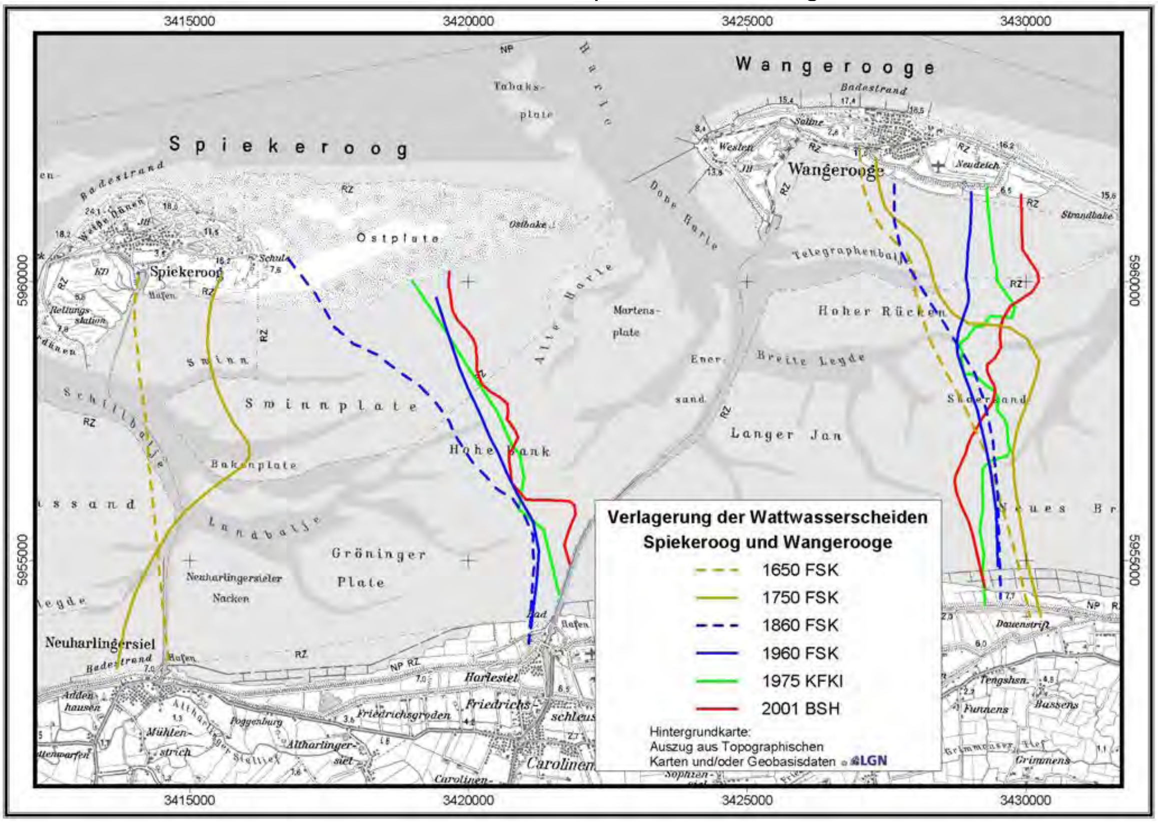


Figure 6.8.4: Shift of the watersheds through time (Ladage & Stephan, 2004).

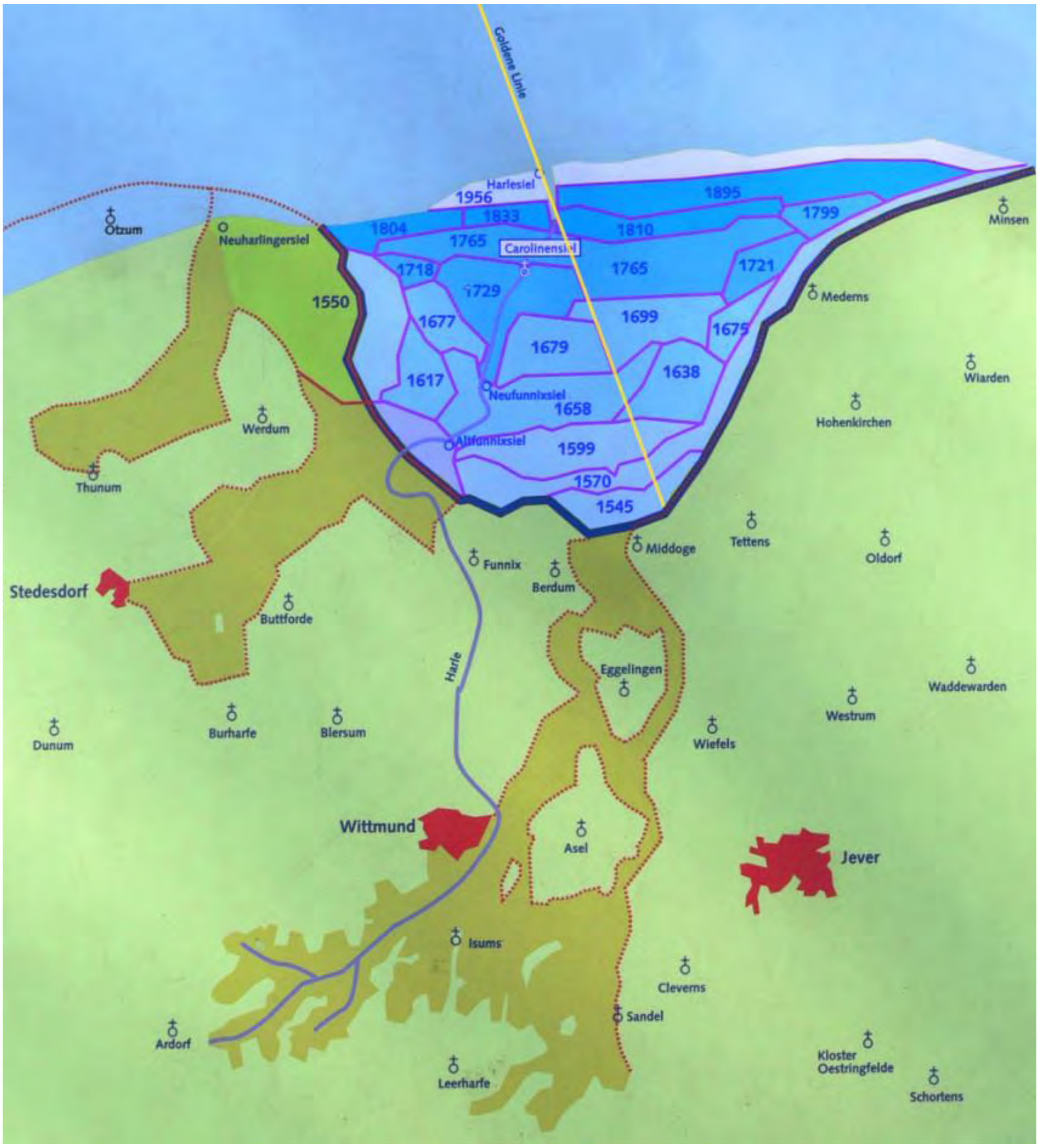


Figure 6.8.5: Poldering history of the Harle Bay (Wikipedia, after Homeier, 1979). Yellow line is newly established border between Jeverland and Ostfriesland.

Development of the ebb-tidal delta

In the period 1859 to 1890 the main ebb-tidal delta channel rotated slightly counter clockwise over 3 degrees, thereafter it rotated up to 1940 over some 26 degrees in a clockwise direction (Ladage & Stephan, 2004). In the period 1940-1984 the main ebb-tidal delta channel rotated some 40 degrees counter clockwise (Figure 6.8.6). This has been attributed to the extension of the dam Buhne H in 1941 (Ladage & Stephan, 2004). In the period 1987-1993 the channel rotated clockwise over 6-9 degrees, which might be related to the growing importance of the Dove Harle according to Ladage & Stephan (2004).

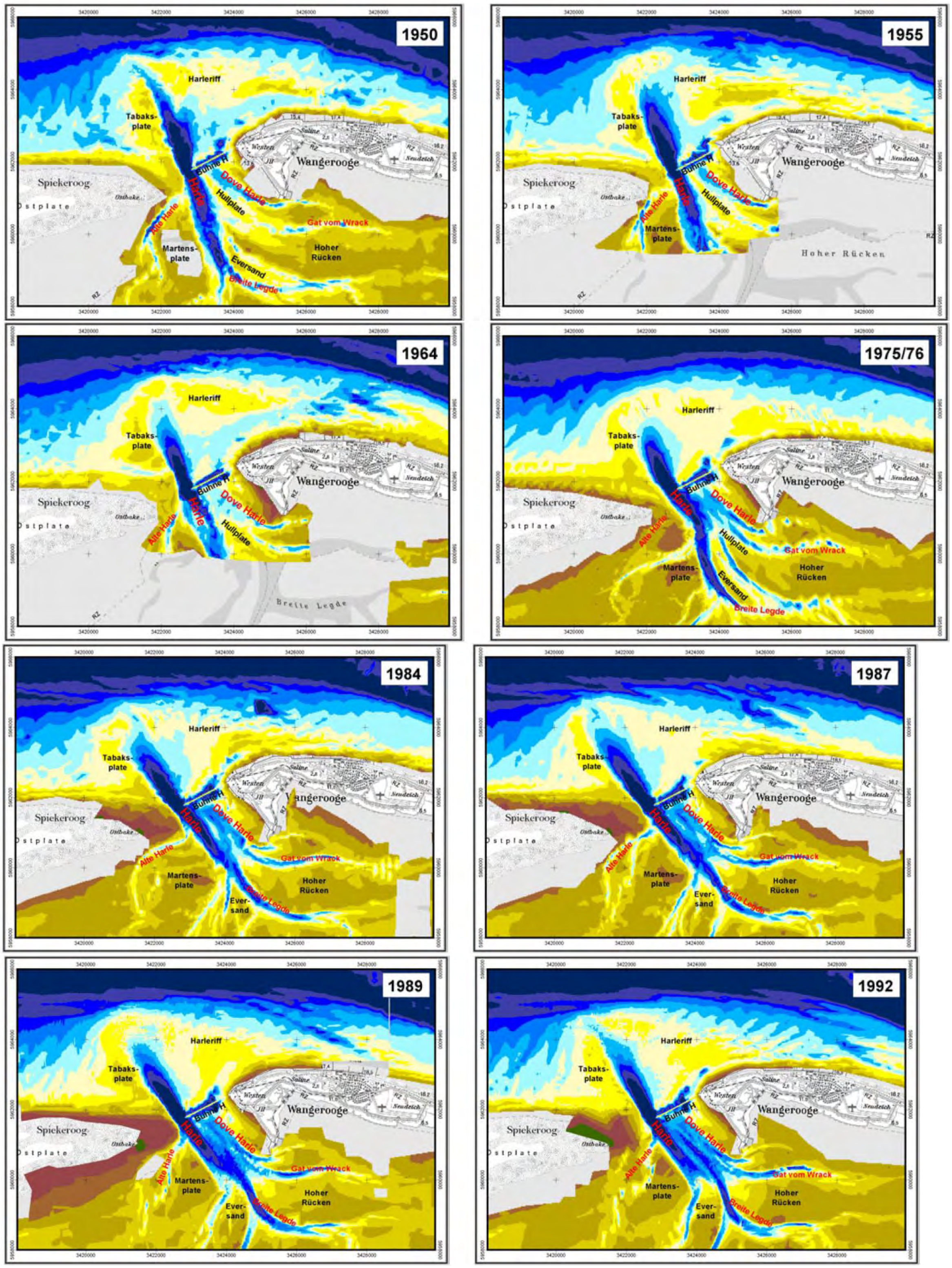
The wet cross sectional area of the inlet decreased over the period 1950-1975 from ca. 10500 to 9300 m^2 to increase again in the period 1975-2002/03 to 11800 m^2. Cross sectional areas are according to the regional relation with tidal volume (Ladage & Stephan, 2004).

The volume of the ebb-tidal delta increases over the period 1950-1964 from ca. 33 to $40*10^6$ m^3, after which it was reduced to $14*10^6$ m^3 by 1995 and increased again to $23*10^6$ m^3 in 2001 (Ladage & Stephan, 2004). It should be noted that all these observations were done with reference to a fixed coastal plain (coast 1995). If a variable coastal plain is used the variations are still there but much less pronounced and circle around $20*10^6$ m^3 (Ladage & Stephan, 2004). There is no clear relation between tidal volume and sediment volume of the ebb-tidal delta (Ladage & Stephan, 2004).

A more comprehensive parameter for sediment gain or loss is the position of the coast NHN -5 m line of the ebb-tidal delta (Figure 6.8.7). By and large, the Riffbogen position showed little variation in the period 1950-2002. There has been a slight retreat of the northeast side of the delta during the period 1950-1987, which is attributed to the westward shift of the Harle in that period, which diminishes the shelter for the northeast side (Ladage & Stephan, 2004). At the northwest side there is a clear relation with the seaward extension of the main ebb channel and the position of the NHN -5 m line (e.g. 1987 and 1950).

Relation with the island coasts

The development of the beach and shoreface of the Harlehörn area is influenced by both the developments in the backbarrier and the inlet. Although they result in accumulation of sediments S of Buhne W the major part was being eroded due to the expansion of the Dove Harle. Shoals that are migrating via the Riffbogen of Seegat Harle to the island were studied by Ridderinkhof (2016) for the periods 1986-1990 and 2002-2014. In these periods shoals were observed to attach to the coast of Wangerooge around 1990, 2006, and 2011. The depth sounding data suggest that in the in-between period 1990-2002 shoals merged with the island around 1992 and 2001 (see figure 6.8.8). Based upon these observations, the time scale at which these shoals attach to the coast is estimated at 5-6 years. Based upon the track of the last two shoals, it was established that the mean migration velocity of the shoals was 340 m yr^{-1} (STD: 147 m yr^{-1}; Ridderinkhof, 2016). Apparently these mergers by and large suffice to maintain the beach and dunes at the North Sea side of the island (which are partly protected by groins), as no measures were foreseen to protect that coast in the protection plans of NLWKN (2010).


1950
1955
1964
1975/76
1984
1987
1989
1992
Harleriff
Tabaks-plate
Spiekeroog
Wangerooge
Bunne H
Dove Harle
Harle
Alte Harle
Hullplate
Martens-plate
Gat vom Wrack
Hoher Rücken
Eversand
Ever-sand
Breite Legde

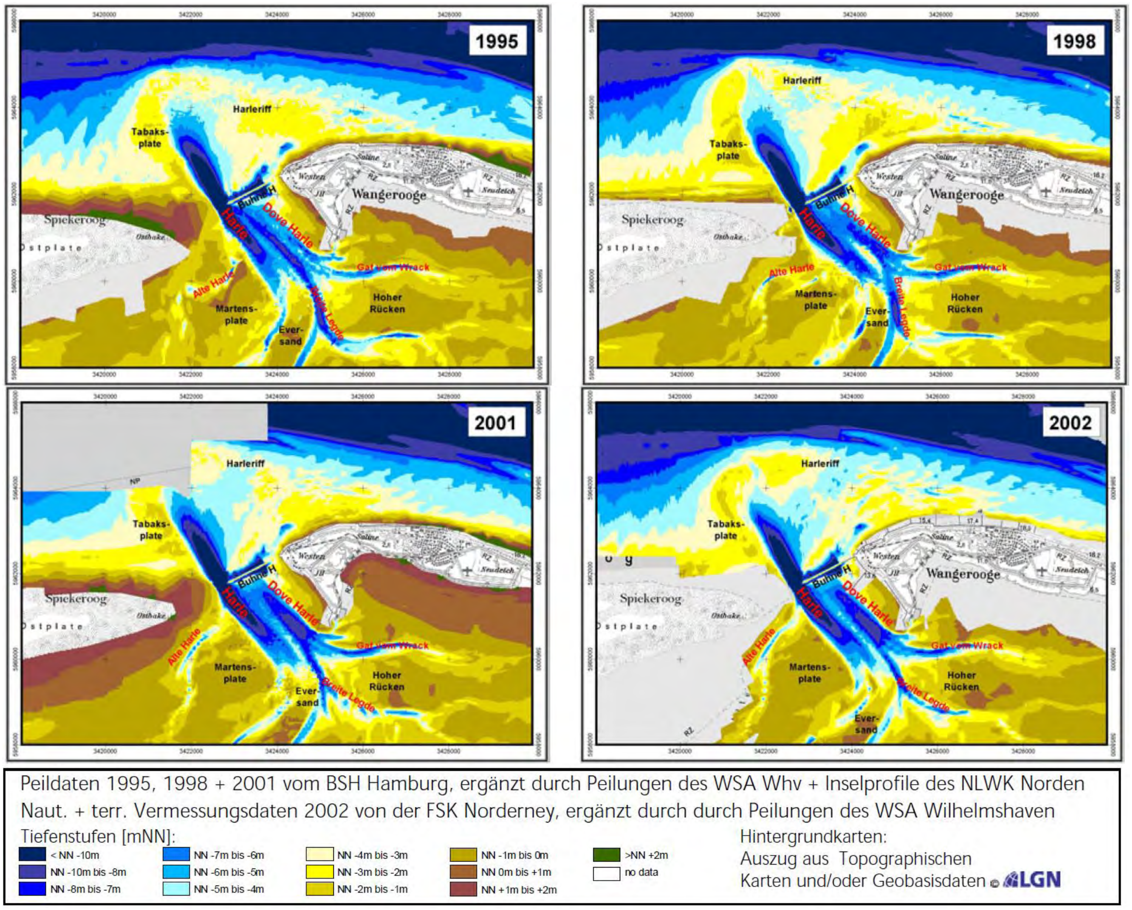


Figure 6.8.6: The development of the ebb-tidal delta of the Harle in the period 1950-2002 (Ladage & Stephan, 2004).

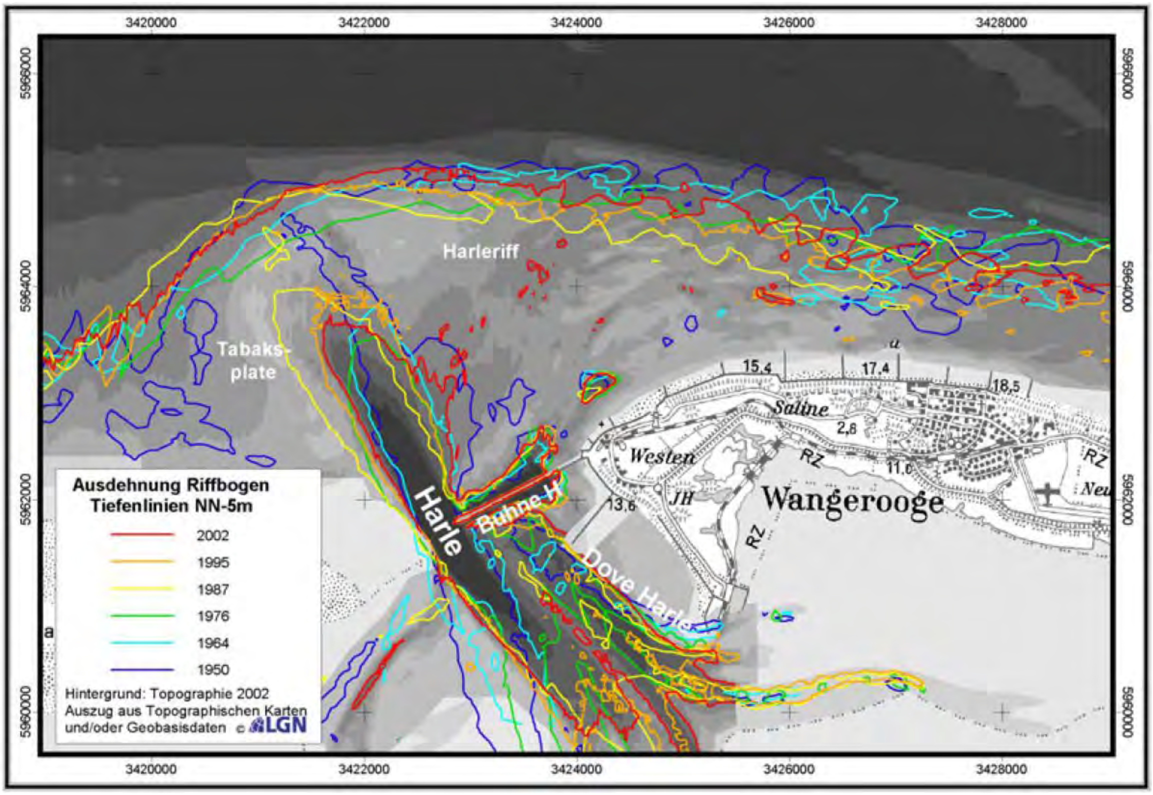


Figure 6.8.7: position of the NHN -5 m lines of the ebb-tidal delta (Ladage & Stephan, 2004).

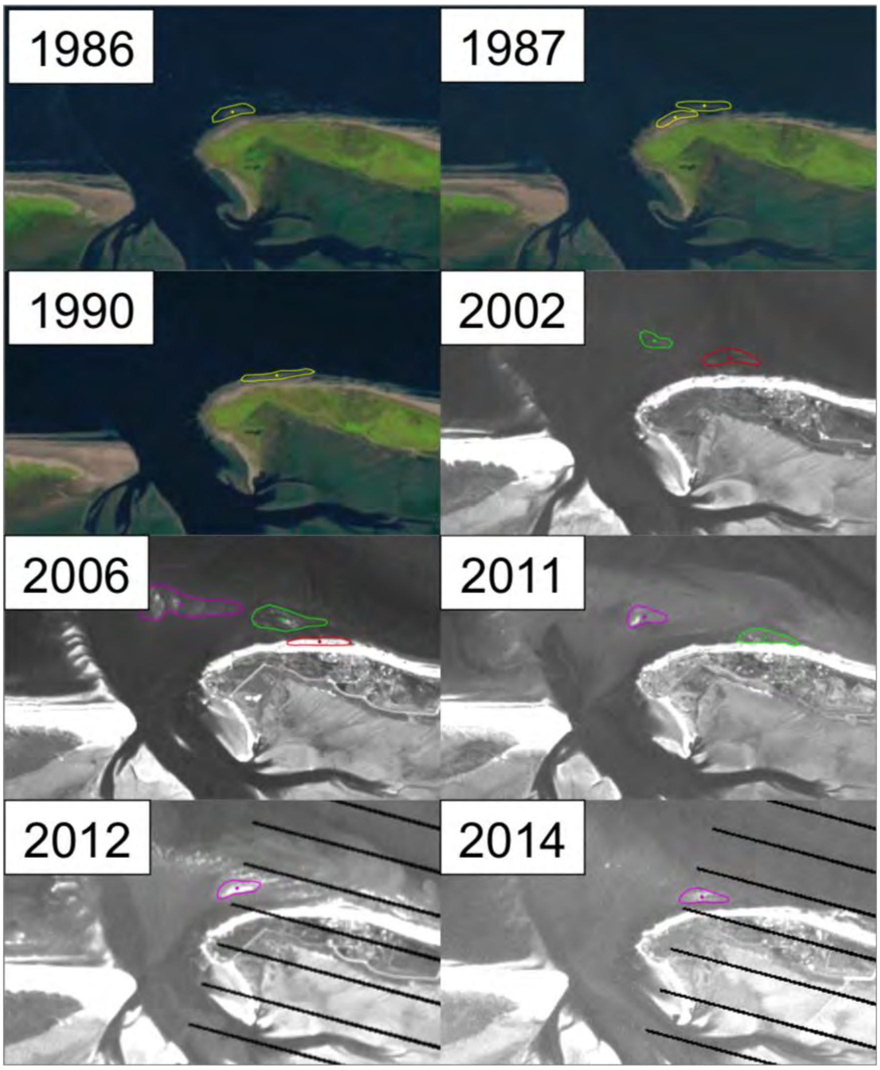


Figure 6.8.8: Landsat images of the ebb-tidal delta of Harle Inlet showing migrating shoals that attach to the coast of Wangerooge in the period 1986-2014 (Ridderinkhof, 2016).

6.9 Blaue Balje

Basic data

For Figures see 6.8.

Table 6.8: Facts and figures Blaue Balje (see also appendix I)

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	2.0	1891 - 2001	1 (station Norderney)	0.3	1903 - 2001	9 (station Alte Weser)	2.4	1960-2003	2 (= (MWHR + MLWR)/2
Hs (m)	0.93		CoastDat						
Tp (s).	4.97		CoastDat						
Tf/Te	0.85	2017	3 (station Wangerooge Ost)						
$L_{ebb\text{-}tidal\ delta}$ (km)	2.2	2012	-6 m	2.3	2012	-10m			
MHW (m NHN)	1.5	2017	6 (station Wangerooge Ost)						
MLW (m NHN)	-1.5	2017	3 (station Wangerooge Ost)						
MTR (m)	2.9	1982	4	3.0	2016	3 (station Wangerooge Ost)			
Surge height (m to MSL)									
Mean annual max surge height (m to AOD)	3.1		CoastDat						
A_{MHW} (km^2)	40	1995?	5	39 ±0	~2000	6			
A_{MLW} (km^2)	8 ±2	~2000	6						
A_{cross} (m^2)									
V_{MHW} (10^6 m^3)	80±10	~2000	6						
V_{MLW} (10^6 m^3)	12±2	~2000	6						
P (10^6 m^3)	68±12	~2000	6 (Pcom)	70 (68-72)	2004-2005	3 (Pcom) (flood resp. ebb volume)			
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)									
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	+1	1990-2012 & 2006-2009	7	+1.1 to +1.4	1990-2012 & 2006-2009	7 (stations Elbe & Schiermonnikoog)			
Sediment transport direction?	E?								
Development island coasts	Relatively stable on both sides of inlet								

1 = Jensen & Mudersbach, 2007; 2 = Ladage & Stephan, 2004; 3 = BSH, 2016; 4 = Postma, 1982; 5 = Herrling, 2014 ; 6 = Stanev et al., 2003 (± indicating neap and spring tide conditions); 7 = Ridderinkhof, 2016.

Description of the inlet system
Location: Germany, Lower Saxony, between the barrier island (west) Wangerooge and (east) Minsener Oog. Over the past century, the changes in the inlet Blaue Balje and the protection works on the 2 km long islet of Minsener Oog have influenced the backbarrier S of Wangeroog. It cannot be excluded that this also exerted influence on the Harle system, which is considered to be closely “coupled”. Around 1650 the island of Minsener Oog was probably around 5 km long and oriented WNW-OSO (Homeier, 1974). At its eastern tip the Jade eroded some 2.9 km of its length (Ladage & Stephan, 2004). This might well be an example of the shift from a barrier coast to an open coast with elongated linear sand ridges due to the gradual increase in tidal amplitude (see chapter 3). At the same time there was some erosion at the west side due to the increasing length of Wangeroog. The island expanded in a SW ward direction into the backbarrier area. That it did not disappear is most likely due to the many dams build since 1908, which were meant to guide the sands and with it the Jade to protect the route to Wilhelmshaven (Schubert, 1970).

Since 1950 the backbarrier area has changed. The northern part of the watershed of Wangeroog has migrated to the E; a change which coincided with the gradual infill of the westward protruding secondary backbarrier channel (Figures 6.8.4 &. 6.9.1). Around 1975 the southern part of the watershed of Wangeroog starts to shift to the W. The development coincides with an ever stronger development of the central channel (Mittelbalje), which extents in a more or less straight line to the SW (Figure 6.9.1; Ladage & Stephan, 2004). The channel was mainly artificially straightened (Wurpts, pers. comm.) but does not seem to re-meander so far.

Description of the ebb-tidal delta
The main channel in the small ebb-tidal delta has its orientation from more N to NE in the period 1950-2001. Possible reasons for this change are: 1) inertia of the water flow coming from the central channel which is nowadays quite straight; 2) possible decrease in tidal prism due to the shift of the watershed; 3) sediment accumulation at the west side of the channel in front of Wangeroog. The straight line which thus developed is strongly reminiscent of the elongated line-ar sand ridges more to the E (see also chapter 3).

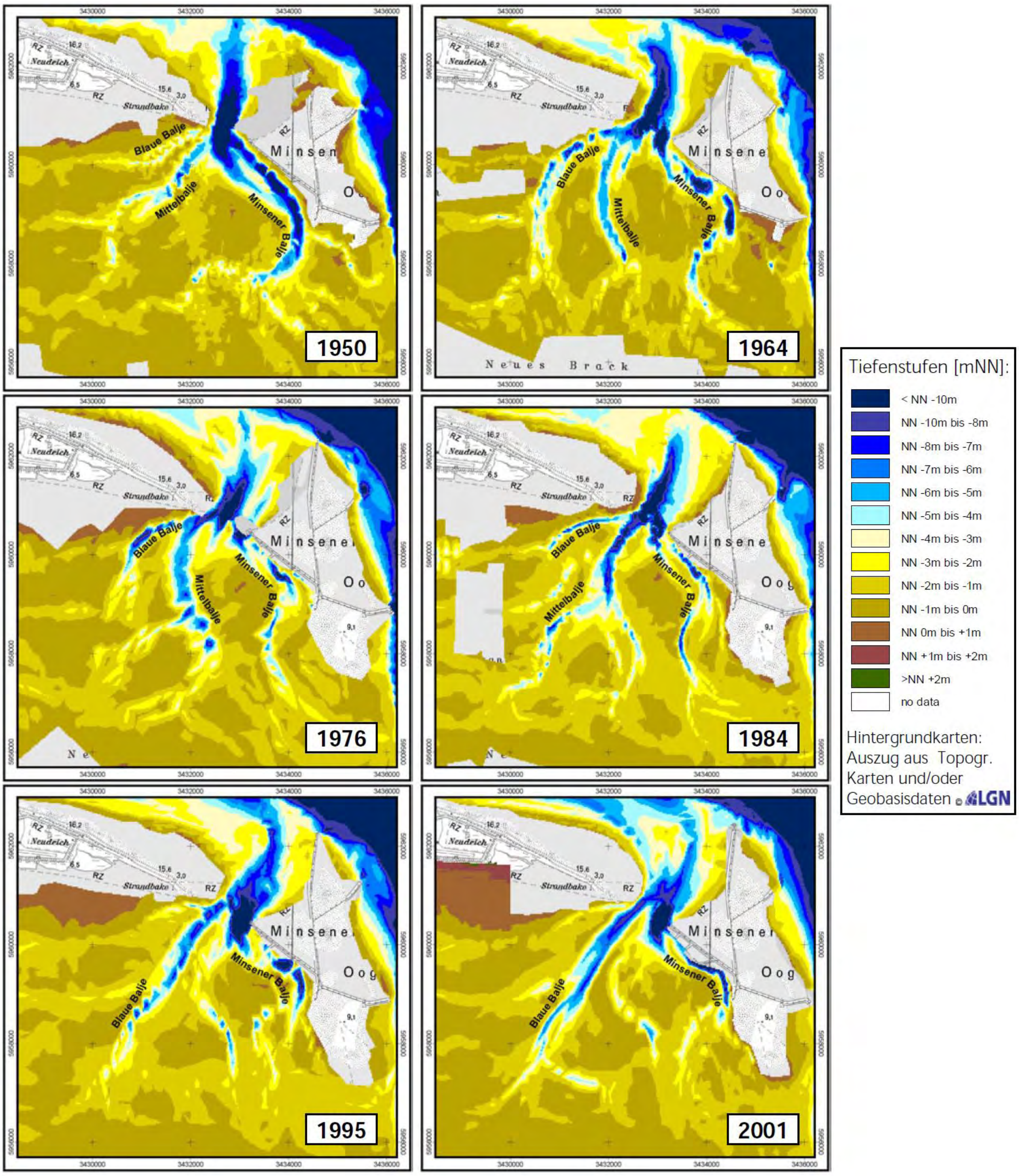


Figure 6.9.1: Overview of the development of the Blaue Balje (Ladage & Stephan, 2004).

7 Ebb-tidal deltas of Schleswig Holstein

7.1 General description of the Schleswig Holsteinian area

Characteristics

The S to N trending World Heritage Wadden area of Schleswig Holstein has a total surface area of 4,367 km² from the mouth of the river Elbe up to the Danish border by the island Sylt. The Wadden Sea itself has a total area of some 2.350 km^2 and consists of Halligen (12%), tidal marshes (4%), tidal flats (51%) and tidal channels (33%; Figure 7.1.1; MELUR, 2013).

Figure 7.1.1: The inlet systems of which ebb-tidal deltas are described in the Wadden area of Schleswig Holstein: Norderhever-Heverstrom to Hörnum Tief (Courtesy, Wadden Sea Secretariat).

The area consists of fourteen inlet systems, from S to N: Schatzkammer, Neufahrwasser, Flackstrom, Piep/Meldorfer Bucht, Wesselburener Loch, Eidermündung, Tümlauer Bucht, Norderhever-Heverstrom, Rummelloch-West, Hooger Loch , Aue (a combined inlet for the systems Süderaue & Norderaue), Hörnum Tief and Lister Tief (Lister Dyb; Figure 7.1.2).

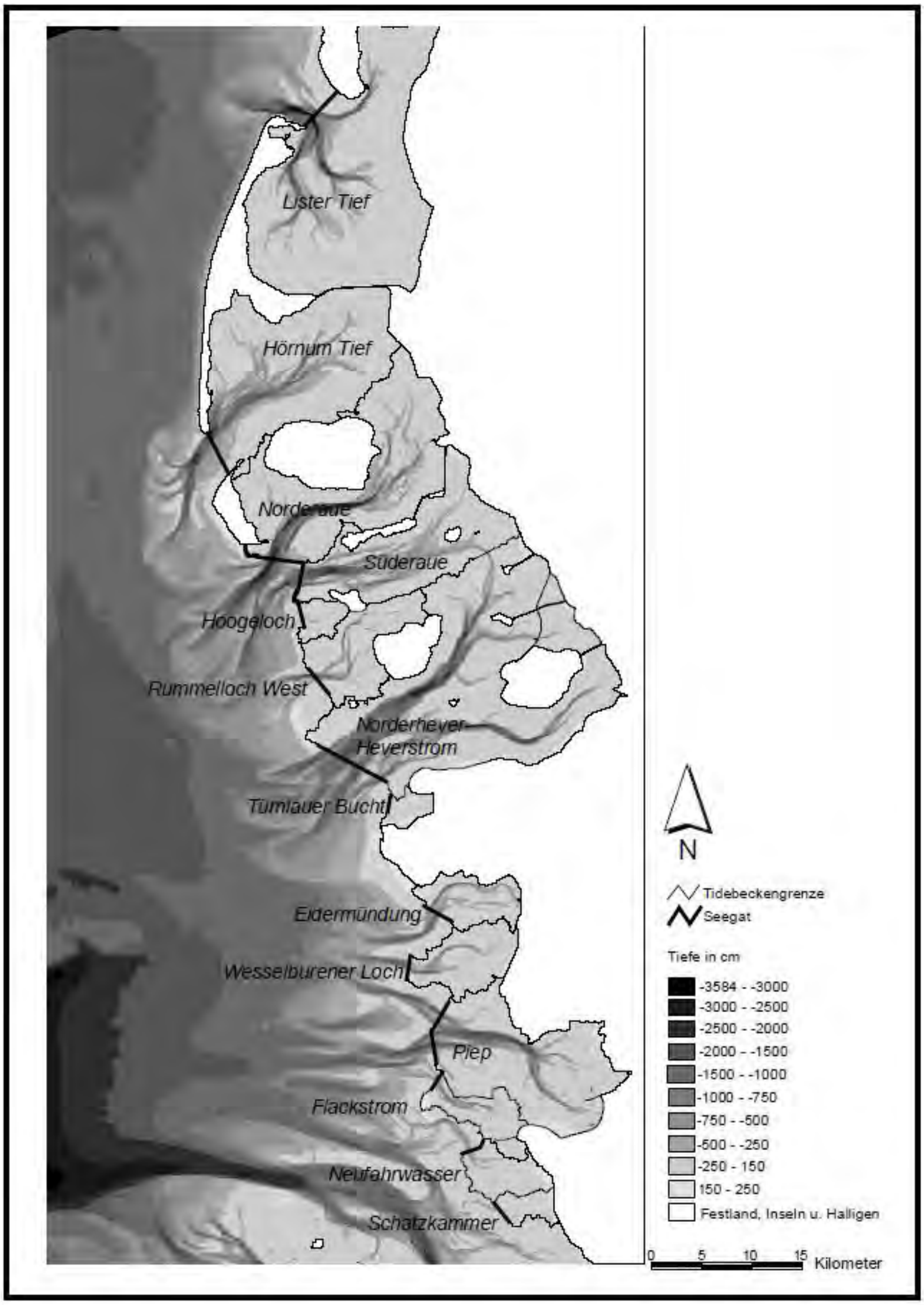


Figure 7.1.2: Detailed overview of the inlet systems of Schleswig Holstein.

Figure 7.1.3: Littoral drift as determined on stations Helgoland (HLG) and Sylt (SLT) in 10^6 m^3/yr (From: Ridderinkhof, 2016).

Several small rivers are entering the backbarrier; the major ones are the Eider and Aue. Five of the inlets have islands both sides and clearly distinguishable ebb-tidal deltas, namely Norderhever-Heverstrom, Rummelloch-West, Aue, and Lister Tief. These will be discussed in the text below with the exception of Lister Tief which will be discussed in chapter 8. Most of the systems will only be discussed shortly due to limited information.

Tidal amplitude increases from N to S from 1.8 m at List on Sylt up to 3.5 m in Husum (MELUR, 2013). Along the North Sea coast of Schleswig Holstein littoral drift is directed to the S, calculated to be 0.2-1.5*10^6 m^3/yr (Figure 7.1.3; Ridderinkhof, 2016). Prevailing westerly winds exceed 10 m/s for 25% of the time and 20 m/s for 0.5% of the time. During storm surges significant wave heights may reach heights up to 5 m (MELUR, 2013). Normally, the mean significant wave height increases from 1.3 m in the Hever to 1.5 m in the Lister Dyb/Lister Tief (Coast Dat data).

Observations over the period 1940-2007 show that MHW increase in the North Frisian Wadden Sea is 3.8 mm/yr, whereas MLW is decreasing with some 0.3 mm/yr. This results in a mean tidal halfwater level increase of 1.8 mm/yr (Figure 7.1.4; MELUR, 2013). Over the period 1875-2007 the highest storm surges at the Husum tidal gauge show a linear increase of 7.3 mm/yr (Figure 7.1.5; MELUR, 2013). Also, the annual cumulative duration of storm surges has increased since 1900 (Figure 7.1.6). Figures 7.1.5 and 7.1.6 show a strong increase in storm surge intensity from the early 1960ies up to the early 1990ies. Afterwards, storm surge climate became less energetic.

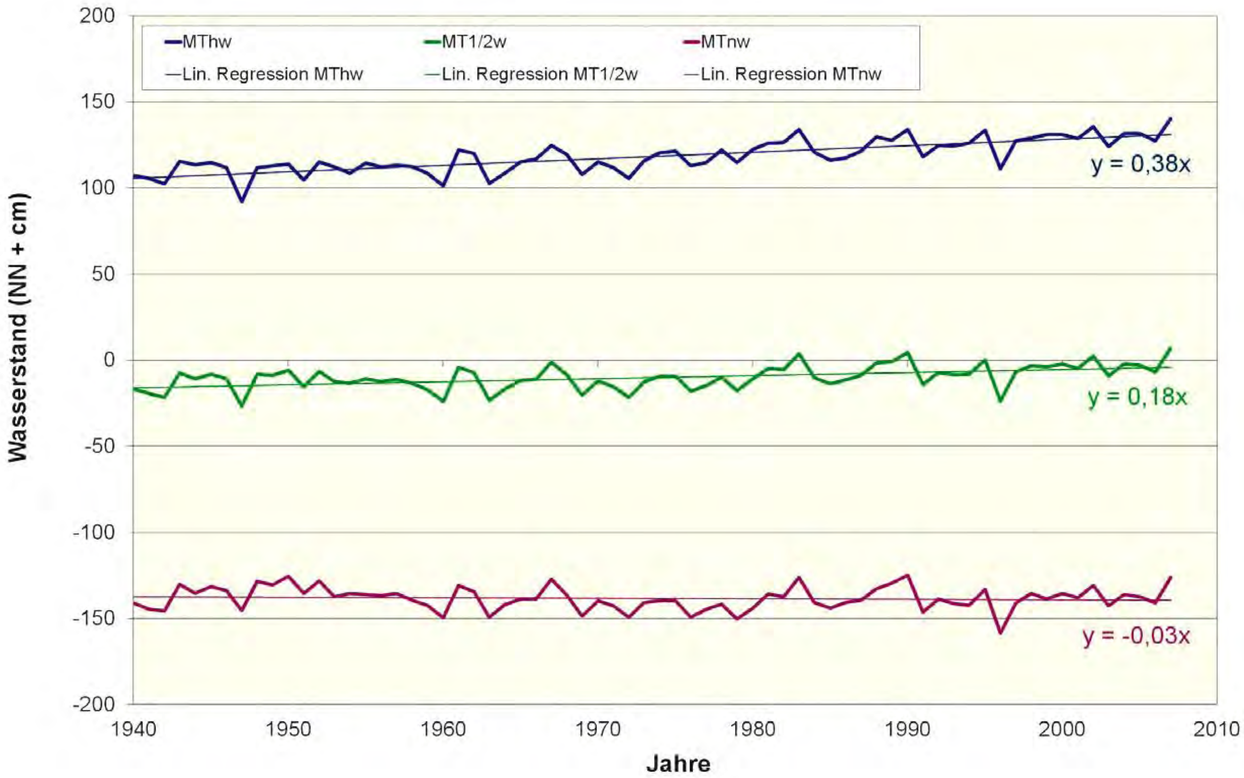


Figure 7.1.4: Development of the MHW, Halftide and MLW over the period 1940-2007 as a mean of the stations: List, Hörnum, Wittdünn, Dagebüll, Husum, Büsum and Helgoland (MELUR, 2013).

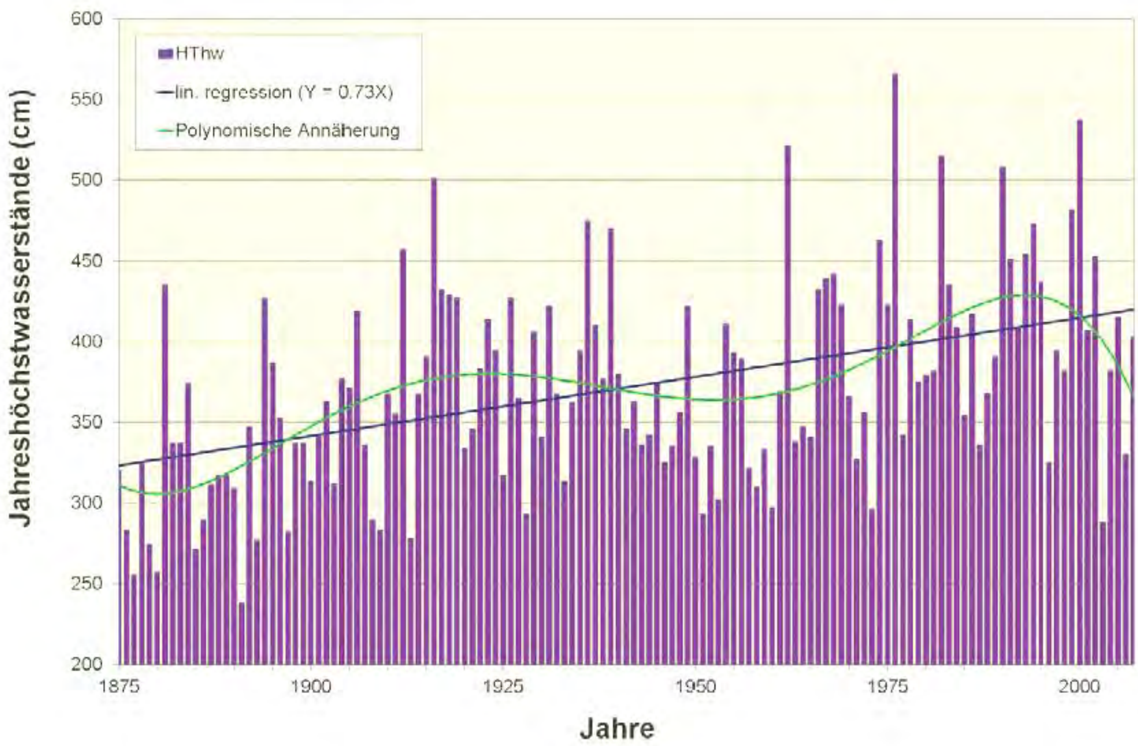


Figure 7.1.5: Observations of the annual highest storm surges at Husum gauge (MELUR, 2013)

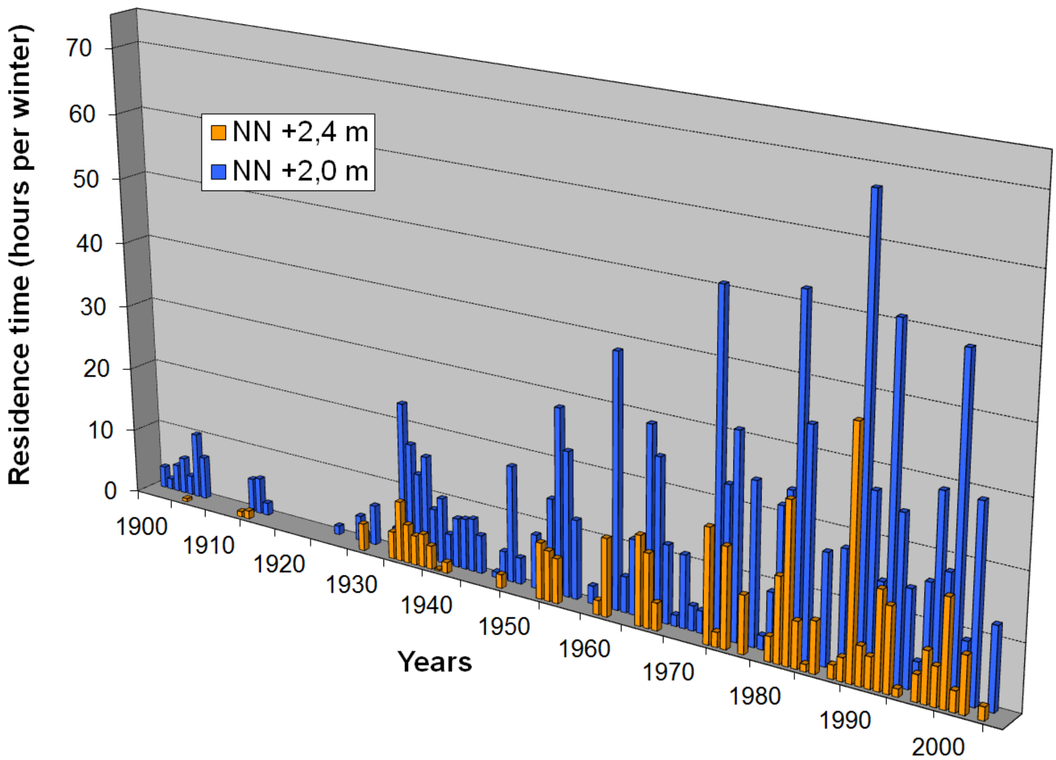


Figure 7.1.6: Annual hours of storm surges higher than +2.0 and 2.4 m NHN at tidal gauge station List on Sylt over the period 1900-2004 (MELUR data, courtesy of Hofstede).

Several large engineering interventions have been carried out in the area. The most important are the dams to Sylt and the diking of some parts of the backbarrier area of Hörnum Tief and Hever. Calculations for the area Heverstrom, Norderhever, Rummelloch West, Hooger Loch and Süderaue over the period 1936-2000 suggest that the water volume between MHW and MLW decreases, whereas the data on the water volume of the area below MLW show a less clear trend (using the data of van Riesen & Winskowsky, 2007). This suggests sedimentation in the intertidal reach and erosion or sedimentation stillstand in the subtidal areas.

Geology

A large part of the geomorphology of Schleswig-Holstein was created during the Saale glaciation. Then the moraines of Sylt, Föhr and Amrum were deposited and also the high sandy Geest deposits between Amrum and Eiderstedt. Sediments more westward have been eroded. The eastern Wadden Sea boundary is formed by Lecker-Bredstedter and Husumer Geest area. During the Eemian transgression extensive clayey and sandy deposits were formed (Ahrendt et al., 2006a). During the last Ice Age (Weichsel) no land ice was present in the area. The sea was some 110 m lower than today and rivers scoured valleys into the Saalian deposits. Aeolian and fluvioglacial sediments were deposited.

After the last Ice Age relative sea-level rise was initially rapid (up to 2 m/century), but decelerated significantly after 7,500-7,000 a BP (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.

In Schleswig-Holstein the areas of Nordfriesland and Dithmarschen were developed under different geological conditions. This resulted in a barrier system, consisting of geest Islands and extensive “Außensänden” in Nordfriesland, and the lack of thereof in Dithmarschen (Schmidtke, 1995).

The occurrence of locally elevated Pleistocene (or older) outcrops and headlands consisting of moraine deposits of the Saalian (second-last) glaciation, and sandy meltwater deposits of the Weichselian (last) glaciation, especially formed the North Frisian Wadden area (Bartholdy & Pejrup, 1994; Lindhorst, 2007). Nordfriesland can be considered as the remnant of an area W of the present-day eastern edge of the Geest. Here, the decelerating sea-level rise resulted in increased sedimentation and led even to a prograding coast. The source of the sediments were the Saalian Geestland sediments, W of today's Geest islands Sylt, Föhr and Amrum. S-ward coast-parallel transport of these sediments resulted in the formation more or less closed barrier spit, behind which a landscape developed of swamps, bogs and forests (Bantelmann, 1966).

Around the year 1,000, the land was cultivated by man. He lived on dwelling hills and built drainage systems. In combination with peat excavation the area became vulnerable to flooding. The Halligen islands in the North Frisian back-barrier area were at that time still much larger than at present, although 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; Hoffmann, 2004; Meier, 2004; Kühn, 2007). At the same time import of sediments from the deeper North Sea ended and erosion started to dominate and the area was flooded from time to time. From 1,200 a BP onwards, dwelling mounds were once more constructed in the North Frisian region (Vollmer et al., 2001) as had been done before. Between 1,000-1,100 AD, storm-flood 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. This occurred from medieval times onwards and large areas were changed into Wadden Sea areas (Schmidtke, 1995, Higelke, 1998). In 1634 a last big storm surge occurred, after which the present-day appearance of the North Frisian Wadden Sea with its (Geest) Islands, Halligen and “Außensänden” remained approximately the same.

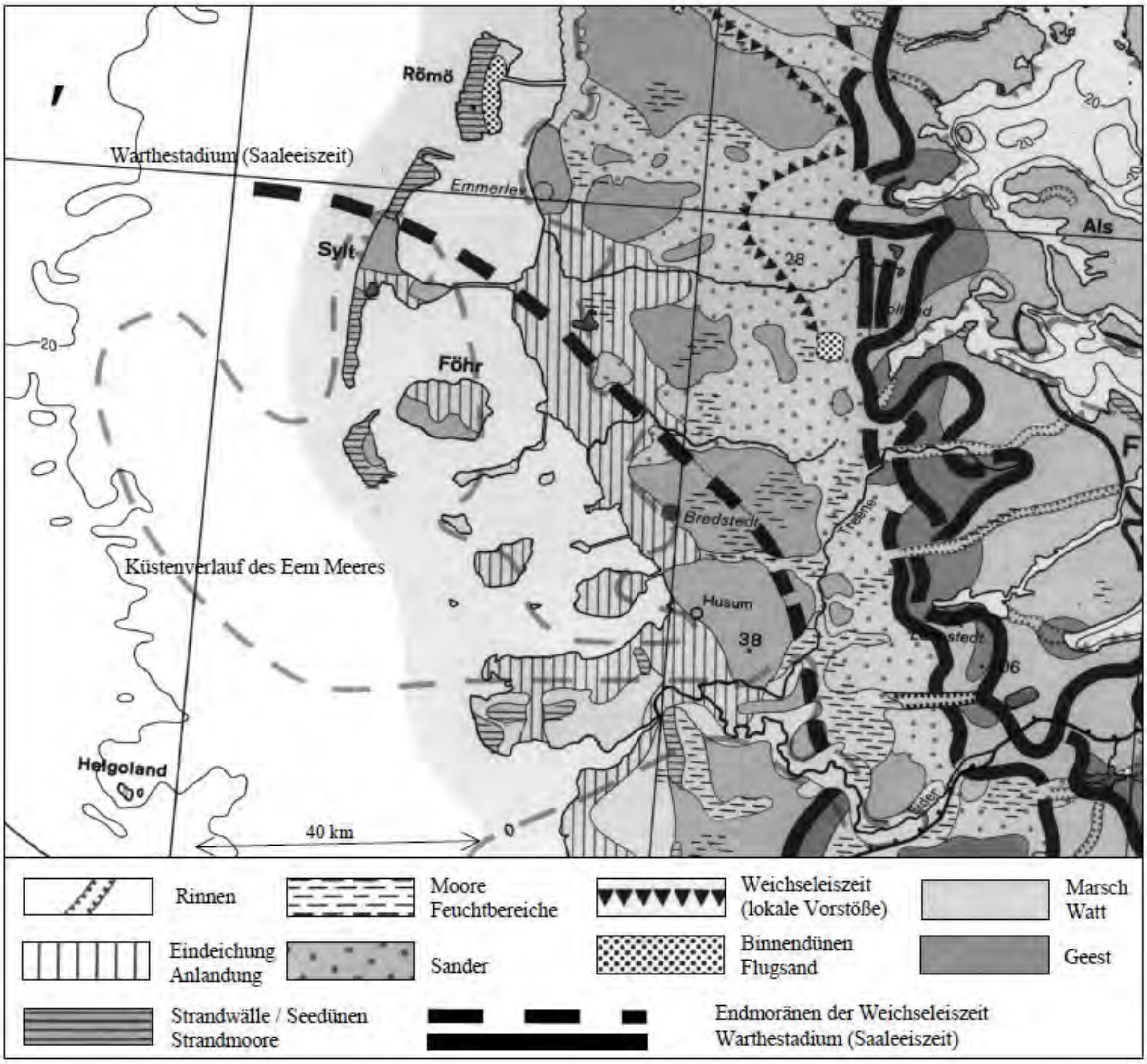


Figure 7.1.7: Geological map of the Schleswig Holstein (Falk, 2001).

The larger part of the sediments of the tidal area consists of medium sized quartz sands. But it is clearly visible on Figure 7.1.8 that the channels of Hever, Aue, and especially Hörnum Tief and Lister Tief are characterized by coarse grained sediments. This indicates that these inlets are eroding into the Pleistocene moraine deposits, the sturdy boulder clays. This might be an explanation to the general lack of meandering in the deeper inlet channels. The sand is mainly derived from the North Sea coastal area, which, as a result, retreated; the mud is mainly riverine or biogenetic of origin (Figure 7.1.8; Ahrendt, 2006b; MELUR, 2013).

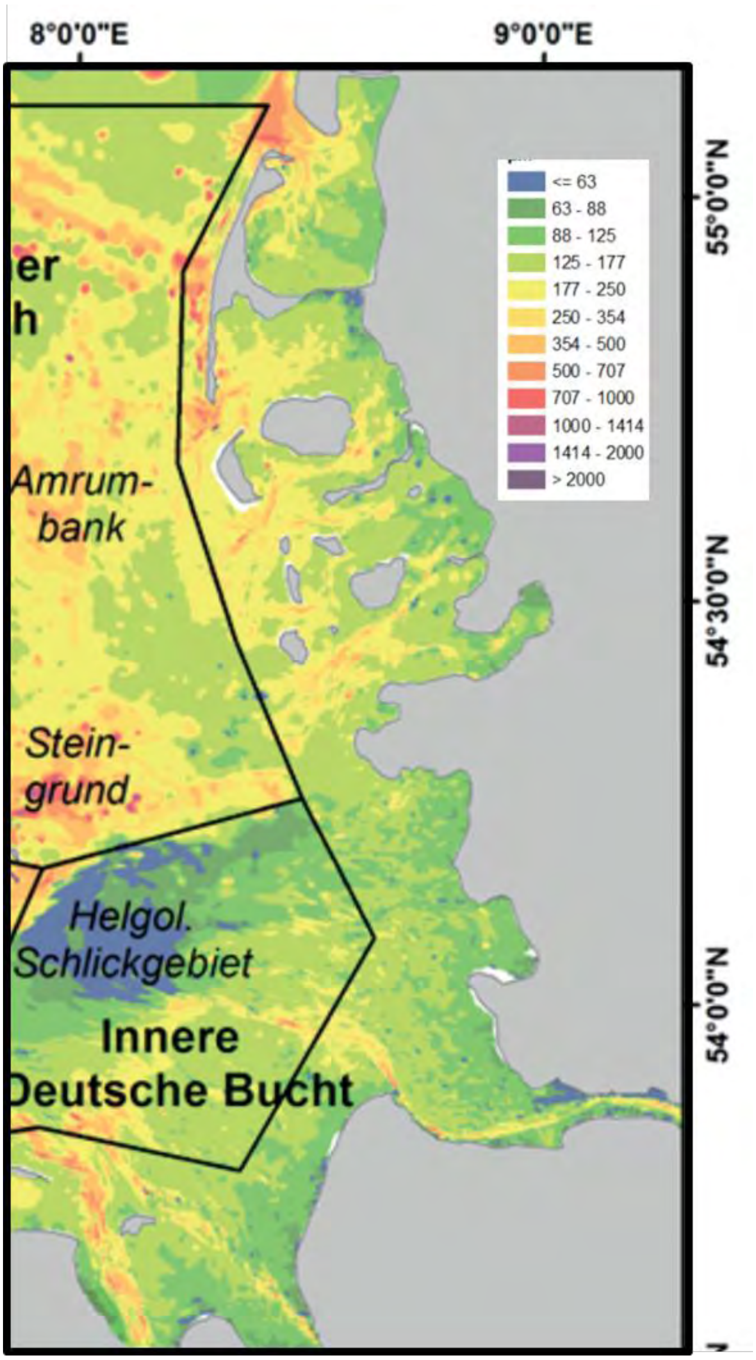


Figure 7.1.8: Median grain size distribution in micrometer-classes of the Schleswig Holsteinian area as given in the functional bottom model (Milbradt et al. 2015).

7.2 Norderhever-Heverstrom

Basic data

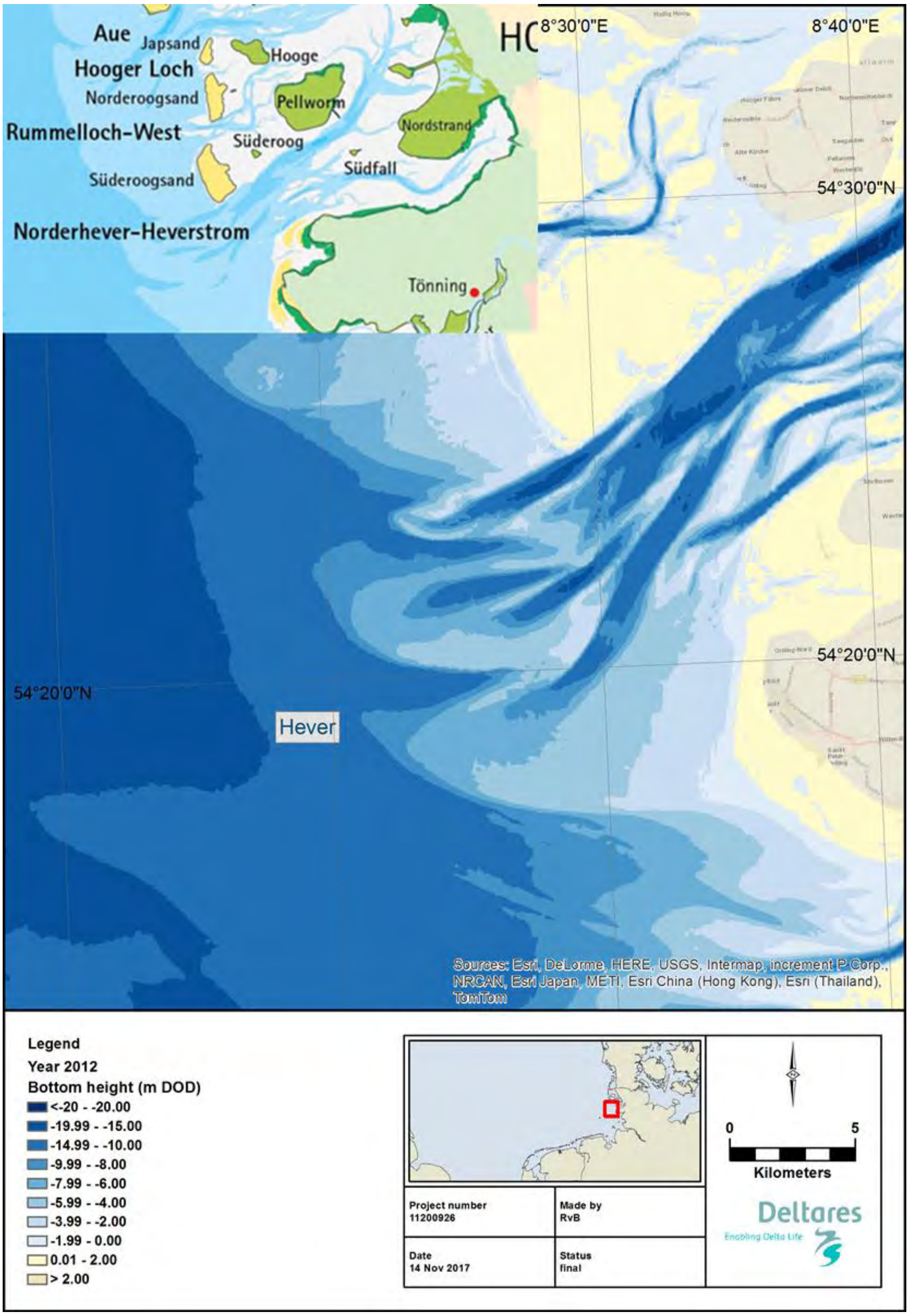


Figure 7.2.1: Overview of the ebb-tidal delta of the Hever (with overview in-set).

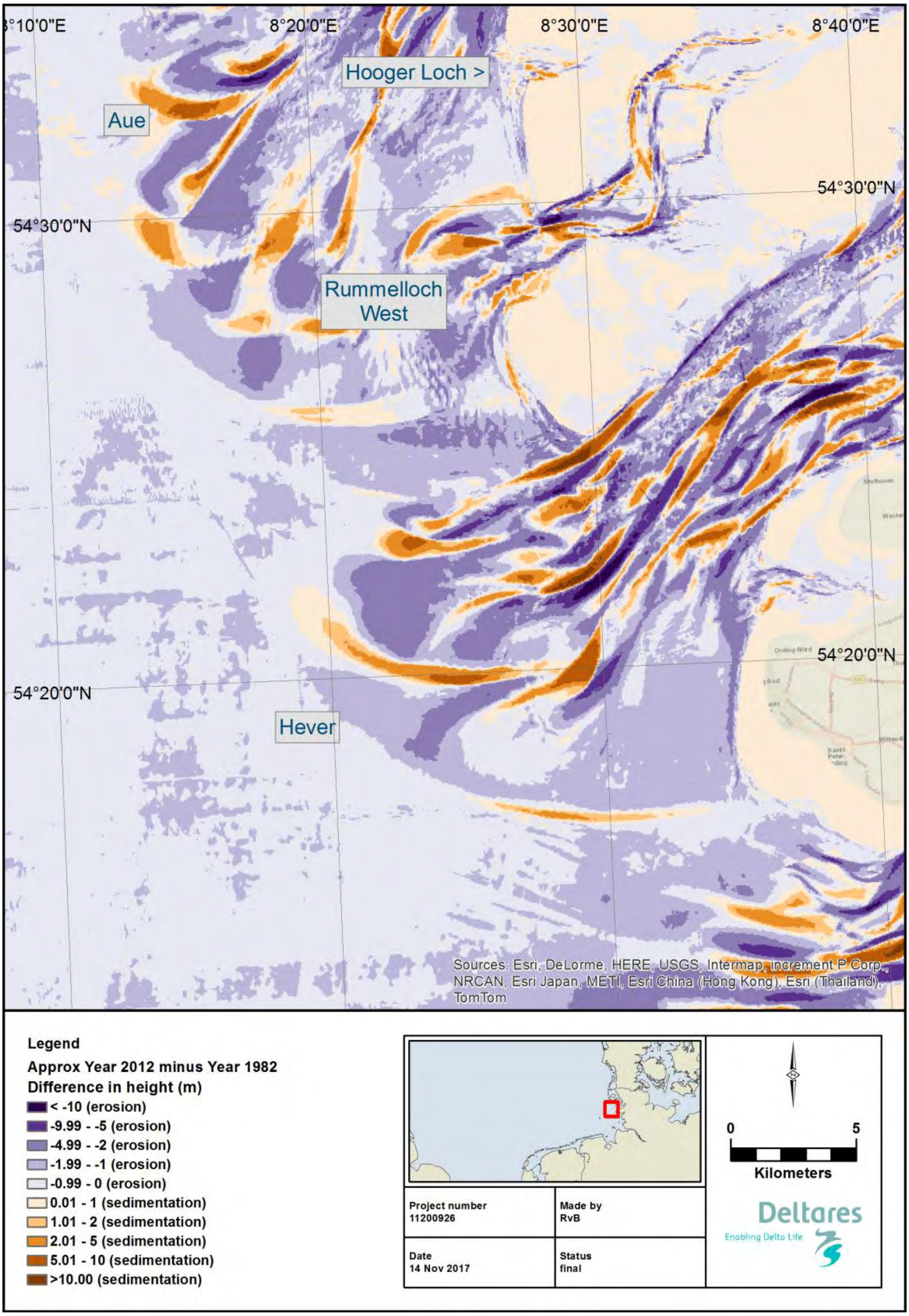


Figure 7.2.2: Overview of the ebb-tidal delta of the Hever showing erosion and deposition over approximately the period 1982-2012.

Table 7.1: Facts and figures Hever in total. Please note that Norderhever + Heverstrom is a bigger area than the two separate because van Riesen & Winskowsky(2007) did not measure the whole area. (see also appendix I)

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2	1940-2010	1 (station Husum)						
Hs (m)	1.33		CoastDat						
Tp (s).	5.43		CoastDat						
Tf/Te	0.85	2017 (2 tidal cycles of 3 jan)	2 (station Süder-oogsand)						
$L_{ebb\text{-}tidal\ delta}$ (km)	6.1	2012	-6 m	15.1	2012	-10m			
MHW (m NHN)	1.4	2017	2 (station Sü-deroogsand)						
MLW (m NHN)	-1.5	2017	2 (station Sü-deroogsand)						
MTR (m)	2.9	2017	2 (station Süder-oogsand)						
Surge height (m to MSL)	25 y: 5.41	???	1 (station Husum)	50 y: 5.67	???	1 (station Husum)			
Surge height (m to MSL)	100 y: 5.91	???	1 (station Husum)	250 y: 6.19	???	1 (station Husum)	500 y: 6.38)	???	1 (station Husum)
Mean annual max surge height (m to AOD)	2.81		CoastDat						
A_{MHW} (km^2)	441.8	1974/76	3						
A_{MLW} (km^2)	139.9	1974/76	3						
A_{cross} (m^2)	65031	1974/76	3						
V_{MHW}	1780	1974/76	3						
V_{MLW} ($10^6 m^3$)	899	1974/76	3						
P ($10^6 m^3$)	881	1974/76	3						
$SV_{backbarrier}$ ($10^6 m^3$)	504.3	1974/76	3						
$AS_{backbarrier}$ ($10^6 m^3$/yr)	3.8	1990-2000	4						
$AS_{ebb\text{-}tidal\ delta}$ ($10^6 m^3$/yr)									
Longshore drift ($10^6 m^3$/yr)	-1.4	2006-2009	5	-1.3 to -1.5 Hever	2006-2009 & 2006-2009	5 (stations Sylt & Helgo-land)			
Sediment transport direc-tion?									
Development island coasts	Sedimentation at St. Peter-Ording-Sand; Sedimentation S Süderoogsand								

1 = ; MELUR, 2013; 2 = BSH, 2016; 3 = Floser et al., 2011; 4 = van Riesen & Winskowsky, 2007.1 = 5 = Ridderinkhof, 2016.

Table 7.2: Facts and figures Heverstrom (see also appendix I)

Parameter	**Obs**	**Year**	**Reference**	**Obs**	**Year**	**Reference**	**Obs**	**Year**	**Reference**
MSLR (mm/yr)	2	1940-2010	1 (station Husum)						
Hs (m)	1.33		CoastDat						
Tp (s).	5.43		CoastDat						
Tf/Te	0.85	2017 (2 tidal cycles of 3 jan)	2 (station Süderoogsand)						
MHW (m NHN)	1.4	2017	2(station Süder-oogsand)						
MLW (m NHN)	-1.5	2017	2 (station Süderoogsand)						
MTR (m)	2.9	2017	2 (station Süderoogsand)						
Surge height (m to MSL)	25 y: 5.41	???	1 (station Husum)	50 y: 5.67	???	1 (station Husum)			
Surge height (m to MSL)	100 y: 5.91	???	1 (station Husum)	250 y: 6.19	???	1 (station Husum)	500 y: 6.38)	???	1 (station Husum);
Mean annual max surge height (m to AOD)	2.81		CoastDat						
A_{MHW} (km^2)	135.3	1981	3	135.3	1990	3	135.3	2000	3
A_{MLW} (km^2)		1974/76	4						
V_{MHW} (10^6 m^3)	466	1981	3 (Fixed MHW and MLW)	481	1990	3 (Fixed MHW and MLW)	463	2000	3 (Fixed MHW and MLW)
V_{MLW} (10^6 m^3)	193	1981	3 (Fixed MHW and MLW)	206	1990	3 (Fixed MHW and MLW)	203	2000	3 (Fixed MHW and MLW)
A_{cross} (m^2)									
P (10^6 m^3)	273	1981	3 (Pbat)	272	1990	3 (Pbat)	260	2000	3 (Pbat)
$SV_{backbarrier}$ (10^6 m^3)	160	1981	3	158	1990	3	173	2000	3
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	1.8	1990-2000	3	0,6	1981-2000	3			
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	-1.4	2006-2009	5	-1.3 to -1.5 Hever	2006-2009 & 2006-2009	5 (stations Sylt & Helgo-land)			
Change ebb-tidal delta?									
Sediment transport direc-tion?	S								
Development island coasts	Sedimentation at St. Peter-Ording-Sand								

1 = MELUR, 2013; 2 = BSH, 2016; 3 = van Riesen & Winskowsky, 2007; 4 = Floser et al., 2011; 5 = Ridderinkhof, 2016.

Table 7.3: Facts and figures Norderhever (see also appendix I)

Parameter	**Obs**	**Year**	**Reference**	**Obs**	**Year**	**Reference**	**Obs**	**Year**	**Reference**
MSLR (mm/yr)	2	1940-2010	1 (station Husum)						
Hs (m)	1.33		CoastDat						
Tp (s).	5.43		CoastDat						
Tf/Te	0.85	2017 (2	2 (station						

		tidal cycles of 3 jan)	Süderoogsand)						
MHW (m NHN)	1.4	2017	2 (station Süderoogsand)						
MLW (m NHN)	-1.5	2017	2 (station Süderoogsand)						
MTR (m)	2.9	2017	2 (station Süderoogsand)						
Surge height (m to MSL)	25 y: 5.41	???	1 (station Husum)	50 y: 5.67	???	1 (station Husum)			
Surge height (m to MSL)	100 y: 5.91	???	1 (station Husum)	250 y: 6.19	???	1 (station Husum)	500 y: 6.38)	???	1 (station Husum)
Mean annual max surge height (m to AOD)	2.81		CoastDat						
A_{MHW} (km^2)	118.9	1981	3	118.9	1990	3	118.9	2000	3
A_{MLW} (km^2)		1974/76	4						
V_{MHW} (10^6 m^3)	915	1981	3	935	1990	3	915	2000	3
V_{MLW} (10^6 m^3)	446	1981	3	466	1990	3	459	2000	3
A_{cross} (m^2)		1974/76	4						
P (10^6 m^3)	469	1981	3 (Pbat)	469	1990	3 (Pbat)	456	2000	3 (Pbat)
$SV_{backbarrier}$ (10^6 m^3)	84	1981	3	64	1990	3	72	2000	3
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	2	1990-2000	3	-0.7	1981-2000	3			
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	-1.4	2006-2009	5	-1.3 to -1.5 Hever	2006-2009 & 2006-2009	5 (stations Sylt & Helgoland)			
Change ebb-tidal delta?									
Sediment transport direction?									
Development island coasts	Sedimentation S Süderoogsand								

1 = MELUR, 2013; 2 = BSH, 2016; 3 = van Riesen & Winskowsky, 2007; 4 = Floser et al., 2011; 5 = Ridderinkhof, 2016.

Description of the tidal inlet system

The Hever tidal inlet lies between the barrier Süderoogsand to the North and the peninsula of Eiderstedt to the south (Figures 7.2.1-7.2.2). In 1987 the Hattstedter Marsch was diked resulting in a reduction off the area of the Hever system with some 32 km^2. With a present total basin area of about 464 km^2, about 65% of the area is intertidal, the rest subtidal (Spiegel, 1997). Tidal prism amounts to about 881*10^6 m^3, intertidal sediment volume to about 504*10^6 m^3. For the back-barrier basin, Witez et al. (1998) established a sedimentation of about about 51*10^6 m^3 over the period 1935 to 1975, but van Riesen & Winskowsky (2007) concluded that it was some 19*10^6 m^3 only for the period 1936-1981 (see extended tables). The latter authors concluded that for the entire Hever annually some 3.8*10^6 m^3/yr is deposited over the period 1990-2000, mainly in the intertidal zone.

Development of the ebb-tidal delta

In general the ebb- and flood-oriented ebb-tidal delta channels seem to migrate towards the S; i.e. in the direction from which the tide is coming. These developments might be brought about by the rather complicated backbarrier situation which leads to far seaward extending ebb-channels separated by flood-oriented channels which are slightly W of WNW oriented.

Coastal development

Around 1990 a shoal attached to the shore of St. Peter-Ording-Sand (Fig. 7.2.3). This was also described by Hofstede (1999a), who stated that this shoal attached to the shore in 1988 and followed a shoal that attached to the coast in 1964. In 2006 another, smaller shoal attaches to the coast. Based upon these observations it was established that shoals attach to St. Peter-Ording- Sand approximately every 21 years (std: 7 yr). Since the shoals are not visible before they attach to the coast of St. Peter-Ording-Sand, a migration velocity could not be determined (Ridderinkhof, 2016).

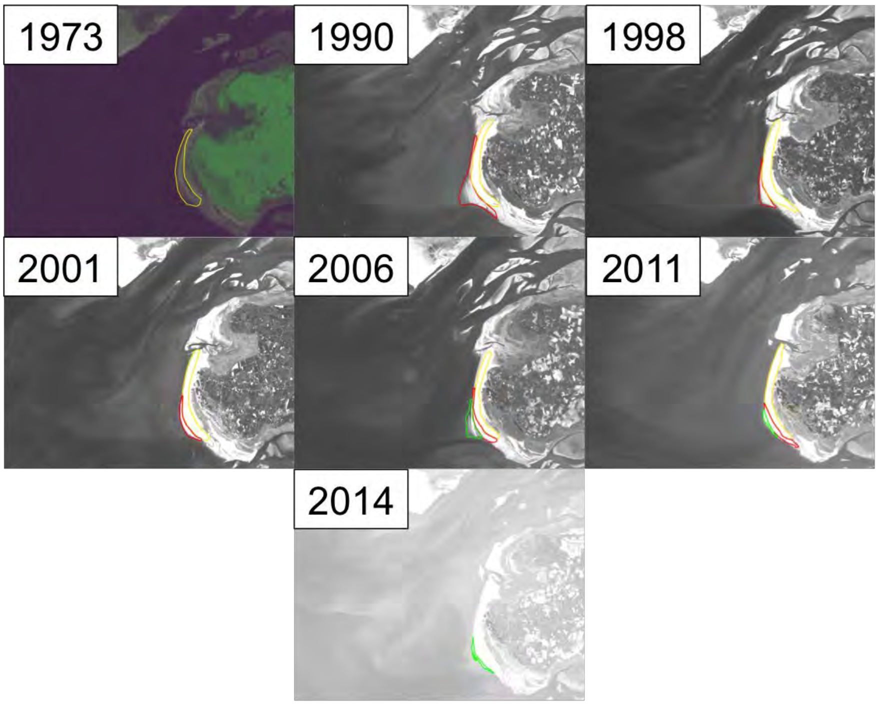


Figure 7.2.3: Landsat images of the Hever inlet in the period 1973–2014 showing attachment of shoals in 1990 and 2006 to the coast of St. Peter-Ording-Sand (Ridderinkhof, 2016).

7.3 Rummelloch-West

Basic data

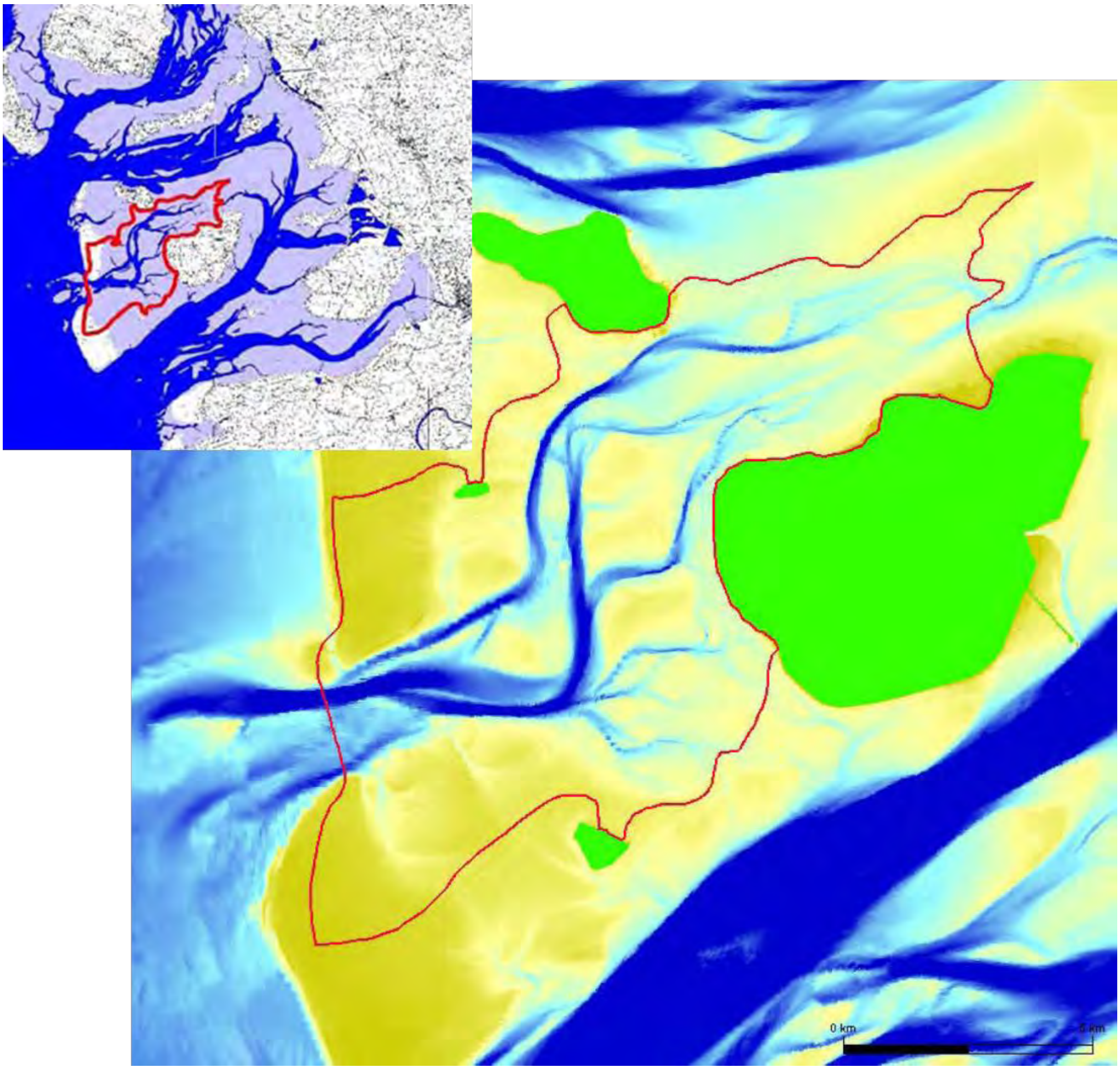


Figure 7.3.1: overview of the inlet system in 2000 (van Riesen & Winskowsky, 2007).

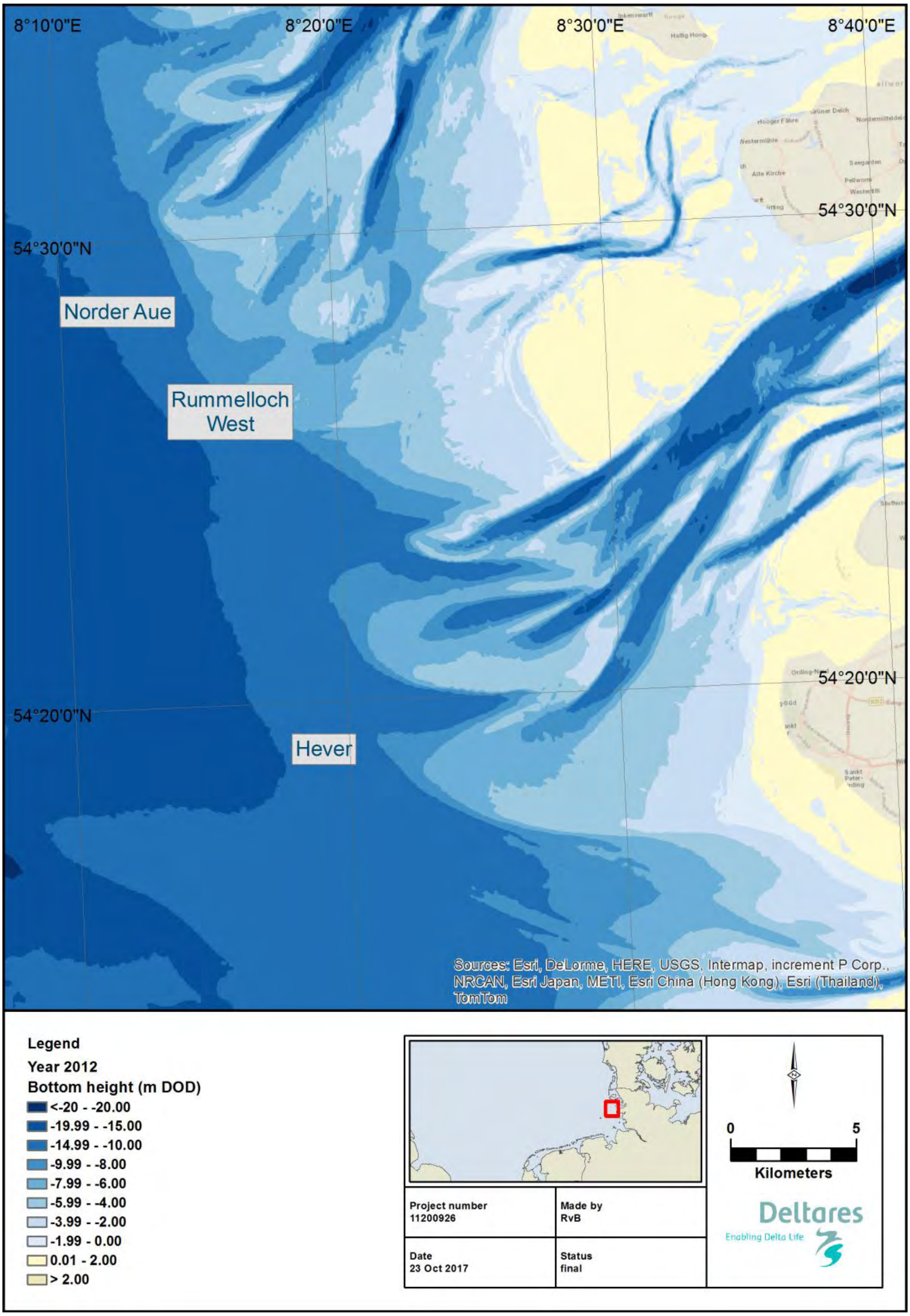


Figure 7.3.2: overview of the ebb-tidal delta of Rummelloch.

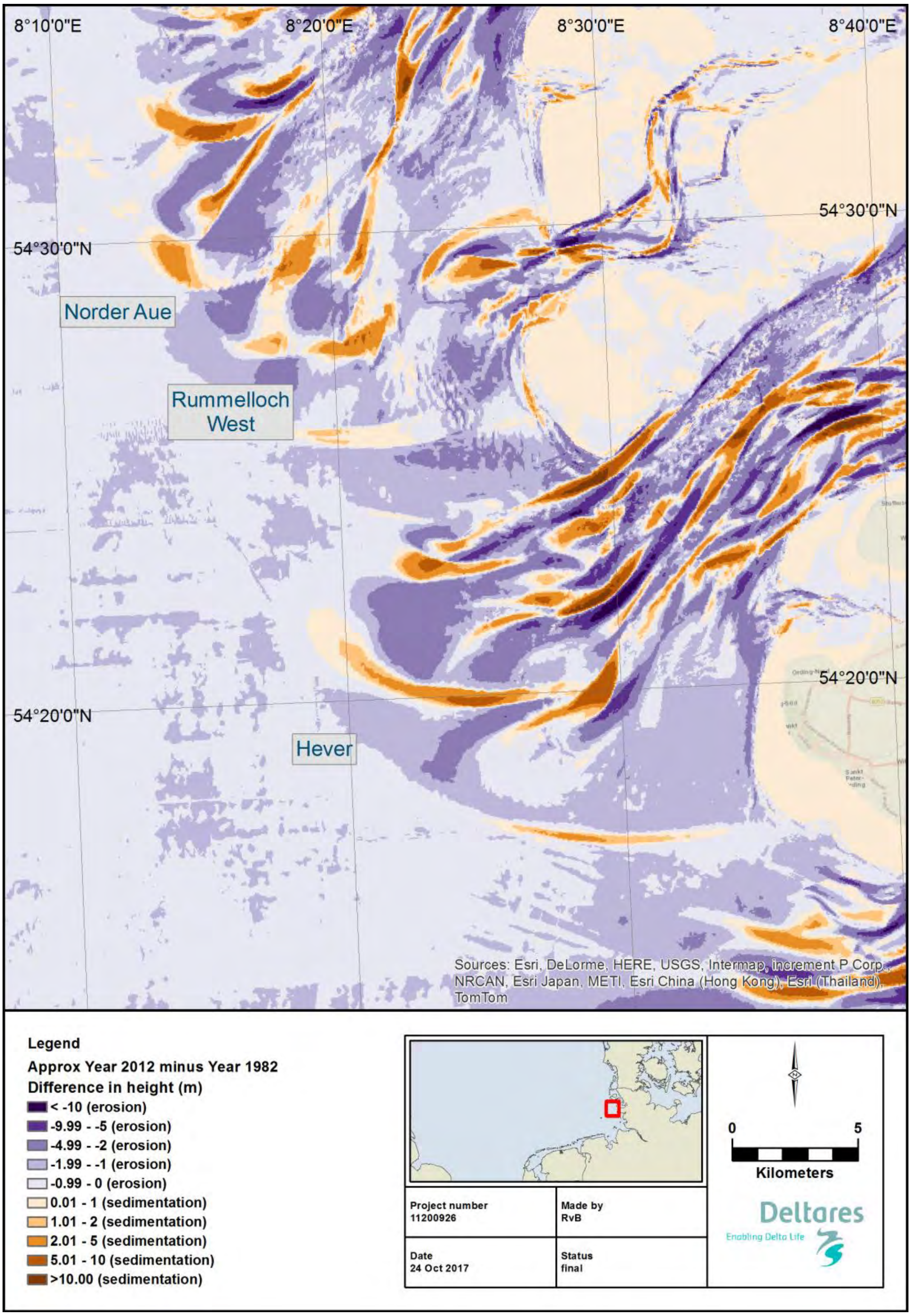


Figure 7.3.3: Rummelloch erosion and deposition over the period 1982-2012.

Table 7.4: Facts and figures Rummelloch-West (see also appendix I)

Parameter	Observ	Year	Reference	Observ	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2.2	1940-2010	1 (station Wittdun)						
Hs (m)	1.35		CoastDat						
Tp (s).	5.44		CoastDat						
Tf/Te	0.81	2017 (2 tidal cycles of 3 jan)	2 (Rum-meloch West)						
$L_{ebb\text{-}tidal\ delta}$ (km)	6.2	2012	-6 m	7	2012	-10m			
MHW (m NHN)	1.4	2017	2 (Rum-meloch West)						
MLW (m NHN)	-1.4	2017	2 (Rum-meloch West)						
MTR (m)	2.8	2017	2 (Rum-meloch West)						
Surge height (m to MSL)	25 y: 5.41	???	1 (station Husum)	50 y: 5.67	???	1 (station Husum)			
Surge height (m to MSL)	100 y: 5.91	???	1 (station Husum)	250 y: 6.19	???	1 (station Husum)	500 y: 6.38)	???	1 (station Husum)
Mean annual max surge height (m to AOD)	2.76		CoastDat						
A_{MHW} (km^2)	95.5	1981	3	95.5	1990	3	95.5	2000	3
A_{MLW} (km^2)	17.6	1974/76	4						
A_{cross} (m^2)	8996	1974/76	4						
V_{MHW} ($10^6 m^3$)	235	1981	3 (Fixed MHW)	250	1990	3 (Fixed MHW)	251	2000	3 (Fixed MHW)
V_{MLW} ($10^6 m^3$)	64	1981	3 (Fixed MLW)	75	1990	3(Fixed MLW)	79	2000	3 (Fixed MLW)
P ($10^6 m^3$)	172	1981	3 (Pbat)	175	1990	3 (Pbat)	172	2000	3 (Pbat)
$SV_{backbarrier}$ ($10^6 m^3$)	121	1981	3	118	1990	3	122	2000	3
$SV_{ebb\text{-}tidal\ delta}$ ($10^6 m^3$)									
$AS_{backabrrier}$ ($10^6 m^3$/yr)	-0.5	1968-1994	5 enlarge-ment of channels	0.5	1981-2000	3	0,1	1990-2000	
$AS_{ebb\text{-}tidal\ delta}$ ($10^6 m^3$/yr)									
Longshore drift ($10^6 m^3$/yr)	0	2006-2009	6	-0.2 to +0.2 (Norder- & Süder-oogstrand)	2006-2009 & 2006-2009	6 (stations Sylt & Helgoland)			
Sediment transport direction?	landward								
Development island coasts	Sedimentation NW Süderoogsand; Sedimentation and ero-sion SW Norderoogsand								

1 = MELUR, 2013; 2 = BSH, 2016; 3 = van Riesen & Winskowsky, 2007; 4 = Floser et al., 2011;;5 = Hofstede & Spitta, 2000; 6 = Ridderinkhof, 2016.

Description of the tidal inlet system

Rummelloch (Rummelloch West) in Schleswig Holstein is a small inlet system situated between Süderoog- and Norderoogsand and more basin inward between the Hallig Hooge and Pellworm.

The small inlet, with a depth of only 5 m below MSL drains a tidal area of about 95.5 km² of which less than 20% is subtidal area. In general the Außensände which form the seaward border of the small inlet system are retreating. Due to this the tidal area has decreased somewhat (see: Van Riesen & Winskowsky, 2007). At the same time sedimentation dominates in the remaining part and some $0.5*10^6$ m^3/yr has been deposited over the period 1981-2000 (Van Riesen & Winskowsky, 2007).

Development of the ebb-tidal delta
The ebb-tidal delta is totally surrounded by the ebb-tidal delta of the Aue and forms a small lobe on it. The images in Figure 7.3.4 show the ebb-tidal delta in different years. Channels that are located seaward of Rummeloch-West slowly rotate in a clockwise direction.

Coastal development
In the period 1986-2002 the shoal that is located seaward of the coast south of the inlet in 1986, migrates towards the coast and attaches to it. At the north side of the inlet another shoal attaches in the period 1986-1998. Apparently this shoal was eroded in the period 2006-2011.

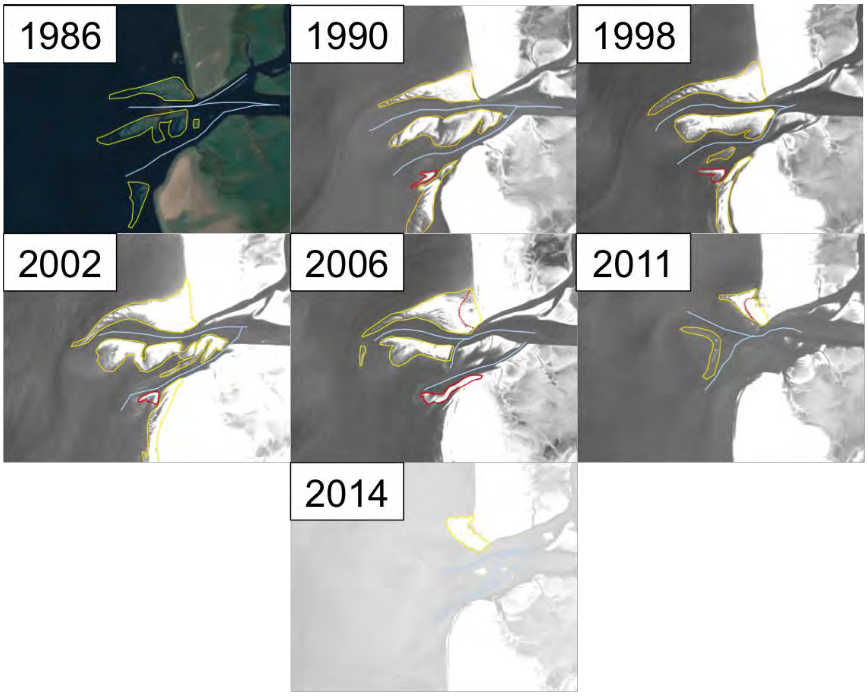


Figure 7.3.4: Landsat images of the ebb-tidal delta of Rummelloch-West in the period 1986-2011 (Ridderinkhof, 2016).

7.4 Hooger Loch

Basic Data

For figures see 7.3.1 & 7.3.2: it is the small inlet system immediately N of Rummelloch-West.

Table 7.5: Facts and figures Hooger Loch (see also appendix I)

Parameter	Observ	Year	Reference	Observ	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	3	1936-1990	1 (station Wittdun)						
Hs (m)	1.35		CoastDat						
Tp (s).	5.44		CoastDat						
Tf/Te									
$L_{ebb-tidal\ delta}$ (km)	3	2012	-6 m						
MHW (m GNN)	1.4	2017	2 (Rummeloch West)						
MLW (m GNN)	-1.4	2017	2(Rummeloch West)						
MTR (m)	2.8	2017	2 (Rummeloch West)						
Surge height (m to MSL)	25 y: 4.23	??	1	50 y: 4.44	??	1			
Surge height (m to MSL)	100 y: 4.62	??	1	250 y: 4.85	??	1	500 y: 5.00	??	1
Mean annual max surge height (m to AOD)	2.76		CoastDat						
A_{MHW} (km^2)	17.8	1981	3	17.8	1990	3	17.8	2000	3
A_{MLW} (km^2)									
A_{cross} (m^2)	2038	1974/76	4						
V_{MHW} (10^6 m^3)	23	1981	3	22	1990	3	20	2000	3
V_{MLW} (10^6 m^3)	1	1981	3	1.1	1990	3	0.6	2000	3
P (10^6 m^3)	22	1981	3(Pbat)	21	1990	3(Pbat)	19	2000	3(Pbat)
$SV_{backbarrier}$ (10^6 m^3)	31	1981	3	33	1990	3	34	2000	3
$SV_{ebb-tidal\ delta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)				0.2	1981-2000	4			
$AS_{ebb-tidal\ deltar}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	0	2006-2009 & 2009-2009	5	-0.2 to +0.2 (Norder- & Süder-oogstrand)	2006-2009 & 2009-2009	5 (stations Sylt & Helgo-land)			
Sediment transport direction?	Landward Retreat of Japsand and Norderoogsand								

1 = MELUR, 2013; 2 = BSH, 2016; 3 = Floser et al., 2011; 4 = van Riesen & Winskowsky, 2007; (calculated with fixed borders and tides from 1981 onwards new borders due to retreat Außensande); 5 = Ridderinkhof, 2016.

Description of the tidal inlet system

Hooger Loch in Schleswig Holstein is a small inlet system situated between Noorderoogsand and Japsand. Its eastern border is formed by the Hallig Hooge. With only a tidal prism of $19*10^6$ m^3 it is the smallest inlet system of the Wadden Sea area. The volume at MHW is only slightly higher indicating that the water volume below MLW is very small. The inlet straddles the south side of the huge Aue system and appears to be strongly influenced by it. In general the Außensände which form the seaward border of the small inlet system are retreating. Due to this the tidal area has decreased somewhat in area (see: Van Riesen & Winskowsky, 2007). At the same time sedimentation dominates in the remaining part and some $0.2*10^6$ m^3/yr has been deposited over the period 1981-2000 (Van Riesen & Winskowsky, 2007).

Development of the ebb-tidal delta

The ebb-tidal delta is totally surrounded by the ebb-tidal delta of the Aue and forms a small lobe on it. The -6 m line of the ebb-tidal delta extents some 3 km seaward of the inlet gauge; further seaward it cannot be distinguished.

Coastal development

The Außensände have retreated during the period 1947-1991 with some 250 m in the S (Süderooge) and 1600 m in the N (Japsand; Hofstede, 1999a; Figure 7.4.1). As a result the coasts lose sediment, partly in the form of washover formation, eolian transport, but probably partly also in the form of sediment loss (spit formation; Hofstede 1999a) to the Aue system under the influence of storminess. The ebb-tidal delta does not seem to make a large difference to that behaviour.

Figure 7.4.1: The Hooger Loch inlet in 1990 and 2008.

7.5 Aue

Basic data

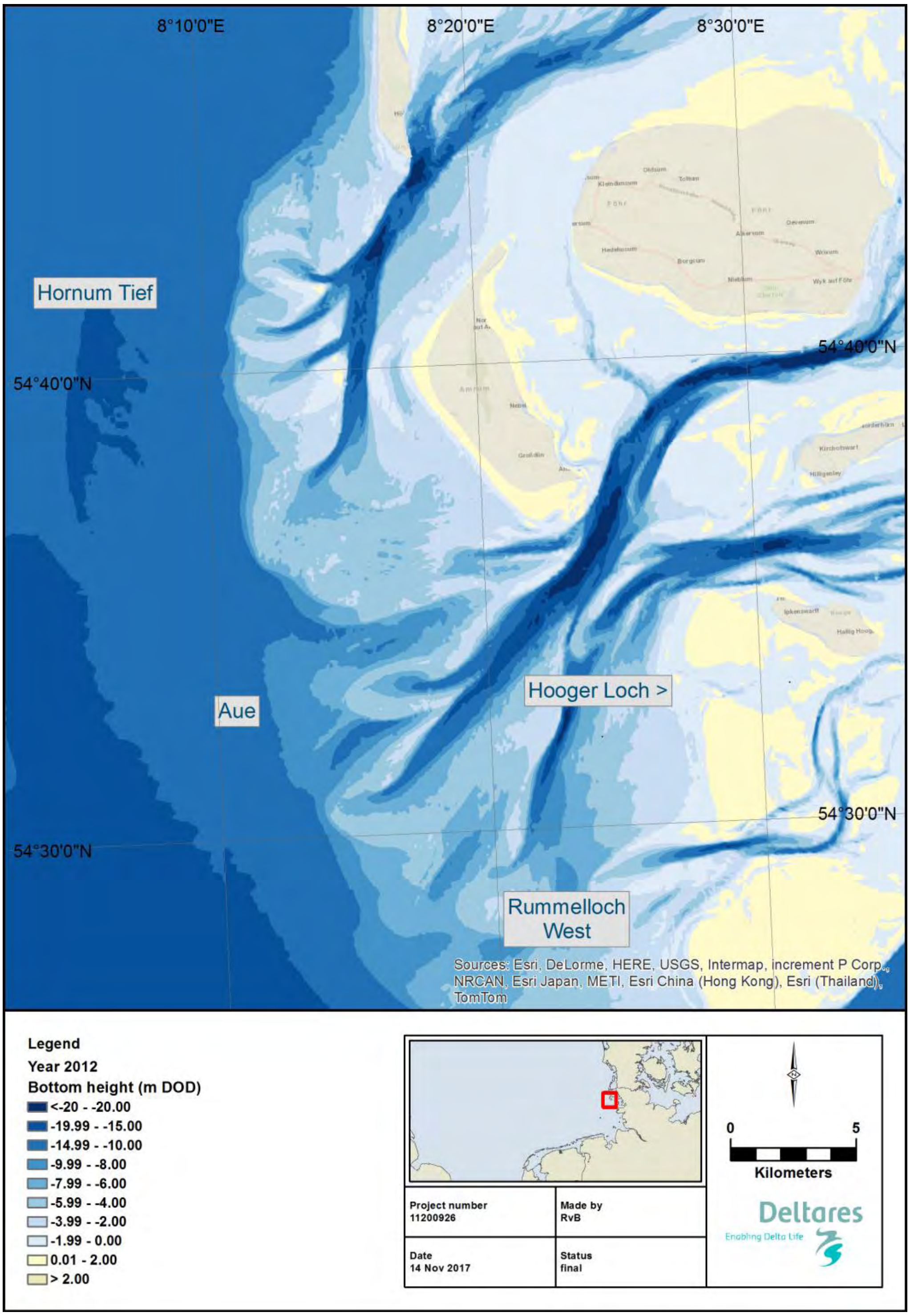


Figure 7.4.1: Overview of the ebb-tidal delta of the Aue

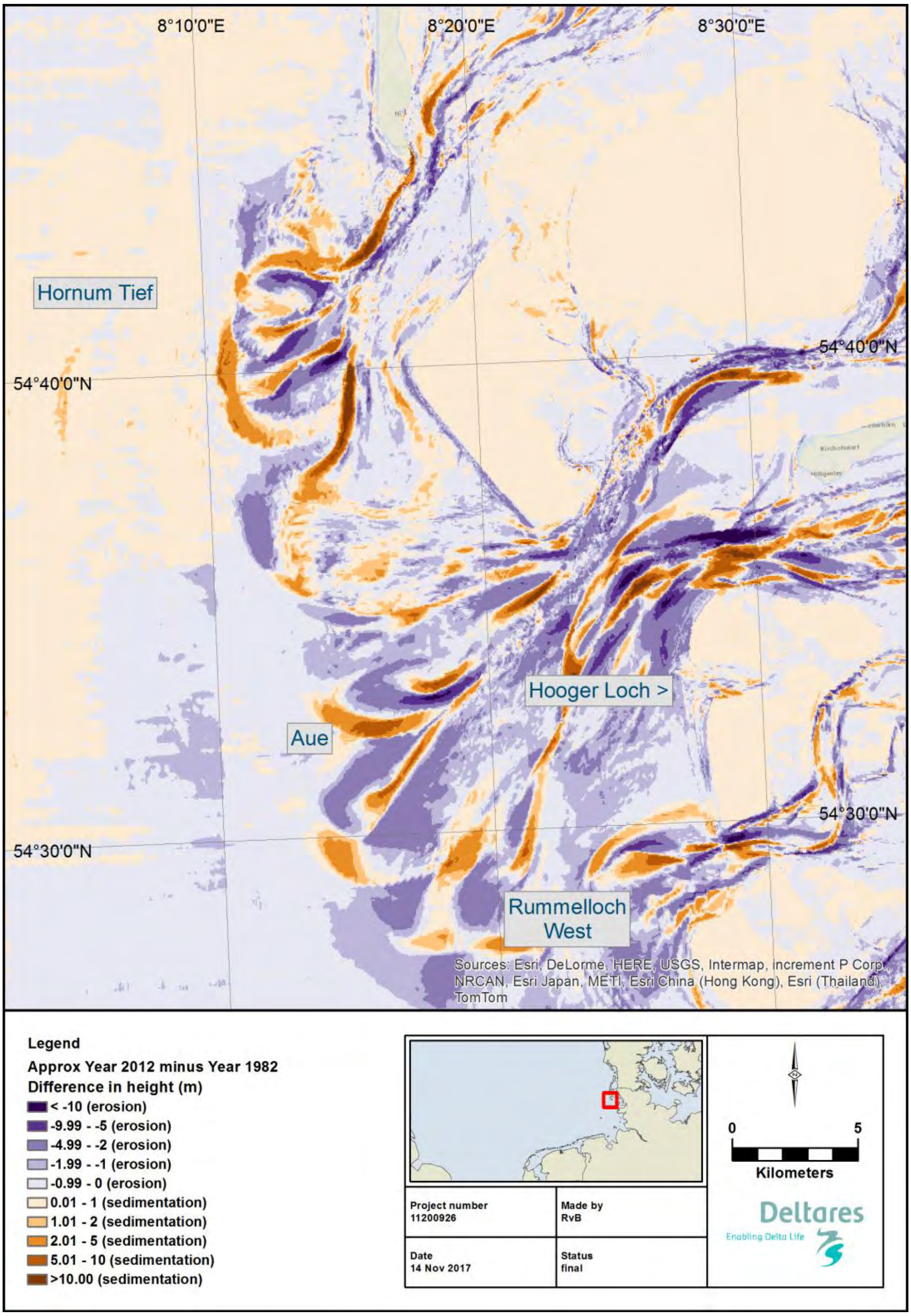


Figure 7.4.2: Overview of the ebb-tidal delta of the Aue showing erosion and deposition over approximately the period 1982-2012.

Table 7.6: Facts and figures Süderaue (see also appendix I)

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	2.2	1940-2010	1 (station Wittdun)						
Hs (m)	1.35		CoastDat						
Tp (s).	5.44		CoastDat						
Tf/Te	0.85	2017 (2 tidal cycles of 3 jan)	2 (average of Langeness, Hilligenley & Hooge, Anleger						
MHW (m NHN)	1.4	2017	2 (average of Langeness, Hilligenley & Hooge, Anleger						
MLW (m NHN)	-1.5	2017	2 (average of Langeness, Hilligenley & Hooge, Anleger						
MTR (m)	2.9	2017	2 (average of Langeness, Hilligenley & Hooge, Anleger						
Surge height (m to MSL)	25 y: 4.23	??	1	50 y: 4.44	??	1			
Surge height (m to MSL)	100 y: 4.62	??	1	250 y: 4.85	??	1	500 y: 5.00	??	1
Mean annual max surge height (m to AOD)	2.76		CoastDat						
A_{MHW} (km^2)	153.2	1981	3	53.2	1990	3	53.2	2000	3
A_{MLW} (km^2)	76,1	1974/76	4						
A_{cross} under MSL (m^2)	25153	1974/76	4						
V_{MHW} (10^6 m^3)	600	1981	3 (Fixed MHW)	610	1990	3 (Fixed MHW)	606	2000	3 (Fixed MHW)
V_{MLW} (10^6 m^3)	242	1981	3 (Fixed MLW)	253	1990	3 (Fixed MLW)	250	2000	3 (Fixed MLW)
P (10^6 m^3)	358	1981	1 (Pbat)	357	1990	1 (Pbat)	357	2000	1 (Pbat)
$SV_{backbarrier}$ (10^6 m^3)	102	1981	1 (Pbat)	103	1990	1 (Pbat)	103	2000	1 (Pbat)
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	0.1	1981-2000	1 (Pbat)						
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m3/yr)	-1.4	2006-2009	5	-1.3 to -1.5 Amrum	2006-2009 & 2006-2009	5 (stations Sylt & Helgoland)	-0.2 to +0.2 (Norder- & Süderoogstrand)	2006-2009 & 2009-2009	5 (stations Sylt & Helgoland)
Sediment transport direction?									
Development	Erosion N & W								

island coasts	Japsand								

1 = MELUR, 2013; 2 = BSH, 2016; 3 = van Riesen & Winskowsky, 2007; (calculated with fixed borders and tides from 1981 onwards new borders due to retreat Außensande); 4 = Floser et al., 2011; 5 = Ridderinkhof, 2016.

Table 7.7: Facts and figures Norderaue (see also appendix I)

Parameter	**Obs.**	**Year**	**Reference**	**Obs.**	**Year**	**Reference**	**Obs.**	**Year**	**Reference**
MSLR (mm/yr)	2.2	1940-2010	1 (station Wittdun)						
Hs (m)	1.39		CoastDat						
Tp (s).	5.51		CoastDat						
Tf/Te	0.87	2017 (2 tidal cycles of 3 jan)	2 (Amrum Hafen (Wittdün)						
$L_{ebb\text{-}tidal\ delta}$ (km)	11	2012	-6 m	17.1	2012	-10m			
MHW (m NHN)	1.2	2017	2 (Amrum Hafen (Wittdün)						
MLW (m NHN)	-1.4	2017	2 (Amrum Hafen (Wittdün)						
MTR (m)	2.7	2017	2 (Amrum Hafen (Wittdün)						
Surge height (m to MSL)	25 y: 4.23	??	1	50 y: 4.44	??	1			
Surge height (m to MSL)	100 y: 4.62	??	1	250 y: 4.85	??	1	500 y: 5.00	??	1
Mean annual max surge height (m to AOD)	2.69		CoastDat						
A_{MHW} (km^2)	245,2	1974/76	3						
A_{MLW} (km^2)	94,4	1974/76	3						
A_{cross} (m^2)	*42082*	1974/76	3						
V_{MHW} (10^6 m^3)	914	1974/76	3						
V_{MLW} (10^6 m^3)	400,8	1974/76	3						
P (10^6 m^3)	513,2	1974/76	3						
$SV_{backbarrier}$ (10^6 m^3)	146,9	1974/76	3						
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)									
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	-1.4	2006-2009	4	-1.3 to -1.5 Amrum	2006-2009 & 2006-2009	4 (stations Sylt & Helgoland)	-0.2 to +0.2 (Norder- & Süderoogstrand)	2006-2009 & 2009-2009	4 (stations Sylt & Helgoland)
Sediment transport direction?	??								
Development island coasts	No clear development Amrum								

1 = ; MELUR, 2013; 2 = BSH, 2016; 3 = van Riesen & Winskowsky, 2007 (calculated with fixed borders and tides from 1981 onwards new borders due to retreat Außensande); 4 = Ridderinkhof, 2016.

Description of the tidal inlet system

The Aue tidal inlet lies between the barriers Amrum to the North and Japsand to the South. It drains and waters two back-barrier basins: Süderaue and Norderaue. These basins are separated from each other by the Halligen Oland and Langeness, which are connected to each other and the mainland by dams. The marsh island Föhr lies in the Norderaue basin; the Halligen Hooge, Gröde and Habel in the Süderaue basin. With a total basin area of about 423 km^2, about 58% of the two basins is intertidal area, the rest subtidal (Spiegel, 1997). Tidal prism amounts to about $883*10^6$ m^3, intertidal sediment volume to about $262*10^6$ m^3. For the Süderaue back-barrier basin, Witez et al. (1998) established an erosion volume of $20*10^6$ m^3 over the period 1935-1975; for the Norderaue basin an erosion volume of $12*10^6$ m^3 over the period 1950-1975. For the Süderaue back-barrier basin van Riesen & Winskowsky (2007) calculated a sedimentation of some $13*10^6$ m^3 over the period 1936-1981 and a small erosion of some $3*10^6$ m^3 over the period 1981-2000. The differences can be explained by the differing approaches and different borders.

Development of the ebb-tidal delta

The Aue ebb-tidal delta consists of the amalgamed ebb-tidal deltas of the dominant Norderaue and the smaller Süderaue. The Norderaue develops clear outer ebb-tidal delta channels with ebb- and flood orientations; the Süderaue has a less clear developed ebb-tidal delta. Sedimentation and erosion is mainly concentrated in the channels and on the ebb-tidal delta rim.

Coastal development

Japsand retreated some 860 m in the period 1947-2001 (Figure 7.4.3; Hofstede 1999a; Van Riesen & Winskowsky, 2007). Japsand is eroded by wave action and overwash processes (Hofstede, 1999a). Due to the strong retreat the backbarrier areas of the Aue become smaller and also tidal prism decreases (see: Van Riesen & Winskowsky, 2007). More into the backbarrier (for instance Langeness and Hooge, waves still lead to erosion, but also channel and shoal erosion are important (Taubert, 2002).

The Landsat images of Amrum Inlet reveal that shoals are present at the sides of the main channels seaward of the Aue inlet, which do not seem to migrate (Figure 7.4.4; Ridderinkhof, 2016).

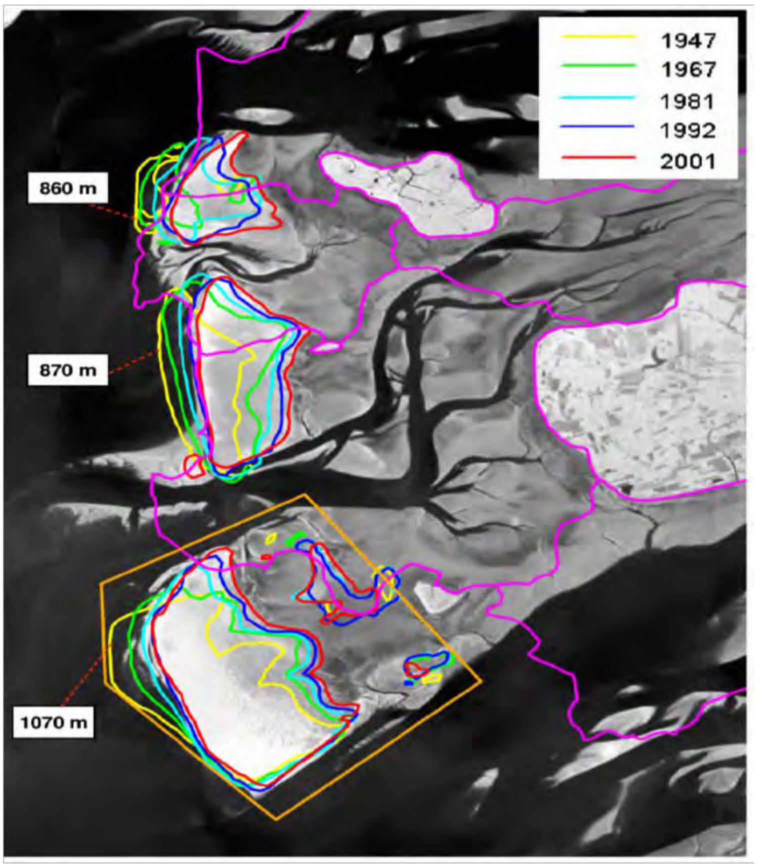


Figure 7.4.3: Retreat of the Außensande coasts. From N to S: Japsand, Norderooge, Süderooge.

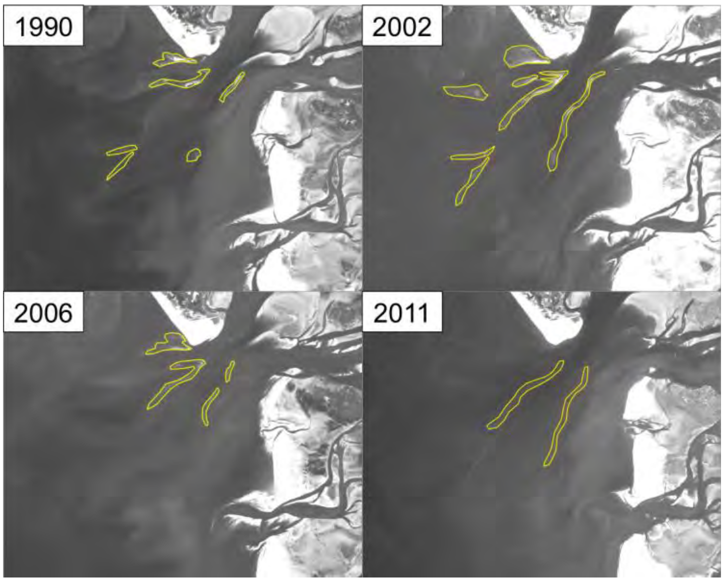


Figure 7.4.4: Landsat images of the ebb-tidal delta of the Aue Inlet. Shoals on the ebb-tidal delta could only be observed in the satellite images taken in 1990, 2002, 2006, and 2011. Cyclically migrating shoals could not be identified (Ridderinkhof, 2016).

7.6 Hörnum Tief

Basic data

Figure 7.5.1: Overview of the ebb-tidal delta of the Hörnum Tief

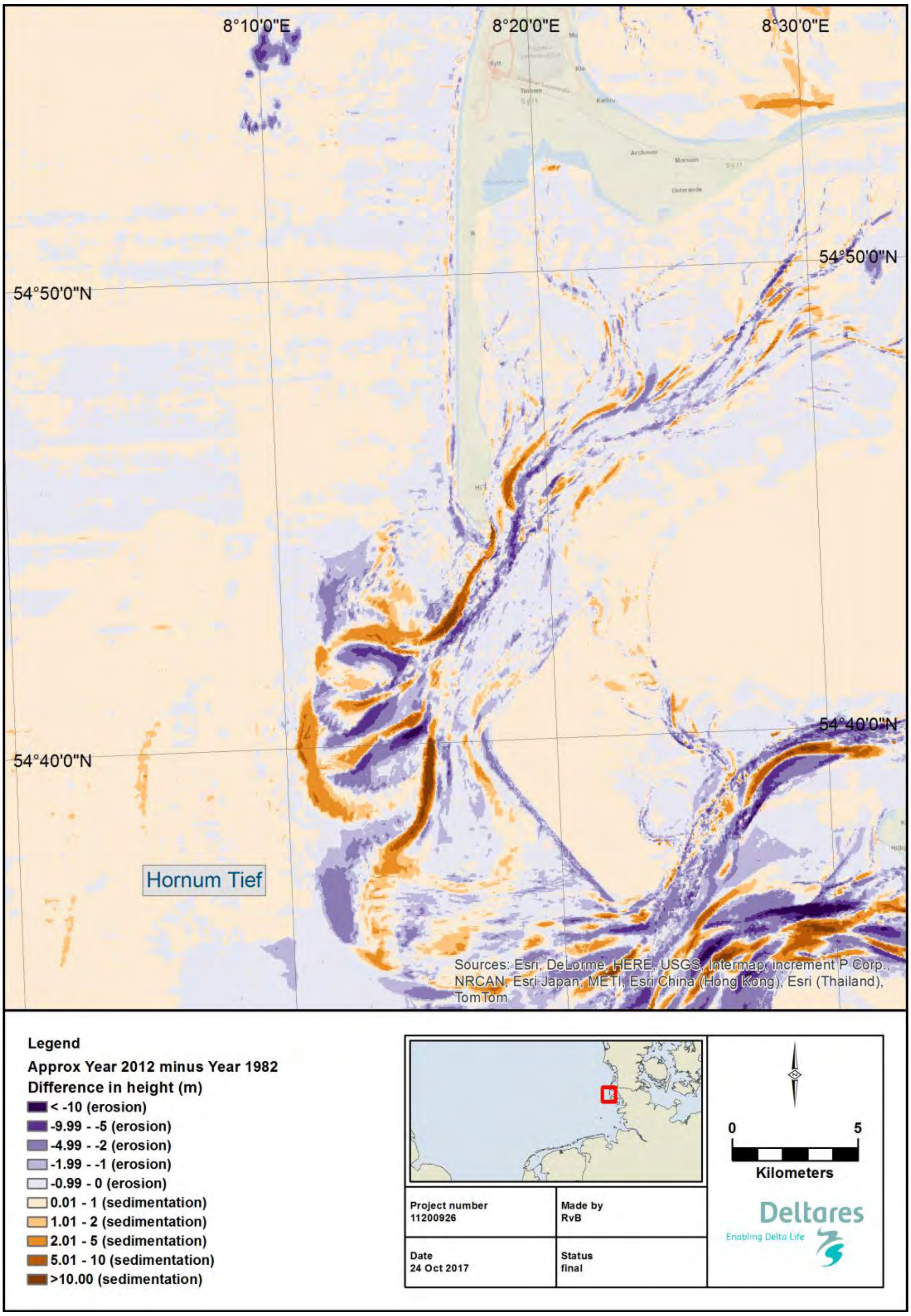


Figure 7.5.2: Overview of the ebb-tidal delta of the Hörnum Tief showing erosion and deposition over approximately the period 1982-2012.

Table 7.8: Facts and figures Hörnum Tief (see also appendix I)

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	2.0	1940-2010	1 (station Sylt)	1.4 mm/yr (Hörnum)	1939-1994	2			
Hs (m)	1.40		CoastDat						
Tp (s).	5.60		CoastDat						
Tf/Te	0.79		3	0.8	2017 (2 tidal cycles of 3 jan)	4 (station Hörnum West)			
$L_{ebb\text{-}tidal\ delta}$ (km)	7.3	2012	-6 m	7.7	2012	-10m			
MHW (m NHN)	0.7	1939	2,5 (station Hörnum West)	0.91 (	1998	2, 5 (station Hörnum West)	1.0	2017	4 (station Hörnum West)
MLW (m NHN)	-1.08	1939	2,5 (station Hörnum West)	-1.08	1998	4 (station Hörnum West)	-1.1	2017	4 (station Hörnum West)
MTR (m)	2.1	2017	4 (station Hörnum West)						
Surge height (m to MSL)	25 y: 4.01	??	1	50 y: 4.2	??	1			
Surge height (m to MSL)	100 y: 4.37	??	1	250 y: 4.58	??	9	500 y: 4.72	??	1
Mean annual max surge height (m to AOD)	2.61		CoastDat						
A_{MHW} (km^2)				290,2	1974/76	6			
A_{MLW} (km^2)				152.9	1974/76	6			
A_{cross} (m^2)	44.318	1994	1						
V_{MHW} (10^6 m^3)				936.3	1974/76	6			
V_{MLW} (10^6 m^3)				408.9	1974/76	6			
P (10^6 m^3)	509.9	1952	7	527.5	1974/76	6, 7			
$SV_{ebb\text{-}tidal\ delta}$ (10^6 m^3)	474.7	1978	2	412.6	1987	2	397.1	1994	2
$AS_{backbarrier}$ (10^6 m^3/yr)									
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)				-3.5	1968-1994	2			
Longshore drift (10^6 m^3/yr)	-0.4	2006-2009 & 2006-2009	8	-0.3 to -0.6 Sylt	2006-2009 & 2006-2009	8 (stations Sylt & Helgo-land)			
Sediment transport direc-tion?									
Development island coasts	Erosion S Sylt and N Amrum								

*1 = MELUR, 2013; 2 = Hofstede, 1999b & Hofstede & Spitta, 2000; 3 = Daul et al., 2006; 4 = BSH, 2016; 5 = Jensen et al., 2006; 6 = Floser et al., 2011; 7 = Witez et al., 1974; 8 = Ridderinkhof.*2015.

Description of the tidal inlet system

The Hörnum Tief tidal inlet lies between the barriers Sylt to the North and Amrum to the South. The backbarrier basin of Hörnum Tief was closed at the mainland by dikes and between the barrier island Sylt and the mainland by the Hindenburgdam. Mean wave height for the period 1986-1993 was between 1-1.25 m (Hinrichsen & Beismann, 1998 in: Hofstede & Spitta, 2000). Wind and waves come in mainly from the S to NW (Hofstede & Spitta, 2000). With a total basin area of about 290 km^2, about 47% of the area is intertidal, the rest subtidal (Spiegel, 1997). Tidal prism amounts to about 528*10^6 m^3, intertidal sediment volume to about 83*10^6 m^3. For the backbarrier basin, Witez et al. (1998) established a sedimentation volume of 41*10^6 m^3 over the period 1950 to 1975.

Development of the ebb-tidal delta

The ebb-tidal delta of Hörnum Tief has a surface area 111 km^2 within the -10 m NHN, of which 13.4 km^2 consists of channels (Hofstede & Spitta, 2000; Figures 7.5.1 & 7.5.2). To the N it merges with the shoreface of Sylt. To the S the delta merges with the delta of the Aue. The main channel deflects to the SSW and is aligned with the main channel in the backbarrier. The orientation and position of the main channel are quite stable (Figure 7.5.3). Over the period 1939-1994, the wet cross-sectional area in the pass of the inlet increased by ca. 32 % (Hofstede, 1999b). This has been related to the increase in ebb-tidal current (r = 0.87; Hofstede, 1999b). The ebb-tidal currents increased by about 19% over the period 1939-1994 (based on tidal gauge observations; Hofstede & Spitta, 2000). Tidal prism may have increased with as much as 35% over the period 1959-1994 if the A_c to P calculations is to be trusted). Sand supply to the terminal lobe of the ebb-tidal delta probably increased, which may there have helped to partially balance the loss of sediment at the terminal lobe caused by storm surges (see next alinea; Hofstede & Spitta, 2000).

In the period 1968-1994 the ebb-tidal delta sand volume decreased with some 18% (Hofstede, 1999). There was only a weak negative correlation between the increase in ebb-tidal currents and the development of the ebb-tidal delta volume (Hofstede, 1999b). The reduction of the ebb-tidal delta volume has been attributed to increased storminess over the period 1960-1994, coinciding with the reduction of the ebb-tidal delta (Hofstede & Spitta, 2000). The swash bars on the seaward part of the ebb-tidal delta were strongly reduced in size between 1939 and 1994, which might be expected upon an increase in storminess (Figures 7.5.3 & 7.5.4).

The ebb-tidal delta separates in several ebb-dominated channels. Locally, less well developed flood channels are present. One runs coast-parallel to the coast of NW Amrum and seems to have led to some erosion and steepening of the N coast. Another part might be related to more wave attack. This flood channel and the main channel have both been rather stable in the period 1939-1994. The other outer ebb-tidal delta channels are more mobile; from Figure 7.5.2 it can be concluded that the channels migrate somewhat to the S. Figure 7.5.5 shows the ebb-tidal delta of Hörnum Tief in different years. The shoals on the ebb-tidal delta hardly migrate in the period 1973-2014 and no attachment of shoals to the coasts adjacent to the inlet was observed (Ridderinkhof, 2016).

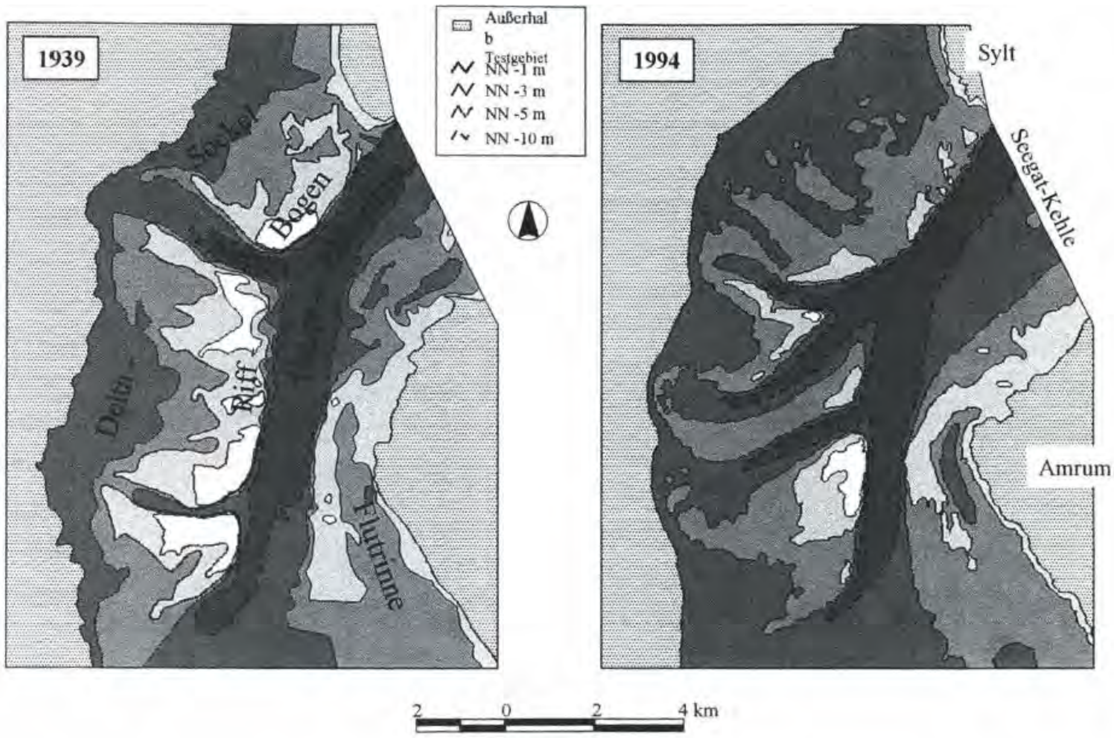


Figure 7.5.3: Ebb-tidal delta of the Hörnum Tief in 1939 with extensive intertidal banks and in 1994 (Hofstede & Spitta, 2000).

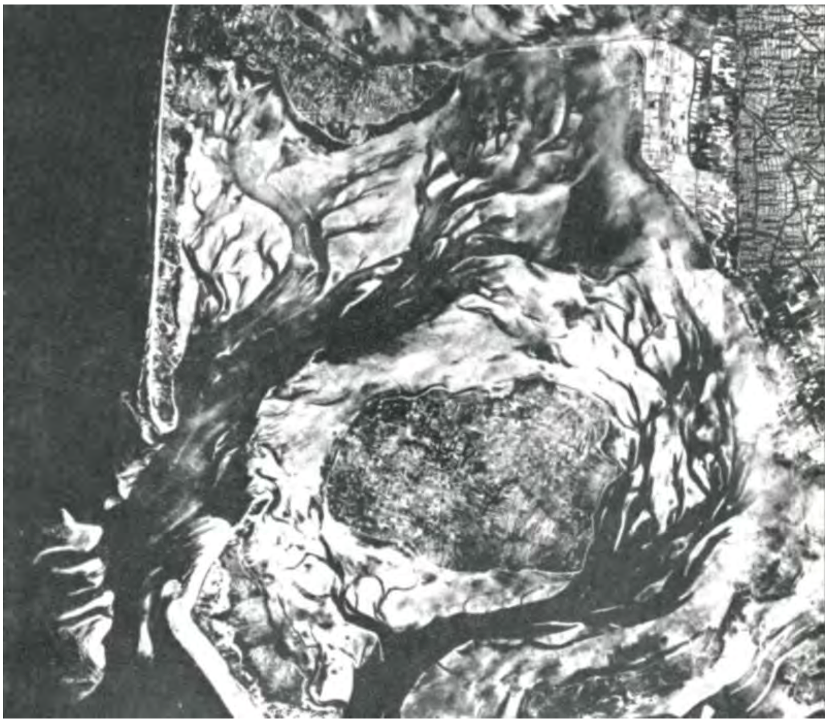


Figure 7.5.4: Hornum Tief in summer 1955. Extensive intertidal swash bars at the Northsea side of the ebb-tidal are still visible in 1955, which are largely absent in 2015, indicating that the changes took place after 1955.

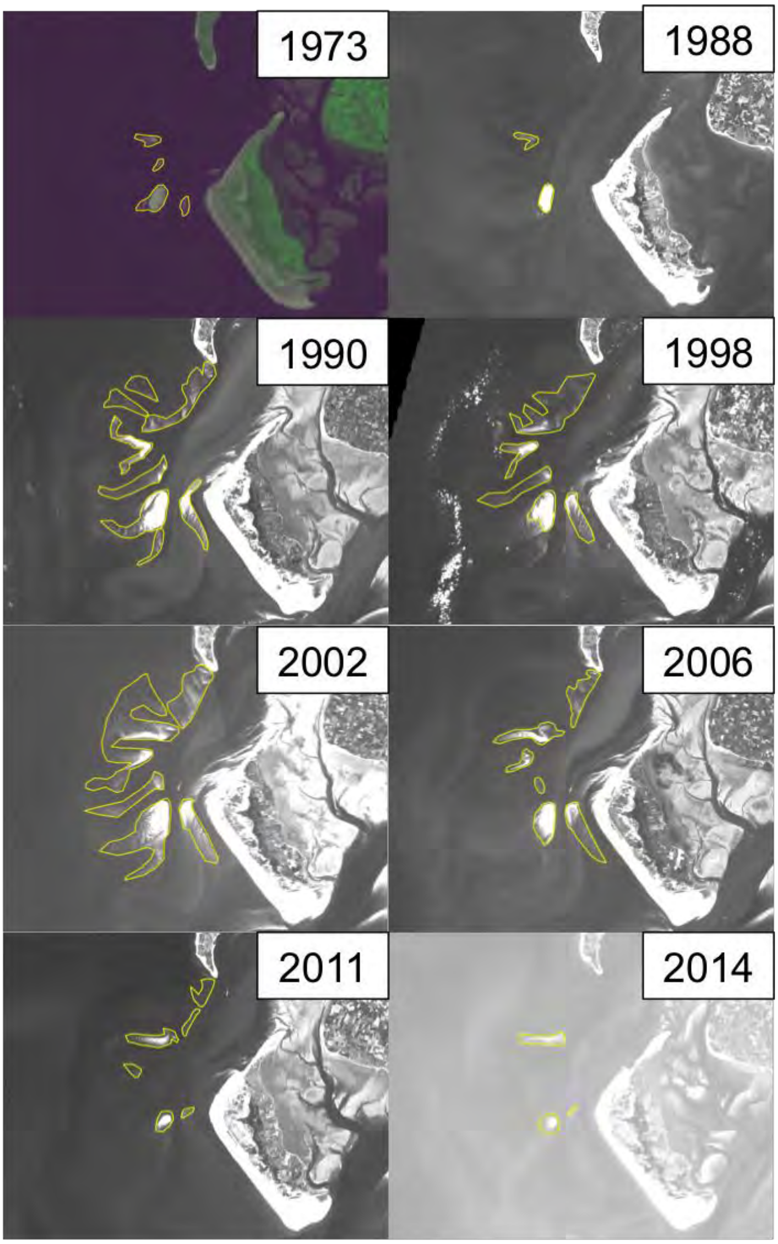


Figure 7.5.5: Landsat images of the ebb-tidal delta of Hörnum Inlet between 1973 and 2014 (Ridderinkhof, 2016).

On a smaller scale it has been observed that there are huge differences in tidal flow direction dominance. From the Hörnum Odde to the middle of Hörnum Tief ebb-oriented transport is dominant, both in velocity and in duration. In the remaining southern part of the inlet to the island of Amrum the flood is dominant in current velocity, but the ebb flow lasts longer (Ross, 1998). This leads to marked residual transport patterns, with a residual flow towards the N sea at the north side of the inlet of 13 km/tide and a flow of 2 km/tide in other directions in the S part of the inlet (Ross, 1998).

Coastal development

Sylt's beach near Hörnum has been eroding over the period 1870 to 1984 with some 2 m/yr (Ahrendt, 1993; Jessel, 2001; Sistermans & Nieuwenhuis, 2002). Since 1983, sand nourishments have been carried out to counter coastal erosion (Ahrendt, 1993). Originally the spit of S Sylt has been prograding to the S and SE by recurved barrier spit growth, due to S ward longshore drift of sediments which probably were released during storm surges (figure 7.5.6; period 1870-1930; Tillman & Wunderlich, 2013). Growth was interrupted by erosional events during severe storm surges (Tillman & Wunderlich, 2013). Nowadays, spit growth is limited by the strong ebb-currents of Hörnum Tief and the human interventions during the past decades which have stabilized the shoreline with hard measures (Tillman & Wunderlich, 2013). Amrum has been eroded at its north side over the period 1939-1994, which may be related to the increase in the cross-sectional area of the inlet pass.

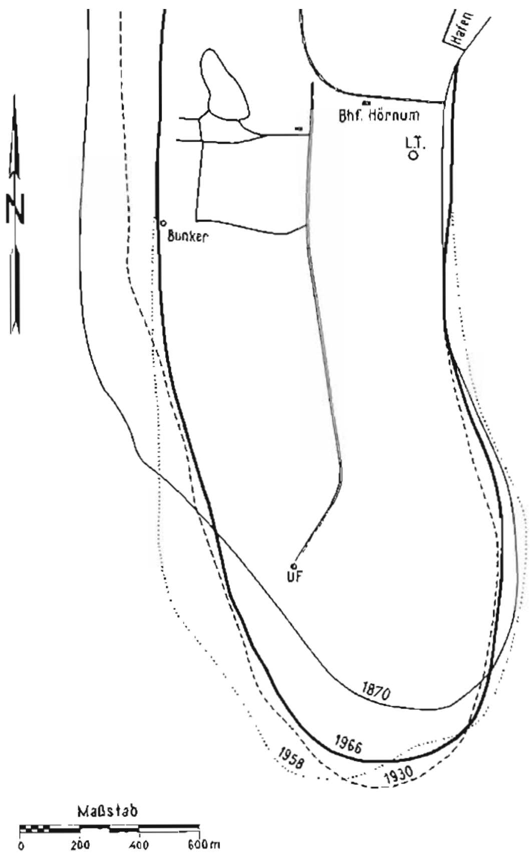


Figure 7.5.6: Development of the S-tip of Sylt 1870-1966 (Gripp, 1968).

8 Ebb-tidal deltas of Denmark

8.1 General description of the Danish area

Characteristics

The S to N trending Danish Wadden area has a total area of some 1.500 km^2 (Figure 8.1.1: Lauresen & Frikke 2016; 800 km^2 backbarrier area; 300 km^2 of land) consists of four inlet systems, from S to N: Lister Dyb (Lister Tief), Juvre Dyb, Knude Dyb and Grådyb, situated between Sylt, Rømø, Mandø, Fanø and the Skallingen peninsula (Figure 8.1.1). Several small (compared to German and Dutch Wadden area) fresh water rivers are entering the backbarrier. The major one is the Varde Å entering the Grådyb via an open estuary. In Grådyb and Lister Dyb, the rate of sedimentation exceeds relative sea-level rise (Ingvardsen 2006a, b).

Tidal amplitude is 1.5-2 m (Kystdirektoratet, 1999; Lauresen & Frikke 2016). Mean significant wave height decreases from Lister Dyb (ca. 1.5 m) to Grådyb (around 1.4 m) (Coast Dat data). Along the west coast of Jutland littoral drift is directed to the S, amounting 0.3-1.6*10^6 m^3/yr (Figure 8.1.2; Ridderinkhof, 2016). Prevailing westerly winds exceed 10 m/s for 25% of the time and 20 m/s for 0.5% of the time. The strong littoral drift forces the main inlet channels southwards (DHI & GI, 1992) until the ebb-current will cut through the ebb-tidal delta and forms a more direct route. In the process an elevated ebb-tidal delta sand body is left S of the new ebb channel and transported towards the coast by waves (Bartholdy & Pejrup, 1994).

Observations indicate that MSLR in the Danish Wadden Sea is 1.35 mm/y in the period 1889-2007. Comparison to the average rate of sea-level rise of 1.3 mm/y in the 20th century at Esbjerg, suggests acceleration in recent years (Klagenberg et al., 2008). However, care should be taken, as shorter time series may ignore long-term fluctuations and thus lead to faulty conclusions (Dillingh et al., 2010). Indeed, the acceleration is not observed in North Frisian part of Schleswig Holstein (see there; MELUR, 2013).

Five out of six DMI stations in Jutland inidicate that wind has been increasing over the period 1970 to 2000 with mean wind increasing from 7.5 m/s to 8.0 m/s in the period 1970-1998 (Klagenberg et al., 2008). Prevailing high wind energy from the SW is coincident with the high wave energy periods (Klagenberg et al., 2008). Several large engineering interventions have been carried out in the area. The most important are the dams to Sylt and Rømø and the tidal road to Mandø. Along the mainland coastal protection works and artificial marsh works are present. Along the Grådyb mainland coast the harbor town of Esbjerg has been developed. The waterway to the harbor of Esbjerg has been deepened is maintained by dredging. The Skallingen barrier spit has been left unprotected as it is state owned and there is no urban development (see also Aagaard et al., 1995, 2007).

Figure 8.1.1: The inlet systems of which ebb-tidal deltas are described in the Wadden area of Denmark: Lister Dyb to Grådyb (Courtesy, Wadden Sea Secretariat).

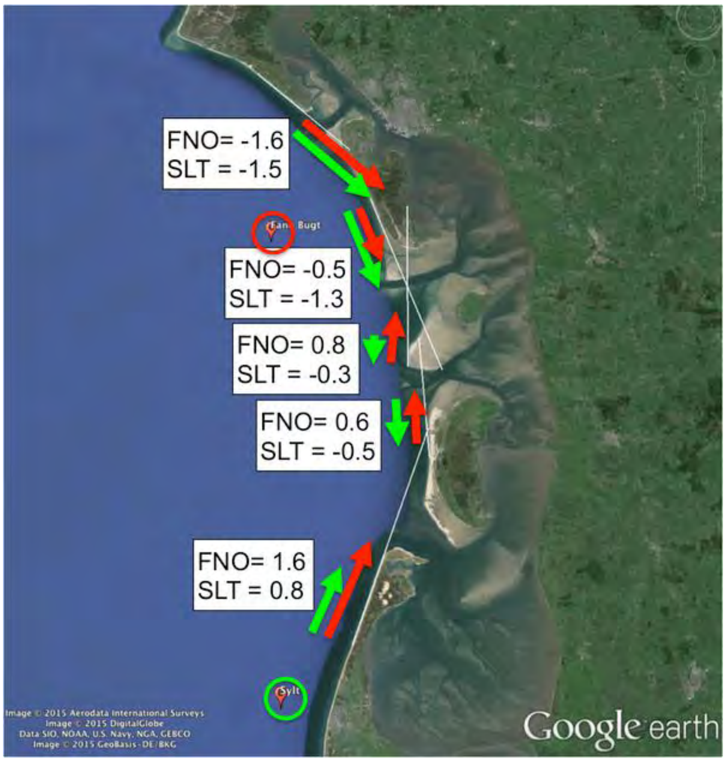


Figure 8.1.2: Littoral drift as determined on stations Fanø (FNO) and Sylt (SLT) in 10^6 m^3/yr (From: Ridderinkhof, 2016).

Geology

During the second last Ice Age (Saalian) the area was glaciated and moraines were deposited which became later elevated. During the last Ice Age (Weichselian) the terminal line of the ice sheet was ca. 80 km E of the present Wadden Sea. Melt waters drained to the W into the North Sea Basin (sea-level about 100 m lower than at present). As a result outwash plains formed between the older moraines (Figure 8.1.3; Jacobsen, 1986; Bartholdy & Pejrup, 1994).

The E and N of Denmark experienced a postglacial isostatic adjustment to the removed ice sheet. In combination with the postglacial eustatic sea-level rise this resulted in regression/transgression-alternations (Bartholdy & Pejrup, 1994). It is generally believed that the Wadden area has been isostatically stable during the Holocene, at least during the present. Initially the postglacial transgression was rapid. However, lateron it was slow. Pedersen et al. (2009) gave only ~12 m over the past 8400 years. This led to a much more restricted erosion of the coast. For instance, the northern spit of Sylt was formed as early as 5000 BP (the seaward part has been eroded; Lindhorst, 2007), whereas Rømø prograded seaward since 8,000 a BP, due to abundant sediment supply (Madsen et al., 2010). Between 5700-2900 yr BP sea-level rise was some 0.1 m/century with likely several highstands. After 2900 yr BP sea-level rise was slow and again likely punctuated by several highstands.

As a result of the flooding the outwash deposits have been reworked into barrier islands. On the mainland the outwash deposits and the moraines were eroded and formed cliffs. Locally tidal marsh deposits formed which have been partially reclaimed.

It is not completely clear when the barrier islands formed. It is thought that Langli, the eastern part of Fanø, Mandø, and Jordsand formed a system of old barrier islands (Bartholdy & Pejrup, 1994; Agaard et al., 1995). The recent barrier islands formed in the period 4000-3000 BP. The development of Koresand is considered to fill the gap in the row of the new, more westerly located barrier Islands, which consist of Skallingen, Fanø, (Koresand) and Rømø (Kystinspektoratet, 1999). Sylt is an eroding Pleisto-Pliocene core (Rotes Kliff and surroundings) which has an even more western position then the Danish islands more to the N.

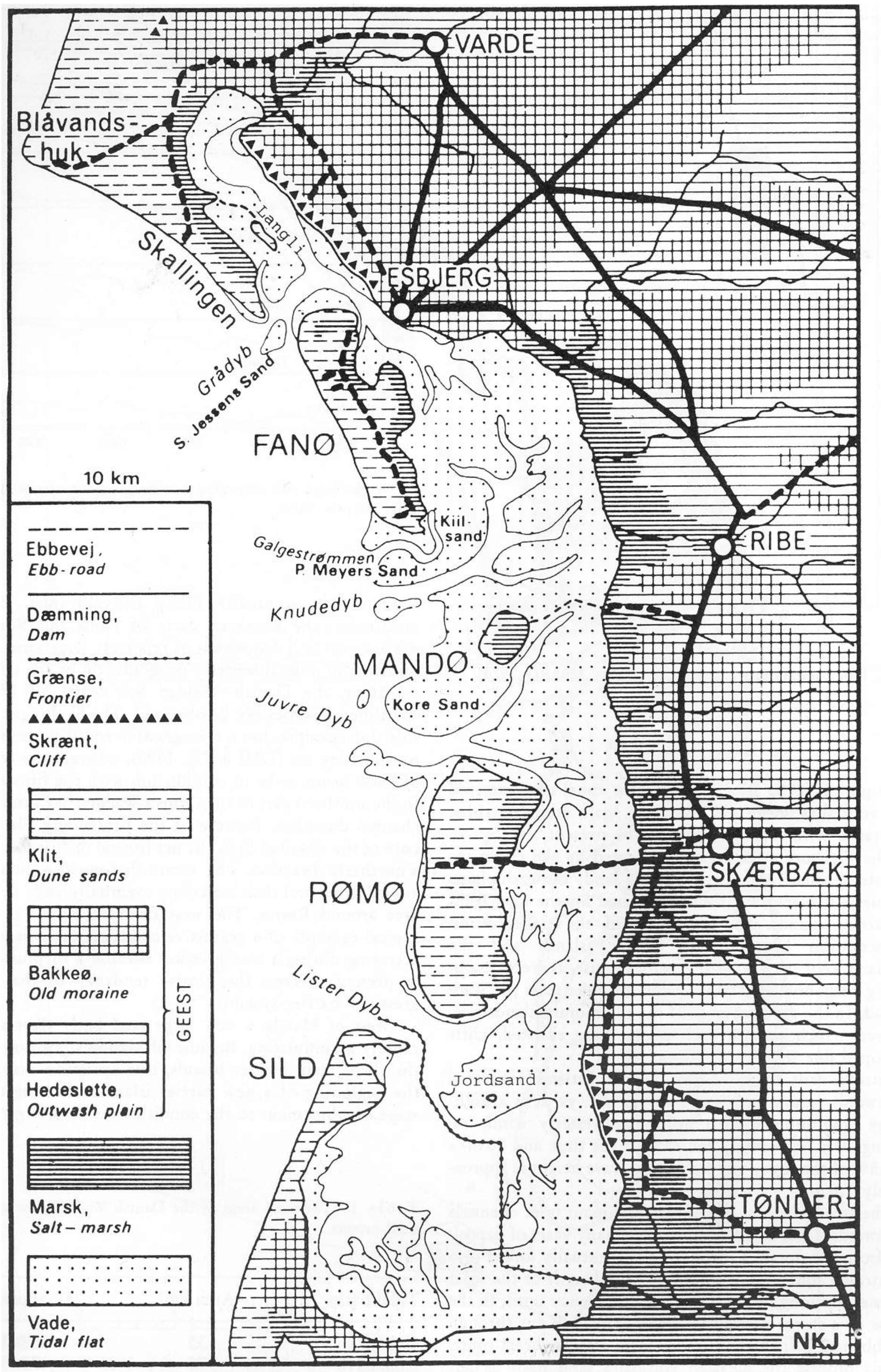


Figure 8.1.3: Geological map of the Danish Wadden Sea (Jacobsen, 1986).

8.2 Lister Dyb (Lister Tief)

Basic data

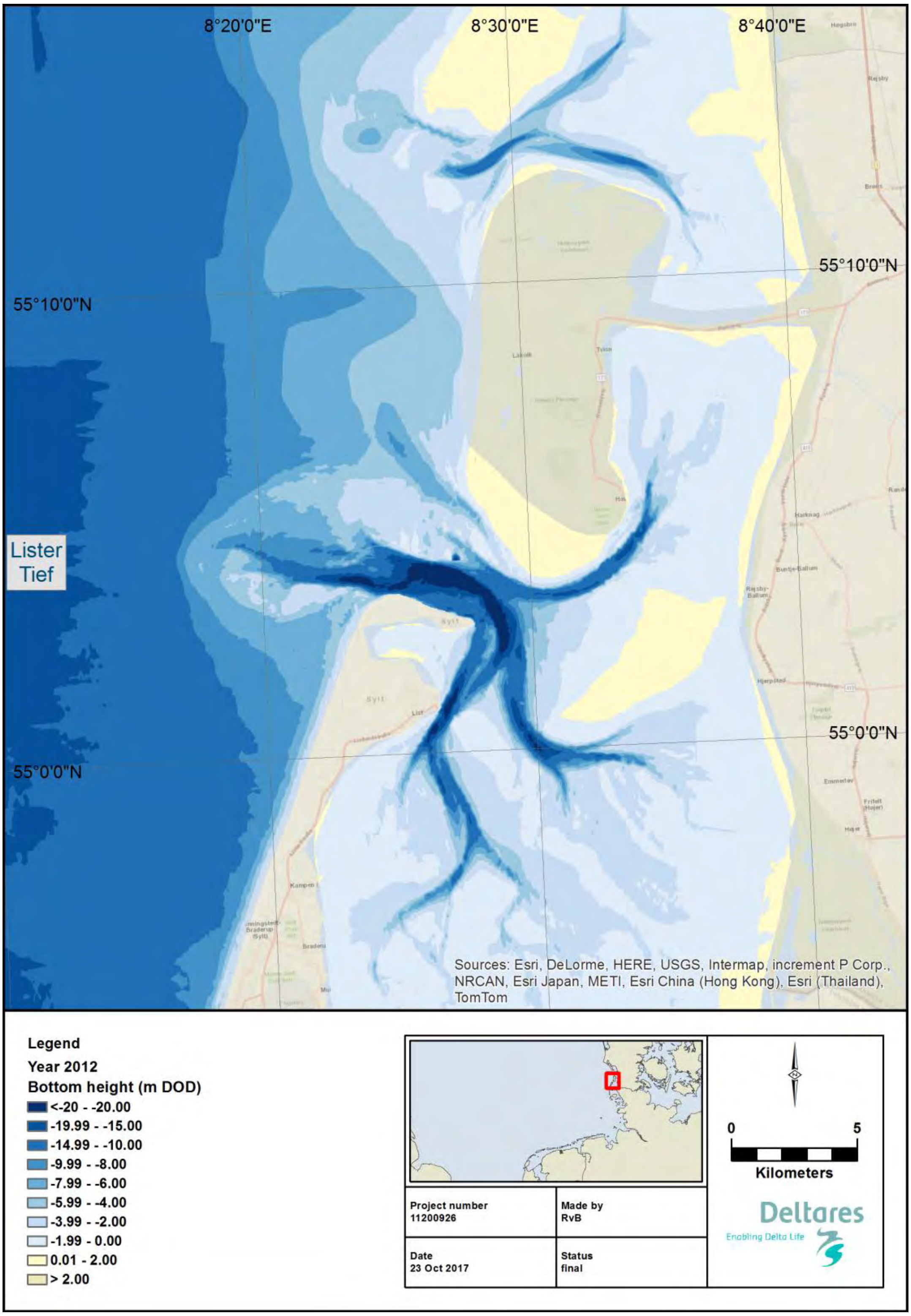


Figure 8.2.1: Overview of the ebb-tidal delta of the Lister Dyb (Lister Tief).

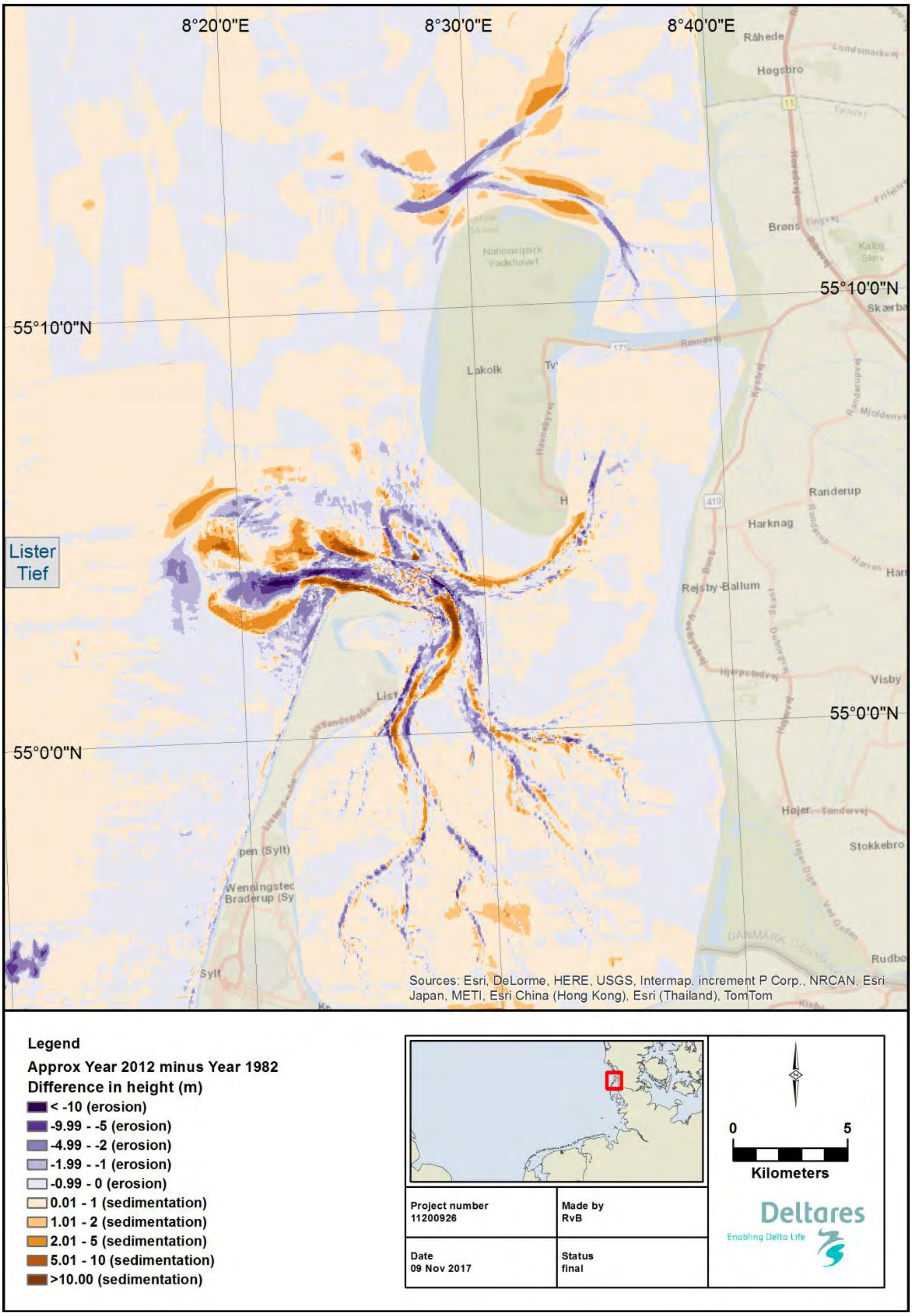


Figure 8.2.2: Overview of the ebb-tidal delta of the Lister Dyb showing erosion and deposition over approximately the period 1982-2012.

Table 8.1: Facts and figures Lister Dyb (see also appendix I)

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.2	1940-2010	1 (station List)	1.4 mm/yr	1889-2006	2 (station Esbjerg)			
Hs (m)	1.47		CoastDat						
Tp (s).	5.80		CoastDat						
Tf/Te	0.83		3	0.87	2017 (2 tidal cycles of 3 jan)	4 (station List West)			
$L_{ebb\text{-}tidal\ delta}$ (km)	10	2012	-6 m	11	2012	-10m			
MHW (m to DVR90)	0.76	1970	2 (station Havneby)	0.85	2001	2 (station Havneby)			
MLW (m to DVR90)	-0.85	1970	2 (station Havneby)	-0.86	2003	2 (station Havneby)			
MHW (m to NHN)							0.7	2017	4 (station List West)
MLW (m to NHN)							-0.9	2017	4 (station List West)
MTR (m)	1.61	1970	1	1.71	2001	1	1.7	2017	4 (station List West)
Surge height (m to MSL)	25 y: 3.93	??	1	50 y: 4.13	??	1			
Surge height (m to MSL)	100 y: 4.30	??	1	250 y: 4.51	??	1	500 y: 4.66	??	1
Mean annual max surge height (m to AOD)	2.26		CoastDat						
A_{MHW} (km^2)	402.8	1968	5	394.6	1994	5			
A_{MLW} (km^2)	205.5	1968	5	209.6	1994	5			
A_{cross} (m^2)	38192	1968	5	38332	1994	5			
V_{MHW} (10^6 m^3)									
V_{MLW} (10^6 m^3)									
P (10^6 m^3)	593	1968	5 (Pbat)	627	1994	5 (Pbat)			
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebbtidal}$ (10^6 m^3)	300 (calculated)	1994	5						
$AS_{backbarrier}$ (10^6 m^3/yr)	-0.5 (-1.3_+0.3)	1968-1994	5						
$AS_{ebb\text{-}tidal\ delta}$ (10^6 m^3/yr)	Nordward deflection	1970-2001	6						
Longshore drift (10^6 m^3/yr)	+1.1	2006-2009 & 1998-2007	6 (stations Sylt & Fanø)	-0.5 to +0.6 Rømø	2006-2009 & 1998-2007	6 (stations Sylt & Fanø)	+0.8 to +1.3 Sylt	2006-2009 & 1998-2007	6 (stations Sylt & Fanø)
Sediment transport direction?	N ward	1989-2013	6						
Development island coasts	Seaward expansion of Rømø, retreat of Sylt								

1 = MELUR, 2013; 2 = Kystdirektoratet, 2012; 3 = Daul et al., 2006; 4 = BSH, 2016; 5 = Kystinspektoratet, 1999; 6 = Ridderinkhof, 2016.

Description of the tidal inlet system

This Danish/German inlet system is situated between the barrier islands of Sylt and Rømø. Lister Dyb is the only tidal basin which is completely closed at all sides: at the mainland by dikes and between the barrier islands Sylt and Rømø and the mainland by respectively the Hindenburgdam and the Rømødam. The only connection to the North Sea is through Lister Dyb, having a depth varying between 25 and 35 m. In the period 1979-81, the size of the backbarrier basin has been reduced by the diking of Margrethe Kog by the construction of the

Forward Dike, which protects the area, stretching from Emmerlev Klev in Denmark down to the Hindenburg Dam in Germany. The Lister Dyb backbarrier receives a freshwater input from two small rivers (Brede Å and Vidå) with seasonally varying discharges between 4 and 10 m^3/s and an annual rainfall of 0.8 m (Purkiani et al., 2014). For data see table 8.1. With a total basin area of about 420 km^2, about 49% of the basins area is intertidal, the rest subtidal (Spiegel, 1997). Tidal prism amounts to about 580*10^6 m^3, intertidal sediment volume to about 166*10^6 m^3.

Sedimentation in the backbarrier basin was calculated to be -13*10^6 m^3 (erosion of 111*10^6 m^3 and deposition of 98*10^6 m^3) over the period ca. 1968-1994, albeit with such huge uncertainties that sedimentation cannot be excluded (Kystinspektoratet, 1999). There is evidence from the evaluated historical maps that the tidal channels in the basin have grown in depth and width (Higelke, 1998), also suggesting increase in tidal prim, although no net import or SPM export could be measured in the inlet during campaigns in 1992 and 1993 (Kappenberg et al., 1998). The amount of tidal marshes has doubled in the same period at the cost of the tidal flats (Kystinspektoratet, 1999).

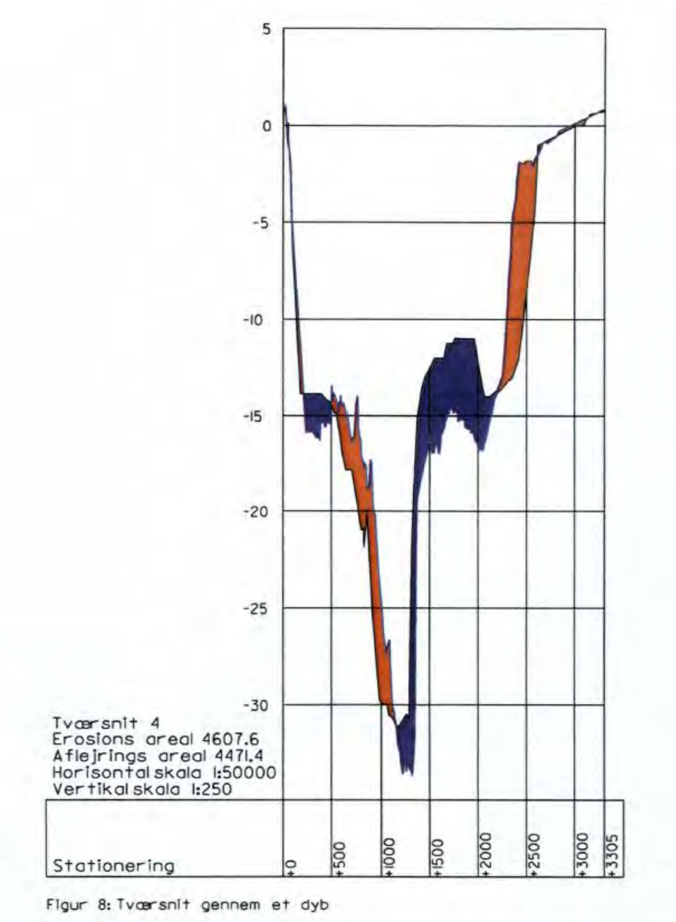


Figure 8.2.3: cross-section through the pass of the Lister Dyb main channel over the period 1968 to 1994 (Kystinspektoratet, 1999).

In the study concerning Lister Dyb by Kystinspektoratet (1999), there is only information based on depth soundings available for the morphological development of the backbarrier area. However there has been made a cross-section in the pass of Lister Dyb (Figure 8.1.3;

Kystinspektoratet, 1999). From that it can be observed that erosion occurs at the north side and deposition at the south side below -12 m and strong sedimentation at the north side above that water depth. Also, the maximum depth increased with ca. 1- 1.5 m to approximately 29 meters from 1968 to 1994. In total the wet cross sectional area here increased with ca. 140 m^2 at 25 years, which is an increase of 0.4% (Kystinspektoratet, 1999) and hence not significant enough to conclude upon an increase in tidal prism.

Development of the ebb-tidal delta

The main channels are mainly present along the southern part of the ebb-tidal delta along the coast of Sylt (Figure 8.1.1). The northern part of the ebb-tidal delta consists of a huge swash platform which is separated from Rømø by a small channel and is characterized by sedimentation (Figure 8.1.1). The images in Figure 8.1.4 show several shoals on the ebb-tidal delta of Lister Dyb between 1990 and 2014 attaching to the Rømø coast north of the inlet (Ridderinkhof, 2016). Judging from these developments sediment is transported via the ebb delta to Rømø.

Coastal development

Sylt's beach has retreated 1–2 m/yr in the last century, while the Rømø beach prograded seaward (Bartholdy & Pejrup 1994). An alternative explanation is that (part of) the growth of Rømø beach is caused by coast-parallel transport from the N.

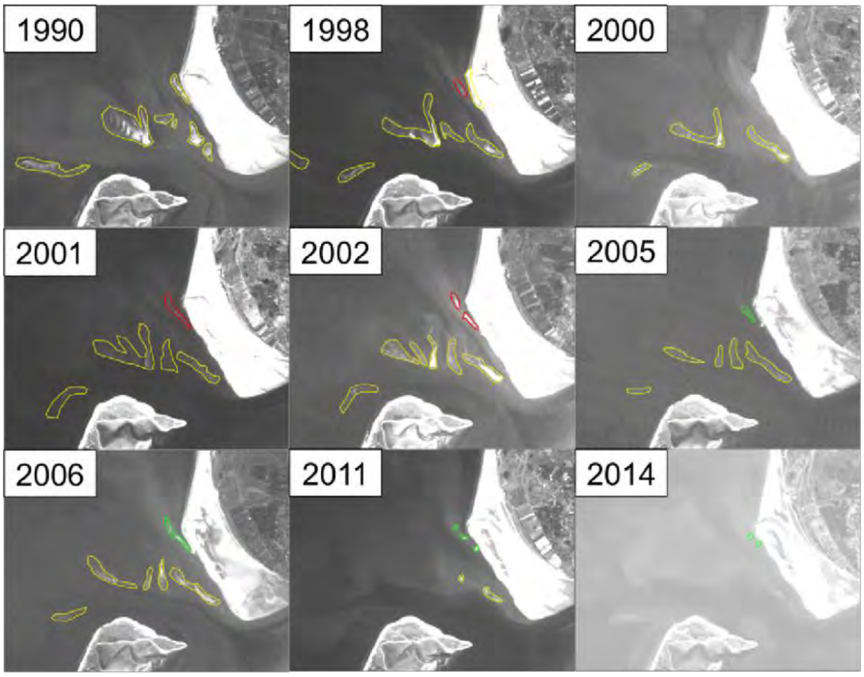


Figure 8.2.4: Landsat images of the ebb-tidal delta of Lister Dyb in different years from 1990 to 2014. It is not possible to distinguish between the successive/different shoals north of the inlet (Ridderinkhof, 2016).

The eroding shore of Sylt has a steep beachface (slope of 2–4°) and further offshore the profile is rather steep with the -6 m depth contour within 1 km of the shoreline (Menn, 2002). The sediment on the Sylt shore is coarse to medium and moderately well sorted. In contrast, the accreting Rømø shore has a wide and flat beachface (slope = 1°). The beach is separated by a trough from the swash platform of which the profile is flat, with the 6 m depth contour occurring 5 km west of the shoreline providing substantial shelter from waves. As a result the

Rømø beachface receives less wave energy than the Sylt beachface (Menn, 2002). The sediment at Rømø consists of medium to fine sand and is well sorted (Menn, 2002). If sand is (partially) derived from the Sylt, then strong sorting processes have to be assumed, trapping the coarser grains in the channels and only allowing the finer grains to pass (suspension load). Indeed, studying heavy minerals, Veenstra & Winkelmolen (1976) and Winkelmolen & Veenstra (1974, 1980) indicated that such processes are important when sediment is transported over an ebb-tidal delta.

8.3 Juvre Dyb

Basic data

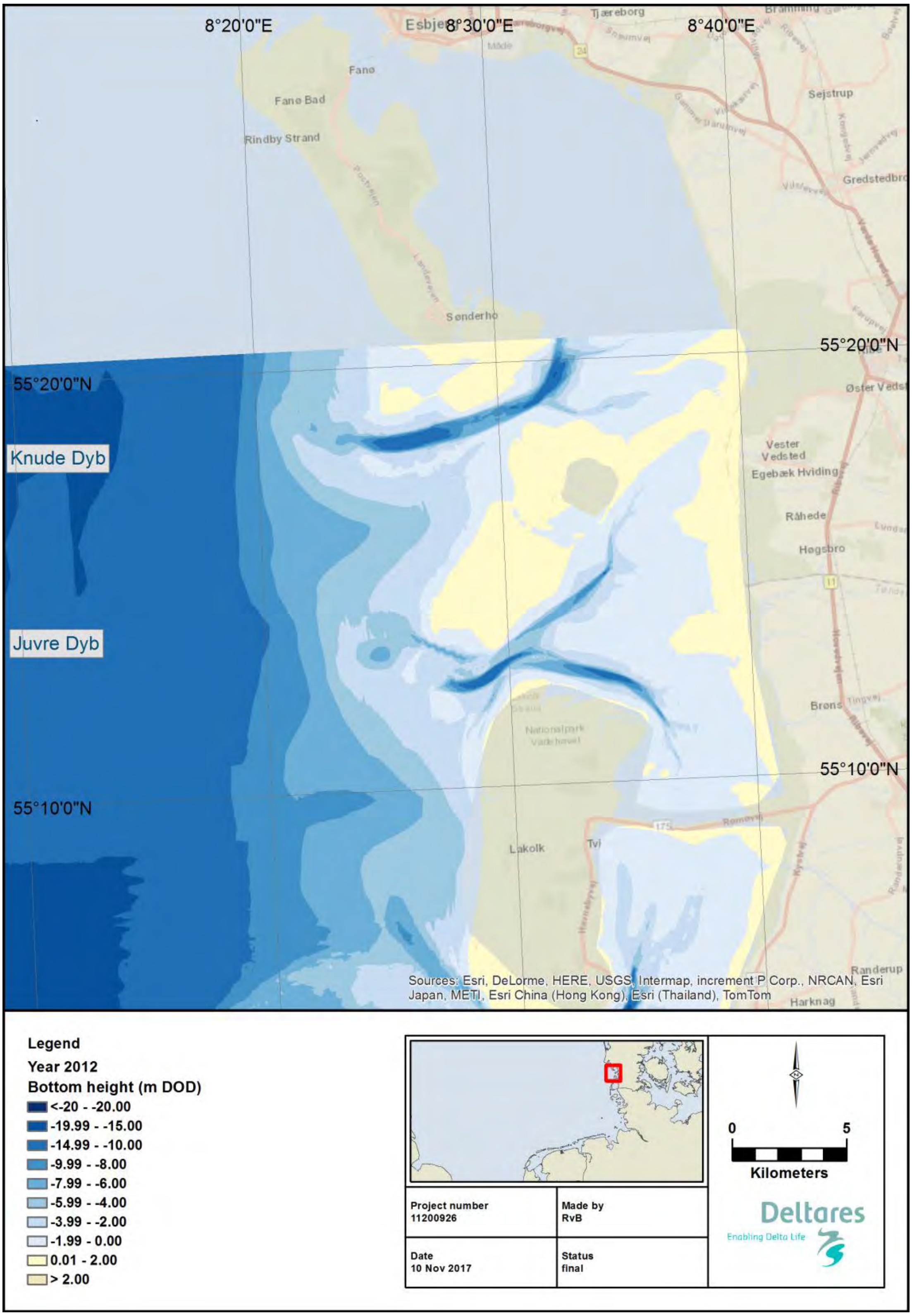


Figure 8.3.1: Overview of the ebb-tidal delta of the Juvre Dyb

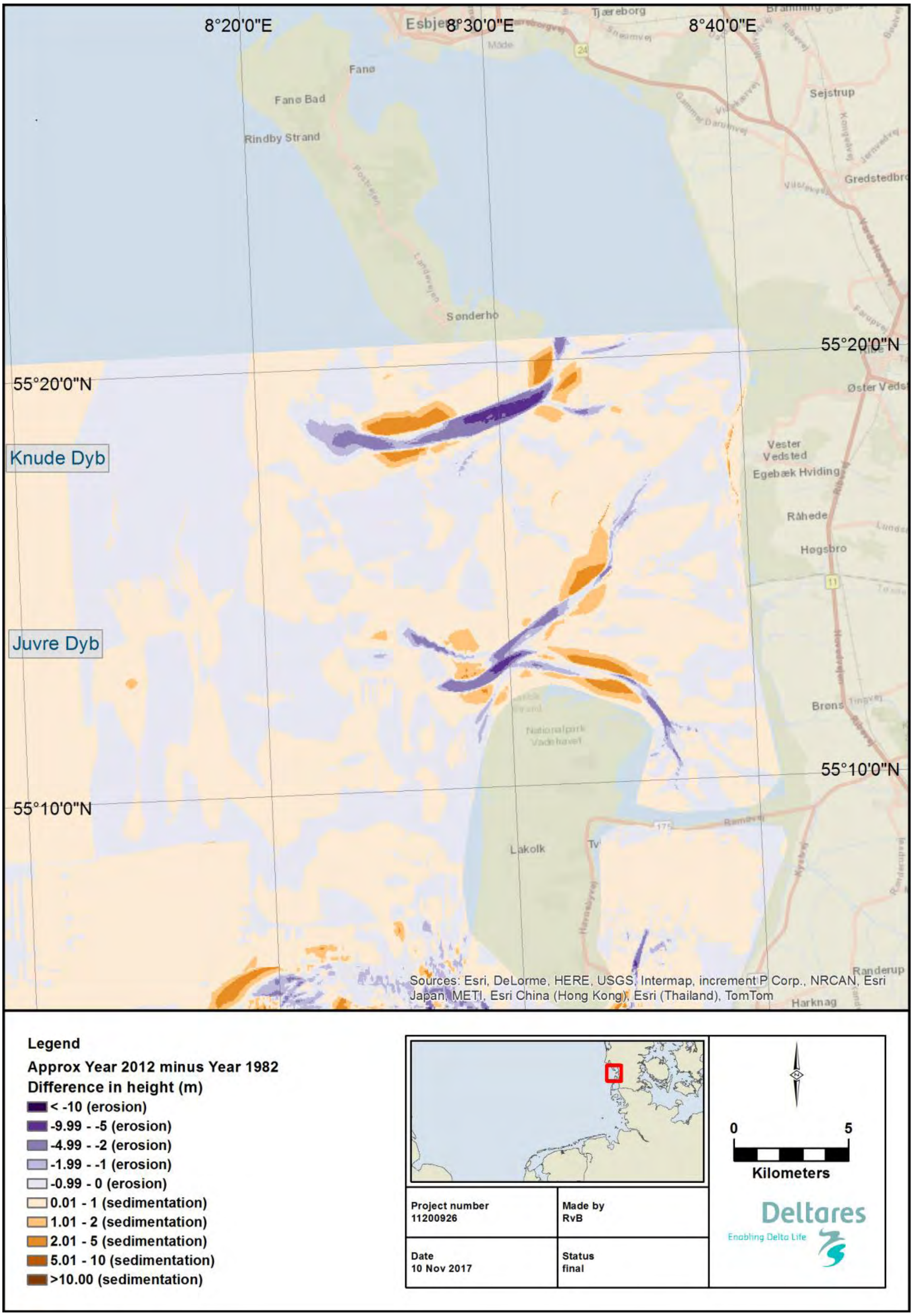


Figure 8.3.2: Overview of the ebb-tidal delta of the Juvre Dyb showing erosion and deposition over approximately the period 1982-2012.

Table 8.2: Facts and figures Juvre Dyb (see also appendix I)

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.35 mm/yr	1889-2006	1 (station Esbjerg)	4 mm/yr	1972-2007	1 (station Esbjerg)	5 mm/yr	1993-2003	1 (station Esbjerg)1
Hs (m)	1.42		CoastDat						
Tp (s).	5.65		CoastDat						
Tidal asymmetry degrees	-158.1		2						
$L_{ebb-tidal\ delta}$ (km)	6.8	2012	-6 m	10	2012	-10m			
MHW (m to DVR90)	0.76	1970	3	0.85	2001	3			
MLW (m to DVR90)	-0.85	1970	3	-0.86	2003	3			
MTR (m)	1.69	1970	3	1.71	2001	3			
Surge height (m to MSL)	20 y 3.76 (+/-0.31)	2000-2012	1 (station Mandø)	50 y 4.03 (+/-0.44)	2000-2012	1 (station Mandø)	100 y 4.24(+/-0.54)	2000-2012	1 (station Mandø)
Mean annual max surge height (m to AOD)	2.28		CoastDat						
A_{MHW} (km^2)	128.7	2001	3						
A_{MLW} (km^2)	37.3	2001	3						
A_{cross} (m^2)	11,070	2001	3						
V_{MHW} (10^6 m^3)	229.5	2001	3						
V_{MLW} (10^6 m^3)	82.9	2001	3						
P (10^6 m^3)	146.5	2001	3						
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebb-tidal\ delta}$ (10^6 m^3)	172.5	1970	3	126.6	2001	3			
$AS_{backbarrier}$ (10^6 m^3/yr)	-0.6	1970-2001	3enlargement of channels						
$AS_{ebb-tidal\ delta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	+0.2	2006-2009 & 1998-2007	4(stations Sylt & Fanø)	-0.5 to +0.6 Rømø	2006-2009 & 1998-2007	4(stations Sylt & Fanø)	-0.3 to +0.8 Koresand	2006-2009 & 1998-2007	4 (stations Sylt & Fanø)
Change ebb-tidal delta?	Nordward deflection	1970-2001	3						
Sediment transport direction?	Both sides								
Development island coasts	Growth of Rømø and Koresand								

1 = Kystdirektoratet, 2012; 2 = Wang & van der Weck, 2002; 3 = Ingvarsen, 2006a; 4 = Ridderinkhof, 2016.

Description of the tidal inlet system

This Danish inlet system is situated between the barrier islands of Rømø and Mandø/Koresand (Figures 8.3.1 to 8.3.5). The Koresand area seems to develop as a new barrier in the line of Rømø and Fanø. The tidal basin of Juvre Dyb almost completely closed at all sides: at the mainland by dikes and between the barrier island Rømø and the mainland by the Rømødam and to the island of Mandø by the tidal road towards the mainland. For data the reader is referred to table 8.2 The Juvre Dyb backbarrier receives a freshwater input from several small streams (Sand-Jensen et al., 2006).

Sedimentation in the channels was calculated to be -20*10^6 m^3 (erosion of 97*10^6 m^3 and deposition of 77*10^6 m^3; 2 mm/yr on average over the period ca. 1970-2001, albeit with uncertainties (Ingvarsen, 2006a). Erosion in the backbarier area is dominant near the inlet mouth whereas deposition takes place at the east side of the area on the tidal flats and tidal marshes near the mainland (Ingvarsen, 2006a).

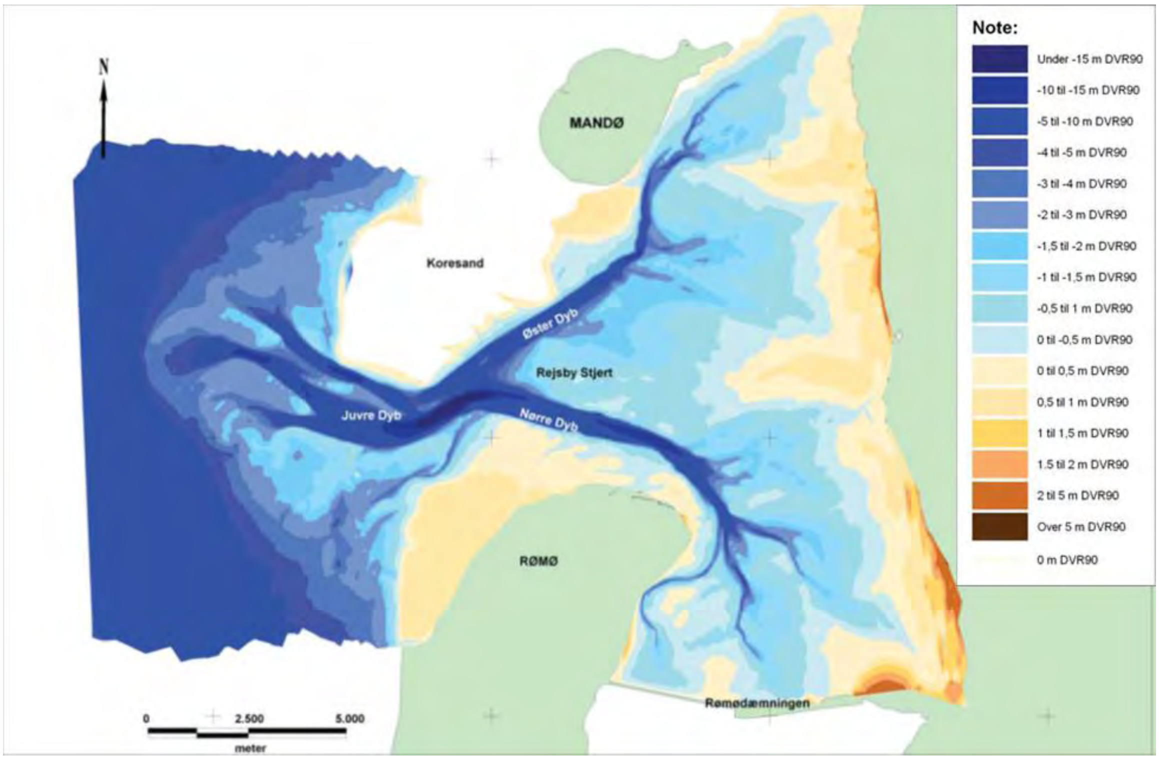


Figure 8.3.3: Depth sounding map of Juvre Dyb in 1970 (Ingvarsen, 2006a)

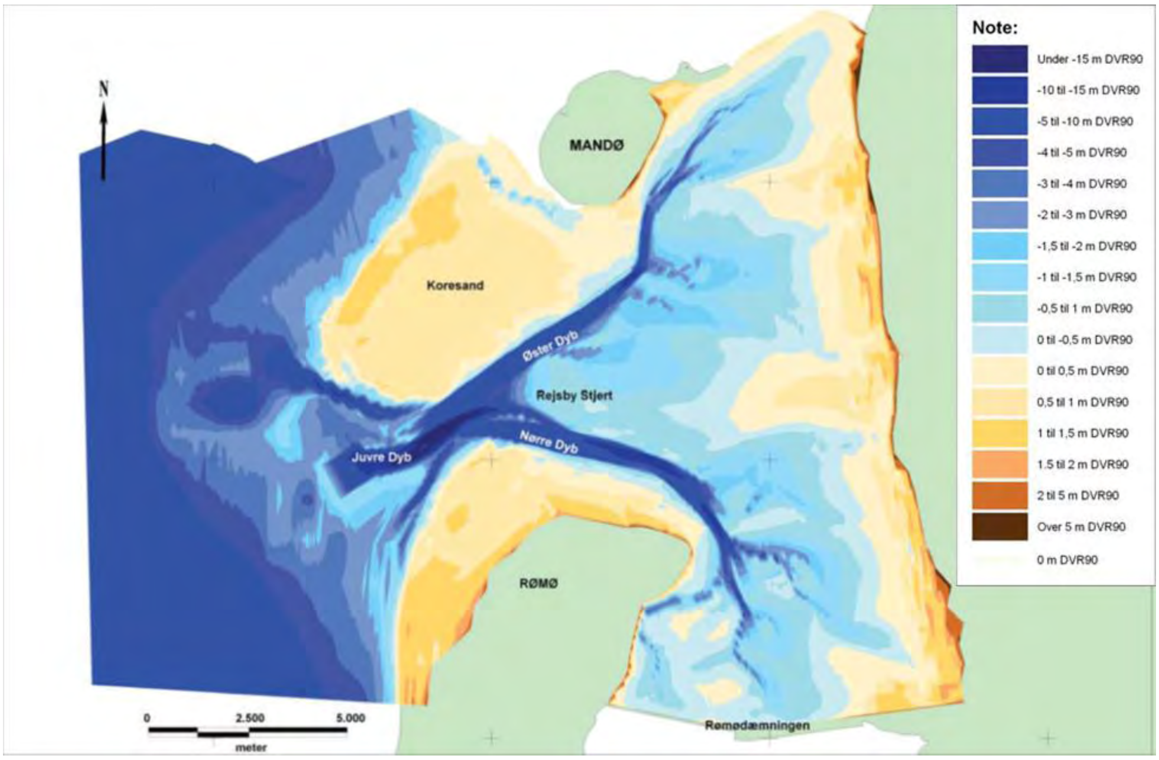


Figure 8.3.4: Depth sounding map of Juvre Dyb in 2001 (Ingvarsen, 2006a)

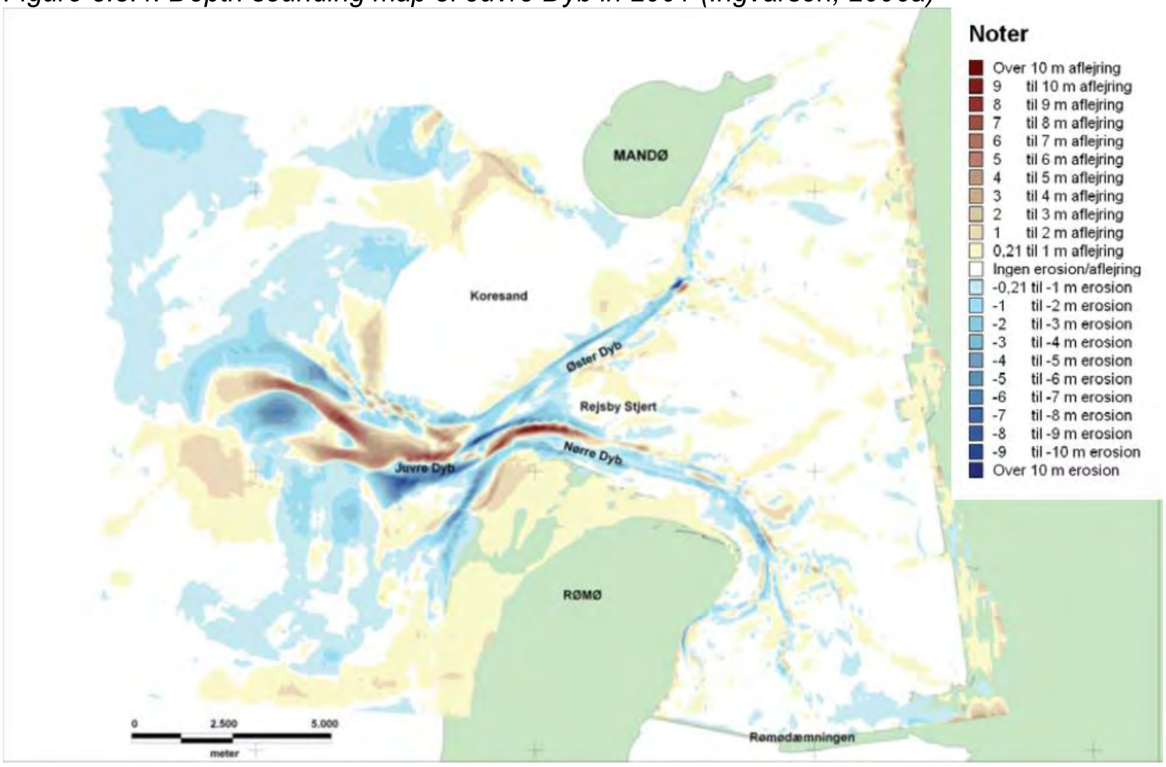


Figure 8.3.5: Difference map of Juvre Dyb in 1970-2001 (Ingvarsen, 2006a)

Development of the ebb-tidal delta

The depth maps reveal that in 1970 the ebb-tidal delta and the main channel were clearly deflected towards the North. In 2001 the situation had changed: the main channel became somewhat oriented towards the WSW. Landsat images of the ebb-tidal delta of Juvre Dyb reveal that in the period 1985 - 2014, the two northern channels migrated clockwise and partially merged around 2000 to become separated by bars again (Ridderinkhof, 2016). Also, shoal migration points to a N-ward displacement. The net littoral drift based on the Fanø station (Figure 8.1.2) suggests a net transport from S to N. However, a N to S transport is calculated based on the Sylt station (Ridderinkhof, 2016). The latter seems in agreement with the observation that the dominant wind direction over the period 1970-2001 was from the W and NW (Ingvarsen, 2006a) and the strong sedimentation on Rømø. In 1970 the sand volume of the ebb-tidal delta was about $173*10^6$ m³ and decreased to $127*10^6$ m³ in 2001, albeit with uncertainties (Ingvarsen, 2006a).

Coastal development
A large part of the sediment which was eroded from the ebb-tidal delta was most likely deposited on Rømø's coastline which accreted strongly (Ingvarsen, 2006a). Another part may have been deposited on Koresand. Unfortunately the 1970 survey did not include the larger part of Koresand (Ingvarsen, 2006a). The difference map of the period 1970 and 2001 indicate some vertical growth at the SW and northwest side. Landsat images show shoal attachment at the southwest side occurred around 1989 and 1998 (Figure 8.3.6; Ridderinkhof, 2016).

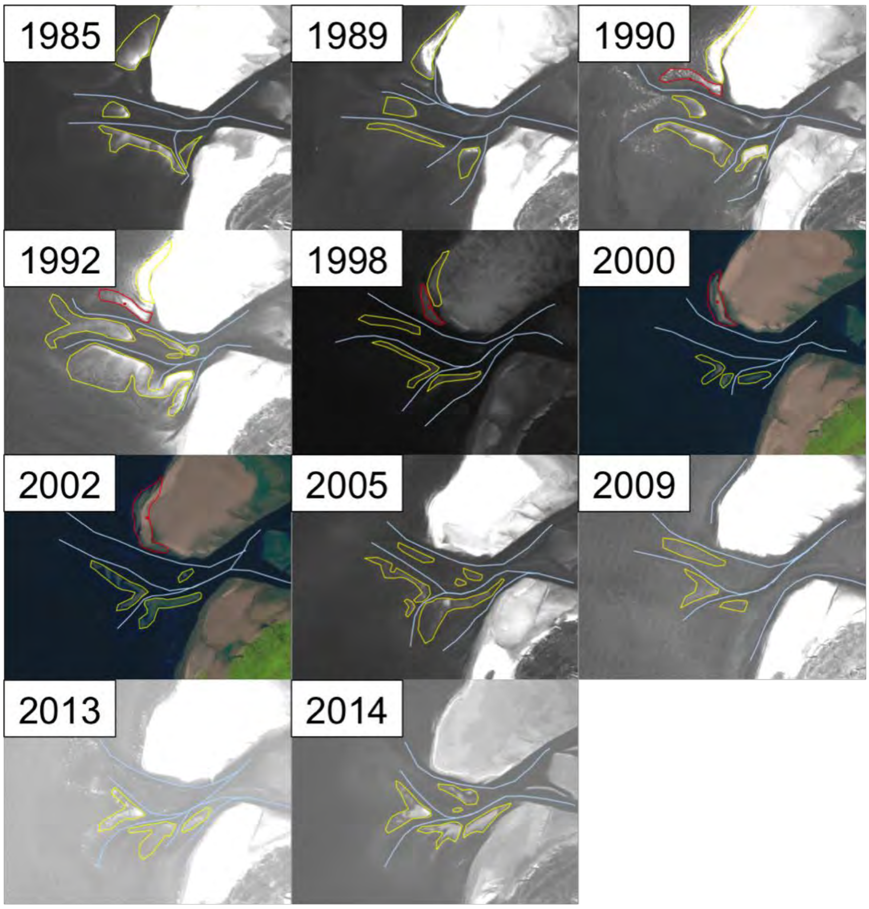


Figure 8.3.6: Landsat images of the ebb-tidal delta of Juvre Dyb over the period 1985-2014 (Ridderinkhof, 2016).

During the 20th century the strongest development of Koresand occurred before 1970 when a strong growth in NE direction and a seaward extension towards the SW occurred (Jespersen & Rasmussen, 1994). Comparison of aerial photos of 1968/69 and 1990 reveals that the total surface area did not change strongly, although welding of bars to the SW and erosion N of it changed the landscape somewhat. Also, the height of a 1900 m broad strip at the W increased some 0.2 m between 1966 to 1991 (Jespersen & Rasmussen, 1994). Comparing the aerial photo of 1990 (Figure 8.3.7) with the depth soundings of 2001, reveals that the total surface area of Koresand did not change considerably.

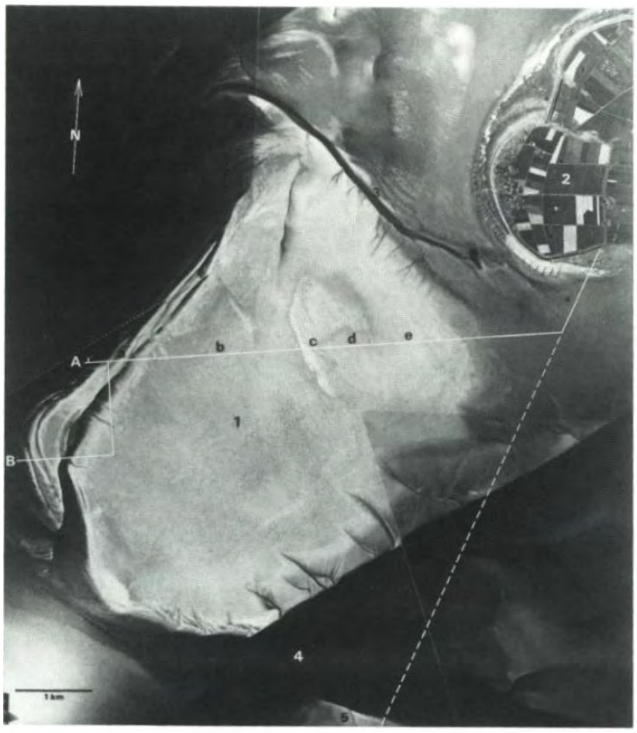


Figure 8.3.7: Koresand 1990 photo mosaic (Jespersen & Rasmussen, 1994).

8.4 Knude Dyb

Basic data

See figures 8.3.1 & 8.3.2.

Table 8.3: Facts and figures Knude Dyb (see also appendix I)

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.35 mm/yr	1889-2006	1 (station Esbjerg)						
Hs (m)	1.41		CoastDat						
Tp (s).	5.64		CoastDat						
Tidal asym-metry degrees	-158.1	1902-2002	2						
$L_{ebb-tidal\ delta}$ (km)	5	2012	-6 m	6.5	2012	-10m			
MHW (m to DVR90)	0.80 Havneby 0.7 Esbjerg	1970	3	0.91 Havneby 0.8 Esbjerg	2003	1			
MLW (m to DVR90)	-0.82 Havneby -0.91 Esbjerg	1970	3	-0.93 Havneby -0.77 Esbjerg	2003	1			
MTR (m)	1.71 Havneby 1.52 Esbjerg	1970	3	1.84 Havneby 1.61 Esbjerg	2003	1			
Surge height (m to MSL)	20 y 3.76 (+/-0.31)	2000-2012	1 (station Mandø)	50 y 4.03 (+/-0.44)	2000-2012	1 (station Mandø)	100 y 4.24(+/- 0.54)	2000-2012	1 (station Mandø)
Mean annual max surge height (m to AOD)	2.27		CoastDat						
A_{MHW} (km^2)	175	1966	3	175	2003	3			
A_{MLW} (km^2)	46.4	1966	3	52.3	2003	3			
A_{cross} (m^2)	11,054	1966	3	11,873	2003	3	1		
V_{MHW} ($10^6 m^3$)									
P ($10^6 m^3$)	143.3	1970	3	153.3	2003	3			
$SV_{ebb-tidal\ delta}$ ($10^6 m^3$)									
$AS_{backbarrier}$ ($10^6 m^3$/yr)	-0.1	1966-2003	3 enlarge-ment of channels						
$AS_{ebb-tidal\ delta}$ ($10^6 m^3$/yr)									
Longshore drift ($10^6 m^3$/yr)	0	2006-2009 & 1998-2007	4 (stations Sylt & Fanø)	-0.5 to -1.3 Fanø	2006-2009 & 1998-2007	4 (stations Sylt & Fanø)	-0.3 to +0.8 Ko-resand	2006-2009 & 1998-2007	4 (stations Sylt & Fanø)
Change ebb-tidal delta?	Hardly, some seaward expan-sión at the NW side (Fanø) and	1966-2003	3						

	erosion at the SW side								
Sediment transport direction?	N								
Development island coasts	Growth of S/ Fanø; Slight growth of NW Koresand								

1 = Kystdirektoratet, 2012; 2 = Wang & van der Weck, 2002; 3 = Klagenberg et al., 2008; 4 = Ridderinkhof, 2016.

Description of the tidal inlet system

This Danish inlet system is situated between the barrier islands of Mandø/Koresand and Fanø (Figures 8.3.1, 8.3.2 and 8.4.1 to 8.4.3). The Koresand area seems to develop as a new barrier in the line of Rømø and Fanø. The tidal basin of Knude Dyb is partially closed: at the mainland by dikes and by the tidal road between the island of Mandø and the mainland. For data see table 8.3.

As a result of the increase in tidal amplitude and the high relative sea-level rise tidal prism increased from 143.3 to 153.5**10^6 m^3 for the backbarrier area of Knude Dyb over the period 1970-2003. The tides are calculated to be ebb-dominant in the vertical (for Esbjerg Harbour the relative tidal phase is -158.1 degrees; Wang & van der Weck, 2002; Ingvarsen, 2006a). The Knude Dyb backbarrier receives a freshwater input from several small streams of which the most important are the Ribe Å, Konge Å and Sneum Å (Sand-Jensen et al., 2006).

The overall development reveals a tendency towards accumulation on the intertidal and supratidal flats and a deepening of the tidal channels. The accumulation was most pronounced on the inner flats along the mainland coast on the tidal flats southeast of Fanø. Here, the supratidal flats have experienced the establishment of vegetation and dune formation since 1966. Subtidally, both a widening and deepening of the majority of the tidal channels have occurred and a net erosion in the backbarrier area of 5.1 10^6 m^3 has been calculated. One area that had not experienced accumulation on the tidal flats was the area around the tidal water divide towards Grådyb. The topographic divide had lowered and moved further north into the Grådyb tidal area over the period which led to a potentially larger water exchange between the two tidal areas (Klagenberg et al., 2008).

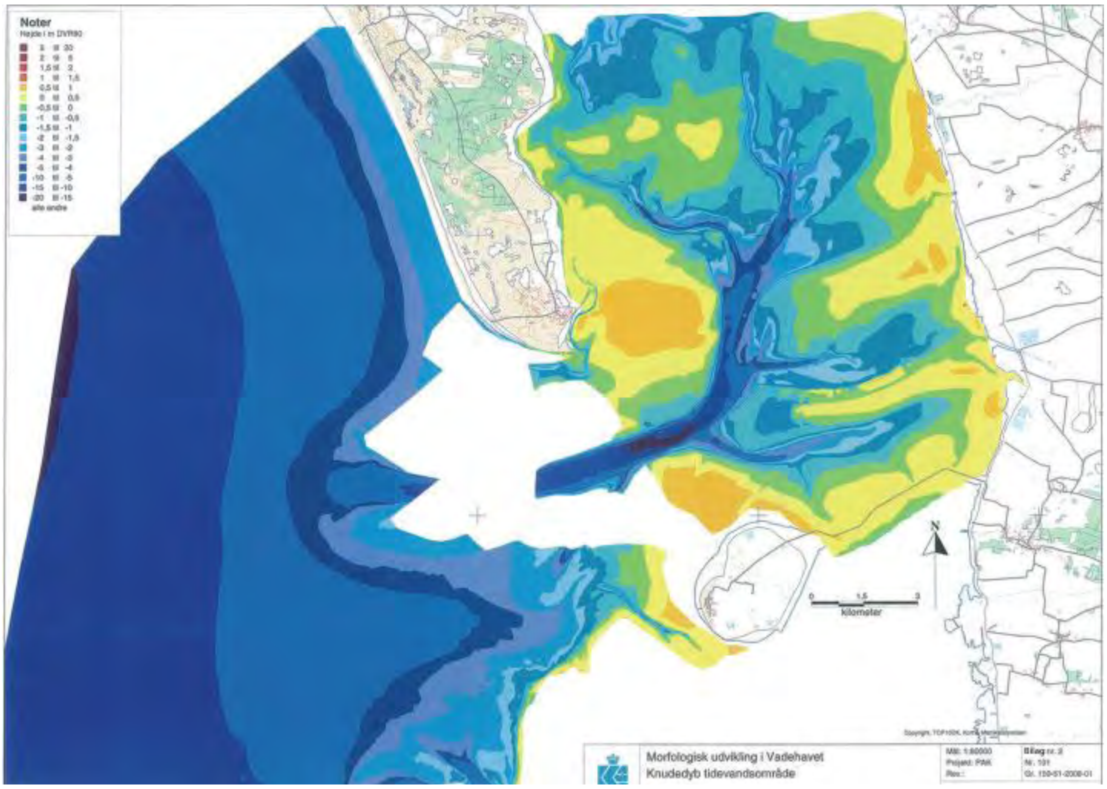


Figure 8.4.1: Depth sounding map of Knude Dyb in 1966 (Klagenberg et al., 2008)

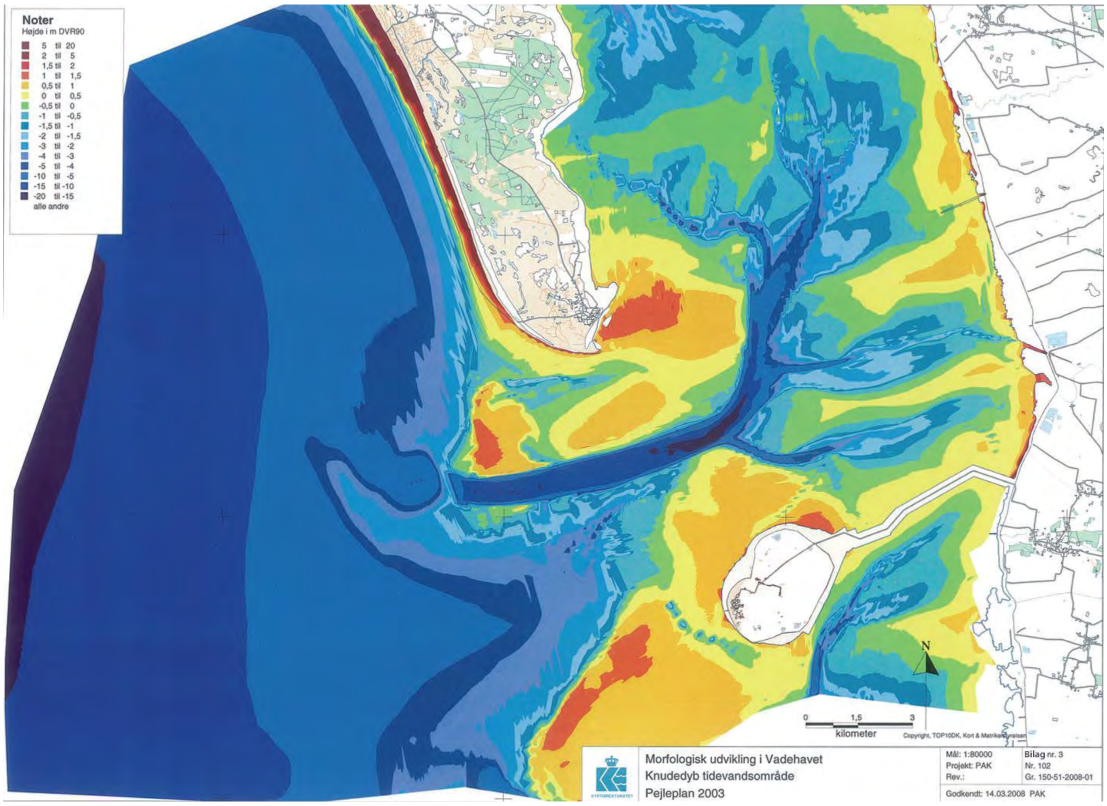


Figure 8.4.2: Depth sounding map of Knude Dyb in 2003 (Klagenberg et al., 2008)

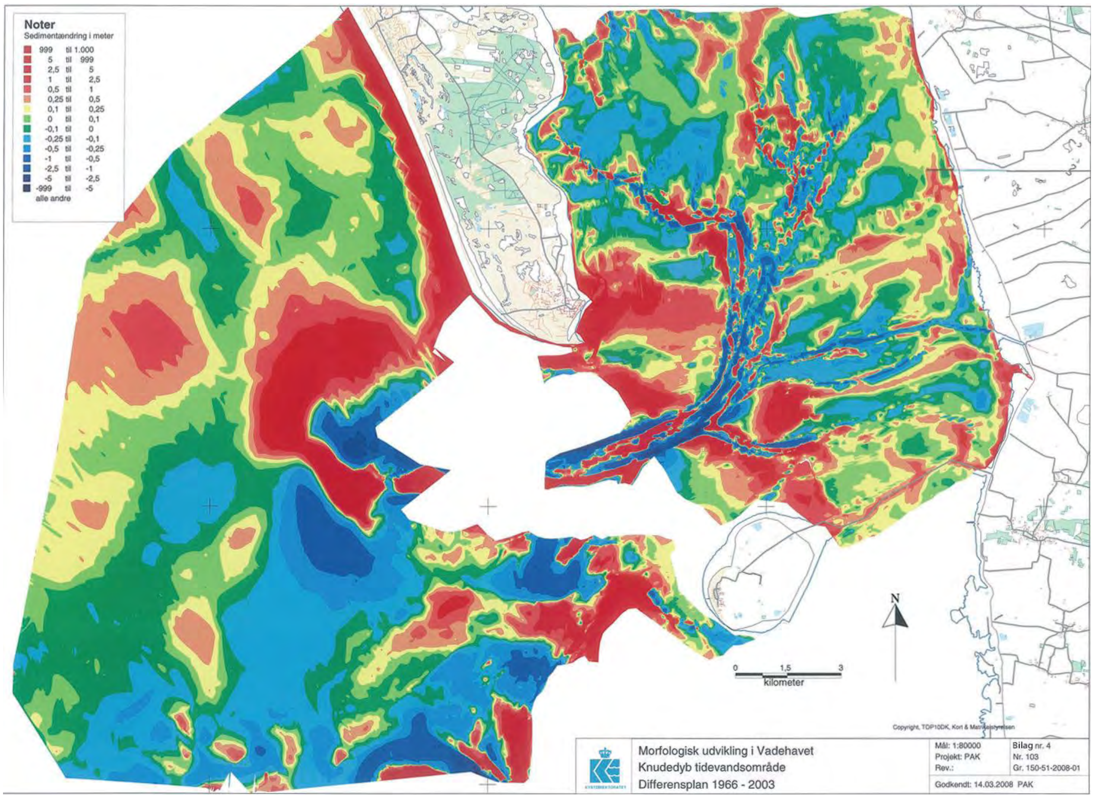


Figure 8.4.3: Difference map of Knude Dyb in 1966-2003 (Klagenberg et al., 2008)

Development of the ebb-tidal delta

The ebb-tidal delta is exposed to the strong westerly winds; however, the influence of waves in the inlet channel is small due to the shallow ebb-tidal delta (Ernstsen et al., 2013). Knude Dyb is a tidal inlet with a width of 8 km where a large sandy shoal separates a small northern flood-channel from the main inlet channel. The main channel is ~1 km wide with mean depths in the range of 10-20 m (Ernstsen et al., 2013) and drains most of the back-barrier basin (Ridderinkhof, 2016). The channels seem rather stable in position, but seem to have deepened seaward of the pass of the inlet. This and the almost symmetrical position of the main channel seem to indicate that the net littoral drifts from Fanø and Koresand are nearly in balance. From Ridderinkhof (2016) it appears that the drifts which are calculated based on Fano station would result in such a balance. However a small N- ward drift seems to dominate as shoals migrate in that direction along the rim of the terminal lobe of the main channel. Every 8 year (std: 2.1 yr) shoals which formed in the terminal lobe attach to the large shoal (Figure 8.4.5; Ridderinkhof, 2016). The shoals migrate with a mean velocity of 103 m/yr (std: 31 m/yr; Ridderinkhof, 2016). The observed movement of the shoals is in agreement with the shift over the period 1966-2003 of the orientation of the ebb-tidal delta as a whole to the N with erosion at the southwest side (Klagenberg et al., 2008).

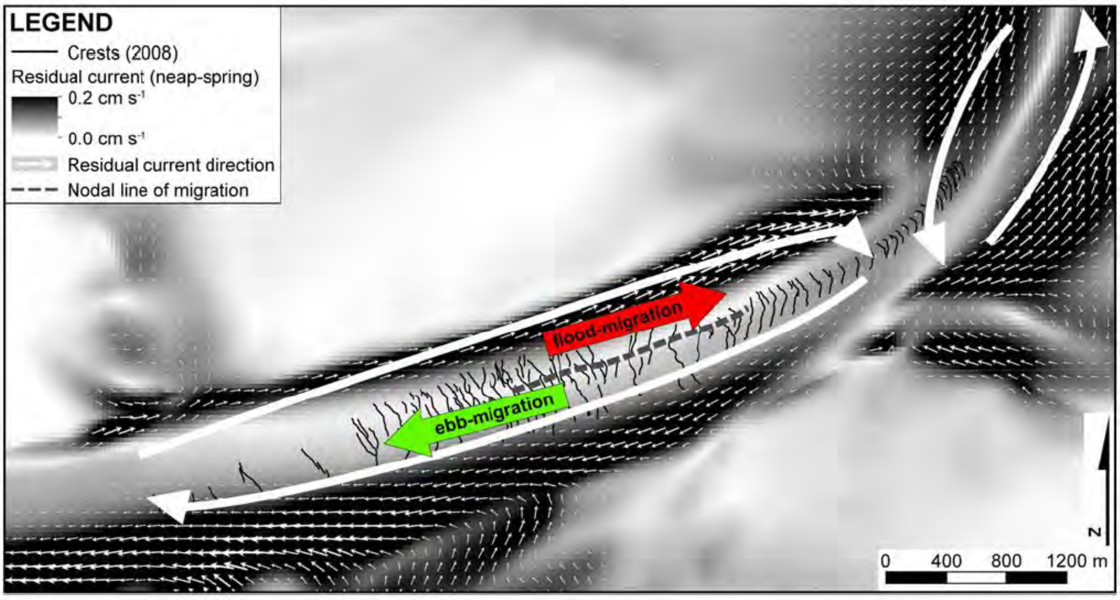


Figure 8.4.4: Map of the residual currents calculated over a neap-spring cycle (Fraccascia et al., 2016).

The main channel is ebb-dominated with maximum ebb and flood depth-averaged current velocities around 1.2 m/s and 1.0 m/s, respectively (Figure 8.4.4; Lefebvre *et al.*, 2013). From observations and computations over a neap-spring cycle Fraccascia et al. (2016) found that there was a clockwise circulation with net flood dominance at the N of the main channel and, largest, ebb dominance at the south side. This is a comparable pattern as observed in Hörnum Tief, be it with ebb- and flood-dominance reversed. On the swash platform N of Knude Dyb, large swash bars migrate towards the tidal basin (Ernstsen et al., 2013). The observed sediment transport directions are in line with the generally accepted net sand transport patterns on an ebb-tidal delta (Ernstsen et al., 2013).

A large part of the tidal area was not covered by the 1966 survey, but aerial photography indicates an enlargement of the ebb-tidal delta. Eroded sand from the backbarrier area may have been deposited on the ebb-tidal delta. Furthermore the relatively strong southward littoral drift along the coast of Fanø may have contributed to the sediment accumulation S of the island.

Coastal development

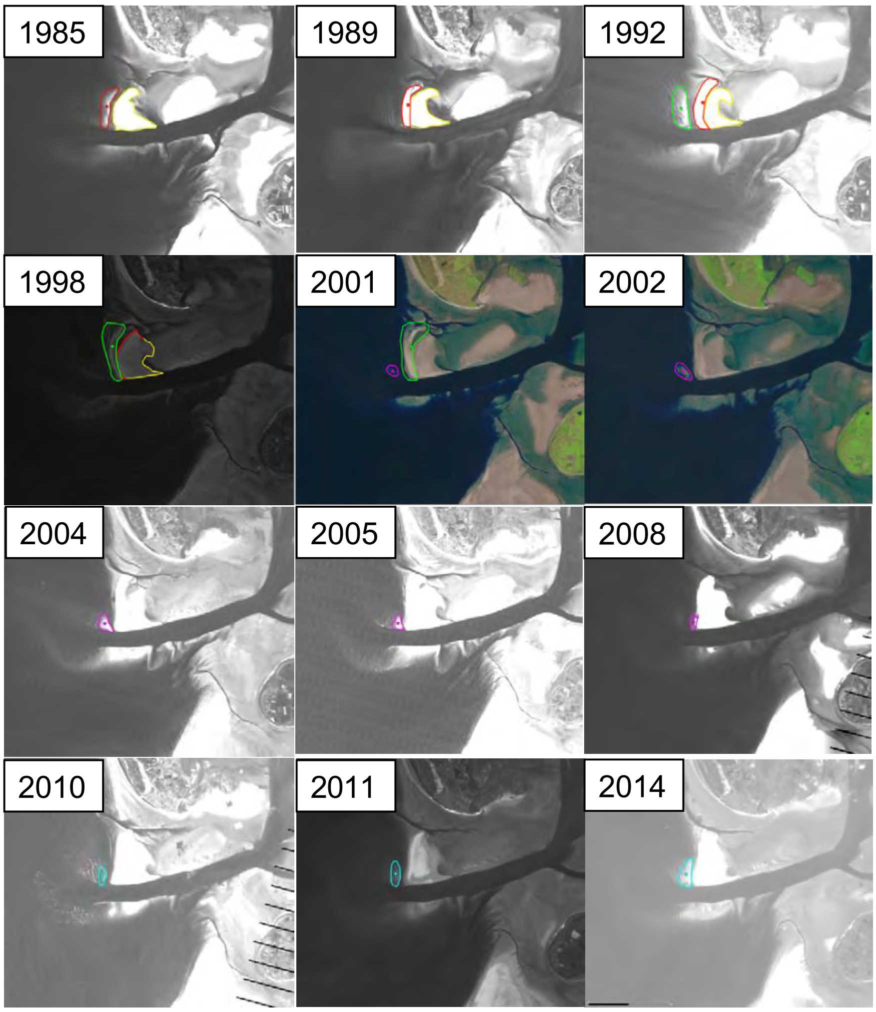


Figure 8.4.5: Landsat images of the ebb-tidal delta of Knude Dyb, for the period 1985-2014. The shoals are marked by coloured polygons (Ridderinkhof, 2016).

Sediment transport from the ebb-tidal delta towards Koresand seems to be small. The difference map of the period 1966 and 2003 indicates vertical growth at the northwest side (Ingvarsen, 2006a; 2008), for which the sand might either be derived from the Juvre Dyb or the Knude Dyb. Landsat images show attachment of shoals migrating from the terminal lobe N of the main inlet channel (Figure 8.4.5; Ridderinkhof, 2016). The strong development of the Fanø coast might partially be attributed by southward littoral drift. For the southern tip of the island sedimentation was probably enhanced by the fact that there was a flood channel and that both along the north side of the main channel and over the shoal flood oriented sediment transport dominates (Ernstsen et al., 2013; Fraccascia et al., 2016).

8.5 Grådyb

Basic Data

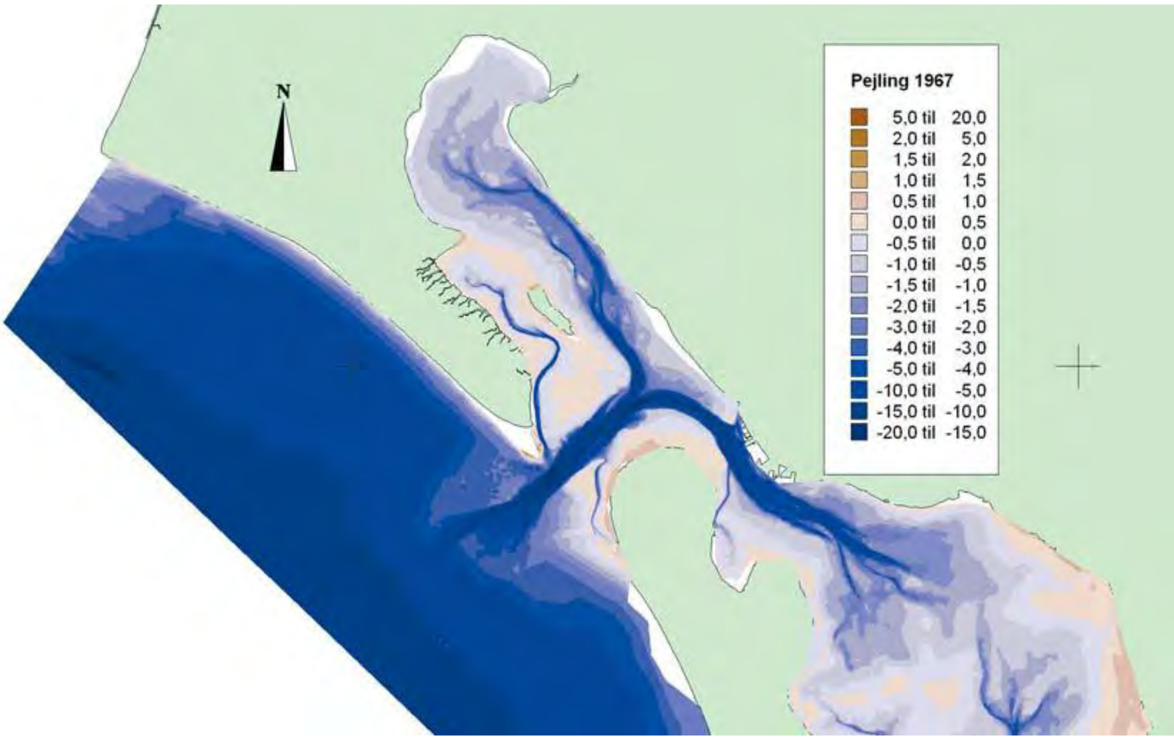


Figure 8.5.1: Depth sounding map of Grådyb in 1967 (1969: Skallingen; Ingvarsen, 2006b)

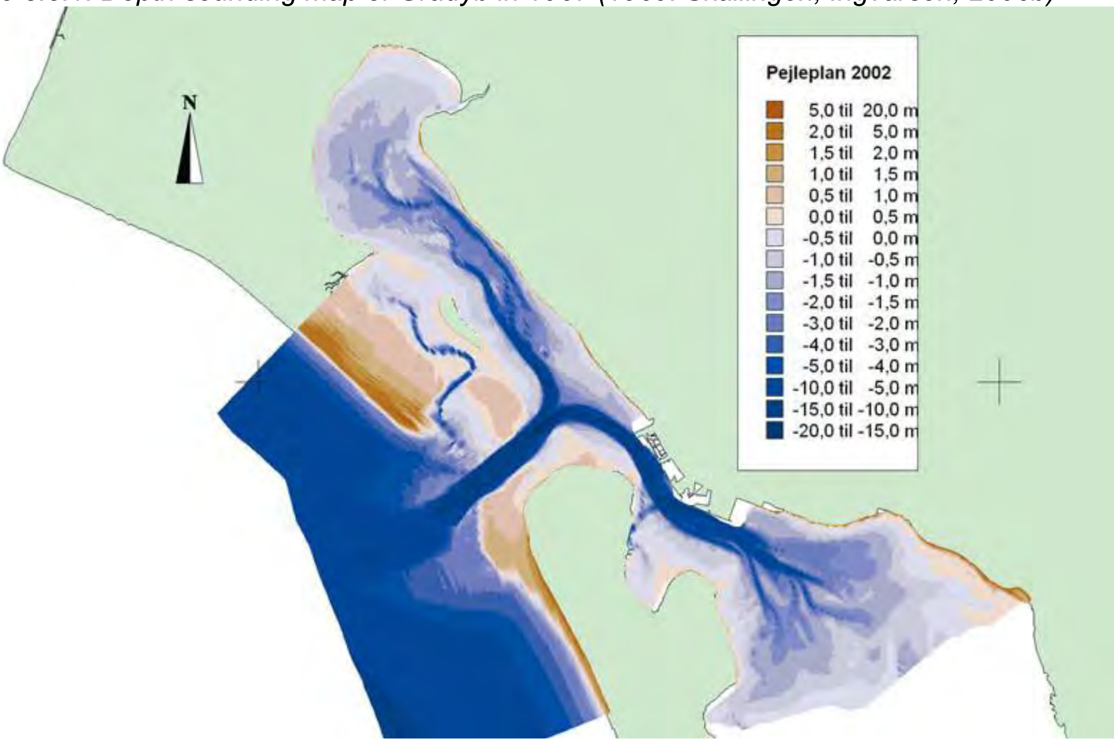


Figure 8.5.2: Depth sounding map of Grådyb in 2002 (Ingvarsen, 2006b).

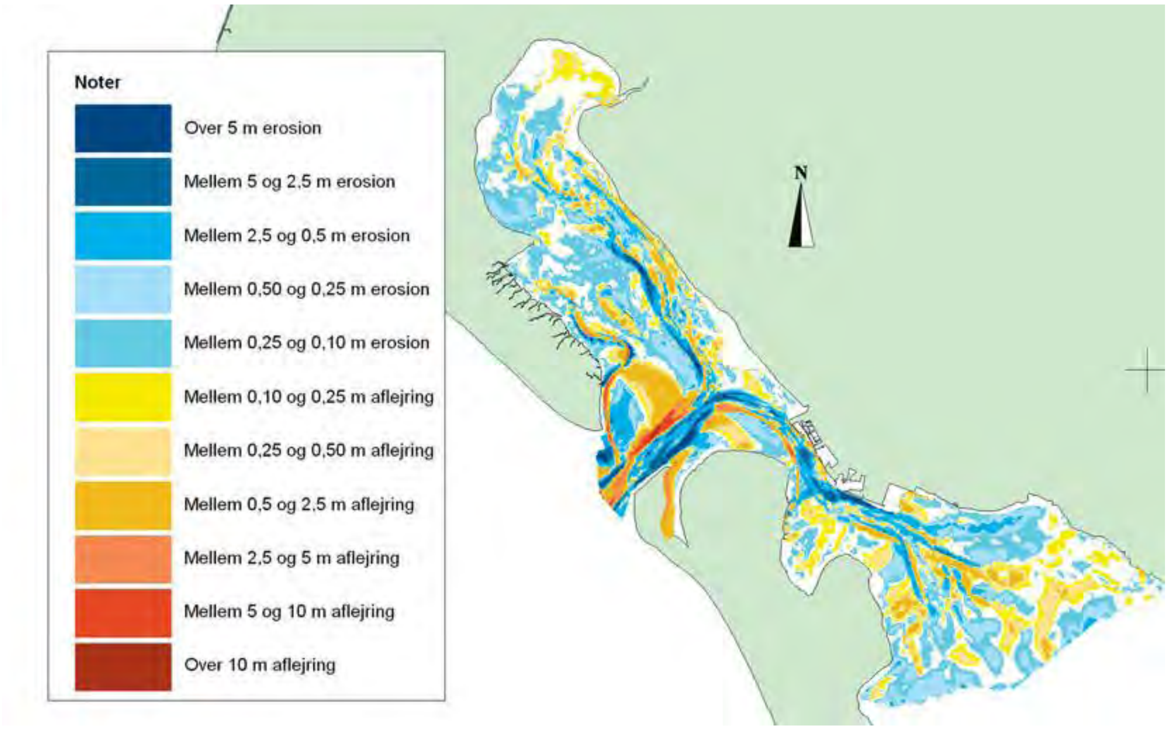


Figure 8.5.3: Difference map of Grådyb in 1967-2002 (Ingvarsen, 2006b).

Table 8.4: Facts and figures Grådyb (see also appendix I)

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (m to DVR90)	1.35 mm/yr	1889 - 2006	1 (station Esbjerg)		2002	1			
Hs (m)	1.39		CoastDat						
Tp (s).	5.65		CoastDat						
Tf/Te	0.9	1902-2002	2						
$L_{ebb\text{-}tidal\ delta}$ (km)	5.5	2012	-6 m	8,5	2012	-10m			
MHW (m to DVR90)	0.73	1967	2	0.79	2002	2			
MLW (m to DVR90)	-0.77	1967	2	-0.78	2002	2			
MTR (m)	1.5	1967	2	1.57	2002	2			
Surge height (m to MSL)	20 y 3.62 (+/- 0.11)		1 (station Esbjerg)	50 y 3.88 (+/- 0.13)		1 (station Esbjerg)	100 y 4.05 (+/- 0.16)		1 (station Esbjerg)
Mean annual max surge height (m to AOD)	2.27		CoastDat						
A_{MHW} (km^2)	131	1967	2	129	2002	2			
A_{MLW} (km^2)	68	1967	2	69	2002	2			
A_{cross} (m^2)									
V_{MHW} ($10^6 m^3$)									
P ($10^6 m^3$)	157	1967	2	165	2002	2			
$SV_{backbarrier}$ ($10^6 m^3$)									
$SV_{ebb\text{-}tidal\ delta}$ ($10^6 m^3$)	44	1967	2	37	2002	2			
$AS_{backbarrier}$ ($10^6 m^3/yr$)	-0.4 (-0.9_+0.2)	1967-2002	2 Sedimen-tation above 0 m DVR90 and						

			enlarge-ment of channels						
$AS_{ebb\text{-}tidal\ delta}$ ($10^6\ m^3/yr$)									
Longshore drift ($10^6\ m^3/yr$)	-0.6		3 (based on 4)	-1.5 to -1.6	2006-2009 & 1998-2007	2 (stations Sylt & Fanø)			
Change ebb-tidal delta?									
Sediment transport direction?	S: Skallingen to deliver ca. $0.4*10^6\ m^3/yr$	1989-2013	3						
Development island coasts	Sedimentation Fanø; Erosion of Skallingen		5						

1 = Kystdirektoratet, 2012; 2 = Ingvarsen, 2006b; 3 = Ridderinkhof, 2016; 4 = Aagaard & Sørensen, 2013; 5 = Klagenberg et al., 2008.

Description of the tidal inlet system

The Grådyb is the most northern inlet system of the Wadden Sea situated between the barrier island Fanø and the peninsula of Skallingen (Figures 8.5.1 to 8.5.3). The tidal basin of Grådyb is partially closed: at the mainland by dikes and high lands and the tidal marshes of Skallingen spit. The Grådyb backbarrier receives a freshwater input from several small streams of which the most important is the Varde Å (Sand-Jensen et al. 2006). For data the reader is referred to table 8.4.

Since Esbjerg Harbour was established, there has been an ongoing deepening of the port and the shipping lane. The water depth is now -10.3 m MSLT, which corresponds to a deepening of in total 7 m, since the harbour was opened. The dredging amounted to, on average, 1.2 $10^6\ m^3/yr$, which corresponds to approx. 9 % of sediment export of sand from the Grådyb backbarrier area. The port itself serves as a trap for fine-grained sediment and some 0.46 $10^6\ m^3/yr$ is dredged of which 10% is dumped on land and the rest is dumbed in the Grådyb backbarrier area and is thought to contribute to sedimentation in the backbarrier area.

Inside the Grådyb backbarrier area erosion dominated in the channels and on the flats under 0 m DVR90. Above 0 m DVR90 deposition was dominant. In the period 1967-2002 deposition in the area amounted to $27*10^6\ m^3$. During the same period an erosion of $40*10^6\ m^3$ occurred, resulting in net erosion at $13*10^6\ m^3$. The standard deviation is estimated to be $20*10^6\ m^3$. Grådyb's backbarrier has a huge subtidal area, which in theory should lead to the import of sediment. This is not true for the sands, but holds for the fine sediments. The tidal divide between Grådyb and Knude Dyb has moved towards the N and has lowered.

Development of the ebb-tidal delta

As the inlet is the main shipping route to the harbor of Esbjerg, its main channel is dredged, also seaward of the inlet on the ebb-tidal delta. Therefore, the ebb-tidal delta cannot be considered as undisturbed (Ridderinkhof, 2016). The ebb current is of very similar magnitude along the whole channel axis, whereas the flood current is of similar magnitude in the inner half, but reaches only about half of the maximum ebb current velocity in the outer section (Bartholdy et al., 2002). The inlet is ebb-dominated (dominant ebb current: 1.01 m/s; dominant flood current: 0.79 m/s; Bartholdy et al., 2002). Judging from dune development in the inlet pass sediment transport is also ebb-dominated in the inlet itself (Ernstsen et al., 2006). The ebb-tidal delta is very pronounced. In 1967 the volume of the ebb-tidal delta was $44*10^6$

m^3. In 2002 no complete survey of the outer delta was made and hence observations of 1999 and 2002 were added. The volume of ebb-tidal delta in 2002 was ca. $37*10^6$ m^3 (Ingvarsen, 2006b).

Attachment of outer delta shoals to the coast south of the inlet occurred in 1989, before 1998, 2005, and 2013 (Figure 8.5.4). In 2005 and 2013 multiple smaller shoals are associated with the attachments. The mean period between successive attachments is 8 years (std: 1 yr; Ridderinkhof, 2016).

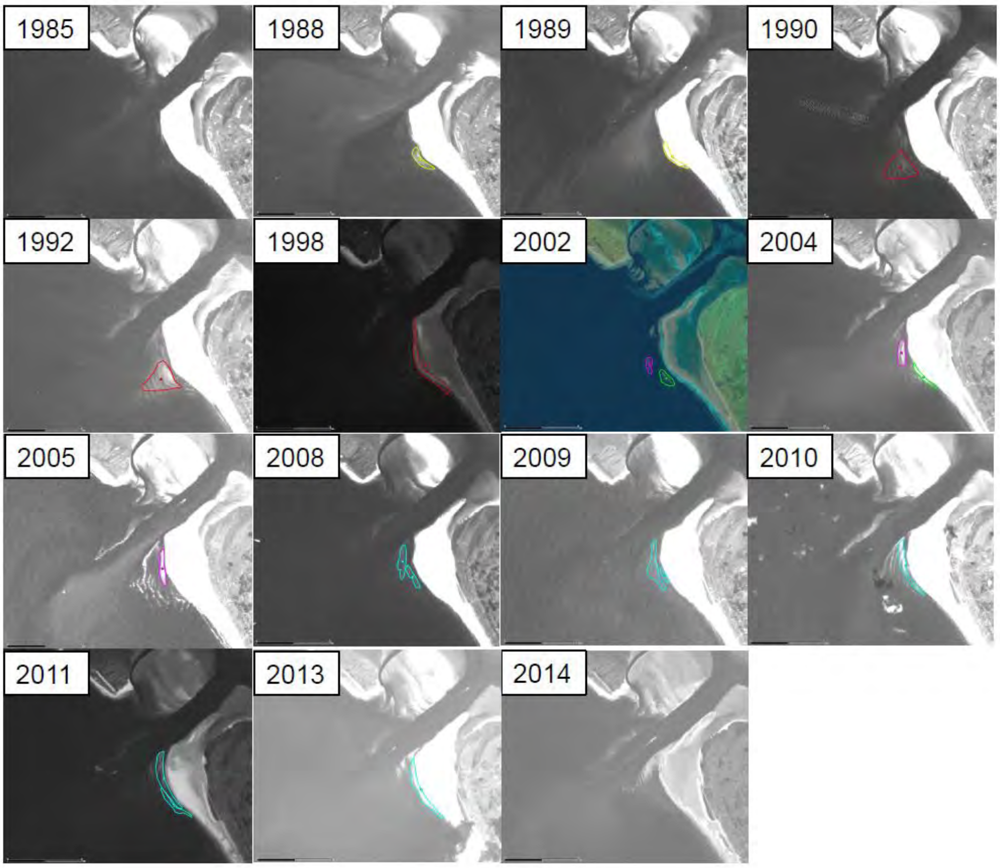


Figure 8.5.4: Landsat images of the ebb-tidal delta of Grådyb inlet in different years from 1985 to 2014. Migrating shoals are marked by coloured polygons.

Coastal development

The peninsula Skallingen and the island Fanø are the barriers facing the North Sea. Especially the morphological development of Skallingen has probably been essential to the developments in Grådyb and vice versa (Christiansen et al., 2004; Ingvarsen, 2006b). Skallingen was likely formed as a long sandy spit and is merely 400 years old. Nowadays it is considered a transgressive barrier and it loses some $0.4*10^6$ m^3/yr (average period: 1973 to 2003) and a coastal retreat of 6.8 m/yr on average (Ingvarsen, 2006b). Strong changes (both seaward and landward) occurred in the period from 1972 to 1983, and especially between 1978 and 1981 which was most likely due to changes in wind direction in the late 1970s and early 1980s for the southernmost North Sea coast on Skallingen.

Volume calculations of Skallingen's coastal profile indicate sand transport from N to S along the Northsea coast towards the end of Skallingen. However, Skallingen peninsula protruded more to the SE in 1967 than at present (Ingvarsen, 2006b), leading to the conclusion that the sediment which reaches the end of Skallingen is nowadays deposited in the inlet. Indeed, during periods of high erosion on Skallingen's westcoast the amount of dredging needed in the inlet increases (Ingvarsen, 2006b). Vinther et al. (2005) show that the sediment transport is probably indirect via complicated transport patterns which involve major flood- and less important ebb-transport over the end to the spit before it is transported into the inlet.

Reversely the developments on the outer delta also influenced the development of the southern tip of Skallingen. Due to the reduced volume of an ebb-tidal shoal N of the inlet (Tørrebjælke) waves from the S have greater opportunity to erode Skallingen End. It therefore can be stated that the dredging and deepening of the Grådyb attributed to the observed retreat of Skalling, although it is not the only reason (Ingvarsen, 2006b).

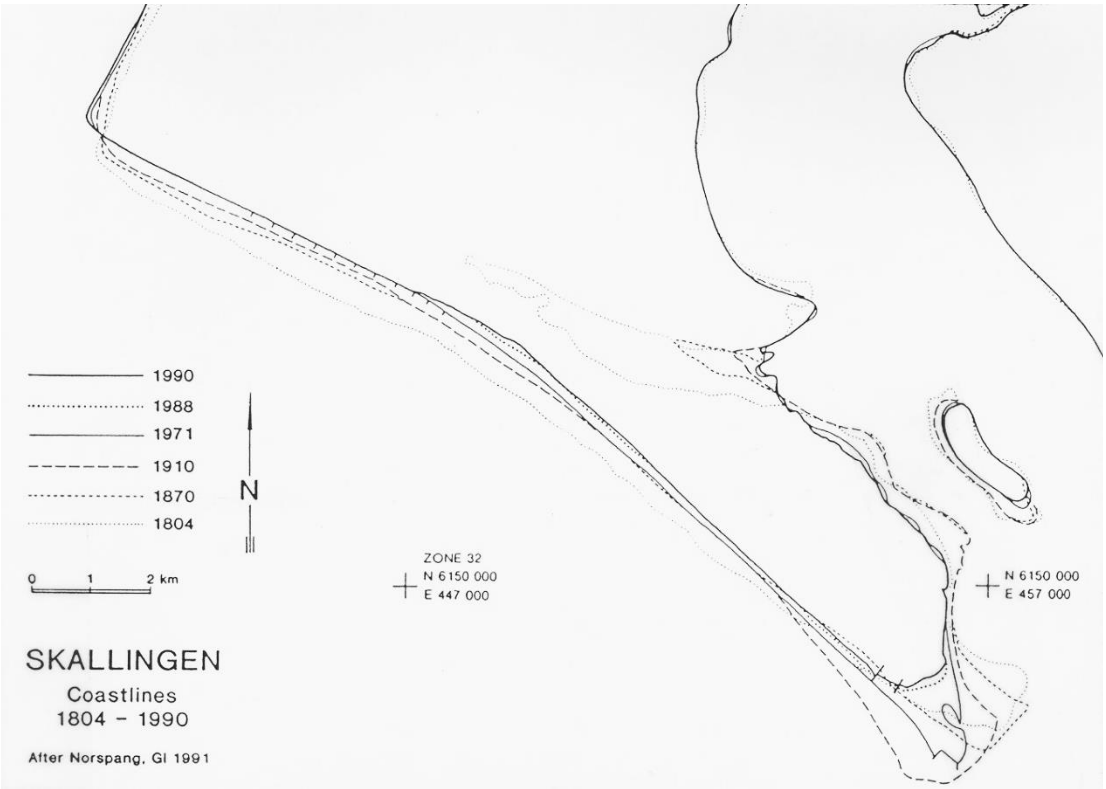


Figure 8.5.5: Changes of the Skallingen coastline over the period 1804-1990 (Aagaard et al., 1995).

9 Classification ebb-tidal deltas Wadden Sea

9.1 Introduction

Here the data collected for the most recent time frames are used to classify the ebb-tidal deltas of the Wadden Sea based on the classifications discussed in chapter 3 and the data collected in chapters 5 to 8. In paragraph 9.2 the various geometric classifications are discussed and in paragraph 9.3 various hydrodynamic classifications will be given.

9.2 Geometric classifications

Extension of the ebb-tidal delta

The seaward extension of the ebb-tidal delta and the tidal prism are plotted in Figure 9.2.1. There is a general trend of increasing size with increasing tidal prism, be it with a large scatter, for both the -6 m extension and -10 m extension. The relations are not as strong as suggested by Sha (1990a).

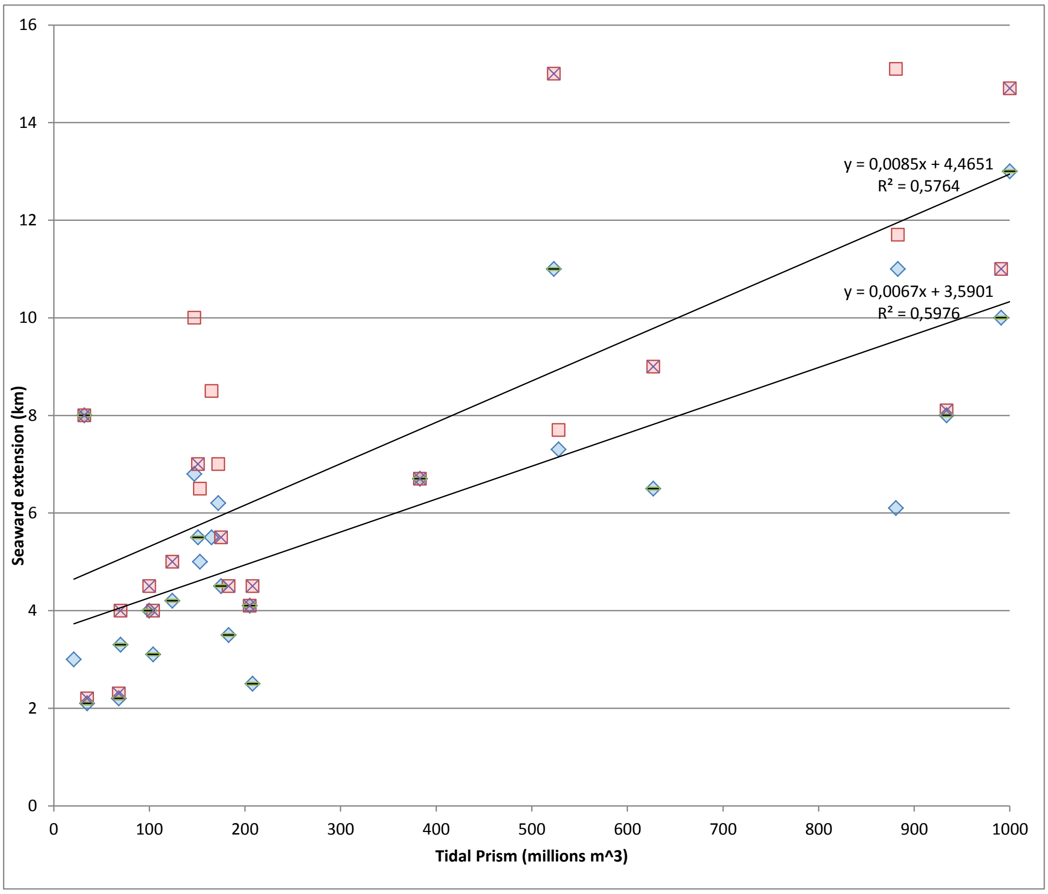


Figure 9.2.1: Overview of the tidal prism versus seaward extension of the ebb-tidal delta: blue diamonds = -6 m MSL; red squares = -10 m MSL; blue diamonds with stripe = West and East Frisian observations; red squares with cross = West and East Frisian observations.

In general -10 m extension of the ebb-tidal deltas is larger for the North Frisian coast than for the West and East Frisian coasts. The reason for this is not known, but might be due to the different shape of the backbarrier channels, which are far less meandering, which is attributed to the fact they are incised in the Pleistocene sediments (see below). The straight backbarrier channels will allow for a faster outflow of waters and might lead to a further extension of the ebb-tidal deltas.

Orientation of the tidal basin

The tidal wave propagates from W to E and from S to N along the Wadden Sea. Especially in the North Frisian coast the littoral drift is often in the reverse direction. The orientation of the Wadden backbarrier basins is often mainly to one side with the backbarrier basin in the direction of the tidal wave propagation (Basic cases 2 and 4; Figure 9.2.2). Although there are very symmetrical backbarrier basins (e.g. Grådyb), most are semi-symmetrical with the dominant part in the direction of the tidal wave propagation and a (often separate) subordinate part against that direction. In this context it is important to stress that many of the inlet systems actually consist of two more or less separate inlet systems between two barrier islands (Figure 9.2.3): a big one of which the backbarrier basin is oriented in line with the direction to which the tidal wave travels and a small one of which the backbarrier basin is oriented in the direction from which the tidal wave comes. With exception of the Pinkegat & Zoutkamperlaag systems and the Eilanderbalg & Zeegat van de Lauwers systems such inlets are not considered as separate inlet systems (see below). This causes basic case 5 in figure 9.2.2 to be relatively large. Smaller inlet systems such as the Pinkegat, Eilanderbalg and Wichter Ee have a tidal basin oriented against the direction of tidal wave propagation. Due to the reverse direction of the littoral drift along parts of the North Frisian coast many of these ebb-tidal deltas fall into basic cases 4 and 6. The overview reveals that of the larger inlet systems most are mainly oriented in line with the propagation direction of the tidal wave with ebb-tidal delta channels (slightly) oriented into the direction from which the tidal wave comes. This suggests that littoral drift is secondary to the development of the systems and hence to the orientation of ebb-tidal deltas.

To check this idea in more detail the classification proposed by Sha (1990a; Figure 3.2.2), dividing ebb-tidal delta inlets into oriented against the tidal wave propagation direction and with it (downdrift for Lower Saxony and the Netherlands), is shown in table 9.1. Comparing table 9.1 to Figure 9.2.1 indicates that, indeed, almost all of basic cases 2 and 4 basins (Niemeyer, 1990) have an orientation of the inlet channels (slightly) against the tidal wave propagation direction, with exception of Knude Dyb. This can be readily explained, because these are in general large backbarrier basins characterized by large tidal prisms. Given the generally small phase differences for most of the basins of the Dutch and Lower Saxonian coast between the coast-parallel tide and the tide coming through the inlet, the channels will orient against the tidal wave propagation direction. Phase differences might play a role along the North Frisian coast. Furthermore small basins of basic case 1 have ebb-tidal delta channels, which are oriented with the tidal wave propagation direction due to the relative large influence of the littoral drift for such small basins, confirming the ideas of Sha & van den Berg (1993). The exception is the Eilanderbalg, of which the orientation is likely forced by the orientation of the Zeegat van de Lauwers ebb-tidal delta, which is strongly oriented against the tidal wave propagation direction. The Knude Dyb is a relatively small system and may thus be forced by the littoral drift as well.

As for the symmetrical basins of basic case 5 most of the inlets and ebb-tidal deltas of the larger systems are oriented fully or partially against the tidal wave propagation direction, the only exception being the Norderneyer Seegat. The ebb-tidal delta channels of the smaller inlet systems of Schild and Blaue Balje, oriented with the direction of tidal wave propagation, just as those of group 1. The symmetrical Lister Dyb results in a symmetrical ebb-tidal delta.

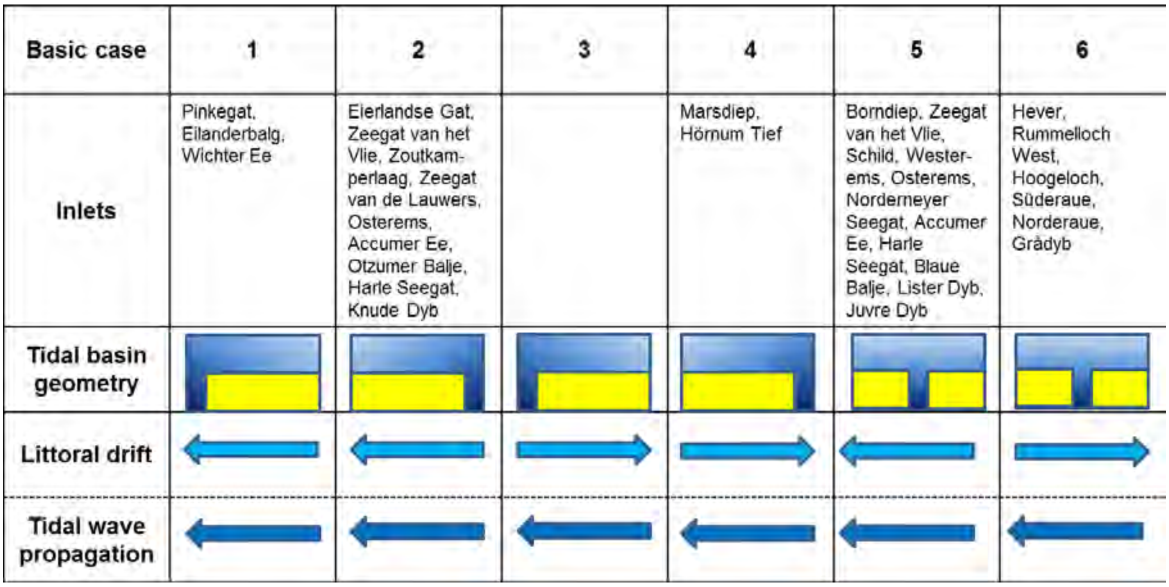


Figure 9.2.2 Classification of the Wadden Sea inlets following classification of Niemeyer (1990). Eierlandse Gat has no clear littoral drift direction.

Table 9.1: Orientations of the Wadden Sea ebb-tidal inlets.

Against tidal wave propagation direction			**With tidal wave propagation direction**	
Fully	***Slightly***	***Symmetrical***	***Slightly***	***Fully***
Marsdiep, Eierlandse Gat, Zeegat van het Vlie, Zoutkamperlaag, Eilanderbalg, Zeegat van de Lauwers, Westerems, Osterems, Accumer Ee, Harle Seegat, Süderaue, Hörnum Tief.	Borndiep, Otzumer Balje, Norderaue, Juvre Dyb.	Hever, Rummelloch West, Lister Dyb, Grådyb.	Norderneyer Seegat, Knude Dyb.	Pinkegat, Het Schild, Wichter Ee, Blaue Balje, Hooger Loch.

For group 6 the picture is less clear. Although it might be expected that all these basins would orient partially against the tidal wave propagation direction this is only visible for the Süderaue and the Norderaue. The Hooger Loch and Rummelloch West might be influenced by the flood currents towards the Süderaue. As for the Hever, the strong currents during the ebb might be an explanation for its symmetrical form. Also, phase differences might be part of the explanation (see Sha & van Den Berg, 1993), but data to confirm this were not available. The very symmetrical Grådyb system produces a very symmetrical ebb-tidal delta.

To resume: in general the tidal currents seem to dominate the development of the orientation of many of the backbarrier basins, especially in the West- and East-Frisian Wadden Sea, where the larger (part of the) basin is mostly oriented to the east, thus in line with the direction of tidal wave propagation. The mostly large tidal volumes of such basins seem to determine the orientation of the ebb-tidal deltas which are directed (slightly) against the tidal wave propagation direction. Ebb-tidal deltas of systems with a small tidal prism are relatively more susceptible to littoral drift and in general have downdrift oriented ebb-tidal deltas. The systems of basic case 6 (symmetrical backbarrier basins and tides in the opposite direction of the littoral drift) have less clear oriented ebb-tidal deltas.

Double inlets between two islands

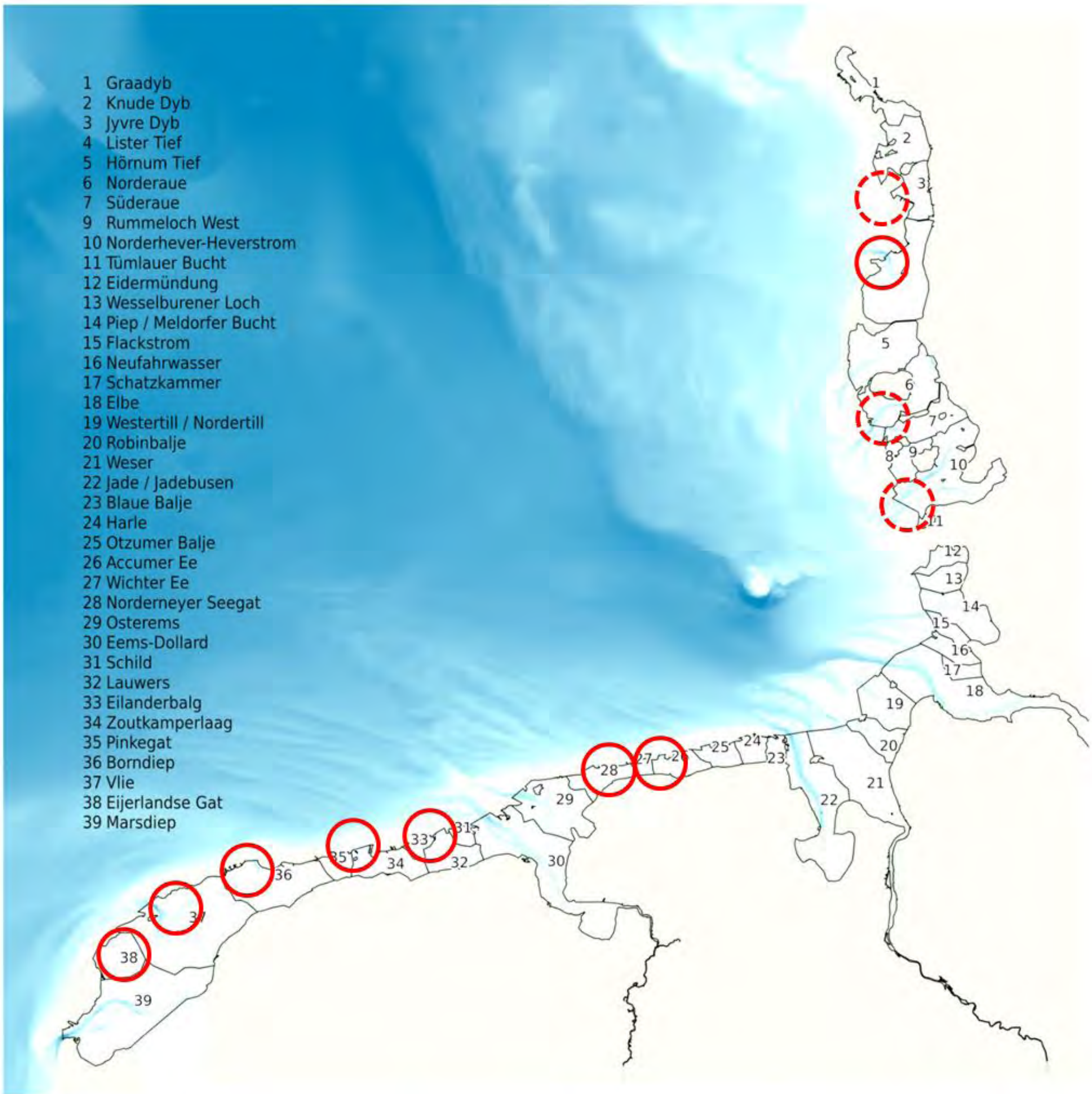


Figure 9.2.3: Overview of double inlet systems between two islands: broken circle: partly; closed circle: clearly.

It is important to realize that especially the smaller inlets or the separate, small, sub-inlet channels within an inlet are relatively strongly influenced by waves and longshore drift due to their relatively smaller tidal prisms (e.g. Pinkegat). Furthermore, smaller inlets and inlet channels can be influenced relatively strongly by shifts of their watersheds brought about by relatively small changes in the bigger systems at either side of them. This results in relatively large changes in tidal volume for the smaller systems, which may lead to strong changes in its channel orientations on the ebb-tidal delta. On top of that, such small systems are often characterized by strong internal dynamics leading to marked changes in tidal prism as is illustrated by the ca. 10% change of the Pinkegat system when it cyclically changes from a multiple to a single inlet. Due to this the related ebb-tidal delta (lobe) developments of such small systems may be highly dynamic. Knock-on effects can be generated which even may influence substantial parts of the inlet system (see below the case of the Norderneyer Seegat) for periods up to several decades. All in all, it may be concluded that the ebb-tidal deltas of smaller systems (both the small inlets such as Pinkegat and Eilanderbalg and the separate small western inlet channels which are part of a larger inlet system) are relatively sensitive to changes and can be highly dynamic over relatively short spans of time.

9.3 Hydrodynamic classification

Classification based on tidal range

Table 9.2 sorts the ebb-tidal deltas according to tidal range indicating that at present tidal ranges vary between 1.4 to 2.9 m. Figure 9.3.1 shows that the tidal range increases from W to E along the West and East Frisian coasts towards the inner German Bight and then it decreases again from S to N along the North Frisian coasts. It should be noted that in almost all tidal station near the coast an increase in tidal range can be observed over time (see the various tables per inlet). An unknown part is due to human interferences; another part might be due to ongoing sea-level rise which allows for a more pronounced tide in the North Sea (Franken, 1987; Van der Molen & De Swart, 2001)

Table 9.2: Sorting of the ebb-tidal deltas according to tidal range: yellow = lower mesotidal, orange = higher mesotidal.

Inlet	MTR (m)
Marsdiep	1,4
Grådyb	1,6
Eijerlandsche Gat	1,7
Lister Tief/Lister Dyb	1,7
Juvre Dyb	1,7
Zeegat van het Vlie	1,8
Knude Dyb	1,8
Borndiep	2,0
Pinkegat	2,0
Zoutkamperlaag	2,0
Hörnum Tief	2,1
Eilanderbalg	2,1
Zeegat van de Lauwers	2,1
Het Schild	2,1
Eems/Westerems	2,1
Norderneyer Seegat	2,5
Wichter Ee	2,5
Hooger Loch	2,5
Osterems	2,6
Accumer Ee	2,7
Otzumer Balje	2,7
Rummeloch West	2,8
Aue	2,8
Harle Seegat	2,9
Blaue Balje	2,9
Hever	2,9

As stated in chapter 3 barrier islands and ebb-tidal deltas can exist, up to 3.0 m tidal range, but it already becomes difficult at 2.7 m. Ebb-tidal deltas in the high tidal ranges above approximately 2.7 m, thus Harle Seegat, Blaue Balje, Hever, Rummeloch West and Süder Aue are all in the zone where a slight increase in range would be sufficient to theoretically end their existence (Compare figure 3.2.3 with figure 9.3.1). However, it should be realized that many of the island heads are enforced along the inlets and as such will, even after they are given up, probably exist for a long period. An example is the completely enforced islet of Minsener Oog. However, at the island tails enforcement is often lacking. This opens the possibility that elongate linear sand ridges might form, which process will destroy part of the island. Such a development might lead to less pronounced inlets and hence to the disappearance of the ebb-tidal deltas. Such a development might set off a chain reaction influencing the islands and the backbarrier coast. In this context the development the main Blaue Balje (but also the Harle Seegat, Hever, Rummeloch West and Süder Aue) might be interesting to study in more detail. The straight morphology of the backbarrier channel was initially introduced by dredging works (Wurpts, pers. comm.), but seems not to return to a meandering state. It would be interesting to see if it develops into an inlet system with linear sand ridges and no ebb-tidal delta.

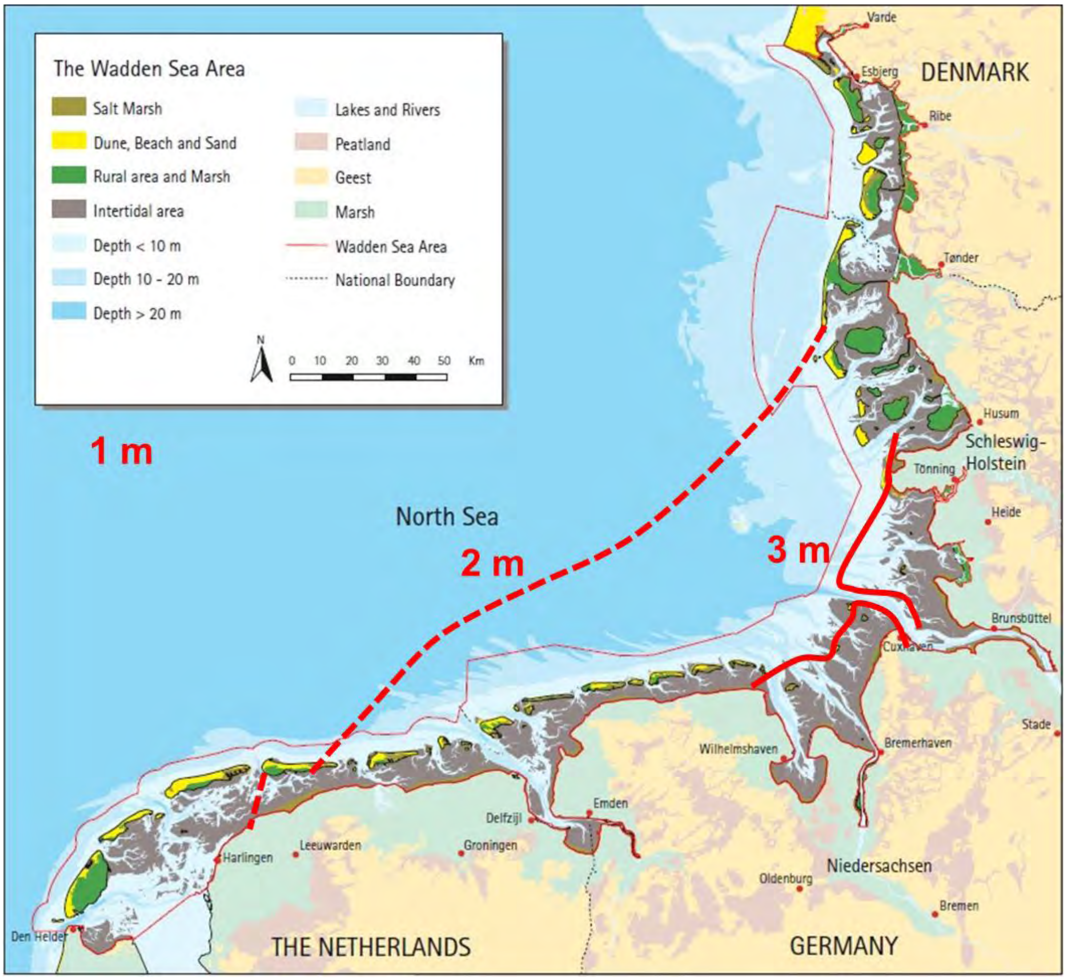


Figure 9.3.1: Overview of tidal range of the Wadden Sea area; comparing figure 3.2.3 with this figure indicates that ebb-tidal deltas near the 3 m tidal range are at the upper limits of the zone where they can exist.

Classification based on tidal range and mean significant wave height
Classification taking tidal range into account and the mean significant wave height, indicates that according to the classification of Davis Jr. & Hayes (1984) that three types of barrier coasts exist along the Wadden Sea (Figure 9.3.2; table 9.3), namely:

- Wave dominated coasts, with long continuous barriers, a few inlets and many washovers.
- Mixed energy coasts (wave dominant) are characterized by less long islands and more inlets and somewhat larger ebb-tidal deltas.
- Mixed energy coasts (tide dominant) are characterized by drumstick barrier islands many tidal inlets and larger ebb-tidal deltas.

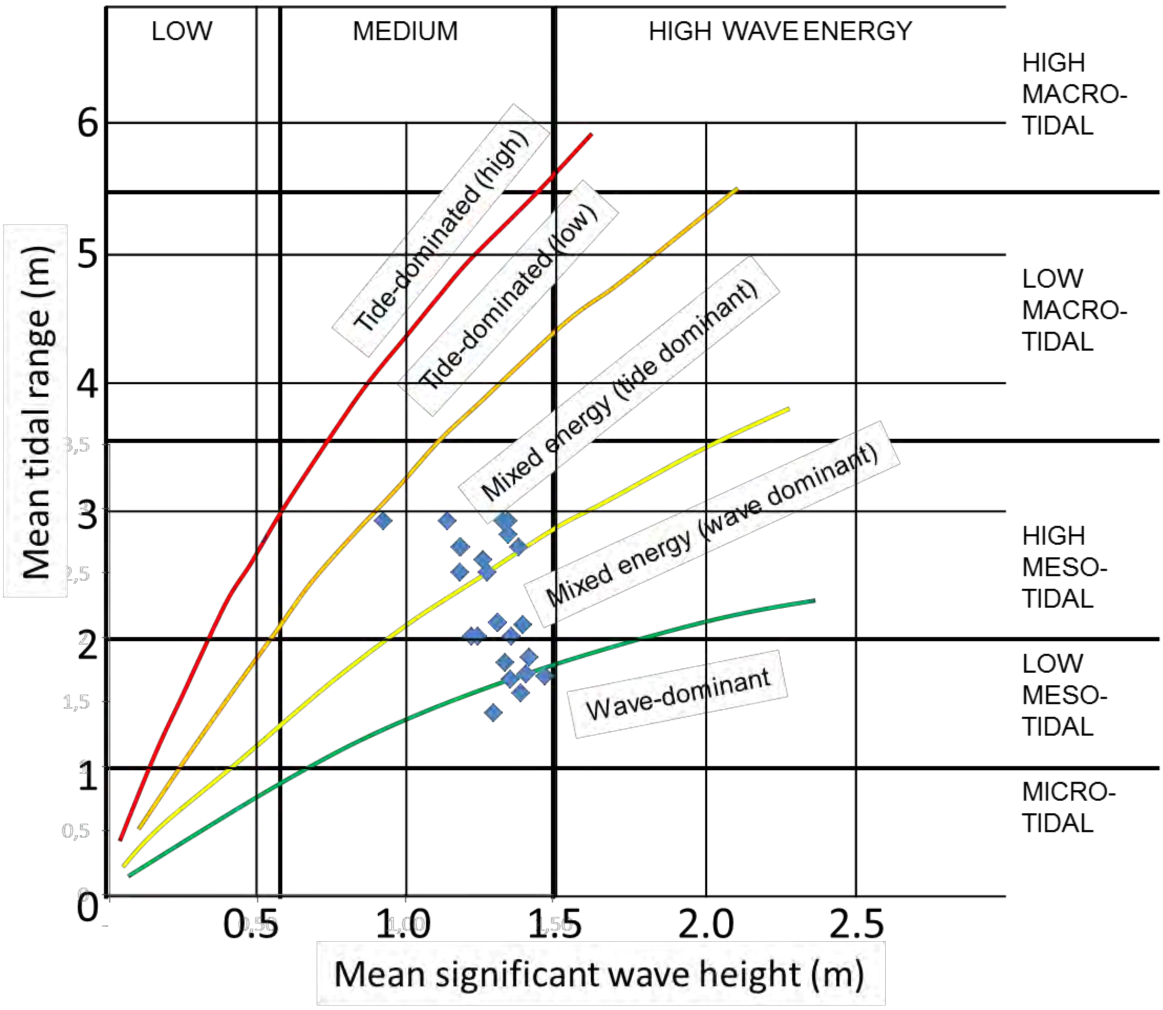


Figure 9.3.2: The Wadden Sea inlet system based on tidal range (mostly determined at open sea) versus offshore mean significant wave height (data: CoastDat diagram: Davis Jr. & Hayes, 1984). Mean significant wave height roughly increases going from S to N and from E to W, whereas tidal ranges increase from W to E along the coast of West and East Frisia and decreases again going from S to N along the coast of North Frisia. For the exact location of each system, please see table 9.3.

It will be clear from the overview that slight changes in tidal range or wave climate will, by and large, not bring about significant changes in the inlet systems of the Wadden Sea, possibly with exception of those in the >2.7 m tidal range (see above).

Table 9.3: Classification of the various ebb-tidal deltas, sorted on mean tidal range and then on mean significant wave height: green = wave dominated; yellow = mixed energy wave dominant; orange = mixed energy tide dominant.

Inlet system	Mean significant wave height Hs (m)	MTR (m)
Marsdiep	1,30	1,41
Grådyb	1,39	1,57
Eijerlandsche Gat	1,36	1,67
Lister Tief/Lister Dyb	1,47	1,7
Juvre Dyb	1,41	1,71
Zeegat van het Vlie	1,34	1,8
Knude Dyb	1,42	1,84
Zoutkamperlaag	1,22	2,01
Pinkegat	1,25	2,01
Borndiep	1,36	2,01
Hornum Tief	1,40	2,1
Eems/Westerems	1,31	2,11
Eilanderbalg	1,32	2,11
Zeegat van de Lauwers	1,32	2,11
Het Schild	1,32	2,11
Wichter Ee	1,19	2,5
Norderneyer Seegat	1,28	2,5
Osterems	1,26	2,6
Accumer Ee	1,19	2,7
Otzumer Balje	1,19	2,7
Norder Aue	1,39	2,7
Rummeloch West	1,35	2,8
Blaue Balje	0,93	2,9
Harle Seegat	1,14	2,9
Hever	1,33	2,9
Suder Aue	1,35	2,9
Hoogeloch	0,75	

Classification based on tidal prism

Sorting the inlets to tidal prism reveals that these range between 21 and 1000*10^6 m^3 (Table 9.4). Unfortunately there are not much ebb-tidal deltas with a sediment volume measurement according to the method of Walton & Adams (1976). However, from the available measurements it can be concluded that the general trend of increasing tidal prism and increasing sand volumes of the ebb-tidal delta is visible, be it with strong fluctuations. Also there are well described cases where, if tidal prism decreases/increases that the ebb current through the inlet decreases/increases and that the ebb-tidal delta becomes smaller/larger in sand volume. An example of such changes occurs after the closure of the Lauwers Sea embayment in 1969. As a result, the tidal prism of the Zoutkamperlaag inlet decreased from ca. 305 to $200*10^6$ m^3. In response the sand volume of the ebb-tidal delta decreased with some $26*10^6$ m^3 over the period 1970 to 1987 (Oost, 1995). Another case is the Otzumerbalje, where, due to natural developments, tidal prism increased as well as the ebb-tidal delta volume.

Many of the ebb-tidal deltas of the Wadden area have a lower sediment volume then might be anticipated based on tidal prism and the Walton & Adams' relation (Niemeyer et al., 1995; Ladage & Stephan, 2005; Meyer, 2014) although there are exceptions such as the Juvre Dyb. Another sign that the relation sand volume to tidal prism is not so clear-cut, is that many of the ebb-tidal deltas in the North Frisian Wadden area are comparable in size to the West Frisian ebb-tidal deltas which have bigger tidal prisms (compare Aue & Lister Dyb with Marsdiep & Vlie). This might imply that other equilibrium relations may prevail (Niemeyer et al., 1995), or that the ebb-tidal deltas are not in equilibrium conditions. A third alternative, namely that Walton & Adams-like relations are not so widely applicable (Elias, comm.), seems not so likely given the relations found by Niemeyer et al. (1995) for the East Frisian ebb-tidal deltas. Ladage & Stephan (2005) suggest that there are probably other factors which should, as well be taken into account. Possible factors might be:

- Geological structure of the subsurface

In the subsurface of especially the North Frisian area Pleistocene deposits are present in at shallow depths. It is likely that part of the channels follow older relief, especially old river valleys incised in Pleistocene deposits (Hofstede, pers. comm.), which might explain the observation that backbarrier channels are relatively straight, compared to the West and East Frisian area. The lack of meanders might well lead to fast outflow into the North Sea, which brings out sediments far into the North Sea and results in large ebb-tidal deltas. This might be the reason why North Frisian ebb-tidal deltas with a comparable tidal prism differ strongly in sediment volume (compare for instance Grådyb ($P=165*10^6$ m^3 and $S = 37*10^6$ m^3), to Juvre Dyb ($P=147*10^6$ m^3 and $S = 127*10^6$ m^3). Furthermore for the North Frisian area, the differences may partly be brought about by the fact that part of the area has only developed since medieval times and is, geo-morphologically speaking still young. Due to this a part of the systems might still not be in balance with the hydrodynamic conditions, leading to sediment export or differing sand volumes stored in the ebb-tidal deltas. *Research is recommended.*

- Influence of the configuration of the backbarrier area

Ridderinkhof et al. (2014a) concluded from numerical model studies that the length of the backbarrier area affects tidal prism, the amplitude and phase of the primary tide and its overtides, and the residual currents. Together these determine the magnitude and direction of net sediment transport and thus the sand volume of the ebb-tidal delta. In a comparable study numerical modelling studies found that in a long (short) backbarrier basin sediment transport is seaward (landward) directed and the associated ebb-tidal deltas have sand volumes that are relatively large (small) compared to the tidal prism (Ridderinkhof et al., 2014b). Ridderinkhof et al. (2014b) state: *".it is found that no unique relationship exists between tidal prism and sand volume of an ebb-tidal delta."* It should be noted, however, that the numerical modelling studies only have been done for basins with a small tidal flat to tidal channel width ratio (maximum 0.6); at the moment it is not certain how relations are for basins with a larger ratio (van der Vegt, pers. comm.). In the Wadden area ratios of 1 to 4 are common and for the large part of these there have been found relations between tidal prism and the size of the ebb-tidal delta (e.g. Niemeyer et al., 1995).

Table 9.4: Classification of the various ebb-tidal deltas on tidal prism; colours give various groups; inlets given in italics are situated along the North Frisian Wadden Sea coast.

Inlet	**Tidal prism backbarrier area (10^6 m^3) Pdis of Pmod of Pbat**	**Sediment volume ebb-tidal delta (10^6 m^3)**	**Net sedimentation ebb-tidal delta (10^6 m^3/yr)**	**Period**	**Net sedimentation back-barrier area (10^6 m^3/yr)**	**Period**
Hooger Loch	21					
Het Schild	32				See Lauwers	
Wichter Ee	35	10	0.5	1988/92-2004		
Blaue Balje	68					
Eilanderbalg	70				-0.3	1990-2002
Pinkegat	100		0.4		0.3	
Harle Seegat	104	23	-0.7	1964-2001		
Otzumer Balje	124	38	1.1	1988/92-2004	Ca. 0.1	
Juvre Dyb	147	127	-1.5	1970-2001	-0.3	1970-2001
Zoutkamper-laag	151		-1.5		2.6	
Knude Dyb	153				-0.1	1966-2003
Grådyb	165	37	-0.2	1967-2002	<-0.2	1967-2002
Rummeloch West	172				0.1	1990-2000
Accumer Ee	175					
Norderneyer Seegat	183	54	0.6	1990-2004/6		
Eijerland-sche Gat	205	130	-0.8	1990-2005	-0.2	1990-2005
Zeegat van de Lauwers	208				0.2	1990-2002 (incl. Schild)
Borndiep	383	121	-0.4	1990-2005	1.4	1990-2005
Osterems	523				0	1990-2004/5
Hörnum Tief	528	397	-3.6	1959-1994		
Lister Tief/Lister Dyb	627	300			<-1.3	1968-1994
Hever	881				3.8	1990-2000
Aue	883				-1	
Zeegat van het Vlie	934	355	-1.8	1990-2005	3.5	1990-2005
Marsdiep	991	489	-3.6	1990-2005	-1.3	1990-2005
Eems/Westerems	1000				4.7 (3.9-5.7)	1985-2002

- Influence of sediment deficit of the backbarrier area

It can be assumed that an extremely large sediment demand in the backbarrier basin (closure of tidal embayments, after which remaining tidal channels become (partially) abandoned; massive sand mining works) may increase the trapping efficiency of the backbarrier basin for sediment which is imported and may influence the size of the ebb-tidal delta. An example can be found in the decrease of sand volume of the ebb-tidal delta occurred after the closure of the Zuiderzee embayment. By the closure, the tidal amplitude in the basins W of the watershed of Borndiep increased due to tidal amplification. As expected by Lorentz (1926), the tidal prism of the Marsdiep increased: in the period 1916-1967 from 890 to 1066*10^6 m^3. Based on the relation of Walton and Adams (1976) it might be expected that an increase in sand volume of the ebb-tidal delta would follow. This did not happen. The sediment demand in the backbarrier areas of Marsdiep and Vlie combined may reach ca. 1500*10^6 m^3 (Wang et al., 2013), so that sediment can be trapped rather efficiently in the backbarrier basins. On top of that phase shifts between the coast-parallel tides and the horizontal and vertical tides coming from the backbarrier basin may have increased imports (Ridderinkhof et al., 2015a&b). Some 253*10^6 m^3 of sediment were transported into the backbarrier area of Marsdiep between 1935 and 1990, or 4.6*10^6 m^3/yr (Elias et al., 2012)With a coast-parallel drift transport of the order of 0.2*10^6 m^3/yr (Ridderinkhof, 2016), it can be expected that net erosion occurs of the ebb-tidal delta. Indeed, in the same period 245*10^6 m^3 has been removed from the ebb-tidal delta, or 4.5*10^6 m^3/yr (Elias et al., 2012). A comparable development was observed for the Vlie tidal inlet system's ebb-tidal delta (Elias et al., 2012). A sign that also other ebb-tidal deltas might be out of balance due to sediment losses is the observation that out of the 13 ebb-tidal deltas of which sediment budget changes are known, 9 of them are losing sediment, which apparently is not compensated by littoral drift. Furthermore 9 out of 16 backbarrier areas have in recent times been accumulating sediment.

- Changing channel patterns and knock-on effects

Changing channel patterns over the ebb-tidal delta may bring about rather complicated chain reactions of knock-on processes on the ebb-tidal delta, as is illustrated by the development of Norderneyer Seegat. The ebb-tidal delta was rather compact up to the 70-ies. In the period 1975-1990 the tidal prism of the inlet increased from ca. 181 to 195*10^6 m^3, mainly by taking over part of the Osterems inlet drainage area and becoming deeper at its west side. Tidal water exchange thus especially increased at the western inlet channels (esp. via Kalfamergats), which became wider and deeper, leading to shoal erosion. The strong erosion by channels contributed to the sediment loss on the ebb-tidal delta (below NN -4m; Meyer, 2014). The concentrated tidal water exchange at the west side of the inlet system (via Kalfamergats), resulted in a strong seaward extension towards the NNW in the period 1983/84-1992 so that the channel cut through the Riffbogen. Contemporaneous lowering of the backbarrier tidal flats occurred (Meyer & Stephan, 2000; Meyer, 2014), perhaps due to increased wave penetration, as is suggested by the lowering E of the Busetief channel, along the line of the ebb-tidal delta channel of the Kalfamergat. This must locally have led to a further increase in tidal prism. The cutting of the Riffbogen hindered the development of shoals at the outer rim of the delta. The smaller shoals were no longer able to push the main inlet channel (Norderneyer Seegat) to the NE and it shifted towards the NW. Also, the merger point of the shoals with the barrier island Norderney seems to have shifted towards the E after 1975 (Meyer & Stephan, 2000). Despite new shoals forming on the west side of the Norderneyer Seegat and a shift of this channel to the N in the period 1992-2008 the shoal merger point stays situated more to the E then before 1975 which might be attributed to the elongating of the main channel (Bremermann & Meyer, 2012; Meyer, 2014). Comparable influences have been observed in the Pinkegat-Zoutkamperlaag system (Oost et al., 2014).

- Storm surge frequencies

For the North Frisian coast it seems likely that the coast has been influenced by erosion due to the increase in storm surge frequency between the early sixties and the mid-nineties (Figures 7.1.5 & 7.1.6), as was described in some detail for the Hörnum inlet. Arguments for this idea are:

1) the increase in storm surges was not a local phenomenon restricted to Hörnum inlet and therefore likely to have influenced a large part of the North Frisian coast;
2) the coast between Hever and Aue (Außensande) retreated twice as fast in the period 1965/67-1991 then in the period 1947-1965/67 and as a result part of the backbarrier was eroded as well; (Hofstede, 1993);
3) the 3 known sediment balances for ebb-tidal deltas are all negative;
4) the 7 known sediment balances for backbarrier areas along the North Frisian coast are all negative with exception of Hever (of which part was reclaimed, leading to infill of the backbarrier channels) and Rummeloch. In most cases basins are sedimentating on the intertidal area (Heverstrom, Norderhever, Rummelloch West, Hooger Loch and Süderaue in the period 1936-2000; van Riesen & Winskowsky, 2007). It indicates that erosion is mainly restricted to the channels, which might be attributed to stronger ebb-currents (Hörnum Tief; Hofstede, 1999b) and landward retreat of the inlet mouths;
5) The barrier of Amrum was eroded which has been partially attributed to the lowering of the ebb-tidal delta of the Hörnum inlet.

It suggests that an increase in storm surges may lead to erosion of ebb-tidal deltas and the backbarrier areas. It should be remarked that the only part which has been studied in detail and related to storm surges is the Hörnum inlet, whereas erosion has been studied in detail of the Außensande. Most of the other observed erosional trends in the other inlets are weak and probably insignificant in themselves. *Additional studies are recommended.*

Classification according to littoral drift and tidal prism

The ratio of tidal prism to drift is given for the larger part of the inlets (table 9.5). Sometimes littoral drift was calculated to be 0 and hence no ratio could be calculated. It reveals that there are three groups present in the Wadden Sea:

$20 < r < 50$: sediment transport takes characteristically place via bar-by-passing where bars move over the ebb delta fringe

$50 < r < 150$: sediment transport takes characteristically place via both bar by-passing and flow by passing. Bars near the entrance are still pronounced.

$R > 150$: sediment transport occurs predominantly by tidal flow bypassing (bars are small and there is a good flushing of the inlet).

The findings are more or less in agreement with the observation that many of the ebb-tidal deltas have a Riffbogen characterized by shoals moving over the delta platform in especially the inlets with a smaller tidal prism and those of the West and East Frisian inlet systems. Also, the somewhat bigger systems are characterized by shoals for some of the time while in other periods more clear-cut bars and channels appear. However, it is felt that from the third group up to Borndiep the ebb-tidal deltas would better fit into the middle group.

In this chapter it has been shown that the ebb-tidal deltas along the Wadden Sea coasts are characterized by a huge variability in their morphological and hydrodynamical characteristics and that they are to be understood in relation with the external influences and the hydromorphology of the related backbarrier basin and adjacent islands and inlet systems. In general it can be stated that there are marked differences between the North Frisian and the West and East Frisian systems.

Table 9.5: ratio tidal prism versus littoral drift; Colors give the three groups.

Inlet	**R = Prism/Drift**
Het Schild	**27**
Wichter Ee	**29**
Eilanderbalg	**54**
Blaue Balje	**68**
Pinkegat	**71**
Harle Seegat	**104**
Zoutkamperlaag	**108**
Otzumer Balje	**113**
Norderneyer Seegat	**141**
Accumer Ee	**146**
Zeegat van de Lauwers	**160**
Grådyb	**275**
Borndiep	**383**
Lister Tief/Lister Dyb	**570**
Hever	**629**
Aue	**631**
Osterems	**654**
Juvre Dyb	**735**
Eems/Westerems	**909**
Hörnum Tief	**1320**
Zeegat van het Vlie	**2335**
Marsdiep	**4955**

10 Climate change and ebb-tidal deltas

10.1 Introduction

Here, as part of the study requested, a short overview is provided of the insights on climate change and possible related effects for the Wadden Sea area as far as relevant to ebb-tidal deltas in paragraph 10.2. In paragraph 10.3, it will be discussed to what extent ebb-tidal deltas might be influenced by these changes.

10.2 Climate change general

Global climate change

In 2014, the Intergovernmental Panel on Climate Change (IPCC, 2013, 2014) stated in its Fifth Assessment Report (AR5) that "Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea-level rise, and in changes in some climate extremes [.]. This evidence for human influence has grown since AR4. It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century." (IPCC, 2014; Figure 10.2.1; Clark et al., 2016).

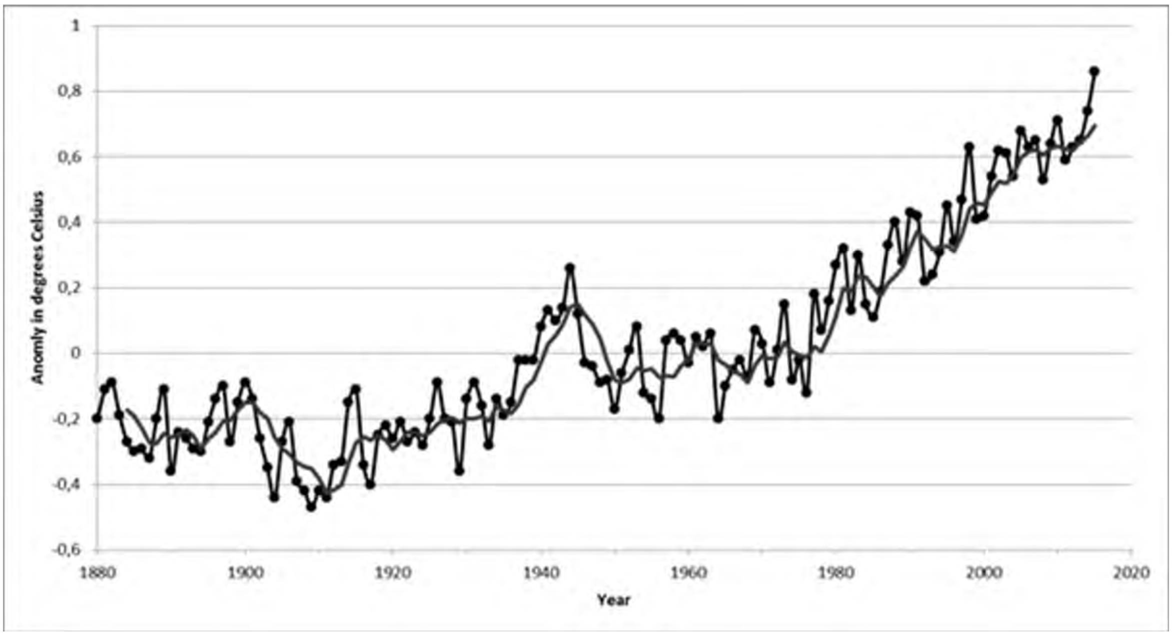


Figure 10.2.1: Global mean air temperature changes 1880-2015, relative to the mean temperature 1951-1980 with 5 year running average (Source data: http://data.giss.nasa.gov/gistemp/graphs_v3/).

Local changes Wadden Sea area: general

The IPCC's AR5 projections of global climate change have been translated to local climate scenarios (for instance KNMI'14). The Danish, German and Dutch local climate scenarios and sea-level rise projections differ somewhat in their ranging and use different periods of the past to compare results. For comparison several climate scenarios are given in Appendix II. For storm surges and wave climate the major part of the information is derived from Weisse et al.

(2012). In general the following paragraphs discuss the general pattern using the projections which give the widest range.

Local changes Wadden Sea area: Sea level changes
In 2014 KNMI projected sea-level developments for the North Sea basin, taking many physical processes into account (Figure 10.2.2; Appendix II; KNMI, 2014). Most extreme local projections are from DMI (2014) which predict a sea-level rise in 2071-2100 relative to 1986-2005 of 34 cm (10 to 60 cm) to 61 cm (30 to 90 cm)[4].

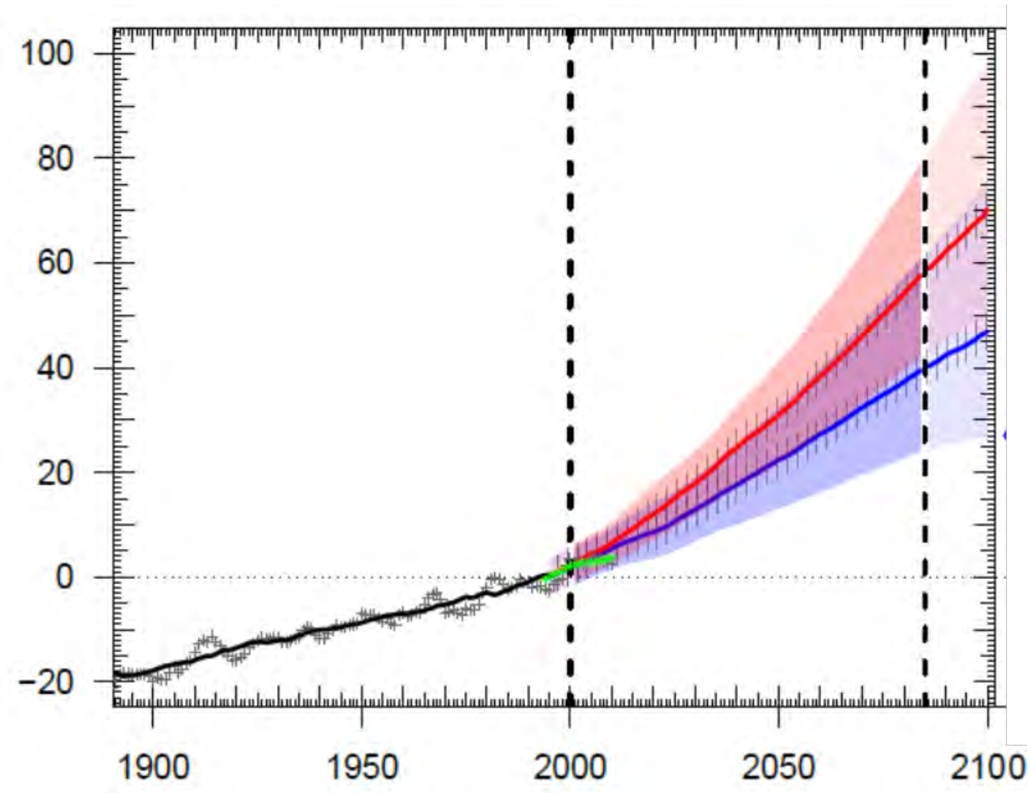


Figure 10.2.2: KNMI'14 scenarios for North Sea basin mean sea-level rise and its likely range, relative to 1986-2005 mean. Observational data consists of the average of 6 stations in The Netherlands. The green symbols indicate the 5-year running means obtained from satellite altimetry (1993-2013) over the North Atlantic, with respect to 1993-1998 (source observations: Permanent Service for Mean Sea Level, http://www.psmsl.org). For years before 2000 and beyond 2085 (vertical dashed line), the mean was taken over a smaller window and is therefore drawn in a different shading. Natural variability at 5-year time-scale is included in the range and also shown as vertical bars. The black line denotes the 30-year running mean through the observations (1890-2009), symbols denote the 5-year running means. Observational data: PSMSL database (Church & White 2011; KNMI, 2014).

However, more extreme projections also exist (Katsman et al., 2011). Recently KNMI (2017) even gave values of 2.5-3 m as the high end projection for 2100. New insights suggest that increasing temperatures due to continued high greenhouse-gas emissions over the next dec-

[4] *On top of sea-level rise subsidence due to isostasy (order 0.3 mm/yr) and, after 1950, mining activities and water-management works (several mm/yr; Kooi et al., 1998; CPSL, 2005; Katsman et al., 2008) and peat subsidence (up to 10-20 mm/yr) should locally be added.*

ades may lead to an unstoppable collapse of West-Antarctica's glaciers (Joughin et al., 2014; Pollard & De Conto, 2015; McMillan et al., 2015). Research is ongoing.

Local changes Wadden Sea area: Wind, storms, wave conditions & storm surges
Windiness (climate of mean wind), storminess (climate of high winds), wave conditions and related storm-surge conditions along the Wadden Sea have shown pronounced, highly correlated inter-annual and inter-decadal variations during the 20th century, of which the driving forces are not yet fully understood (Alexandersson et al., 2000; Hofstede, 2007; Wang et al., 2009; Bakker & van den Hurk, 2012, KNMI, 2014). As for wind direction: for the period 1948-2007 the share of westerly winds increased in the late winter and early spring, the number of N to NW winds is not changing (Van Oldenborgh et al., 2009). Any projected future changes ought to be considered in combination with these natural fluctuations.

Windiness, storminess and wave conditions were high at the beginning of the 20th century, decreased towards the mid-century and rose until the beginning of the 1990s, when a maximum was reached, after which they sharply declined over the North Sea by the end of the 20th century (Figure 10.2.3; Flather et al., 1998; Langenberg et al., 1999; Schmidt, 2001; Chang & Fu, 2002; Weisse et al., 2002, 2005, 2012; Matulla et al., 2007; Bakker & van den Hurk, 2012; KNMI, 2014). This is in agreement to the findings of Chang et al. (2012) for the Northern Hemisphere. There is no discernible trend over the whole period of 140 years (Weisse et al., 2012; KNMI, 2014). Analyses of a time series for the period 1843-2006 (Cuxhaven) reveal that extreme sea-levels have increased over more than 150 years due to mean sea-level rise with the above discussed variations superimposed (Weisse & von Storch, 2009; Weisse et al., 2012).

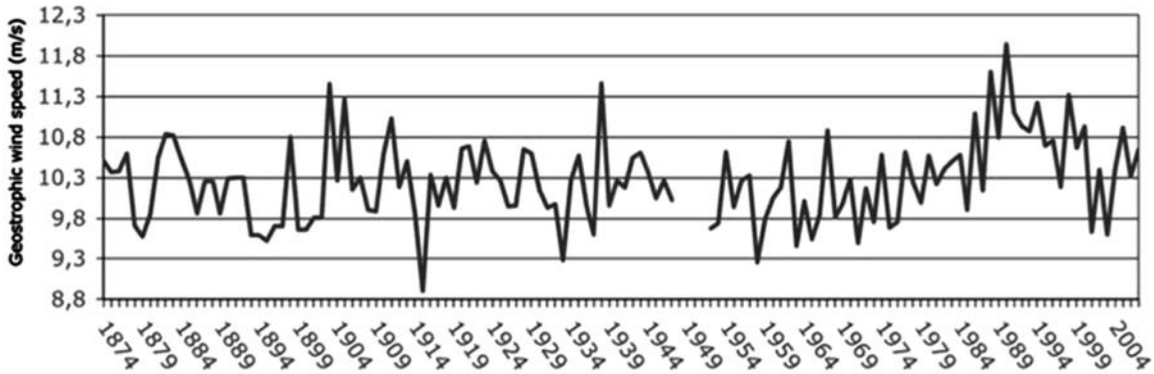


Figure 10.2.3: Annual mean geostrophic wind (as a measure of windiness) for the pressure triangle Aberdeen-Thyborøn-De Bilt, which covers the whole North Sea (Sterl et al., 2015).

Results from climate model studies suggest no statistically significant changes in long-term mean wind conditions, low wind conditions and extreme wind speeds, with natural variability being large and dominant for the century to come for the Wadden Area (Chang et al., 2012; KNMI, 2014; Sterl et al., 2015). The atmospheric wind and pressure fields projections have a high degree of uncertainty resulting in high uncertainties in the projection of storm surges (e.g. 1/50 year storm surge height around 2100 increasing with 0-70 cm (Lowe & Gregory, 2005; Woth, 2005; Woth et al., 2006; Christensen et al., 2007; Debernhard & Roed, 2008; Sterl et al., 2009; for underlying causes, see: Weisse et al., 2012). High resolution models, moreover, suggest that within estuaries and narrow bays of the Wadden Sea the projected changes show a stronger climate change response than open North Sea, but with large uncertainties (Woth et al., 2006; Figure 10.2.4). Furthermore, models point to an increase in frequency of extremes coming from westerly directions (KNMI, 2014; compare also: Bengtsson et al., 2009), which may result in an increase in impact on the N-S oriented coasts of the Wadden Sea and a decrease for the E-W oriented coasts. Most extreme wave heights may increase towards the end of the 21st century, especially in the German Bight, but the magnitude and the pattern of these changes are highly variable and uncertain (Weisse et al., 2012).

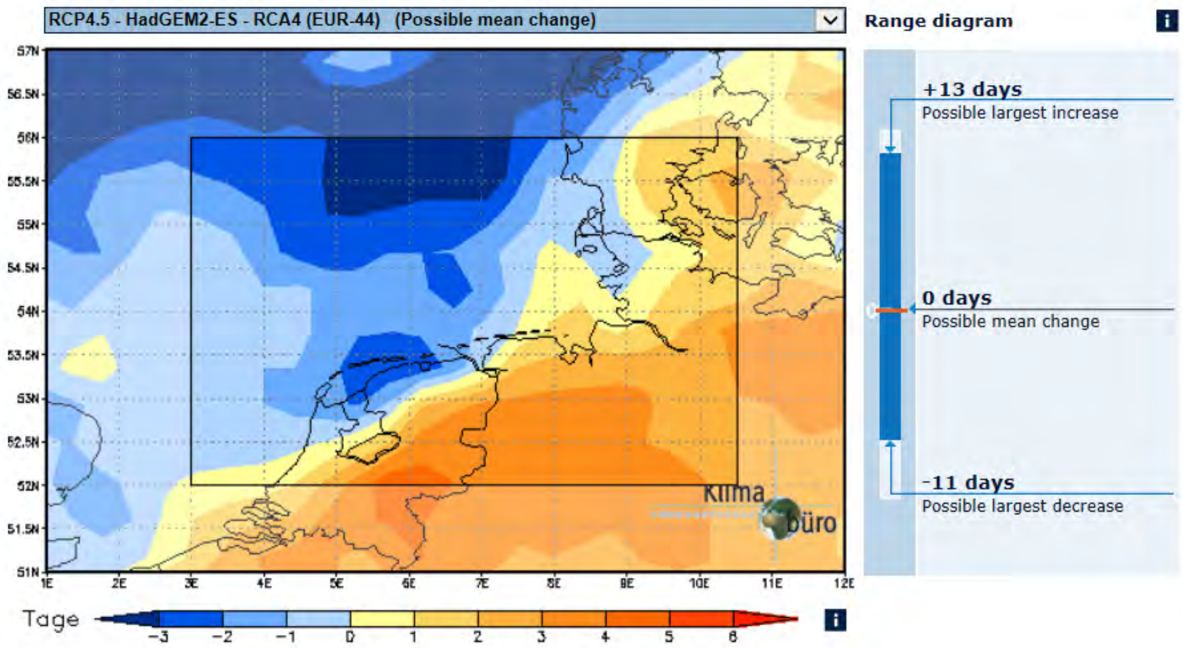


Figure 10.2.4: Possible mean change of the annual stormy days until the end of the 21st century (2071-2100) compared to today (1961-1990).
http://www.coastalatlas.org/coastalatlas/2071-2100/year/stormy-days/wadden-sea-region/mean-change.html

High-resolution atmosphere-only model runs suggest that in a warmer climate, tropical cyclones might reach the North Sea, leading to very high wind speeds (Bf 11 and more) as early as September (KNMI, 2014). The results are still uncertain and research is on-going.

From several tide-surge model simulations it appears that as a first order approximation, changes in mean high water level will lead to an exponential rise of storm surges (Sterl et al., 2009; Howard & Lowe, 2010; Weisse et al., 2012), implying that for a fixed height of the land the number of storm surges flooding the area would increase considerably upon a rise in MHWL (Figure 10.2.5).

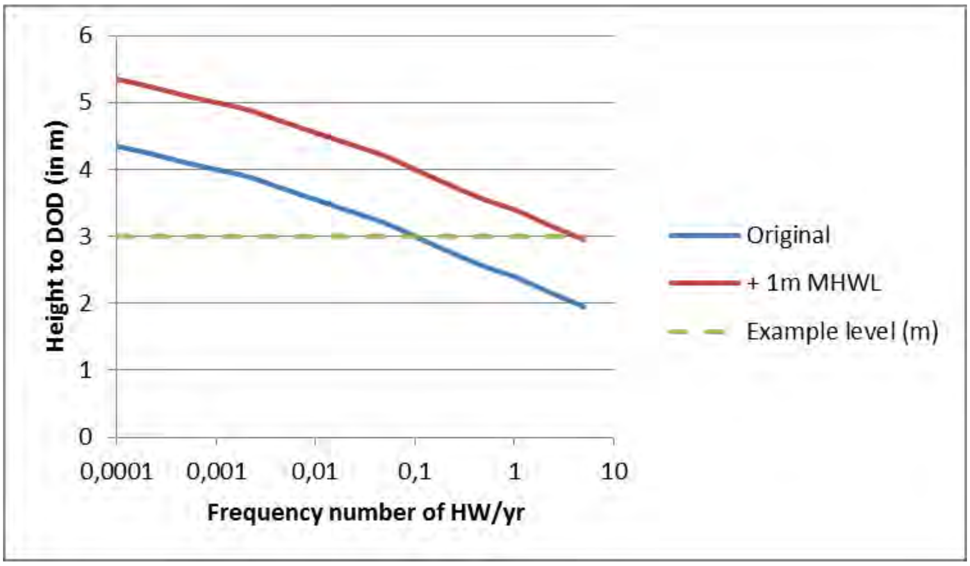


Figure 10.2.5: Hypothetical effect of a 1 m mean high water level (MHWL) rise on the storm surge frequency for West-Terschelling. For areas with a height of +3 m Dutch Ordnance Datum, the number of storm surges reaching this level would increase by a factor of ca. 50. Note that in reality the effect might be more severe due to the increase in water depth in the North Sea.

10.3 Impact climate change on ebb-tidal deltas

Introduction

Ebb-tidal deltas have to be understood as an integral part of the tidal basin dynamics linking them to the outer system in terms of water and sediment supply and controlling the way sediment is distributed along the coast. The ebb-tidal deltas function as a filter to the backbarrier for outside influences. These outside influences and the influences exerted by the backbarrier basin and by the adjacent inlet systems and the geology, together determine the development of the morphology of the ebb-tidal deltas.

The strong changes which have been observed to occur over the time span of only a decade imply that the ebb-tidal deltas are quite dynamic as might be expected given the fact that they are influenced by tides along the coast and through the inlet, as well as waves, storm surges and changes in the morphology of the backbarrier area. Changes in internal or external drivers may bring about changes in the ebb-tidal deltas which in several cases (Norderneyer Seegat, Marsdiep, Zoutkamperlaag, Hörnum Tief, and Grådyb) have proven to be of influence on the barrier islands or the backbarrier area. Here the effect of changes in external drivers related to climate change is discussed.

Sea-level rise

Due to sea-level rise the tidal wave can propagate more easily through the North Sea basin leading to an increase in tidal amplitudes (Van der Molen & de Swart, 2001). As discussed in chapter 9 ebb-tidal deltas currently in the tidal range zone of approximately more than 2.7 m are in the zone where they might develop into inlets with linear sand ridges and no clear ebb-tidal deltas. For these ebb-tidal deltas it may become more difficult to continue to exist.

Sea-level rise can also become a problem for the morphological development for the Wadden Sea at large, because basically the area (up to the -20 m line) is receiving almost no sand from outside: it is a closed system, with exception of a relatively small littoral drift contribution. It is known that the backbarrier responds to increases in sea level (MHW) and channel abandonment due to closure works and to subsidence by mining (e.g. sand or gas) by importing more sediment. The annual sediment import is limited as can be concluded from the import in Marsdiep and Vlie after the closure of the Zuiderzee: the “sediment demand” is estimated to be of the order of $1500*10^6$ m^3, but sediment import was only of the order of $6*10^6$ m^3/yr. Due to the limitations to net sedimentation some of the tidal flats may start to drown within this century, although resilience might be higher than previously assumed for some basins (Hofstede, 2002; Kragtwijk et al., 2004; Van Goor et al., 2008; Oost et al., 1998, 2014; Waddenacademie, in prep.). Also, fines may contribute to the preserving of mud flats in the backbarrier basin (see van Ledden, 2003). Drowning would lead to an increase in tidal prism, which may lead to changes in size (tendency to increase in sediment volume), orientation of the ebb-tidal delta (tendency to reorient towards the direction the tide is coming from) and position of ebb-delta channels.

The sand needed for backbarrier sedimentation will be derived from the North Sea coasts and ebb-tidal deltas (CPSL, 2001, 2005, 2010). If the sediment import to the backbarrier area is more than can be replenished by the littoral drift, ebb-tidal deltas will most likely erode and become smaller. Indeed, this has been observed for the ebb-tidal deltas of Marsdiep and Zeegat van het Vlie. At first sight such developments seem at odds with the relations between tidal prism and sediment volume of the ebb-tidal deltas as for instance found by Niemeyer et al. (1995). However, it should be realized that under natural conditions barrier island coasts are allowed to retreat along with the ebb-tidal delta. Due to this the ebb-tidal delta volume with reference to the (retreating) coast line can remain stable or even grow (See also box 4.1), while at the same time delivering sand to the backbarrier area. Nowadays the barrier island coast position is fixated, but the ebb-tidal delta is not fixated and can still be eroded. If longshore drift does not replenish the lost sand the ebb-tidal delta will become smaller in terms of sand volume. Small ebb-tidal deltas (small available sand volume) in combination with large tidal basins (large sediment demand), such as Grådyb are probably more sensitive than the reverse situation, such as Juvre Dyb.

Furthermore shelter to the barrier coasts and the backbarrier area may change due to the erosion of ebb-tidal deltas. On the largest scale of the inlet system, the high shoals on the protrusion formed by the ebb-tidal delta shelters the backbarrier area and the downwind coast from wave penetration. As such, the island head and the dune arc on it may be considered to result from the shelter and sand supply provided by the ebb-tidal delta (Figure 10.3.1). If the ebb-tidal delta becomes smaller it may be assumed that also the protective function is less extensive and more wave energy will reach the coast. That effects can be quite strong is probably illustrated by the fast erosion over more than 1 km of West-Vlieland in the 16th & 17th century, after the collapse of the ebb-tidal delta (as was stated by contemporaneous sources; Abogado Rios, 2009). It should, however, be realized that under present-day conditions especially the inhabited areas of the barrier islands are no longer allowed to retreat and are kept in place by nourishments and protection works if possible (Oost, 2012; Oost et al., 2012).

To what extent the shelter provided by the ebb-tidal deltas for the barrier coast and the backbarrier will change, will depend on the exact location of the erosion and to what extent channels and shoals develop. Some erosion in deeper water will mostly not be very significant, whereas erosion in the swash zone might strongly alter shelter. Furthermore, changes in channel and shoal configurations can strongly alter the hydrodynamic conditions near the coast and lead to erosion (e.g. Marsdiep). For the backbarrier area wave penetration may lead to erosion of shoals and a widening of the tidal channels in the vicinity of the gorge of the inlet. The developments in the Norderneyer Seegat indicate a knock-on effect in the period 1975-1990 in the lowering of tidal flats and widening of channels in the Kalfamergat-Busetief system (Chapter 9). From those observations it can be concluded that resulting changes in the backbarrier may happen fast and may lead to strong decrease of the shoal heights at least near the gorge of the inlet.

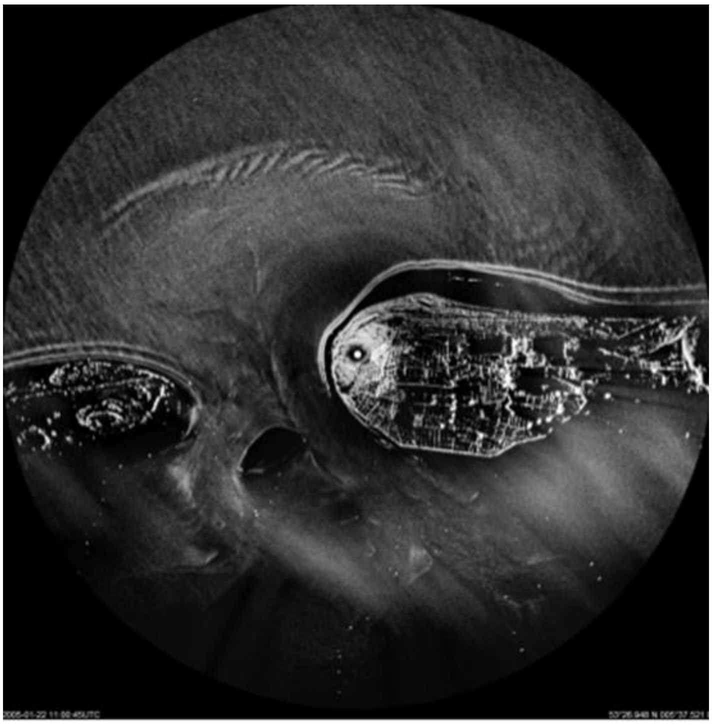


Figure 10.5.1: Radar image of the ebb-tidal delta of Borndiep W of Ameland and the island head. Please note that the dune arc and the western part of the island are lying in the shelter of the ebb-tidal delta as can be observed from the wave patterns.

As stated above, upon an increase in tidal prism the orientation of the main ebb-tidal delta channel may change towards the direction where the tidal wave comes from. A strong shift in orientation of the main ebb-tidal delta channel will result in changing morphology of the ebb-tidal delta and changes in the hydrodynamic conditions on the ebb-tidal delta. Such developments may have a considerable impact on the barrier coasts and the backbarrier area. This was, for instance, observed during the 19-20th century reorientation of Marsdiep ebb-tidal delta, which strongly shifted towards the SSW, and the development of the coast-near Molengat channel. The new hydrodynamic conditions resulted in retreat over 1.5 km of SW Texel, N of the ebb-tidal delta. At the same time large ebb-tidal delta channels were forming along the W coast of the northern part of North Holland, thus steepening the coastal profile and leading to coastal erosion.

Furthermore, the position where merger of bars will take place may shift and sediment deliverance to the islands may decrease, making adjustments of coastal defence necessary (see also, Oertel, 1977). Reduction of sediment supply over the ebb-tidal delta is, however, not entirely certain. It seems likely that larger dimensions of the promontory formed by the ebb-tidal delta will result in larger sediment supplies to the downdrift coast. However, it also generates a stronger eddy at the downdrift coast which results in a reverse sediment transport

(Sha, 1990a) and even coastal erosion (Elias, 2006). The resulting net transport is unclear. *Studies into this aspect are recommended.*

At the moment there seems to be no insurmountable problems along the Wadden coasts due to changes in ebb-tidal deltas. However, if sediment demand increases in the sediment sharing inlet systems it is plausible that the ebb-tidal deltas will retreat faster, comparable to the Marsdiep inlet. At the same time the island coasts are not allowed to retreat. This might result in larger nourishments along the barrier islands. At some places sufficient large nourishments are already difficult to place into the rather small coastal profile (West Ameland); an increase of nourishments would make the problem worse. Also, the costs may increase due to more nourishments and more stone protection works. To tackle eventual future problems and look for even more cost-effective solutions, alternative locations and volumes of sand nourishments might be considered. 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 form. For example, mega-nourishments and closures of an ebb-tidal delta outer-channel are being given thought (Elias et al., 2012b; de Ronde & van Oeveren, 2013). However, it is concluded that the present knowledge is insufficient to carry out such measures without risks. Especially knowledge on system behaviour over the medium term (1 to 25 years) is insufficient. Predictive models for this would greatly benefit from datasets for validation, including data on discharge, currents and waves (de Ronde & van Oeveren, 2013). Currently research is ongoing and measurements are taken in the ebb-tidal delta of Ameland (Coastal Genesis II).

Wave conditions

Even when the number of storm surges would not change, their impact would increase with rising sea-levels if bed levels would not keep up with sea-level rise. Decreases in ebb-tidal delta size and/or insufficient rise of the bed levels along the coast will result in the coast and backbarrier area receiving more wave and storm surge energy. As can be noted from extreme storm surges (e.g. 1976, Otzumer Balje) this will imply that the inlet systems and their ebb-tidal deltas will be brought “out of balance” more often.

Furthermore, changes in wind direction or wind speed may lead to a higher or lower energy exerted on the ebb-tidal delta. It is difficult to assess what will happen. If the fair weather wave base becomes deeper most likely more of the ebb-tidal delta platform will be governed by swash bar formation and the character of the ebb-tidal delta might become more bypassing in character. Depending on the exact nature of sediment transports over the ebb-tidal delta this might lead to extra formation of inter- to supratidal shoals on the ebb-tidal delta platform; this provides extra shelter for the backbarrier area.

If storm surges become more frequent the ebb-tidal delta platform could become deeper. In general a lowering of the ebb-tidal delta shoals will result in less shelter and waves might penetrate deeper into the backbarrier area or larger waves might reach the barrier coasts. Lowering of the ebb-tidal delta shoals has been observed in Hörnum inlet, Schleswig Holstein (Hofstede, 1999b). Erosion of the backbarrier island Amrum due to extra wave-attack is likely partly attributed to that (Hofstede, pers. comm.). Sediment loss or deepening with respect to rising MHW occurs in most of the backbarrier areas from Hörnum Tief up to Grådyb. This might be a sign that the problem is not restricted to Hörnum Tief alone. *A more detailed comparative research is recommended.*

A broader angle over which waves come in from the open North Sea onto the island’s coast does not automatically lead to stronger erosion: locally waves from the new directions may counter the sediment loss by the waves coming from the old directions. This is for instance illustrated by the coastal erosion resulting from the northward expansion of a shoal along the coast of south Texel (Cleveringa, 2001). Also here, present-day insights and modelling tools lack in capability to predict if and where erosion will increase (see also Elias et al., 2012b; de Ronde & van Oeveren, 2013). However, the amount of energy increases in such cases and will most likely lead to more net erosion in general.

It is recommended to study the possible effects of changes in wave direction, energy and storm surges in more detail, as it is obviously one of the changes which might strongly influence the Wadden Sea system at large.

11 Conclusions and recommendations

11.1 Providing an overview

Introduction

First and main goal of this study was to generate an overview of the main hydro-morphological characteristics of the ebb tidal deltas of the trilateral Wadden Sea. As far as information goes this was the first time such an overview was made for the twenty-six Wadden Sea inlet systems with deltas: Marsdiep, Eierlandse Gat, Zeegat van het Vlie, Borndiep, Pinkegat, Zoutkamperlaag, Eilanderbalg, Zeegat van de Lauwers, Schild, Westerems (Eems), Osterems, Norderneyer Seegat, Wichter Ee, Accumer Ee, Otzumer Balje, Harle Seegat, Blaue Balje, Hever, Rummeloch West, Hooger Loch, Aue, Hörnum Tief, Lister Dyb (Lister Tief), Juvre Dyb, Knude Dyb, Grådyb. This report forms a (quick) reference guide on the development of the tidal inlet systems with a special focus on the ebb-tidal deltas.

To provide this overview of the current hydro-morphological knowledge and information on the Wadden Sea ebb-tidal deltas, data from many observations were brought together. From state to state the data on the Wadden Sea were collected and analysed in different ways. It appeared relatively difficult to collect and compare the data.

It is advised to work on a more uniform approach and make data available for other countries for comparison. The current report provides a first overview guide.

Overview of characteristics of ebb-tidal deltas in the Wadden Sea

The study revealed that many of the inlet systems between two islands are actually existing of two separate (sub-) inlet systems: a bigger one in the direction of the tidal propagation and a smaller mostly in the opposite direction. The smaller systems are sensitive to wave climate changes, littoral drift and tidal prism changes (brought about a.o. by the bigger tidal systems at either side). They often show strong channel dynamics and (cyclic) developments. By their changes the main ebb-tidal delta channel may change in form and orientation, the ebb-tidal delta rim may be breached, island tips may expand or erode, backbarrier shoals may change in height, and backbarrier channels can migrate strongly. Even the adjacent larger tidal system may be influenced due to the changes, especially in the ebb-tidal delta where, in certain configurations, channels of the smaller system may provide water and sediment to the bigger system. As such the smaller tidal inlet (sub-) system can exert a relatively strong influence on the ebb-tidal delta as a whole as is illustrated by the Norderney case and the Pinkegat-Zoutkamperlaag interaction.

It is recommended to make the interaction between two (or more) inlet systems between islands a special point of focus when studying ebb-tidal delta development.

In many cases data on the long-term development of the tidal inlet system are available; this is especially true for the West and East Frisian coasts, of which the morphologies are reconstructed over the past five centuries. From these reconstructions some large-scale and quite dramatic events can be observed with infill or closure of embayments as well as strong changes in the position of barrier islands and watersheds and even the disappearance or forming of inlets and large scale shifts of ebb-tidal deltas. Such examples may give clues to the influence of changes in certain parameters (tidal prism, tidal asymmetry, phase differences between inlet tide and open sea tide, etc.) and might thus help to better understand the future of the Wadden Sea. Due to time constraints this could not be investigated in depth in this study.

It is advised to work on a further analysis of the data gathered, focussing on the strong changes observed in several of the inlet systems, such as Marsdiep (historic increase in tidal prism), Eierlandse Gat (strong erosion of the ebb-tidal delta and erosion of West-Vlieland), Zoutkamperlaag & Zeegat van de Lauwers (strong eastward shift), Norderneyer Seegat (disappearance of Buise), Harle Seegat (infill of the Harle embayment), Lister Tief (confined by two supratidal dams).

Classification of ebb-tidal deltas in the Wadden Sea

The study has revealed a huge variability of the morphological and hydrodynamic characteristics of the ebb-tidal deltas of the trilateral Wadden Sea. The ebb-tidal deltas show strong variations on time scales of a decade to more than a century, due to changes in external parameters (e.g. hydraulics, storm surge climate), internal changes (e.g. shifting watersheds in the backbarrier, human interventions) and autonomous behaviour (e.g. cyclical developments). As such it can be said that each ebb-tidal delta is unique. However, the following general conclusions can be drawn:

- The seaward extension of ebb-tidal deltas increases with increasing tidal prism, confirming the ideas of Sha (1990). However, the data, for both the -6 m and -10 m extension, show a large scatter (paragraph 9.2). In general the -10 m extension of the ebb-tidal deltas is larger for the North Frisian coast than for the West and East Frisian coasts. The reason for this is not known, but might be due to the rather straight backbarrier channel patterns for several of the North Frisian inlet systems, which might partially be geological in origin, such as river valleys incised in Pleistocene deposits.

- Classification of the orientation of the backbarrier basin and the directions of tidal wave propagation and littoral drift (paragraph 9.2), reveals that, in general, tidal currents seem to determine the orientation of many of the backbarrier basins and the orientation of the ebb-tidal delta inlet channel. The larger (parts of the) basins are mostly oriented in line with the tidal wave propagation direction. The large tidal volume in combination with generally small differences in tidal phase between the North Sea and the inlet tides orients the inlet channels in the ebb-tidal delta (slightly) against the tidal wave propagation direction. The systems with a small tidal prism have generally downdrift oriented ebb-tidal deltas, because they are overruled by the littoral drift. The above has been concluded for the Dutch and Lower Saxonian inlets and confirms the ideas of Sha & van den Berg (1993). Of the systems with a symmetrical backbarrier basins and tides in the opposite direction of the littoral drift the orientation of the ebb-tidal delta channels varies. Such situations are mainly encountered along the North Frisian coast.

- Hydrodynamic classification on tidal amplitude indicates that in the Wadden Sea barrier islands and ebb-tidal deltas can exist with difficulty at 2.7 m and not above 3.0 m tidal range (paragraph 9.3). Similar to earlier findings above that tidal range the Wadden Sea is dominated by linear sand ridges perpendicular to the coast with no clearly defined ebb-tidal deltas. Thus Harle Seegat, Blaue Balje, Hever, Rummeloch West and Seder Aue are all in the zone where a slight increase in tidal range might be sufficient to end their existence. Whether this will happen in practice remains to be seen as many of the islands are heavily protected at the updrift side which probably hinders the development into a more linear sand ridge dominated coast. However, changes over the island tails are still possible.

It is recommended to focus attention on the above mentioned basins to better understand their possible futures.

- Classification taking both tidal range and mean significant wave height into account according to the classification of Davis Jr. & Hayes (1984) reveals that three types of barrier coasts exist along the Wadden Sea, namely wave dominated coasts, mixed energy coasts (wave dominant) and mixed energy coasts (tide dominant) paragraph 9.3). Judging from the current conditions it seems unlikely that slight changes in tidal range or wave climate will bring about significant changes in the classification and general appearance of inlet systems of the Wadden Sea, possibly with exception of those in the >2.7 m tidal range (see above).

- Comparing tidal prism and ebb-tidal delta sand volume indicates that there is a general trend for ebb-tidal deltas to increase in volume with increasing tidal prism (paragraph 9.3). Most of the ebb-tidal deltas have a smaller volume than might be expected on basis of Walton & Adams (1976). The relation is not very clear-cut and scatter is large. Together with the observation that many ebb-tidal deltas lose sediment it suggests that the ebb-tidal deltas are not in equilibrium. Likely other factors should be taken into account, such as: influence of the configuration of the backbarrier area, leading to changes in the sediment transport direction; influence of sediment deficit of the backbarrier area leading to strong erosion of the ebb-tidal delta (e.g. Marsdiep and Zeegat van het Vlie); changing channel patterns and knock-on effects (e.g. Norderneyer Seegat); geological subsurface morphology, which may influence the backbarrier basin, the tidal channels and thus also the ebb-tidal delta morphology and development (e.g. Hever) and storm surges (North Frisian area: see below).

  It is recommended to study the net sediment loss of ebb-tidal deltas and its effects on the coasts and backbarrier area in more detail, as it is important to understand the mechanisms and the consequences of such losses.

- Classification according to the ratio of tidal prism to littoral drift reveals that there are three groups present in the Wadden Sea: One with sediment transport characteristically taking place via bar-by-passing, where bars move over the ebb delta fringe; One where sediment transport occurs predominantly by tidal flow bypassing (bars are small and there is a good flushing of the inlet); and an intermediate group (paragraph 9.3). Although the classification seems in general to be correct, the natural development suggests that, for the Wadden Sea area, the intermediate group should be extended (to ratios of up to ca. 400).

To summarize: Ebb-tidal deltas have to be understood as an integral part of the tidal basin dynamics linking them to the outer system in terms of water and sediment supply and having a large influence on the way sediment is distributed along the coast. The ebb-tidal deltas function as a filter to the backbarrier for outside influences. These outside influences, the influences exerted by the backbarrier basin and the adjacent inlet systems and, likely, geology, together determine the (development of the) morphology of the ebb-tidal deltas.

The strong changes which have been observed to occur over the time span of a decade and longer and more show that the ebb-tidal deltas are highly dynamic. This is what might be expected given the fact that they are influenced by tides along the coast and through the inlet, as well as by waves, storm surges and changes in the morphology of the backbarrier area. The study reaffirms that the ebb-tidal deltas play an important role in the sedimentary development of the inlet systems and may be indicative of relatively strong morphological changes in the sediment sharing inlet system at a relatively early stage. As such, recent research focussing on the predicting the morphological development of tidal inlet systems and more specific ebb-tidal deltas (e.g. within the Dutch Delta program and within Kustgenese 2.0) may open the pathway to a more robust and timely prediction of inlet system development.

It is recommended to continue research on management options in tidal inlet systems. In the Netherlands nourishment of sand on ebb-tidal deltas is currently under investigation as a possible measure to counterbalance (future) erosion.

11.2 Demonstrating functioning and long-term stability in times of climate change

With respect to climate change, especially sea-level rise may be influential to the development of ebb-tidal deltas and of tidal basins. Wave and storm surge climate are characterized by strong variations and future prognoses have a high degree of uncertainty. The following conclusions can be drawn with respect to climate change:

- Ebb-tidal deltas in the tidal range between approximately 2.7 and 3.0 m are at the upper limit in which such features can exist. If, due to the increasing sea levels, tidal amplitudes increase above 3.0 m, it may be expected that inlet systems with clear-cut main channels and ebb-tidal deltas give way to linear ridges without ebb-tidal deltas, unless measures prevent such.

  It is recommended to monitor the morphological development of Harle Seegat, Blaue Balje, Hever, Rummeloch West and Süder Aue with a special focus on the possibility that these ebb-tidal delta systems may transform to linear ridges.

- The ebb-tidal deltas might respond to sea-level rise by losing sand to the backbarrier areas. It is known from human interferences that sand loss can be so quick that an ebb-tidal delta can get a smaller sand volume, perhaps leading to a disbalance between ebb-tidal delta sediment volume and tidal prism. Depending on the exact depth of erosion, a decrease in ebb-tidal delta size might provide less shelter to the barrier island, which may lead to erosion (e.g. Amrum). Local effects can differ from such a general trend. Also, a smaller ebb-tidal delta might provide less shelter to the backbarrier area, depending on the specific location of the erosion of the delta. As learned from observations chain reactions may go off, which may lead to a loss of tidal flats and a widening channels. If sea-level rise becomes too fast, shoals in the backbarrier start to drown and the tidal prism increases. As a result the ebb-tidal delta might shift its orientation more towards the direction where the tide is coming from, which might result in changes of shelter for the barrier islands and the backbarrier area and changes in channel configurations in front of the coasts (e.g. Marsdiep). The changes described in this alinea might result in less sediment supply to the downdrift island or a different place of merger of swash bars coming from the ebb-tidal delta. All of the above changes have been observed, but little is known about how these come about and how the changes in the ebb-tidal delta are related to changes in the backbarrier area or the barrier island coasts.

It is recommended to look at examples of strong changes in ebb-tidal delta size which occurred in the past and –by modelling- try to understand the driving processes and resulting morphological changes.

- Changes in wave climate and storm surges may change the ebb-tidal delta as is shown convincingly by the developments between the early sixties and the mid-nineties of Hörnum Tief, the Außensande and probably the rest of the North Frisian coast upon an increase in storm frequency. Sea-level rise causes the frequency of occurrence of a certain flood level to increase non-linearly. If storm surges become stronger or due to sea-level rise, more frequent, the ebb-tidal deltas will spent more time “off balance” and morphological behaviour might change as is illustrated by the Hörnum Tief case and observations on the Otzumer Balje. It is considered possible that such changes are further be amplified due to knock-on effects.

  To better understand what morphological changes might be brought about by changes in storm climate it is recommended to study the North Frisian changes in more detail.

Given the observed strong responses on changes in drivers in the past, it can be concluded that especially the smaller ebb-tidal delta (sub-) inlets may respond relatively fast (within a decade or so) and relatively strongly to accelerated sea-level rise and changes in storm surges caused by climate change. As described above many developments are thought possible that have impact on management of the Wadden Sea or the islands. More system knowledge to weigh and better predict the development of ebb-tidal deltas is necessary.

A joint trilateral approach to data analysis and research to gain more insight in the possible consequences of (rapid) changes of ebb-tidal deltas and to develop inventories of management options is recommended. The aim should be to develop a system understanding which allows predicting inlet system development over the course of decades.

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Appendix I: Extended data overviews per inlet system

A substantial part of the work on the extended tables has been made possible through the co-financing of the project “KPP Kennisontwikkeling Morfologie Waddenzee” (KPP Knowledge Development Morphology Wadden Sea)

Extended Table 5.1: Facts and figures Marsdiep

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.5	1890-2008	1 (station Den Helder)						
Hs (m)	1.3		CoastDat	1.37	1990 - 2012	2 (station Eierlandse Gat)	1.37 & 1.29	1990 - 2012	2 (stations Eierlandse Gat & Ijmuiden)
Tp (s)	5.49		CoastDat	6.00	1990 - 2012	2 (station Eierlandse Gat)	6.00 & 5.82	1990 - 2012	2 (stations Eierland & Ijmuiden)
Tf/Te	0.86	2011 Slot-gemiddelde	3 (station Den Helder)						
MHW (m AOD)	0.61	2011 slot-gemiddelde	3						
MLW (m AOD)	-0.8	2011 slot-gemiddelde	3						
SHW (m AOD)	0.66	2011 slot-gemiddelde	3						
SLW (m AOD)	-0.89	2011 slot-gemiddelde	3						
NHW (m AOD)	0.47	2011 slot-gemiddelde	3						
NLW (m AOD)	-0.67	2011 slot-gemiddelde	3						
MTR (m)	1.41 (114-155)	2011 slot-gemiddelde	3	1.15	1870-1910	4			
$L_{ebbdelta}$ (km)	8	2012	-6 m	8.1	2012	-10 m	11	1989	5
Surge height (m to AOD)	100 y: 3.40	2011	3 (station Den Helder)	200 y: 3.60	2011	3(station Den Helder)	500 y: 3.80	2011	3 (station Den Helder)
Mean annual max surge height (m to AOD)	2.4		CoastDat						
A_{MHW} (km^2)	696	1933	6	700	1951	6	700	1965	6
A_{MHW} (km^2).	706	1972	6	708	1977	6	712	1977	7
A_{MHW} (km^2).	704	1982	6	712	~1990				
A_{MLW} (km^2).	561	1933	6	591	1951	6	700	1965	6
A_{MLW} (km^2).	568	1972	6	564	1977	6	590	1977	7
A_{MLW} (km^2).	567	1982	6				591	~1990	sss
A_{cross} (m^2)	66700	1695	8 (map)	62560	1748	8 (map)	40996	1774	8 (map)
A_{cross} (m^2)	49740	1796	8 (map)	45572	1816	8 (map)	55590	1840	8 (map)
A_{cross} (m^2)	52996	1851	8 (map)	53848	1857	8 (map)	50808	1863	8 (map)
A_{cross} (m^2)	50728	1895	8 (map) 2 channels	43874	1909	8 (map)	52475	1925	8 (map)
A_{cross} (m^2)	55734	1930	8 (map)	53956	1933	8 (map)	47745	1936	8 (map)
A_{cross} (m^2)	49933	1939	8 (map)	51615	1942	8 (map)	48003	1945	8 (map)
A_{cross} (m^2)	51557	1950	8 (map)	51490	1970	8 (map)	48145	1976	8 (map)
A_{cross} (m^2)	49182	1980	8 (map)	54994	1981	8 (map)			
V_{MHW} (10^6 m^3)	3470	1933	11	3380	1951	11	3330	1965	11
V_{MHW} (10^6 m^3)	3280	1972	11	3280	1977	11	3357	1977	13
V_{MHW} (10^6 m^3)	3320	1982	11						
V_{MLW} (10^6 m^3)	2390	1933	11	2290	1951	11	2250	1965	11
V_{MLW} (10^6 m^3)	2210	1972	11	2210	1977	11	2303	1977	13
V_{MLW} (10^6 m^3)	2240	1982	11						
P (10^6 m^3)	75	1388	5 (Pd ≈ Schild)	210	1500	3 (Pd)	350	1583	3 (Pd)
P (10^6 m^3)	400	1608	3&8 (Pd)	630 ± 14	1695	3&8 (Pd)	631 ± 68	1748	3&8 (Pd)

P (10^6 m^3)	669±36	1774	3&8 (Pd)	616	1796	3&8 (Pd)	675	1816	3&8 (Pd)
P (10^6 m^3)	599	1840	3&8 (Pd)	616±140	1851	3&8 (Pd)	610	1857	3&8 (Pd)
P (10^6 m^3)	795	1863	3&8 (Pd)	795	1895	3&8 (Pd)	756	1909	3&8 (Pd)
P (10^6 m^3)	890	1916	3&8 (Pd)	616	1925	3&8 (Pd)			
P (10^6 m^3)				1080	1933	6 (Pbat)	797	1939	11 (Pdis)
P (10^6 m^3)	848	1951	6 (Pdis)	1090	1951	6 (Pbat)	870	1958	11 (Pdis)
P (10^6 m^3)	1080	1965	6 (Pbat)	996	1965	10 (Pdis)	1077	1966	11 (Pdis)
P (10^6 m^3)	1036	1970	3&8 (Pd)	1070	1972	6 (Pbat)	994	1974	11 (Pdis)
P (10^6 m^3)	999	1975	11 (Pdis)	1070	1977	6 (Pbat)	1054	1977	11
P (10^6 m^3)	1036	1980	3&8 (Pd)	1070	1982	6 (Pbat)	990.5±177	2009/2010	12 (Pcom)
$SV_{ebbdelta}$ (10^6 m^3)	596.5	1925	10	649.9	1933	10	601.8	1950	10
$SV_{ebbdelta}$ (10^6 m^3)	509.1	1972	10	489.1	1981	10			
$AS_{backbarrier}$ (10^6 m^3/yr)	4.6	1935-1990	13	-1.3	1990-2005	13			
$AS_{ebbdelta}$ (10^6 m^3/yr)	-4.5	1935-1990	13	-3.6	1990-2005	13			
AS_{coast} (10^6 m^3/yr)	-0.7	1935-1990	9	-2.6	1990-2005	9			
Longshore drift (10^6 m^3/yr)	-0.2	1990-2012	2	-0.3 to +0.1	1990-2012	2 (stations Ijmuiden, K13 & Eierland)			
Sediment transport direction?	Towards inlet								
Development island coasts	Erosion at both sides of inlet								

*1 = Dillingh et al., 2010; 2 = Ridderinkhof, 2016 ; 3= = Dillingh, 2013); 4 = Sha, 1990; 5= Sha, 1989; 6 = Biegel, 1992 (fixed tidal heights); 7 = Kool et al., 1984; 8 = Klein Wassink, 1991 (Adapted for A_{cross} under AOD: by adding inlet width*0.8 before closure Zuiderzee and 0.9 after (=AOD-MLW)); 9 = Oost et al., 2004; 10 =Eysink, 1993; 11 = de Reus, 1980; 12 = Duran-Matute, 2014; 13 = Elias et al., 2012 (incl. dredging and dumping).*

Extended Table 5.2: Facts and figures Eierlandse Gat

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (m)	1.5	1890-2008	1 (station Den Helder)						
Hs (m)	1.36		CoastDat	1.37	1990 - 2012	2 (station Eierland)			
Tp (s)	5.69		CoastDat	6.00	1990 - 2012	2 (stations Eierland)			
Tf/Te	No data								
MHW (m)	0.74	2011 Slot-gemiddelde	1,3 (est. from station Texel Noordzee)						
MLW (m)	-0.93	2011 Slot-gemiddelde	1,3 (est. from station Texel Noordzee)						
SHW (m AOD)	0.82	2011 Slot-gemiddelde	1,3 (est. from station Texel Noordzee)						
SLW (m AOD)	-1.08	2011 Slot-gemiddelde	1,3 (est. from station Texel Noordzee)						
NHW (m AOD)	0.57	2011 Slot-gemiddelde	1,3 (est. from station Texel Noordzee)						
NLW (m AOD)	-0.74	2011 Slot-gemiddelde	1,3 (est. from station Texel Noordzee)						
MTR (m)	1.67 (1.31-1.9)	2011 Slot-gemiddelde	1,3 (est. from station Texel Noordzee)						
$L_{ebbdelta}$ (km)	4.1	2012	-6 m	4.1	2012	-10 m	3.9	1989	4
Surge height (m to AOD)	100 y: 3.30	2011	3 (station Texel Noor-dzee)	200 y: 3.50	2011	3 (station Texel Noor-dzee)	500 y: 3.70	2011	3 (station Texel Noor-dzee)
Mean annual max surge height (m to AOD)	2.49		CoastDat						
A_{MHW} (km^2)	153	1933	5	153	1949	5	154	1962	5
A_{MHW} (km^2)	153	1971	5	153	1976	5	153	1976	6
A_{MHW} (km^2)	153	1982	5				153	~1990	7
A_{MLW} (km^2)	57.1	1933	5	64.5	1949	5	63.2	1962	5
A_{MLW} (km^2)	57.4	1971	5	58.3	1976	5	47	1976	6
A_{MLW} (km^2)	58.9	1982	5						
A_{cross} (m^2)	10626	1694	8	11784	1722	8	9552	1796	8
A_{cross} (m^2)	6959	1809	8	8867	1852	8	9782	1864	8
A_{cross} (m^2)	8578	1886	8	5963	1902	8	10519	1920	8
A_{cross} (m^2)	8293	1926	8	15650	1979	5	9721	1981	8
.V_{MHW} (10^6 m^3)	285	1933	5	299	1949	5	304	1965	5
V_{MHW} (10^6 m^3)	300	1971	5	300	1976	5	313	1976	6
V_{MHW} (10^6 m^3)	306	1982	5						
V_{MLW} (10^6 m^3)	83	1933	5	93.8	1949	5	103	1965	5
V_{MLW} (10^6 m^3)	108	1971	5	109	1976	5	106	1976	6
V_{MLW} (10^6 m^3)	114	1982	5						
P (10^6 m^3)	202	1933	5 (Pbat)	205	1949	5 (Pbat)	149	1949	5 (Pdis)
P (10^6 m^3)	202	1962	5 (Pbat)	192	1971	5 (Pbat)	162	1971	5 (Pdis)
P (10^6 m^3)	191	1976	5 (Pbat)	203	1976	6 (Pmod)	193	1982	5 (Pbat)
P (10^6 m^3)	205	1982	5 (Pdis)				180±41.5	2009-2010	9 (Pcom)
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebbdelta}$ (10^6 m^3)	110.9	1926	10	127.8	1971	10	132.6	1976	10

$SV_{ebbdelta}$ ($10^6 m^3$)	135.1	1982	10	127.6	1987	10			
Longshore drift ($10^6 m^3/yr$)	-0.1	1990-2012	2						
$SV_{backbarrier}$ ($10^6 m^3/yr$)	-0.4	1935-1990	11	-0.2	1990-2005	11			
SVebbdelta (106 m3/yr)	-0.2	1935-1990	11	-0.8	1990-2005	11			
SV_{coast} ($10^6 m^3/yr$)	-0.4	1935-1990	11	-2.3	1990-2005	11			
Sediment transport direction?	E ward								
Development island coasts	Erosion at NW-Texel up to groin; Sedimentation at W- Vlieland								

*1 = Dillingh et al., 2010; 2 = Ridderinkhof, 2016; 3 = Dillingh, 2013; 4 = Sha, 1989; 5 = Biegel, 1992 (fixed tidal heights); 6 = Kool et al., 1984; 7 = Louters & Gerritsen, 1992; 8 = Klein Wassink, 1991 (Adapted for A_{cross} under AOD: by adding inlet width*0.87 before closure Zuiderzee and 0.93 after(=AOD-MLW)); 9 = Duran-Matute et al., 2014; 10 = Eysink, 1993; 11 = Elias et al., 2012.*

Extended Table 5.3: Facts and figures Zeegat van het Vlie

Parameter	Observ	Year	Reference	Ob-serv	Year	Reference	Ob-serv.	Year	Reference
MSLR (mm/yr)	1.3	1890-2008	1 (station Harlingen)						
Hs (m)	1.34		CoastDat	1.37	1990 - 2012	2 (station Eierland)	1.37 & 1.18	1990 - 2012	2 (stations Eierland)
Tp (s)	5.84		CoastDat	6.00	1990 - 2012	2 (stations Eierland)	6.00 & 5.77	1990 - 2012	2 (stations Eierland & Schiermon-nikoog)
Tf/Te	0.89 & 0.95	2011 Slot-gemiddel de	3 (stations Terschel-ling Noordzee & Vlieland haven)						
MHW (m NHN)	0.85	2011 Slot-gemiddel de	3 (station West-terschel-ling)						
MLW (m NHN)	-1.01	2011 Slot-gemiddel de	3 (station West-terschel-ling)						
SHW (m AOD)	0.94	2011 Slot-gemiddel de	3 (station West-terschel-ling)						
SLW (m AOD)	-1.14	2011 Slot-gemiddel de	3 (station West-terschel-ling)						
NHW (m AOD)	0.69	2011 Slot-gemiddel de	3 (station West-terschel-ling)						
NLW (m AOD)	-0.84	2011 Slot-gemiddel de	3 (station West-terschel-ling)						
MTR (m)	1.80	1982	4	1.86	2011 Slot-gemiddel de	3 (station West-terschelling)			
$L_{ebbdelta}$ (km)	8	2012	-6 m	8	2012	-10 m	8.9	1989	5
Surge height (m to AOD)	100 y: 360	2011	3(station West-terschel-ling)	200 y: 370	2011	3 (station West-terschelling)	500 y: 390	2011	3 (station Westterschel-ling)
Mean annual max surge height (m to AOD)	2.48		CoastDat						
A_{MHW} (km^2)	665	1933	6	662	1951	6	665	1965	6
A_{MHW} (km^2)	661	1972	6	668	1977	6	668	1977	7
A_{MHW} (km^2)	665	1982	6						
A_{MLW} (km^2)	418	1933	6	406	1951	6			
A_{MLW} (km^2)	397	1965	6	361	1972	6	349	1977	6
A_{MLW} (km^2)	394	1977	7	368	1982	6			
A_{cross} (m^2)	60800	1796	8	62190	1809	8	64875	1831	8
A_{cross} (m^2)	49200	1853	8	54775	1866	8	53500	1893	8
A_{cross} (m^2)	45800	1904	8	60700	1918	8	52153	1976	6
A_{cross} (m^2)	80550	1982	8						
V_{MHW}	2360	1933	6	2280	1951	6	2320	1965	6

(10^6 m^3)									
V_{MHW} (10^6 m^3)	2270	1972	6	2250	1977	6	2249	1977	7
V_{MHW} (10^6 m^3)	2290	1982	6						
V_{MLW} (10^6 m^3)	1220	1933	6	1170	1951	6	1190	1965	6
V_{MLW} (10^6 m^3)	1160	1972	6	1150	1977	6	1170	1977	7
V_{MLW} (10^6 m^3)	1190	1982	6						
P (10^6 m^3)	1140	1933	6 (Pbat)	1130	1951	6 (Pbat)	1130	1965	5 (Pbat)
P (10^6 m^3)	954	1972	6 (Pdis)	1100	1972	6 (Pbat)			
P (10^6 m^3)	1100	1977	6 (Pbat)	1030	1977	6 (Pdis)	1078	1977	7 (Pcom)
P (10^6 m^3)	1100	1982	6 (Pbat)				934±169	2009-2010	9 (Pcom)
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebbdelta}$ (10^6 m^3)	416.4	1933	10	369.7	1972	10	347.5	1974	10
$SV_{ebbdelta}$ (10^6 m^3)	364.3	1976	10	363.4	1978	10	339.5	1980	10
$SV_{ebbdelta}$ (10^6 m^3)	354.8	1982	10						
$AS_{backbarrier}$ (10^6 m^3/yr)	3	1935-1990	11	3.5	1990-2005	11			
$AS_{ebbdelta}$ (10^6 m^3/yr)	-1.8	1935-1990	11	-1.8	1990-2005	11			
AS_{coast} (10^6 m^3/yr)	-0.2	1935-1990	11	-0.7	1990-2005	11			
Longshore drift (10^6 m^3/yr)	0.4	1990-2012	2	+0.3 to +0.5	1990-2012	2 (stations Eierland & Schiermonnikoog)			
Sediment transport direction?	East-ward								
Develop-ment island coasts	Erosion of East Vlie-land; Sedimentation at Terschelling								

*1 = Dillingh et al., 2010; 2 = Ridderinkhof, 2016; 3 = Dillingh, 2013; 4 = Postma, 1982; 5 = Sha, 1989; 6 = Biegel, 1992 (fixed tidal heights); 7 = Kool et al., 1984; 8 = Klein Wassink, 1991 (Adapted for A_{cross} under AOD: by adding inlet width*1 (=AOD-MLW)); 9 = Duran-Matute et al., 2014; 10 = Eysink, 1993; 11 = Elias et al., 2012.*

Extended Table 5.4: Facts and figures Borndiep

Parameter	Observ	Year	Reference	Observ	Year	Reference	Observ	Year	Reference
MSLR (mm/yr)	1.3	1890-2008	1 (station Harlingen)						
Hs (m)	1.36		CoastDat	1.37	1990 2012	2 (station Eierland)	1.37 & 1.18	1990 2012	2 (stations Eierland & Schiermonnikoog)
Tp (s)	5.89		CoastDat	6.00	1990 2012	2 (stations Eierland & Schiermonnikoog)	6.00 & 5.77	1990 2012	2 (stations Eierland & Schiermonnikoog)
Tf/Te	0.89	2011 Slot-gemiddelde	3 (station Terschelling Noordzee)						
MHW (m AOD)	0.93	2011 slot-gemiddelde	3 (station Wierumergronden)						
MLW (m AOD)	-1.08	2011 slot-gemiddelde	3 (station Wierumergronden)						
SHW (m AOD)	1.05	2011 slot-gemiddelde	3 (station Wierumergronden)						
SLW (m AOD)	-1.23	2011 slot-gemiddelde	3 (station Wierumergronden)						
NHW (m AOD)	0.73	2011 slot-gemiddelde	3 (station Wierumergronden)						
NLW (m AOD)	-0.88	2011 slot-gemiddelde	3 (station Wierumergronden)						
MTR (m)	2.01 (1.61-2.28)	2011 slot-gemiddelde	3 (station Wierumergronden)						
$L_{ebbdelta}$ (km)	6.7	2012	-6 m	6.7	2012	-10m	6	1989	4
Surge height (m to AOD)	100 y: 3.50	2011	3 (station Wierumergronden)	200 y: 3.70	2011	3 (station Wierumergronden)	500 y: 3.90	2011	3 (station Wierumergronden)
Mean annual max surge height (m to AOD)	2.44		CoastDat						
A_{MHW} (km^2)	282	1926	5	284	1950	5	284	1967	5
A_{MHW} (km^2)	283	1973	5	284	1978	5	309	1978	6
A_{MHW} (km^2)	284	1984	5						
A_{MLW} (km^2)	103	1926	5	108	1950	5	98.5	1967	5
A_{MLW} (km^2)	96.4	1973	5	98.2	1978	5	122	1978	6
A_{MLW} (km^2)	105	1984	5						
A_{cross} (m^2)	17700	1831	7	20370	1854	7	16850	1866	7
A_{cross} (m^2)	18570	1893	7	18350	1904	7	24170	1926	7
A_{cross} (m^2)									
V_{MHW} (10^6 m^3)	783	1926	5	793	1950	5	790	1967	5
V_{MHW} (10^6 m^3)	784	1973	5	777	1978	5	812	1978	6
V_{MHW} (10^6 m^3)	790	1984	5						
V_{MLW} (10^6 m^3)	297	1926	5	319	1950	5	305	1967	5
V_{MLW} (10^6 m^3)	313	1973	5	305	1978	5	334	1978	6
V_{MLW} (10^6 m^3)	303	1984	5						
P (10^6 m^3)	486	1926	5 (Pbat)	474	1950	5 (Pbat)	485	1967	5 (Pbat)
P (10^6 m^3)	389	1967	5 (Pdis)	471	1973	5 (Pbat)	472	1978	5 (Pbat)
P (10^6 m^3)	478	1978	6 (Pcom)	430	1982	1	487	1984	5 (Pbat)
P (10^6 m^3)	383±74,5	2009-2010	8 (Pcom)						
$SV_{backbarrier}$ (10^6 m^3)									

$SV_{ebbdelta}$ ($10^6 m^3$)	114.3	1926	9	145.5	1934	9	163.4	1958	9
$SV_{ebbdelta}$ ($10^6 m^3$)	145.7	1966	9	128.4	1974	9	141.3	1976	9
$SV_{ebbdelta}$ ($10^6 m^3$)	120.9	1982	9						
$AS_{backbarrier}$ ($10^6 m^3/yr$)	0.6	1935-1990	10	1.4	1990-2005	10			
$AS_{ebbdelta}$ ($10^6 m^3/yr$)	0.7	1935-1990	10	-0.4	1990-2005	10			
AS_{coast} ($10^6 m^3/yr$)	0.9	1935-1990	10	0.7	1990-2005	10			
Longshore drift ($10^6 m^3/yr$)	1	1990-2012	2	+0.8 to +1.2	1990-2012	2 (Eierland & Schiermonnikoog)			
Sediment transport direction?	Eward								
Development island coasts?	Sedimentatioin on NW Ameland; Boschplaat Terschelling, erosion								

*1 = Dillingh et al., 2010 (lineair trend, corrected data); 2 = Ridderinkhof, 2016; 3 = Dillingh, 2013; 4 = Sha, 1989; 5 = Biegel, 1992 (fixed tidal heights); 6 = Kool et al., 1984; 7 = Klein Wassink, 1991 (Adapted for A_{cross} under AOD: by adding inlet width*1 (=AOD-MLW)); 8 = Duran-Matute, 2014; 9 = Eysink, 1993; 10= Elias et al., 2012.*

Extended Table 5.5: Facts and figures Pinkegat

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)						
Hs (m)	1.25		CoastDat	1.18	1990 - 2012	2 (station Schiermonni-koog)			
Tp (s)	5.93		CoastDat	5.77	1990 - 2012	2 (station Schiermonni-koog)			
Tf/Te	0.93	2011 Slot-gemiddelde	3 (station Wierumer-gronden)						
MHW (m AOD)	0.93	2011 slot-gemiddelde	3 (station Wierumer-gronden)						
MLW (m AOD)	-1.08	2011 slot-gemiddelde	3 (station Wierumer-gronden)						
SHW (m AOD)	1.05	2011 slot-gemiddelde	3 (station Wierumer-gronden)						
SLW (m AOD)	-1.23	2011 slot-gemiddelde	3 (station Wierumer-gronden)						
NHW (m AOD)	0.73	2011 slot-gemiddelde	3 (station Wierumer-gronden)						
NLW (m AOD)	-0.88	2011 slot-gemiddelde	3 (station Wierumer-gronden)						
MTR (m)	2.01 (1.61 - 2.28)	2011 slot-gemiddelde	3 (station Wierumer-gronden)						
$L_{ebbdelta}$ (km)	4	2012	-6 m	4.5	2012	-10m	3.1	1989	4
Surge height (m to AOD)	100 y: 350	2011	3 (station Wierumer-gronden)	200 y: 370	2011	3 (station Wierumer-gronden)	500 y: 390	2011	3 (station Wierumer-gronden)
Mean annual max surge height (m to AOD)	2.53		CoastDat						
A_{MHW} (km^2)	55.3	1959	5	65	Ca. 1982	6			
A_{MLW} (km^2)	16.4	1959	5	23	Ca. 1982	6			
A_{cross} (m^2)									
V_{MHW} (10^6 m^3)	116	1959	5	100	1982	7			
V_{MLW} (10^6 m^3)	24.3	1959	5	20	1982	Estimate based on 7 and 6			
P (10^6 m^3)	103	1937/1939	8 (Pbat)	91.7	1957	7 (Pbat)	100	1982	5
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebbdelta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	+1.1	1927-1949	9	+1.0	1949-1958/59	9	+.3	1958/59 -1967	9
$AS_{backbarrier}$ (10^6 m^3/yr)	+1.4	1967-1971	9	+0.9	1971-1975	9	-0.1	1975-1978	9
$AS_{backbarrier}$ (10^6 m^3/yr)	-0.4	1978-1981	9	+5.5	1981-1987	9			9
$AS_{ebbdelta}$ (10^6 m^3/yr))	+0.1	1927-1949	9	-0.4	1949-1958	9	+0.5	1958-1967	9
$AS_{ebbdelta}$	-0.8	1967-	9	+0.5	1970/71	9	+0.9	1975-	9

(10^6 m^3/yr))		1970/71			-1975			1979	
AS$_{ebbdelta}$ (10^6 m^3/yr))	+0.6	1979-1982	9	-0.4	1982-1987	9			
Longshore drift (10^6 m^3/yr)	+1.4	1990-2012	2 (station Schiermonni-koog)						
Sediment transport direction?	To the E								
Develop-ment island coasts	Growth of East Ameland								

1 = Dillingh et al. 2009; 2 = Ridderinkhof, 2016; 3 = Dillingh, 2013; 4 = Sha, 1989; 5 = Biegel, 1992 (Tidal heights are fixed); 6 = Louters & Gerritsen, 1994; 7 = Min V&W, 1987; 8 = RWS, 1941; 9 = Oost, 1995 (incl. dredging and dumping; basin and ebb-delta area differs before and after 1970/1971).

Extended Table 5.6: Facts and figures de Zoutkamperlaag

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)						
Hs (m)	1.22		CoastDat	1.18	1990 - 2012	2 (station Schiermonnikoog)			
Tp (s)	5.98		CoastDat	5.77	1990 - 2012	2 (station Schiermonnikoog)			
Tf/Te	0.93	2011 Slot-gemiddelde	3 (station Wierumer-gronden)						
MHW (m AOD)	0.93	2011 slot-gemiddelde	3 (station Wierumer-gronden)						
MLW (m AOD)	-1.08	2011 slot-gemiddelde	3 (station Wierumer-gronden)						
SHW (m AOD)	1.05	2011 slot-gemiddelde	3 (station Wierumer-gronden)						
SLW (m AOD)	-1.23	2011 slot-gemiddelde	3 (station Wierumer-gronden)						
NHW (m AOD)	0.73	2011 slot-gemiddelde	3 (station Wierumer-gronden)						
NLW (m AOD)	-0.88	2011 slot-gemiddelde	3 (station Wierumer-gronden)						
MTR (m)	2.01 (1.61-2.28)	2011 slot-gemiddelde	3 (station Wierumer-gronden)	2.2	1982	4			
$L_{ebbdelta}$ (km)	5.5	2012	-6 m	7	2012	-10m	5	1989	5
Surge height (m to MSL)	100 y: 350	2011	3 (station Wierumer-gronden)	200 y: 370	2011	3 (station Wierumer-gronden)	500 y: 390	2011	3 (station Wierumer-gronden)
Mean annual max surge height (m to AOD)	2.55		CoastDat						
A_{MHW} (km^2)	195	1957	6 Incl Lauwerszee	130	Ca. 1982	7			
A_{MLW} (km^2)	61.7	1957	6 Incl Lauwerszee	48	Ca 1982	7			
A_{cross} (m^2)	20450	1809	8	30000	1832	8	25300	1850	8
A_{cross} (m^2)	26840	1854	8	23650	1859	8	25800	1873	8
A_{cross} (m^2)	26690	1891	8	25030	1903	8	24370	1927	8
A_{cross} (m^2)				17793	1968	9	16575	1971	9
A_{cross} (m^2)	15240	1975	9	13875	1981	9			
V_{MHW} (10^6 m^3)	551	1957	6	361	1971	10	362	1975	10
V_{MHW} (10^6 m^3)	349	1981	10						
V_{MLW} (10^6 m^3)	235	1957	6	182	1971	10	175	1975	10
V_{MLW} (10^6 m^3)	156	1981	10						
P (10^6 m^3)	303	1937-1939	11 (Pdis)	316	1957	6 (Pbat)	284	1968	9 (Pdis)
P (10^6 m^3)	133	1971	9 (Pdis)	179	1971	10 (Pbat)	164	1975	9 (Pdis)
P (10^6 m^3)	187	1975	10 (Pbat)	151	1981	9 (Pdis)	193	1981	10 (Pbat)
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebbdelta}$ (10^6 m^3)									
$AS_{backbarrier\ Excl.\ Lauwers}$ (10^6 m^3/yr)	+0.6	1927-1949	12	-1.6	1949-1957/58	12	+0.2	1957/58-1966	12
$AS_{backbarrier\ Lauwers}$	+0.5	1927-1949	12	-0.7	1949-1959	12	+1.5	1959-1967	12

(10^6 m^3/yr)									
$AS_{backbarrier}$ (10^6 m^3/yr)	+2.5	1966-1970	12	+3.0	1970-1975	12	+2.7	1975-1979	12
$AS_{backbarrier}$ (10^6 m^3/yr)	+41.4	1979-1982	12	+0.8	1982-1987	12			
$AS_{ebbdelta}$ (10^6 m^3/yr)	+0.7	1927-1950	12	-1.7	1950-1958	12	-1.7	1958-1965	12
$AS_{ebbdelta}$ (10^6 m^3/yr)	-1.2	1965-1970	12	-2	1970-1975	12	+0.1	1975-1979	12
$AS_{ebbdelta}$ (10^6 m^3/yr)	-3.3	1979-1982	12	-1.3	1982-1987	12			
Longshore drift (10^6 m^3/yr)	+1.4	1990-2012	2	+1.4	1990-2012	2 (station Schier-monnikoog)			
Sediment transport direction?	E ward								
Development island coasts	Growth and erosion of NW Schier-monnikoog								

*1 = Dillingh et al. 2010; 2 = Ridderinkhof, 2016; 3 = Dillingh, 2013; 4 = Min V en W, 1987; 5 = Sha, 1989; 6 = Biegel, 1992 (tidal heights fixed); 7 =Louters & Gerritsen, 1994; 8 = Klein Wassink, 1991 (Adapted for A_{cross} under AOD: by adding inlet width*1 (=AOD-MLW)); 9 = RWS, 1986; 10 = Post-ma & Reenders, 1986 (shift watershed included); 11 = RWS, 1941; 12 = Oost, 1995 (incl. dredg-ing and dumping; basin and ebb-delta area differs before and after 1970);*

Extended Table 5.7: Facts and figures Eilanderbalg

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)						
Hs (m)	1.32		CoastDat	1.18	1990 - 2012	2 (station Schiermonnikoog)			
Tp (s)	5.85		CoastDat	5.77	1990 - 2012	2 (station Schiermonnikoog)			
Tf/Te	0.94	2011 Slot-gemiddelde	3 (station Huibertgat)						
L (km)	3.3	2012	-6 m	4	2012	-10m	3	1989	4
MHW (m AOD)	0.98	2011 slot-gemiddelde	3, 5 (station Huibertsgat +5 cm)						
MLW (m AOD)	-1.13	2011 slot-gemiddelde	3, 5 (station Huibertsgat +5 cm)						
SMHW (m AOD)	1.1	2011 slot-gemiddelde	3, 5 (station Huibertsgat +5 cm)						
SMLW (m AOD)	-1.28	2011 slot-gemiddelde	3, 5 (station Huibertsgat +5 cm)						
NMHW (m AOD)	0.78	2011 slot-gemiddelde	3, 5 (station Huibertsgat +5 cm)						
NMLW (m AOD)	-0.93	2011 slot-gemiddelde	3, 5 (station Huibertsgat +5 cm)						
MTR (m)	2.11 (1.71-2.38)	2011 slot-gemiddelde	3, 5 (station Huibertsgat +5 cm)						
Surge height (m to AOD)	100 y: 360	2011	3 (station Huibertsgat)	200 y: 380	2011	3 (station Hui-bertsgat)	500 y: 400	2011	3 (station Huibertsgat)
Mean annual max surge height (m to AOD)	2.55		CoastDat						
A_{MHW} (km^2)	55	Ca. 1982	6						
A_{MLW} (km^2)	27	Ca. 1982	6						
A_{cross} (m^2)	4851	1891	7	7559	1965	8			
A_{cross} (m^2)	8000	1989	9				5000	2014	9
V_{MHW} (10^6 m^3)									
V_{MLW} (10^6 m^3)									
P (10^6 m^3)	67	1937/39	10 (Pbat)	70	ca. 1982	11			
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebbdelta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	0	1990-2002	12						
$AS_{ebbdelta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	+1.3	1990-2005	Based on 2 (interpolation)						
Sediment transport direction?	Eastward								
Development island coasts	Eastward elongation East-Schiermonnikoog								

*1 = Dillingh et al., 2010; 2 = Ridderinkhof, 2016; 3 = Dillingh, 2013; 4 = Sha, 1989; 5 = Vroom et al., 1989; 6 = Louters & Gerritsen, 1994; 7 = Klein Wassink, 1991 (Adapted for A_{cross} under AOD: by adding inlet width*1 (=AOD-MLW)); 8 = Biegel, 1992; 9 = Van Rooyen & Oost, 2015; 10 = RWS, 1941; 11 = Postma, 1982; 12 = Cleveringa, 2008;*

Extended Table 5.8: Facts and figures Zeegat van de Lauwers

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)						
Hs (m)	1.32		CoastDat	1.18	1990 2012	2 (station Schiermonnikoog)			
Tp (s)	5.85		CoastDat	5.77	1990 2012	2 (station Schiermonnikoog)			
Tf/Te	0.94	2011 Slot-gemiddelde	3 (gauge Huibertgat)						
L (km)	6,5	2012	-6 m	9	2012	-10m	3	1989	4
MHW (m AOD)	0.98	2011 slot-gemiddelde	3, 5 (station Huibertsgat +5 cm)						
MLW (m AOD)	-1.13	2011 slot-gemiddelde	3, 5 (station Huibertsgat -5 cm)						
SHW (m AOD)	1.1	2011 slot-gemiddelde	3, 5 (station Huibertsgat +5 cm)						
SLW (m AOD)	-1.28	2011 slot-gemiddelde	3, 5 (station Huibertsgat -5 cm)						
NHW (m AOD)	0.78	2011 slot-gemiddelde	3, 5 (station Huibertsgat +5 cm)						
NLW (m AOD)	-0.93	2011 slot-gemiddelde	3, 5 (station Huibertsgat -5 cm)						
MTR (m)	2.11 (1.71-2.38)	2011 slot-gemiddelde	3, 5 (station Huibertsgat + 10 cm)						
Surge height (m to MSL)	100 y: 360	2011	3 (station Huibertsgat	200 y: 380	2011	3 (station Huibertsgat	500 y: 400	2011	3 (station Huibertsgat
Mean annual max surge height (m to AOD)	2.55		CoastDat						
A_{MHW} (km^2)	129	1954	6 (level: +1 m AOD)	110	1962	7	139	1980	6 (level +1 m AOD)
A_{MHW} (km^2)	145	Ca. 1982	10						
A_{MLW} (km^2)	36.3	1962	7	53	Ca. 1982	8			
A_{cross} (m^2)	15654	1891	9	12594	1874	9			
A_{cross} (m^2)	17600	1954	10	16402	1962	7	17950	1980	10
A_{cross} (m^2)	13000	1989	11				19500	2014	11
V_{MHW} (10^6 m^3)	303	1962	7						
V_{MLW} (10^6 m^3)	107	1962	7						
P (10^6 m^3)	200	1937/39	12 (Pbat)	196	1962	4 (Pbat)	185	1962	4 (Pbat)
P (10^6 m^3)	160	1982	10	208	1984	11 (Pdis)			
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebbdelta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	1	1990-2005	13 (including Het Schild)						
$AS_{ebbdelta}$ (10^6 m^3/yr)	1.2	1990-2013	14						
Longshore drift (10^6 m^3/yr)	+1.2	1990-2005	Based on 2 (interpolation)						
Sediment	??								

transport direction?									
Development island coasts	Erosion W Rottumer-plaat; Sedimentation N Rottumer-plaat								

*1 = Dillingh et al. 2010; 2 = Ridderinkhof, 2016; 3 = Dillingh, 2013; 4 = Sha, 1989; 5 = Vroom et al., 1989; 6 = Brilhuis et al., 1990; 7 = Biegel, 1992 (tidal heights fixed); 8 = Cleveringa, 2008; 9 = Klein Wassink, 1991 (Adapted for A_{cross} under AOD: by adding inlet width*1.13 (=AOD-MLW)); 10 = Postma, 1982; 11 = Van Rooyen & Oost, 2015; 12 = RWS, 1941; 13 = Pastoor, 1985; 14 = Vermaas & Marges, 2017.*

Extended Table 5.9: Facts and figures het Schild

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)						
Hs (m)	1.32		CoastDat	1.18	1990 2012	2 (station Schiermonni-koog)			
Tp (s)	5.85		CoastDat	5.77	1990 2012	2 (station Schiermonni-koog)			
Tf/Te	0.94	2011 Slot-gemiddelde	3 (station Huibertgat)						
Lebbdelta (km)	2.1	2012	-6 m	2.1	2012	-10m	2	1989	4
MHW (m AOD)	0.98	2011 slot-gemiddelde	3, 5 (station Huibertsgat +5 cm)						
MLW (m AOD)	-1.13	2011 slot-gemiddelde	3, 5 (station Huibertsgat -5 cm)						
SMHW (m AOD)	1.1	2011 slot-gemiddelde	3, 5 (station Huibertsgat +5 cm)						
SMLW (m AOD)	-1.28	2011 slot-gemiddelde	3, 5 (station Huibertsgat -5 cm)						
NMHW (m AOD)	0.78	2011 slot-gemiddelde	3, 5 (station Huibertsgat +5 cm)						
NMLW (m AOD)	-0.93	2011 slot-gemiddelde	3, 5 (station Huibertsgat -5 cm)						
MTR (m)	2.11 (1.71-2.38)	2011 slot-gemiddelde	3, 5 (station Huibertsgat + 10 cm)						
Surge height (m to MSL)	100 y: 360	2011	3 (station Huibertsgat)	200 y: 380	2011	3 (station Hui-bertsgat)	500 y: 400	2011	3 (station Hui-bertsgat)
Mean annual max surge height (m to AOD)	2.55		CoastDat						
A_{MHW} (km^2)	41.4	1962	6	55	1970	12			
A_{MHW} (km^2)	28	1980	5 (before take over of Lau-wers)	18	1980	5 (after take-over of Lauwers)	16	1990	5
A_{MLW} (km^2)	11.6	1962	6						
A_{cross} (m^2)	1902	1958	6	1722	1962	6			
A_{cross} (m^2)	5200	1989	7				6900	2014	7
V_{MHW} (10^6 m^3)	78.9	1962	6						
V_{MLW} (10^6 m^3)	19.1	1962	6						
P (10^6 m^3)	75	1938	8 (Pdis), might be somewhat higher.	48	1954	9 & 10 (Pdis)	48	1960	10 (Pdis)
P (10^6 m^3)	59.8	1962	6 (Pbat)	45	1965	10 (Pdis)	44	1969	10 (Pdis)
P (10^6 m^3)	41	1976	10 (Pdis)	42	1978	10 (Pdis)	40	1980	11 after take over by Lauwers
P (10^6 m^3)	36	1984	9 (Pbat)	41	1989	10 & 11 (Pdis)	32	1992	10 (Pdis)
$SV_{backbarrier}$ (10^6 m^3)									

$SV_{ebbdelta}$ ($10^6 m^3$)									
$AS_{backbarrier}$ ($10^6 m^3/yr$)									
$AS_{ebbdelta}$ ($10^6 m^3/yr$)									
Longshore drift (10^6 m^3/yr)	+1.2	1990-2005	Based on 2 (interpola-tion)						
Sediment transport direction?	To the E								
Develop-ment island coasts	Erosion of N Rottume-roog								

1 = Dillingh et al., 2010; 2 = Ridderinkhof, 2016; 3 = Dillingh, 2013; 4 = Sha, 1989; 5 = Vroom et al., 1989; 6 = Biegel, 1992 (tidal heights fixed); 7 = Van Rooijen & Oost, 2015; 8 = RWS, 1941; 9 = Brilhuis et al., 1990; 10 = Huizing & Ariaans, 1995; 11 = Huizing, 1993; 12 = van Weerden et al, 1991.

Extended Table 6.1: Facts and figures Westerems

Parameter		Year	Reference		Year	Reference		Year	Reference
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)	2.2	1934 - 2001	2 (station Borkum)			
MHWR (mm/yr)	3.2	1934-2001	2 (station Borkum)						
MLWR (mm/yr)	1.0	1934-2001	2 (station Borkum)						
MTRI (mm/yr)	2.2	1934-2001	2 (station Borkum)						
Hs (m)	1.31		CoastDat	1.18	1990 2012	3 (station Schiermonni-koog)	1.07 & - 1.18	2006 - 2009 & 1990 - 2012	3 (stations Elbe & Schiermonni-koog)
Tp (s)	5.80		CoastDat	5.77	1990 – 2012	3 (station Schiermonni-koog)	5.75 & 5.77	2006 - 2009 & 1990 - 2012	3 (stations Elbe & Schiermonni-koog)
Tf/Te	0.94	2011 Slot-gemiddelde	4 (station Hui-bertgat)	0.98	2017 (2 tidal cy-cles of 3 jan)	5 (station, Borkum Fischerbalje)			
MHW (m NHN)	0.98	2011 slot-gemiddelde	4, 6 (station Huibertsgat +5 cm)	1,1	2017	5 (station Borkum, Südstrand)			
MLW (m NHN)	-1.13	2011 slot-gemiddelde	4, 6 (station Huibertsgat -5 cm)	-1,2	2017	5 (station Borkum, Südstrand)			
SHW (m NHN)	1.1	2011 slot-gemiddelde	4, 6 (station Huibertsgat +5 cm)						
SLW (m NHN)	-1.28	2011 slot-gemiddelde	4, 8 (station Huibertsgat -5 cm)						
NHW (m NHN)	0.78	2011 slot-gemiddelde	4, 6 (station Huibertsgat +5 cm)						
NLW (m NHN)	-0.93	2011 slot-gemiddelde	4, 6 (station Huibertsgat -5 cm)						
MTR (m)	2.11 (1.71-2.38)	2011 slot-gemiddelde	4, 6 (station Huibertsgat + 10 cm)	2,3	2017	5 (station Borkum, Südstrand)			
$L_{ebbdelta}$ (km)	13	2012	-6 m	14.7	2012	-10m	15	1989	7
Surge height (m to MSL)	100 y: 360	2011	4 (station Hui-bertsgat	200 y: 380	2011	4 (station Hui-bertsgat	500 y: 400	2011	4 (station Hui-bertsgat
Mean annual max surge height (m to AOD)	2.57		CoastDat						
A_{MHW} (km^2)	520	~1990	8						
A_{MLW} (km^2)	306	~1990	8						
A_{cross} (m^2)	69700	1833	9	96226	1859	9	56601	1874	9
A_{cross} (m^2)	55476	1887	9	5657	1911	9	6048	1975	10

				6			3		
V_{MHW} (10^6 m^3)									
V_{MLW} (10^6 m^3)									
P (10^6 m^3)	1000	1982	11						
$SV_{ebbdelta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	4,7 (3,9-5,7)	1985-2002	12						
$AS_{ebbdelta}$ (10^6 m^3/yr)	-0,3	1990-2013	13						
Longshore drift (10^6 m^3/yr)	+1.1	1990-2012	3 (station Schiermonni-koog)	+1.1 to +1.5	1990 - 2012 & 2006 - 2009	3 (stations Schiermonni-koog & Elbe)			
Sediment transport direction?	Ew-ard?								
Develop-ment island coasts	Growth of NW Borkum; Erosion N side of Rottumer-oog								

*1 = Dillingh et al., 2010; 2 = Jensen & Mudersbach, 2007; 3 = Ridderinkhof, 2016; 4 = Dillingh, 2013; 5 = BSH, 2016; 6 = Vroom et al., 1989; 7 = Sha, 1989; 8 = Louters & Gerritsen, 1992; 9 = Klein Wassink, 1991 (Adapted for A_{cross} under AOD: by adding inlet width*1.13 (=AOD-MLW)); 10 = Biegel, 1992 (tidal heights fixed); 11 = Postma, 1982; 12 = Cleveringa, 2008; 13 = Vermaas & Marges, 2017.*

Extended Table 6.2: Facts and figures Osterems

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	1.9	1890-2008	1 (station Delfzijl)	2.2	1934-2001	2 (station Borkum)			
Hs (m)	1.26		CoastDat	1.18	1990 – 2012	3 (station Schiermonnikoog	1.07 & - 1.18	2006-2009 & 1990-2012	3 (stations Elbe & Schiermonnikoog)
Tp (s)	5.84		CoastDat	5.77	1990 – 2012	3 (station Schiermonnikoog	5.75 & 5.77	2006-2009 & 1990-2012	3 (stations Elbe & Schiermonnikoog)
Tf/Te	0.99	2017 (2 tidal cycles of 3 jan)	4 (station Juist, Hafen)						
MHWR (mm/yr)	3.2	1934-2001	2 (station Borkum)						
MLWR (mm/yr)	1.0	1934-2001	2 (station Borkum)						
MTRI (mm/yr)	2.2	1934-2001	2 (station Borkum)						
MHW (m AOD)	+1.2	2017	4 (station Juist, Hafen)						
MLW (m AOD)	-1.3	2017	4 (station Juist, Hafen)						
SHW (m AOD)									
SLW (m AOD)									
NHW (m AOD)									
NLW (m AOD)									
MTR (m)	2.4	1982	5	2.6	2017	4 (station Juist, Hafen)			
$L_{ebbdelta}$ (km)	11	2012	-6 m	15	2012	-10m	6	1989	6
Surge height (m to MSL)									
Mean annual max surge height (m to AOD)	2.58		CoastDat						
A_{MHW} (km^2)	358	1650	7	373	1750	7	372	1860	7
A_{MHW} (km^2)				348	1930	7	301	1960	7
A_{MHW} (km^2)	277	1975	7	296	1990	7			
A_{MLW} (km^2)	116	1650	7	127	1750	7	136	1860	7
A_{MLW} (km^2)				143	1930	7	134	1960	7
A_{MLW} (km^2)	112	1975	7	139	1990	7			
A_{cross} (m^2)	46000	Ca. 2000	3						
V_{MHW} (10^6 m^3)									
V_{MHLW} (10^6 m^3)									
P (10^6 m^3)	498	1650	7 (Pmap)	550	1750	7 (Pmap)	584	1860	7 (Pmap)
P (10^6 m^3)	594	1930	7 (Pmap)	525	1960	7 (Pmap)	466	1975	7 (Pmap)
P (10^6 m^3)	525	1990	7 (Pmap)				523 (507-540)	2004-2005	8 Pcom (giving flood resp. ebb volume)
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebbdelta}$ (10^6 m^3)									
$AS_{backbarrier}$	0	1990-2004/5	7 & 8						

(10^6 m^3/yr)									
$AS_{ebbdelta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	+0.8	1990-2012 & 2006-2009	3	+0.5 to 1.5	1990-2012 & 2006-2009	3 (stations Schiermonnikoog & Elbe)			
Sediment transport direction?	E ward								
Development island coasts	Growth of Juist								

1 = Dillingh, 1013; 2 = Jensen & Mudersbach, 2007; 3 = Ridderinkhof, 2016; 4 = BSH, 2016; 5 = Postma, 1982; 6 = Sha, 1989; 7 = Niemeyer, 1995; 8 = Herrling, 2014.

Extended Table 6.3: Facts and figures Norderneyer Seegat

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2.0	1891 - 2001	1 (station Norderney)						
MHWR (mm/yr)	2.2	1891 - 2001	1 (station Norderney)						
MLWR (mm/yr)	1.4	1891 - 2001	1 (station Norderney)						
MTRI (mm/yr)	1.2	1891 - 2001	1 (station Norderney)						
Hs (m)	1.28		CoastDat	1.18	1990 - 2012	2 (station Schiermonnikoog)	1.07 & - 1.18	2006-2009 & 1990-2012	2 (stations Elbe & Schiermonnikoog)
Tp (s)	5.64		CoastDat	5.77	1990 - 2012	2 (station Schiermonnikoog)	5.75 & 5.77	2006-2009 & 1990-2012	2 (stations Elbe & Schiermonnikoog)
Tf/Te	0.97	2017 (2 tidal cycles of 3 jan)	3 (Nor-derney, Riffgat)						
MHW (m NHN)	1.01	1935	4 (station Norderney)	1.13	1958	4 (station Nor-derney)	1.21	1975	4 (station Nor-derney)
MHW (m NHN)	1.18	1985	4 (station Norderney)	1.21	1995	4 (station Nor-derney)	1.23	1998	4 (station Nor-derney)
MHW (m NHN)	1.2	2017	3 (station Norderney, Riffgat).						
MLW (m NHN)	-1.31	1935	4 (station Norderney)	-1.26	1958	4 (station Nor-derney)	-1.22	1975	4 (station Nor-derney)
MLW (m NHN)	-1.25	1985	4 (station Norderney)	-1.26	1995	4 (station Nor-derney)	-1.21	1998	4 (station Nor-derney)
MLW (m NHN)	-1,3	2017	3 (station Norderney, Riffgat).						
MSL (m NHN)	-0.3	1935	4 (station Norderney)	-0.13	1958	4 (station Nor-derney)	-0.01	1975	4 (station Nor-derney)
MSL (m NHN)	-0.07	1985	4 (station Norderney)	-0.05	1995	4 (station Nor-derney)	0.02	1998	4 (station Nor-derney)
NHW (m NHN)									
NLW (m NHN)									
MTR (m)	2.32	1935	4 (station Norderney)	2.39	1958	4 (station Nor-derney)	2.43	1975	4 (station Nor-derney)
MTR (m)	2.43	1985	4 (station Norderney)	2.47	1995	4 (station Nor-derney)	2.44	1998	4 (station Nor-derney)
MTR (m)	2.5	2017	3 (station Norderney, Riffgat).						
$L_{ebbdelta}$ (km)	3.5	2012	-6 m	4.5	2012	-10m	3	1989	5
Surge height (m to MSL)									
Mean annual max surge height (m to AOD)	2.73		CoastDat						
A_{MHW} (km^2)	110	1650	6	102	1750	6	99	1860	6
A_{MHW} (km^2)	103	1912	6	100????	1930	6	103	1960	6
A_{MHW} (km^2)	103	1975	6	106	1990	6	102	1995?	7
A_{MHW} (km^2)	112±2	~2000	8						

A_{MLW} (km^2)	21	1650	6	24	1750	6	22	1860	6
A_{MLW} (km^2)	21	1912	6	25	1930	6	26	1960	6
A_{MLW} (km^2)	20	1975	6	32	1990	6	28±6	~2000	7
A_{cross} (m^2)	15500	1966	9	14940	1975	9	14375	1990	9
A_{cross} (m^2)	15500	1994	9	15500	2001	9	15000	2005	9
A_{cross} (m^2)	15250	2010	9	15750	2012	9			
P (10^6 m^3)	134	1650	6 (Pbat maps)	132	1750	6 (Pbat maps)	136	1860	6 (Pbat maps)
P (10^6 m^3)	143	1912	6 (Pbat maps)	156	1930	6 (Pbat maps)	192	1935	10 (Pbat)
P (10^6 m^3)	177	1958	10 (Pbat)	152	1960	6 (Pbat maps)	172	1960	9 (Pbat, mean tidal range)
P (10^6 m^3)	181	1975	9 (Pbat, mean tidal range)	156	1975	6 (Pbat maps)	195	1990	9 (Pbat, mean tidal range)
P (10^6 m^3)	189	1994	9 (Pbat, mean tidal range)	188	2001	9 (Pbat, mean tidal range)	205± 35	~2000	8 (Pmod)
P (10^6 m^3)	183 (167-199)	2004-2005	11 Pcom (giving flood resp. ebb vol-ume)	179	2005	9 (Pbat, mean tidal range)	177	2010	9 (Pbat, mean tidal range)
P (10^6 m^3)	176	2012	9 (Pbat, mean tidal range)						
$SV_{ebbdelta}$ (10^6 m^3)	60	1936	9 (fixed reference profile)	54	1955	9 (fixed reference profile)	51	1960	9 (fixed reference profile)
$SV_{ebbdelta}$ (10^6 m^3)	58	1964	9 (fixed reference profile)	50	1971	9 (fixed reference profile)	53	1975	9 (fixed reference profile)
$SV_{ebbdelta}$ (10^6 m^3)	48	1979/80	9 (fixed reference profile)	17	1982	9 (fixed reference profile)	40	1990	9 (fixed reference profile)
$SV_{ebbdelta}$ (10^6 m^3)	26	1992	9 (fixed reference profile)	24	1995	9 (fixed reference profile)	34	1998	9 (fixed reference profile)
$SV_{ebbdelta}$ (10^6 m^3)	44	2001	9(fixed reference profile)	50	2004	9 (fixed reference profile)	47	2006	9 (fixed reference profile)
$SV_{ebbdelta}$ (10^6 m^3)	43	2007	9 (fixed reference profile)	54	2008	9 (fixed reference profile)			
$AS_{backbarrier}$ (10^6 m^3/yr)									
$AS_{ebbdelta}$ (10^6 m^3/yr)	0.6	1990-2004/6	9						
Longshore drift (10^6 m^3/yr)	+1.3	1990-2012 & 2006-2009	2	+1.2 to 1.4	1990-2012 & 2006-2009	2 (stations Elbe & Schiermonnikoog)			
Sediment transport direction?	E								
Development island coasts	E Juist more or less stable; Erosion NW Norderney; Sedimentation more to the E								

1 = Jensen & Mudersbach, 2007; 2 = Ridderinkhof, 2016; 3 = BSH, 2016; 4 = Ladage & Stephan, 2004; 5 = Sha, 1989; 6 = Niemeyer, 1995; 7 = Ferk, 1995; 8 = Stanev et al., 2003 (± = indicating neap and spring tide conditions); 9 = Meyer, 2014; 10 = Meyer & Stephan, 2000 (shifting tidal heights); 11 = Herrling, 2014.

Extended Table 6.4: Facts and figures Wichter Ee

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2.0	1891 - 2001	1 (station Norderney)						
MHWR (mm/yr)	2.2	1891 - 2001	1 (station Norderney)						
MLWR (mm/yr)	1.4	1891 - 2001	1 (station Norderney)						
MTRI (mm/yr)	1.2	1891 - 2001	1 (station Norderney)						
Hs (m)	1.19		CoastDat	1.07	2006 – 2009	2 (stationElbe)	1.07 & - 1.18	2006-2009 & 1990-2012	2 (stations Elbe & Schiermonnikoog)
Tp (s)	5.6		CoastDat	5.75	2006 – 2009	2 (station Elbe)	5.75 & 5.77	2006-2009 & 1990-2012	2 (stations Elbe & Schiermonnikoog)
Tf/Te	0.89	2017 (2 tidal cycles of 3 jan)	3 (station Baltrum, Westende)						
MHW (m NHN)	1.3	2017	3 (station Baltrum, Westende)						
MLW (m NHN)	-1.2	2017	3 (station Baltrum, Westende)						
MTR (m)	2.4	1982	4	2.5	2017	3 (station Baltrum, Westende)			
$L_{ebbdelta}$ (km)	2.5	2012	-6 m	4.5	2012	-10m	1.7	1989	5
Surge height (m to MSL)									
Mean annual max surge height (m to AOD)	2.81		CoastDat						
A_{MHW} (km^2)	54	1650	6	49	1750	6	39	1860	6
A_{MHW} (km^2)	30	1912	6	31	1930	6	27	1960	6
A_{MHW} (km^2)	26	1975	6	23	1990	6	23	1995	5
A_{MHW} (km^2)	22 ±0	~2000	7						
A_{MLW} (km^2)	10	1650	6	9	1750	6	4	1860	6
A_{MLW} (km^2)	2	1912	6	3	1930	6	4	1960	6
A_{MLW} (km^2)	2	1975	6	3	1990	6	3 ±1	~2000	7
A_{cross} (m^2)	3800	1950	8	3580	1962	8	2960	1975	8
A_{cross} (m^2)	3560	1979	8	2940	1982	8	3515	1986	8
A_{cross} (m^2)	3310	1988	8	3225	1990	8	3280	1992	8
A_{cross} (m^2)	2830	1995	8	2935	1996	8	3130	1998	8
A_{cross} (m^2)	3300	1999	8	3300	2001	8	2960	2004	8
V_{MHW} (10^6 m^3)	37±6	~2000	7						
V_{MLW} (10^6 m^3)	6±1	~2000	7						
P (10^6 m^3)	66	1650	6 (Pmap)	63	1750	6 (Pmap)	49	1860	6 (Pmap)
P (10^6 m^3)	37	1912	6 (Pmap)	40	1930	6 (Pmap)	37	1960	6 (Pmap)
P (10^6 m^3)	36	1975	6 (Pmap)	42	1982	4	32	1990	6 (Pmap)
P (10^6 m^3)	35±4	~2000	7 (Pcom)	35 (31-38)	2004-2005	8 (Pcom) (flood- resp. ebb volume)			
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebbdelta}$ (10^6	15	1950	8	11	1965	8	9	1973	8

m^3)									
$SV_{ebbdelta}$ (10^6 m^3)	11	1975	8	10	1979	8	10,5	1982	8
$SV_{ebbdelta}$ (10^6 m^3)	6	1986	8	4	1988	8	3	1992	8
$SV_{ebbdelta}$ (10^6 m^3)	1	1995	8	7	1998	8	9	2001	8
$SV_{ebbdelta}$ (10^6 m^3)	10	2004	8						
$AS_{backbarrier}$ ($10^6 m^3/yr$)									
$AS_{ebbdelta}$ ($10^6 m^3/yr$)	0.5	1988/92-2004	8						
Longshore drift (10^6 m^3/yr)	+1.2	1990-2012 & 2006-2009	2	+1 to +1.4	1990-2012 & 2006-2009	2 (stations Elbe & Schiermon-nikoog			
Sediment transport direction?	E								
Development island coasts	Erosion of W Baltrum; extension of E Norderney.								

1 = Jensen & Mudersbach, 2007; 2 = Ridderinkhof, 2016; 3 = BSH, 2016; 4 = Postma, 1982; 5 = Sha, 1989; 6 = Niemeyer, 1995; 7 = Stanev et al., 2003 (± indicating neap and spring tide conditions); 8 = Herrling, 2014.

Extended Table 6.5: Facts and figures Accumer Ee

Parameter		Year	Reference		Year	Reference		Year	Reference
MSLR (mm/yr)	2.0	1891 - 2001	1 (station Norderney)						
MHWR (mm/yr)	2.2	1891 - 2001	1 (station Norderney)						
MLWR (mm/yr)	1.4	1891 - 2001	1 (station Norderney)						
MTRI (mm/yr)	1.2	1891 - 2001	1 (station Norderney)						
Hs (m)	1.19		CoastDat	1.07	2006 – 2009	2 (stationElbe)	1.07 & - 1.18	2006-2009 & 1990-2012	2 (stations Elbe & Schiermonnikoog)
Tp (s)	5.6		CoastDat	5.75	2006 – 2009	2 (station Elbe)	5.75 & 5.77	2006-2009 & 1990-2012	2 (stations Elbe & Schiermonnikoog)
Tf/Te	1.00	2017 (2 tidal cycles of 3 jan)	3 (station Langeoog)						
MHW (m NHN)	1.4	2017	3 (station Langeoog)						
MLW (m NHN)	-1.3	2017	3(station Langeoog)						
MLWS									
MTR (m)	2.6	1982	4	2.7	2017	3 (station Langeoog)			
$L_{ebbdelta}$ (km)	4.5	2012	-6 m	5.5	2012	-10m	3.6	1989	5
Surge height (m to MSL)									
Mean annual max surge height (m to AOD)	2.83		CoastDat						
A_{MHW} (km^2)	100	1650	6	100	1750	6	87	1860	6
A_{MHW} (km^2)	89	1912	6	90	1930	6	92	1960	6
A_{MHW} (km^2)	94	1975	6	102	1990	6	92	1995?	7
A_{MHW} (km^2)	89 ±2	~2000	8						
A_{MLW} (km^2)	20	1650	6	20	1750	6	16	1860	6
A_{MLW} (km^2)	18	1912	6	13	1930	4	24	1960	6
A_{MLW} (km^2)	20	1975	6	25	1990	6	22 ±3	~2000	8
A_{cross} (m^2)									
A_{cross} (m^2)									
A_{cross} (m^2)									
V_{MHW} (10^6 m^3)	209±23	~2000	8						
V_{MLW} (10^6 m^3)	62±5	~2000	8						
Sedimentation backbarrier area (10^6 m^3)									
P (10^6 m^3)	132	1650	6 (Pmap)	137	1750	6 (Pmap)	124	1860	6 (Pmap)
P (10^6 m^3)	129	1912	6 (Pmap)	127	1930	6 (Pmap)	145	1960	6 (Pmap)
P (10^6 m^3)	148	1975	6 (Pmap)	135	1982	4	158	1990	6 (Pmap)
P (10^6 m^3)	147±28	~2000	8 (Pcom)	175 (172-178)	2004-2005	9 (Pcom) (flood resp. ebb volume)			
$SV_{backbarrier}$ (10^6 m^3)									

$SV_{ebbdelta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)									
$AS_{ebbdelta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	+1.2	1990-2012 & 2006-2009	2	+1.1 to +1.4	1990-2012 & 2006-2009	2 (stations Elbe & Schiermonnikoog)			
Sediment transport direction?	E								
Development island coasts	Extension of E Baltrum; Sedi-mentation on Langeoog								

1 = Jensen & Mudersbach, 2007; 2 = Ridderinkhof, 2008; 3 = BSH, 2016; 4 = Postma, 1982; 5 = Sha, 1989; 6 = Niemeyer, 1995; 7 = Ferk, 1995; 8 = Stanev et al., 2003 (± indicating neap and spring tide conditions); 9 = Herrling, 2014.

Extended Table 6.6: Facts and figures Otzumer Balje

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2.0	1891 - 2001	1 (station Norderney)	0.3	1903 - 2001	1 (station Alte Weser)			
MHWR (mm/yr)	2.2	1891 - 2001	1 (station Norderney)	1.2	1903 - 2001	1 (station Alte Weser)			
MLWR (mm/yr)	1.4	1891 - 2001	1 (station Norderney)	-0.7	1903 - 2001	1 (station Alte Weser)			
MTRI (mm/yr)	1.2	1891 - 2001	1 (station Norderney)	1.9	1903 - 2001	1 (station Alte Weser)			
Hs (m)	1.19		CoastDat	1.07	2006 – 2009	2 (stationElbe)	1.07 & -1.18	2006-2009 & 1990-2012	2 (stations Elbe & Schiermonni-koog)
Tp (s)	5.44		CoastDat	5.75	2006 – 2009	2 (station Elbe)	5.75 & 5.77	2006-2009 & 1990-2012	2 (stations Elbe & Schiermonni-koog)
Tf/Te	0.96	2017 (2 tidal cycles of 3 jan)	3 (station Spiek-eroog)						
MHW (m NHN)	1.4	2017	3 (station Spiek-eroog)						
MLW (m NHN)	-1.3	2017	3 (station Spiek-eroog)						
MLWS									
MTR (m)	2.68	1982	4	2.71	2000 - 2004	5	2.7	2017	3 (station Spiek-eroog)
$L_{ebbdelta}$ (km)	4.2	2012	-6 m	5	2012	-10m	5.1	2006	5
Surge height (m to MSL)									
Mean annual max surge height (m to AOD)	2.89		CoastDat						
A_{MHW} (km^2)	57	1650	6	51	1750	6	78	1860	6
A_{MHW} (km^2)	77	1912	6	74	1930	6	78	1960	6
A_{MHW} (km^2)	75	1975	6	74	1990	6	74	1995?	7
A_{MHW} (km^2)	70 ±2	~2000	8						
A_{MLW} (km^2)	10	1650	6	9	1750	6	14	1860	6
A_{MLW} (km^2)	15	1912	6	11	1930	6	23	1960	6
A_{MLW} (km^2)	16	1975	6	27	1990	6	17 ±3	~2000	8
A_{cross} (m^2)	12568	1951	5	10554	1957	5	11903	1960	5
A_{cross} (m^2)	12315	1965	5	11796	1973	5	11718	1975	5
A_{cross} (m^2)	11588	1975 after storm surge	5	12457	1977	5	12204	1979	5
A_{cross} (m^2)	10586	1982	5	10062	1985	5	10427	1986	5
A_{cross} (m^2)	11749	1988	5	11432	1989	5	12121	1990	5
A_{cross} (m^2)	11775	1992	5	1183	1995	5	12136	1998	5

				4					
A_{cross} (m^2)	12151	2001	5	1206 6	2004	5			
V_{MHW} (10^6 m^3)	167±1 7	~2000	8						
V_{MLW} ($10^6 m^3$)	43±4	~2000	8						
P ($10^6 m^3$)	77	1650	6 (Pmap)	72	1750	6 (Pmap)	115	1860	6 (Pmap)
P ($10^6 m^3$)	116	1912	6 (Pmap)	108	1930	6 (Pmap)	138	1960	5 (Pbat)
P ($10^6 m^3$)	140	1975	5 (Pbat)	151	1985	5 (Pbat)	152	1989	5 (Pbat)
P ($10^6 m^3$)	150	1995	5 (Pbat)	151	1998	5 (Pbat)	124±2 1	~2000	8 (Pcom)
P ($10^6 m^3$)	141	2001	5 (Pbat)	151	2005	5 (Pbat)	158 (156-160)	2004-2005	9 (Pcom) (flood resp. ebb vol-umes)
$SV_{backbarrier}$ ($10^6 m^3$)									
$SV_{ebbdelta}$ (10^6 m^3)									
$SV_{ebbdelta}$ (10^6 m^3)	35	1951	5	43	1957	5	41	1965	5
$SV_{ebbdelta}$ (10^6 m^3)	39	1973	5	42	1975	5	35	1979	5
$SV_{ebbdelta}$ (10^6 m^3)	33	1982	5	31	1985	5	22	1988/8 9	5
$SV_{ebbdelta}$ (10^6 m^3)	18	1992	5	13	1995	5	28	1998	5
$SV_{ebbdelta}$ (10^6 m^3)	37	2001	5	38	2004	5			
$AS_{backbarrier}$ ($10^6 m^3$/yr)	ca. 0.1	1989-2005	5						
$AS_{ebbdelta}$ (10^6 m^3/yr)	1.1	1988/92 -2004	5						
Longshore drift (10^6 m^3/yr)	+1.1	1990-2012 & 2006-2009	2	+1.1 to +1.4	1990 - 2012 & 2006 - 2009	2 (stations Elbe & Schiermonni-koog)			
Sediment transport direction?	E								
Develop-ment island coasts	Growth E side Langeoog; Growth W side Spiekeroog								

1 = Jensen & Mudersbach, 2007; 2 = Ridderinkhof et al., 2016; 13 = BSH, 2016; 4 = Postma, 1982; 5 = Ladage et al., 2006; with reference to MTR of the year; 6 = Niemeyer, 1995; 7 = Ferk, 1995; 8 = Stanev et al., 2003; 9 = Herrling, 2014.

Extended Table 6.7: Facts and figures Seegat Harle

Parameter		Year	Reference		Year	Reference		Year	Reference
MSLR (mm/yr)	2.0	1891 - 2001	1 (station Norderney)	0.3	1903 - 2001	1 (station Alte Weser)	2.4	1960-2003	2 (= (MWHR + MLWR)/2
MHWR (mm/yr)	2.2	1891 - 2001	1 (station Norderney)	1.2	1903 - 2001	1 (station Alte Weser)	4.4	1960-2003	2 (station Wangerooge West)
MLWR (mm/yr)	1.4	1891 - 2001	1 (station Norderney)	-0.7	1903 - 2001	1 (station Alte Weser)	-0.4	1960-2003	2 (station Wangerooge West)
MTRI (mm/yr)	1.2	1891 - 2001	1 (station Norderney)	1.9	1903 - 2001	1 (station Alte Weser)	2.0	1960-2003	2 (= (MWHR - MLWR)/2
Hs (m)	1.14		CoastDat	1.07	2006 – 2009	3 (stationElbe)	1.07 & -1.18	2006-2009 & 1990-2012	3 (stations Elbe & Schiermonni-koog)
Tp (s)	5.32		CoastDat	5.75	2006 – 2009	3 (station Elbe)	5.75 & 5.77	2006-2009 & 1990-2012	3 (stations Elbe & Schiermonni-koog)
Tf/Te	0.92	2017 (2 tidal cycles of 3 jan)	4 (station Wangeroog e West)						
MHW (m NHN)	+1.45	2000 (long term aver-age)	2 (station Wangeroog e West)	1.5	2017	4 (station Wangerooge West)			
MLW (m NHN)	-1.42	2000 (long term aver-age)	2 (station Wangeroog e West)	-1.5	2017	4 (station Wangerooge West)			
MTR (m)	2.73	1960	2 (station Wangeroog e West)	2.87	2000 (long term aver-age)	2 (station Wangerooge West)	2.88	2003	2 (station Wangerooge West)
MTR (m)	2.9	2017	4 (station Wangeroog e West)						
$L_{ebbdelta}$ (km)	3.8	1950	2 (NHN -6m)	3.2	1976	2 (NHN -6m)	3.6	1987-2002	2 (NHN -6m)
$L_{ebbdelta}$ (km)	2.6	1989	5	3.1	2012	-6 m	4	2012	-10m
Surge height (m to MSL)									
Mean annu-al max surge height (m to AOD)	2.95		CoastDat						
A_{MHW} (km^2)	156	1650	6	132	1750	6	81	1860	6
A_{MHW} (km^2)	66	1912	6	75	1930	6	64	1960	6
A_{MHW} (km^2)	64	1975	6	68	1990	6	65	1995?	7
A_{MHW} (km^2)	65 ±1	~2000	4						
A_{MLW} (km^2)	35	1650	6	24	1750	6	15	1860	6
A_{MLW} (km^2)	16	1912	6	13	1930	6	16	1960	6
A_{MLW} (km^2)	13	1975	6	15	1990	6	13±3	~2000	8
A_{cross} (m^2)	10500	1950	2	9300	1975	2	11800	2002/03	2
V_{MHW} (10^6 m^3)	126±16	~2000	8						

V_{MLW} ($10^6 m^3$)	23±4	~2000	8						
P ($10^6 m^3$)	229	1650	6 (Pmap)	195	1750	6 (Pmap)	124	1860	6 (Pmap)
P ($10^6 m^3$)	108	1912	6 (Pmap)	117	1930	3 (Pmap)	111	1960	6 (Pmap)
P ($10^6 m^3$)	105	1975	6 (Pmap)				114	1990	6 (Pmap)
P ($10^6 m^3$)	104±29	~2000	8 (Pcom)	124 (118 -129	2004-2005	9 (Pcom) (flood resp. ebb volume)			
$SV_{backbarrier}$ ($10^6 m^3$)									
$SV_{ebbdelta}$ ($10^6 m^3$)	33	1950	2 (fixed reference profile)	40	1964	2 (fixed reference profile)	19	1995	2 (fixed reference profile)
$SV_{ebbdelta}$ ($10^6 m^3$)	23	2001	2 (fixed reference profile)						
$AS_{backbarrier}$ ($10^6 m^3/yr$)									
$AS_{ebbdelta}$ ($10^6 m^3/yr$)	-0.7	1964-2001	2						
Longshore drift ($10^6 m^3/yr$)	+1.0	1990-2012 & 2006-2009	3	+1.1 to +1.4	1990-2012 & 2006-2009	3 (stations Elbe & Schiermonnikoog)			
Sediment transport direction?	E								
Development island coasts	Growth & erosion E Spiekeroog NW Wangerooge stable								

1 = Jensen & Mudersbach, 2007; 2 = Ladage & Stephan, 2004; 3 = Ridderinkhof, 2016; 4 = BSH, 2016; 5 = Sha, 1989; 6 = Niemeyer, 1995, from reconstructions; 7 = Ferk, 1995; 8 = Stanev et al., 2003 (± indicating neap and spring tide conditions); 9 = Herrling, 2014;

Extended Table 6.8: Facts and figures Blaue Balje

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	2.0	1891 - 2001	1 (station Norderney)	0.3	1903 - 2001	1 (station Alte Weser)	2.4	1960-2003	2 (= (MWHR + MLWR)/2
MHWR (mm/yr)	2.2	1891 - 2001	1 (station Norderney)	1.2	1903 - 2001	1 (station Alte Weser)	4.4	1960-2003	2 (station Wangerooge West)
MLWR (mm/yr)	1.4	1891 - 2001	1 (station Norderney)	-0.7	1903 - 2001	1 (station Alte Weser)	-0.4	1960-2003	2 (station Wangerooge West)
MTRI (mm/yr)	1.2	1891 - 2001	1 (station Norderney)	1.9	1903 - 2001	1 (station Alte Weser)	2.0	1960-2003	2 (= (MWHR - MLWR)/2
Hs (m)	0.93		CoastDat	1.07	2006-2009	3 (station Elbe)	1.07 & -1.18	2006-2009 & 1990-2012	3 (stations Elbe & Schiermonni-koog)
Tp (s)	4.97		CoastDat	5.75	2006 – 2009 & 2006-2009	3 (station Elbe)	5.75 & 5.77	2006-2009 & 1990-2012	3 (stations Elbe & Schiermonni-koog)
Tf/Te	0.85	2016	2 (station Wangerooge Ost)						
MHW (m NHN)	1.5	2016	2 (station Wangerooge Ost)						
MLW (m NHN)	-1.5	2016	2 (station Wangerooge Ost)						
MTR (m)	2.9	1982	4	3.0	2016	2 (station Wangerooge Ost)			
$L_{ebbdelta}$ (km)	2.2	2012	-6 m	2.3	2012	-10m	2.2	2001	5
Surge height (m to MSL)									
Mean annual max surge height (m to AOD)	3.1		CoastDat						
A_{MHW} (km^2)	40	1995?	6	39 ±0	~2000	7			
A_{MLW} (km^2)	8 ±2	~2000	7						
A_{cross} (m^2)									
A_{cross} (m^2)									
A_{cross} (m^2)									
V_{MHW} (10^6 m^3)	80±10	~2000	7						
V_{MLW} (10^6 m^3)	12±2	~2000	7						
P (10^6 m^3)	68±12	~2000	7 (Pcom)	70 (68-72)	2004-2005	8 (Pcom) (flood resp. ebb volume)			
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebbdelta}$ (10^6 m^3)									

$AS_{backbarrier}$ (10^6 m^3/yr)									
$AS_{ebbdelta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	+1	1990-2012 & 2006-2009	3 (taken from Harle)	+1.1 to +1.4	1990-2012 & 2006-2009	3 (stations Elbe & Schiermonni-koog)			
Sediment transport direction?	E?								
velopment island coasts	Relatively stable on both sides of inlet								

1 = Jensen & Mudersbach, 2007; 2 = BSH, 2016; 3 = Ridderinkhof, 2016; 4 = Postma, 1982; 5 = Sha, 1989; 6 = Ferk, 1995; 7 = Stanev et al., 2003 (± indicating neap and spring tide conditions); 8 = Herrling, 2014.

Extended Table 7.1: Facts and figures Hever in total. Please note that Norderhever + Heverstrom is a bigger area than the two separate because van Riesen & Winskowsky(2007) did not measure the whole area.

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2	1940-2010	1 (station Husum)						
MHWR (mm/yr)	4	1940-2010	1 (station Husum)						
MLWR (mm/yr)	0.1	1940-2010	1 (station Husum)						
MTRI (mm/yr)	3.9	1940-2010	1 (station Husum)						
Hs (m)	1.33		CoastDat	1.06	2006 - 2009	2 (station Helgoland)	1.02 & 1.06	2006 – 2009 & 2009-2009	2 (stations Sylt & Helgoland)
Tp (s)	5.43		CoastDat	5.91	2006 - 2009	2 (station Helgoland)	6.64 & 5.91	2006 - 2009	2 (station Helgoland)
Tf/Te	0.85	2017 (2 tidal cycles of 3 jan)	3 (station Süderoogsand)						
MHW (m NHN)	1.4	2017	3 (station Süderoogsand)						
MLW (m NHN)	-1.5	2017	3 (station Süderoogsand)						
MTR (m)	2.9	2017	3 (station Süderoogsand)						
$L_{ebbdelta}$ (km)	6.1	2012	-6 m	15.1	2012	-10m			
Surge height (m to MSL)	25 y: 5.41	???	1 (station Husum)	50 y: 5.67	???	1 (station Husum)			
Surge height (m to MSL)	100 y: 5.91	???	1 (station Husum)	250 y: 6.19	???	1 (station Husum)	500 y: 6.38)	???	1 (station Husum)
Mean annual max surge height (m to AOD)	2.81		CoastDat						
A_{MHW} (km^2)	441.8	1974/76	4						
A_{MLW} (km^2)	139.9	1974/76	4						
A_{cross} (m^2)	65031	1974/76	4						
V_{MHW}	1780	1974/76	4						
V_{MLW} (10^6 m^3)	899	1974/76	4						
P (10^6 m^3)	881	1974/76	4						
$SV_{backbarrier}$ (10^6 m^3)	504.3	1974/76	4						
$SV_{ebbdelta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	3.8	1990-2000	5						
$AS_{ebbdelta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	-1.4	2006-2009	2	-1.3 to -1.5 Hever	2006-2009 & 2006-2009	2 (stations Sylt & Helgoland)			
Sediment transport direction?									

Development island coasts	Sedimentation at St. Peter-Ording-Sand; Sedimentation S Süderoogsand						

1 = MELUR, 2013; 2 = Ridderinkhof, 2016; 3 = BSH, 2016; 4 = Floser et al., 2011; 5 = van Riesen & Winskowsky, 2007

Extended Table 7.2: Facts and figures Heverstrom

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2	1940-2010	1 (station Husum)						
MHWR (mm/yr)	4	1940-2010	1 (station Husum)						
MLWR (mm/yr)	0.1	1940-2010	1 (station Husum)						
MTRI (mm/yr)	3.9	1940-2010	1 (station Husum)						
Hs (m)	1.33		CoastDat	1.06	2006 - 2009	2 (station Helgoland)	1.02 & 1.06	2006 – 2009 & 2009-2009	2 (stations Sylt & Helgoland)
Tp (s)	5.43		CoastDat	5.91	2006 - 2009	2 (station Helgoland)	6.64 & 5.91	2006 - 2009	2 (station Helgoland)
Tf/Te	0.85	2017 (2 tidal cycles of 3 jan)	3 (station Süderoogsand)						
MHW (m NHN)	1.4	2017	3 (station Süderoogsand)						
MLW (m NHN)	-1.5	2017	3 (station Süderoogsand)						
MLWS									
MTR (m)	2.9	2017	3 (station Süderoogsand)						
Surge height (m to MSL)	25 y: 5.41	???	1 (station Husum)	50 y: 5.67	???	1 (station Husum)			
Surge height (m to MSL)	100 y: 5.91	???	1 (station Husum)	250 y: 6.19	???	1 (station Husum)	500 y: 6.38)	???	1 (station Husum)
Mean annual max surge height (m to AOD)	2.81		CoastDat						
A_{MHW} (km^2)	135.3	1936	4	135.3	1960	4		1974/76	5
A_{MHW} (km^2)	135.3	1981	4	135.3	1990	4	135.3	2000	4
A_{MLW} (km^2)		1974/76	5						
V_{MHW} (10^6 m^3)	481	1936	4 (Fixed MHW and MLW)	477	1960	4 (Fixed MHW and MLW)		1974/76	5
V_{MHW} (10^6 m^3)	466	1981	4 (Fixed MHW and MLW)	481	1990	4 (Fixed MHW and MLW)	463	2000	4 (Fixed MHW and MLW)
V_{MLW} (10^6 m^3)	205	1936	4 (Fixed MHW and MLW)	205	1960	4 (Fixed MHW and MLW)		1974/76	4 (Fixed MHW and MLW)
V_{MLW} (10^6 m^3)	193	1981	4 (Fixed MHW and MLW)	206	1990	4 (Fixed MHW and MLW)	203	2000	4 (Fixed MHW and MLW)
A_{cross} (m^2)									
P (10^6 m^3)	276	1936	4 (Pbat)	272	1960	4 (Pbat)	142	1974/76	5 (Pbat)
P (10^6 m^3)	273	1981	4 (Pbat)	272	1990	4 (Pbat)	260	2000	4 (Pbat)
$SV_{backbarrier}$ (10^6 m^3)				161	1960	4			
$SV_{backbarrier}$ (10^6 m^3)	160	1981	4	158	1990	4	173	2000	5
$SV_{ebbdelta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	1.8	1990-2000	4	0.6	1981-2000	4			
$AS_{ebbdelta}$ (10^6 m^3/yr)									

Longshore drift ($10^6 m^3/yr$)	-1.4	2006-2009	2	-1.3 to -1.5 Hever	2006-2009 & 2006-2009	2 (stations Sylt & Helgoland)			
Change ebb-delta?									
Sediment transport direction?									
Development island coasts	*Sedimentation at St. Peter-Ording-Sand*								

1 = MELUR, 2013; 2 = Ridderinkhof, 2016; 3 = BSH, 2016; 4= van Riesen & Winskowsky, 2007; 5 = Floser et al., 2011

Extended Table 7.3: Facts and figures Norderhever

Parameter	Obs	Year	Reference	Obs	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2	1940-2010	1 (station Husum)						
MHWR (mm/yr)	4	1940-2010	1 (station Husum)						
MLWR (mm/yr)	0.1	1940-2010	1 (station Husum)						
MTRI (mm/yr)	3.9	1940-2010	1 (station Husum)						
Hs (m)	1.33		CoastDat	1.06	2006 - 2009	2 (station Helgoland)	1.02 & 1.06	2006 – 2009 & 2009-2009	2 (stations Sylt & Helgoland)
Tp (s)	5.43		CoastDat	5.91	2006 - 2009	2 (station Helgoland)	6.64 & 5.91	2006 - 2009	2 (station Helgoland)
Tf/Te	0.85	2017 (2 tidal cycles of 3 jan)	3 (station Süderoogsand)						
MHW (m NHN)	1.4	2017	3 (station Süderoogsand)						
MLW (m NHN)	-1.5	2017	3 (station Süderoogsand)						
MLWS									
MTR (m)	2.9	2017	3 (station Süderoogsand)						
Surge height (m to MSL)	25 y: 5.41	???	1 (station Husum)	50 y: 5.67	???	1 (station Husum)			
Surge height (m to MSL)	100 y: 5.91	???	1 (station Husum)	250 y: 6.19	???	1 (station Husum)	500 y: 6.38)	???	1 (station Husum)
A_{MHW} (km^2)	118.9	1936	4	118.9	1960	4		1974/76	6
A_{MHW} (km^2)	118.9	1981	4	118.9	1990	4	118.9	2000	4
A_{MLW} (km^2)		1974/76	6						
V_{MHW} (10^6 m^3)	919	1936	4	927	1960	4		1974/76	6
V_{MHW} (10^6 m^3)	915	1981	4	935	1990	4	915	2000	4
V_{MLW} (10^6 m^3)	441	1936	4	457	1960	4		1974/76	4
V_{MLW} (10^6 m^3)	446	1981	4	466	1990	4	459	2000	4
A_{cross} .(m^2)		1974/76	6						
P (10^6 m^3)	478	1936	4 (Pbat)	470	1960	4 (Pbat)		1974/76	6 (Pbat)
P (10^6 m^3)	469	1981	4 (Pbat)	469	1990	4 (Pbat)	456	2000	4 (Pbat)
$SV_{backbarrier}$ (10^6 m^3)	85	1936	4	86	1960	4			
$SV_{backbarrier}$ (10^6 m^3)	84	1981	4	64	1990	10	72	2000	10
$SV_{ebbdelta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	2	1990-2000	4	-0.7	1981-2000	4			
$AS_{ebbdelta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	-1.4	2006-2009	2	-1.3 to -1.5 Hever	2006-2009 & 2006-2009	2 (stations Sylt & Helgoland)			
Change ebb-delta?									
Development island coasts	Sedimentation S Süderoogsand								

1 = MELUR, 2013; 2 = Ridderinkhof, 2016; 3 = BSH, 2016; 4 = van Riesen & Winskowsky, 2007; 5 = Floser et al., 2011.

Extended Table 7.4: Facts and figures Rummelloch-West

Parameter	Observ	Year	Reference	Observ	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	2.2	1940-2010	1 (station Wittdun)						
MHWR (mm/yr)	4.5	1940-2010	1 (station Wittdun)						
MLWR (mm/yr)	-0.2	1936-1990	1 (station Wittdun)						
MTRI (mm/yr)	4.3	1936-1990	1 (station Wittdun)						
Hs (m)	1.35		CoastDat	1.06	2006 - 2009	2 (station Helgoland)	1.02 & 1.06	2006 – 2009 & 2009-2009	2 (stations Sylt & Helgoland)
Tp (s)	5.44		CoastDat	5.91	2006 - 2009	2 (station Helgoland)	6.64 & 5.91	2006 - 2009	2 (station Helgoland)
Tf/Te	0.81	2017 (2 tidal cycles of 3 jan)	3 (Rum-meloch West)						
MHW (m NHN)	1.4	2017	3 (Rum-meloch West)						
MLW (m NHN)	-1.4	2017	3 (Rum-meloch West)						
MLWS									
MTR (m)	2.8	2017	3 (Rum-meloch West)						
$L_{ebbdelta}$ (km)	6.2	2012	-6 m	7	2012	-10m			
Surge height (m to MSL)	25 y: 5.41	???	1 (station Husum)	50 y: 5.67	???	1 (station Husum)			
Surge height (m to MSL)	100 y: 5.91	???	1 (station Husum)	250 y: 6.19	???	1 (station Husum)	500 y: 6.38)	???	1 (station Husum)
Mean annual max surge height (m to AOD)	2.81		CoastDat						
A_{MHW} (km^2)	93.1	1936	4	93.1	1960	4	83.7	1974/76	5
A_{MHW} (km^2)	95.5	1981	4	95.5	1990	4	95.5	2000	4
A_{MLW} (km^2)	17.6	1974/76	5						
A_{cross} under MLW (m^2)	7669	1974/76	5						
A_{cross} under MSL (m^2)	8996	1974/76	5						
A_{cross} under MHW (m^2)	11792	1974/76	5						
V_{MHW} ($10^6 m^3$)	252	1936	4 (Fixed MHW and MLW)	245	1960	4 (Fixed MHW and MLW)	197	1974/76	5
V_{MHW} ($10^6 m^3$)	235	1981	4 (Fixed MHW and MLW)	250	1990	4 (Fixed MHW and MLW)	251	2000	4 (Fixed MHW and MLW)
V_{MLW} ($10^6 m^3$)	72	1936	4 (Fixed MHW and MLW)	72	1960	4 (Fixed MHW and MLW)	55	1974/76	4 (Fixed MHW and MLW)
V_{MLW} ($10^6 m^3$)	64	1981	4 (Fixed MHW and MLW)	75	1990	4 (Fixed MHW and MLW)	79	2000	4 (Fixed MHW and MLW)
P ($10^6 m^3$)	180	1936	4 (Pbat)	174	1960	4 (Pbat)	142	1974/76	5 (Pbat)

P ($10^6 m^3$)	172	1981	4 (Pbat)	175	1990	4 (Pbat)	172	2000	4 (Pbat)
$SV_{backbarrier}$ ($10^6 m^3$)	99	1936	4	99	1960	4	25.4	1974/76	5
$SV_{backbarrier}$ ($10^6 m^3$)	121	1981	4	118	1990	4	122	2000	4
$SV_{ebbdelta}$ ($10^6 m^3$)									
$AS_{backabrrier}$ ($10^6 m^3/yr$)	-0.5	1968-1994	6 enlarge-ment of channels	0,5	1981-2000	4	0,1	1990-2000	4
$AS_{ebb-delta}$ ($10^6 m^3/yr$)									
Longshore drift ($10^6 m^3/yr$)	0	2006-2009	2	-0.2 to +0.2 (Norder- & Süderoogstrand)	2006-2009 & 2006-2009	2 (stations Sylt & Helgoland)			
Sediment transport direction?	landward								
Development island coasts	Sedimentation NW Süderoogsand; Sedimentation and erosion; SW Norderoogsand								

1 = MELUR, 2013; 2 = Ridderinkhof, 2016; 3 = BSH, 2016; 4 = van Riesen & Winskowsky, 2007 (calculated with fixed borders and tides from 1981 onwards new borders due to retreat Außensande); 5 = Floser et al., 2011; 6 = Hofstede and Spitta, 2000.

Extended Table 7.5 Facts and figures Hooger Loch

Parameter	Observ	Year	Reference	Observ	Year	Reference	Obs	Year	Reference
MSLR (mm/yr)	3	1936-1990	1 (station Wittdun)						
MHWR (mm/yr)	4.1	1936-1990	1 (station Wittdun)						
MLWR (mm/yr)	-1.1	1936-1990	1 (station Wittdun)						
MTRR (mm/yr)	5.2	1936-1990	1 (station Wittdun)						
Hs (m)				1.06	2006 - 2009	2 (station Helgoland)	1.02 & 1.06	2006 – 2009 & 2009-2009	2 (stations Sylt & Helgoland)
Tp (s)				5.91	2006 - 2009	2 (station Helgoland)	6.64 & 5.91	2006 - 2009	2 (station Helgoland)
Tf/Te									
MHW (m GNN)	1.4	2017	3 (Rum-meloch West)						
MLW (m GNN)	-1.4	2017	3 (Rum-meloch West)						
MLWS									
MTR (m)	2.8	2017	3 (Rum-meloch West)						
$L_{ebbdelta}$ (km)	3	2012	-6 m						
Surge height (m to MSL)	25 y: 4.23	??	1	50 y: 4.44	??	1			
Surge height (m to MSL)	100 y: 4.62	??	1	250 y: 4.85	??	1	500 y: 5.00	??	1
Mean annual max surge height (m to AOD)	2.76		CoastDat						
A_{MHW} (km^2)	22.3	1936	4	22.3	1960	4	22.3	1974/76	5
A_{MHW} (km^2)	17.8	1981	4	17.8	1990	4	17.8	2000	4
A_{MLW} (km^2)		1974/76	5						
A_{cross} under MLW (m^2)	1115	1974/76	5						
A_{cross} under MSL (m^2)	2038	1974/76	5						
A_{cross} under MHW (m^2)	4061	1974/76	5						
V_{MHW} (10^6 m^3)	35	1936	4	33	1960	4	22.8	1974/76	5
V_{MHW} (10^6 m^3)	23	1981	4	22	1990	4	20	2000	4
V_{MLW} (10^6 m^3)	1.6	1936	4	2.2	1960	4	1.5	1974/76	5
V_{MLW} (10^6 m^3)	1	1981	4	1.1	1990	4	0.6	2000	4
P (10^6 m^3)	33	1936	4 (Pbat)	31	1960	4 (Pbat)	21.3	1974/76	5 (Pbat)
P (10^6 m^3)	22	1981	4 (Pbat)	21	1990	4 (Pbat)	19	2000	4 (Pbat)
$SV_{backbarrier}$ (10^6 m^3)	46	1936	4	49	1960	4		1974/76	5
$SV_{backbarrier}$ (10^6 m^3)	31	1981	4	33	1990	4	34	2000	4

$SV_{ebbdelta}$ ($10^6 m^3$)									
$AS_{backbarrier}$ ($10^6 m^3$/yr)				0.2	1981-2000	4			
$AS_{ebbdeltar}$ ($10^6 m^3$/yr)									
Longshore drift (10^6 m^3/yr)	0	2006-2009 & 2009-2009	2	-0.2 to +0.2 (Norder- & Süderoogstrand)	2006-2009 & 2009-2009	2 (stations Sylt & Helgoland)			
Sediment transport direction?	Landward: Retreat of Japsand and Norder-oogsand								

1 = MELUR, 2013; 2 = Ridderinkhof, 2016; 3 = BSH, 2016; 4 = van Riesen & Winskowsky, 2007 (calculated with fixed borders and tides from 1981 onwards new borders due to retreat Außen-sande); 5 = Floser et al., 2011.

Extended Table 7.6: Facts and figures Süderaue

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	2.2	1940-2010	1 (station Wittdun)						
MHWR (mm/yr)	4.5	1940-2010	1 (station Wittdun)						
MLWR (mm/yr)	-0.2	1940-2010	1 (station Wittdun)						
MTRI (mm/yr)	4.3	1940-2010	1 (station Wittdun)						
Hs (m)	1.35		CoastDat	1.06	2006 - 2009	2 (station Helgoland)	1.02 & 1.06	2006 – 2009 & 2009-2009	2 (stations Sylt & Helgoland)
Tp (s)	5.44		CoastDat	5.91	2006 - 2009	2 (station Helgoland)	6.64 & 5.91	2006 - 2009	2 (station Helgoland)
Tf/Te	0.85	2017 (2 tidal cycles of 3 jan)	3 (average of Langeness, Hilligenley & Hooge, Anleger						
MHW (m NHN)	1.4	2017	3 (average of Langeness, Hilligenley & Hooge, Anleger						
MLW (m NHN)	-1.5	2017	3 (average of Langeness, Hilligenley & Hooge, Anleger						
MLWS									
MTR (m)	2.9	2017	3 (average of Langeness, Hilligenley & Hooge, Anleger						
Surge height (m to MSL)	25 y: 4.23	??	1	50 y: 4.44	??	1			
Surge height (m to MSL)	100 y: 4.62	??	1	250 y: 4.85	??	1	500 y: 5.00	??	1
Mean annual max surge height (m to AOD)	2.76		CoastDat						
A_{MHW} (km^2)	159.3	1936	4	159.3	1960	4			
A_{MHW} (km^2)	153.2	1981	4	53.2	1990	4	53.2	2000	4
A_{MLW} (km^2)	76,1	1974/76	5						
A_{cross} under MLW (m^2)	22005	1974/76	5						
A_{cross} under MSL (m^2)	25153	1974/76	5						
A_{cross} under MHW (m^2)	28944	1974/76	5						
V_{MHW} (10^6 m^3)	658.8	1936	4 (Fixed MHW and MLW)	670.4	1960	4 (Fixed MHW and MLW)	666,9	1974/76	5
V_{MHW} (10^6 m^3)	600	1981	4 (Fixed MHW and MLW)	610	1990	4 (Fixed MHW and MLW)	606	2000	4 (Fixed MHW and MLW)

V_{MLW} ($10^6 m^3$)	279	1936	4 (Fixed MHW and MLW)	293	1960	40 (Fixed MHW and MLW)	297	1974/76	5
V_{MLW} ($10^6 m^3$)	242	1981	4 (Fixed MHW and MLW)	253	1990	4 (Fixed MHW and MLW)	250	2000	4 (Fixed MHW and MLW)
P ($10^6 m^3$)	380	1936	4 (Pbat)	377	1960	4 (Pbat)	370	1974/76	5 (Pbat)
P ($10^6 m^3$)	358	1981	4 (Pbat)	357	1990	4 (Pbat)	357	2000	4 (Pbat)
$SV_{backbarrier}$ ($10^6 m^3$)	98	1936	4 (Pbat)	101	1960	4 (Pbat)			
$SV_{backbarrier}$ ($10^6 m^3$)	102	1981	10 (Pbat)	103	1990	10 (Pbat)	103	2000	10 (Pbat)
$SV_{ebbdelta}$ ($10^6 m^3$)									
$AS_{backbarrier}$ ($10^6 m^3/yr$)	0.1	1981-2000	4 (Pbat)						
$AS_{ebbdelta}$ ($10^6 m^3/yr$)									
Longshore drift (10^6 m3/yr)	-1.4	2006-2009	2	-1.3 to -1.5 Amrum	2006-2009 & 2006-2009	2 (stations Sylt & Helgoland)	-0.2 to +0.2 (Norder- & Süderoogstrand)	2006-2009 & 2009-2009	2 (stations Sylt & Helgoland)
Sediment transport direction?									
Development island coasts	Erosion N & W Japsand								

1 = MELUR, 2013; 2 = Ridderinkhof, 2016; 3 = BSH, 2016; 4 = van Riesen & Winskowsky, 2007 (calculated with fixed borders and tides from 1981 onwards new borders due to retreat Außen-sande); 5 = Floser et al., 2011.

Extended Table 7.7: Facts and figures Norderaue

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	2.2	1940-2010	1 (station Wittdun)						
MHWR (mm/yr)	4.5	1940-2010	1 (station Wittdun)						
MLWR (mm/yr)	-0.2	1940-2010	1 (station Wittdun)						
MTRI (mm/yr)	4.3	1940-2010	1 (station Wittdun)						
Hs (m)	1.39		CoastDat	1.06	2006 - 2009	2 (station Helgoland)	1.02 & 1.06	2006 – 2009 & 2009-2009	2 (stations Sylt & Helgoland)
Tp (s)	5.51		CoastDat	5.91	2006 - 2009	2 (station Helgoland)	6.64 & 5.91	2006 - 2009	2 (station Helgoland)
Tf/Te	0.87	2017 (2 tidal cycles of 3 jan)	3 (Amrum Hafen (Wittdün)						
MHW (m NHN)	1.2	2017	3 (Amrum Hafen (Wittdün)						
MLW (m NHN)	-1.4	2017	3 (Amrum Hafen (Wittdün)						
MLWS									
MTR (m)	2.7	2017	3 (Amrum Hafen (Wittdün)						
$L_{ebbdelta}$ (km)	11	2012	-6 m	17.1	2012	-10m			
Surge height (m to MSL)	25 y: 4.23	??	1	50 y: 4.44	??	1			
Surge height (m to MSL)	100 y: 4.62	??	1	250 y: 4.85	??	1	500 y: 5.00	??	1
Mean annual max surge height (m to AOD)	2.69		CoastDat						
A_{MHW} (km^2)	245,2	1974/76	4						
A_{MLW} (km^2)	94,4	1974/76	4						
A_{cross} (m^2)	42082	1974/76	4						
V_{MHW} (10^6 m^3)	914	1974/76	4						
V_{MLW} (10^6 m^3)	400,8	1974/76	4						
P (10^6 m^3)	513,2	1974/76	4						
$SV_{backbarrier}$ (10^6 m^3)	146,9	1974/76	4						
$SV_{ebbdelta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)									
$AS_{ebbdelta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	-1.4	2006-2009	2	-1.3 to -1.5 Amrum	2006-2009 & 2006-2009	2 (stations Sylt & Helgoland)	-0.2 to +0.2 (Norder- & Süderoogstrand)	2006-2009 & 2009-2009	2 (stations Sylt & Helgoland)
Sediment transport direction?	??								

Development island coasts	No clear development Amrum							

1 = MELUR, 2013; 2 = Ridderinkhof, 2016; 3 = BSH, 2016; 4 = Floser et al., 2011.

Extended Table 7.8: Facts and figures Hörnum Tief

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	2.0	1940-2010	1 (station Sylt)	1.4 mm/yr (Hörnum)	1939-1994	1			
MHWR (mm/yr)	4.0	1940-2010	1 (station Sylt)						
MLWR (mm/yr)	0.1	1940-2010	1 (station Sylt)						
MTRI (mm/yr)	3.9	1940-2010	1 (station Sylt)						
Hs (m)	1.40		CoastDat	1.02	2006 - 2009	2 (station Sylt)	1.02 & 1.06	2006 – 2009 & 2009-2009	2 (stations Sylt & Helgoland)
Tp (s)	5.60		CoastDat	6.64	2006 - 2009	2 (station Sylt)	6.64 & 5.91	2006 - 2009	2 (station Helgoland
Tf/Te	0.79		5	0.8	2017 (2 tidal cycles of 3 jan)	3 station Hörnum West)			
MHW (m NHN)	0.7	1939	4,5 (station Hörnum West)	0.91 (	1998	5 (station Hörnum West)	1.0	2017	3 (station Hörnum West)
MLW (m NHN)	-1.08	1939	4,5 (station Hörnum West)	-1.08	1998	5 (station Hörnum West)	-1.1	2017	3 (station Hörnum West)
MTR (m)	1.78	1939	4,5 (station Hörnum West)	1.61	1970	1	2.08	1998	5 (station Hörnum West)
MTR (m)	2.1	2017	3 (station Hörnum West)						
$L_{ebbdelta}$ (km)	7.3	2012	-6 m	7.7	2012	-10m			
Surge height (m to MSL)	25 y: 4.01	??	1	50 y: 4.2	??	1			
Surge height (m to MSL)	100 y: 4.37	??	1	250 y: 4.58	??	1	500 y: 4.72	??	1
Mean annual max surge height (m to AOD)	2.61		CoastDat						
A_{MHW} (km^2)				290,2	1974/76	6			
A_{MLW} (km^2)				152.9	1974/76	6			
A_{cross} (m^2)	33.671	1939	4	35.834	1949	4	32.827	1959	4
A_{cross} (m^2)	34.420	1968	4	38.891	1978	4	41.188	1987	4
A_{cross} (m^2)	44.318	1994	4						
V_{MHW} (10^6 m^3)				936.3	1974/76	6			
V_{MLW} (10^6 m^3)				408.9	1974/76	6			
P (10^6 m^3)	509.9	1952	7	527.5	1974/76	6,7			
$SV_{ebbdelta}$ (10^6 m^3)	483.2	1939	4	466.4	1959	4	487.1	1968	4
$SV_{ebbdelta}$ (10^6 m^3)	474.7	1978	4	412.6	1987	4	397.1	1994	4
$AS_{backbarrier}$ (10^6 m^3/yr)									
$AS_{ebbdelta}$ (10^6 m^3/yr)				-3.5	1968-1994	4			
Longshore drift (10^6 m^3/yr)	-0.4	2006-2009 & 2006-2009	2	-0.3 to -0.6 Sylt	2006-2009 & 2006-2009	2 (stations Sylt & Helgoland)			
Sediment									

transport direction?									
Development island coasts	Erosion S Sylt and N Amrum								

1 = MELUR, 2013; 2 = Ridderinkhof, 2016; 3 = BSH, 2016; 4 = Hofstede, 1999 & Hofstede and Spitta, 2000; 5 = Daul et al., 2006; 6 = Floser et al., 2011; 7 = Witez et al., 1984.

Extended Table 8.1: Facts and figures Lister Dyb

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.2	1940-2010	1 (station List)	1.4 mm/yr	1889-2006	2 (station Esbjerg)			
MHWR (mm/yr)	2.9	1940-2010	1 (station List)						
MLWR (mm/yr)	0.6	1940-2010	1 (station List)						
MTRR (mm/yr)	2.6	1940-2010	1 (station List)						
Hs (m)	1.47		CoastDat	1.04	1998-2007	3 (station Fanø Bugt)	1.04 & 1.02	1998-2007 & 2006-2009	3 (stations Fanø Bugt & Sylt)
Tp (s)	5.80		CoastDat	6.64	2006 - 2009	3 (station Sylt)	5.65 & 6.04	1998-2007 & 2006-2009	3 (stations Fanø Bugt & Sylt)
Tf/Te	0.83		4	0.87	2017 (2 tidal cycles of 3 jan)	5 (station List West)			
MHW (m to DVR90)	0.76	1970	6 (station Havneby)	0.85	2001	6 (station Havneby)			
MLW (m to DVR90)	-0.85	1970	6 (station Havneby)	-0.86	2003	6 (station Havneby)			
MHW (m to NHN)							0.7	2017	5 (station List West)
MLW (m to NHN)							-0.9	2017	5 (station List West)
MLWS									
MTR (m)	1.61	1970	1	1.71	2001	1	1.7	2017	5 (station List West)
$L_{ebbdelta}$ (km)	10	2012	-6 m	11	2012	-10m			
Surge height (m to MSL)	25 y: 3.93	??	1	50 y: 4.13	??	1			
Surge height (m to MSL)	100 y: 4.30	??	1	250 y: 4.51	??	1	500 y: 4.66	??	1
Mean annual max surge height (m to AOD)	2.26		CoastDat						
A_{MHW} (km^2)	402.8	1968	6	394.6	1994	6			
A_{MLW} (km^2)	205.5	1968	6	209.6	1994	6			
A_{cross} (m^2)	38,192	1968	6	38,332	1994	6			
V_{MHW} (10^6 m^3)									
V_{MLW} (10^6 m^3)									
P (10^6 m^3)	593	1968	6 (Pbat)	627	1994	6 (Pbat)			
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebbtidal}$ (10^6 m^3)	300 (calculated)	1994	6						
$AS_{backbarrier}$ (10^6 m^3/yr)	-0.5 (-1.3_+0.3)	1968-1994	6						
$AS_{ebbdelta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	+1.1	2006-2009 & 1998-2007	3 (stations Sylt & Fanø)	-0.5 to +0.6 Rømø	2006-2009 & 1998-2007	3 (stations Sylt & Fanø)	+0.8 to +1.3 Sylt	2006-2009 & 1998-2007	3 (stations Sylt & Fanø)
Sediment transport direction?	N ward	1989-2013	3						
Development island coasts	Expansion of Rømø, retreat of Sylt								

1 = MELUR, 2013; 2 = Kystdirektoratet, 2012; 3= Ridderinkhof, 2016; 4 = Daul et al., 2006; 5 = BSH, 2016; 6 = Kystinspektoratet, 1999.

Extended Table 8.2: Facts and figures Juvre Dyb

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.35 mm/yr	1889-2006	1 (station Esbjerg)	4 mm/yr	1972-2007	1 (station Esbjerg)	5 mm/yr	1993-2003	1 (station Esbjerg)1
Hs (m)	1.42		CoastDat	1.04	1998-2007	2 (station Fanø Bugt)	1.04 & 1.02	1998-2007 & 2006-2009	2 (stations Fanø Bugt & Sylt)
Tp (s)	5.65		CoastDat	5.65	1998-2007	2 (station Fanø Bugt)	5.65 & 6.04	1998-2007 & 2006-2009	2 (stations Fanø Bugt & Sylt)
Tidal asymmetry (Degrees)	-158.1		3 (degrees)						
MHW (m to DVR90)	0.76	1970	4	0.85	2001	4			
MLW (m to DVR90)	-0.85	1970	4	-0.86	2003	4			
MLWS	-0.92	1970	4	-0.96	2001	4			
MTR (m)	1.69	1970	4	1.71	2001	4			
$L_{ebbdelta}$ (km)	6.8	2012	-6 m	10	2012	-10m			
Surge height (m to MSL)	20 y 3.76 (+/- 0.31)	2000-2012	1 (station Mandø)	50 y 4.03 (+/- 0.44)	2000-2012	1 (station Mandø)	100 y 4.24(+/- 0.54)	2000-2012	1 (station Mandø)
Mean annual max surge height (m to AOD)	2.28		CoastDat						
A_{MHW} (km^2)	126.2	1970	4	128.7	2001	4			
A_{MLW} (km^2)	41.4	1970	4	37.3	2001	4			
A_{cross} (m^2)	12,635	1970	4	11,070	2001	4			
V_{MHW} (10^6 m^3)	220.7	1970	4	229.5	2001	4			
V_{MLW} (10^6 m^3)	79.1	1970	4	82.9	2001	4			
P (10^6 m^3)	141.6	1970	4	146.5	2001	4			
$SV_{backbarrier}$ (10^6 m^3)									
$SV_{ebbdelta}$ (10^6 m^3)	172.5	1970	14	126.6	2001	4			
$AS_{backbarrier}$ (10^6 m^3/yr)	-0.6	1970-2001	4 enlargement of channels						
$AS_{ebbdelta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	+0.2	2006-2009 & 1998-2007	2 (stations Sylt & Fanø)	-0.5 to +0.6 Rømø	2006-2009 & 1998-2007	2 (stations Sylt & Fanø)	-0.3 to +0.8 Koresand	2006-2009 & 1998-2007	2 (stations Sylt & Fanø)
Change ebb-delta?	Nordward deflection	1970-2001	4						
Sediment transport direction?	Both sides								
Development island coasts	Growth of Rømø and Koresand								

1 = Kystdirektoratet, 2012; 2 = Ridderinkhof, 2016; 3 = Wang & van der Weck, 2002; 4 = Kystdirektoratet, 2006.

Extended Table 8.3: Facts and figures Knude Dyb

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.35 mm/yr	1889-2006	1 (station Esbjerg)						
Hs (m)	1.41		CoastDat	1.04	1998-2007	2 (station Fanø Bugt)	1.04 & 1.02	1998-2007 & 2006-2009	2 (stations Fanø Bugt & Sylt)
Tp (s)	5.64		CoastDat	5.65	1998-2007	2 (station Fanø Bugt)	5.65 & 6.04	1998-2007 & 2006-2009	2 (stations Fanø Bugt & Sylt)
Tidal asymmetry degrees	-158.1	1902-2002	3						
MHW (m to DVR90)	0.80 Havneby 0.7 Esbjerg	1970	1	0.91 Havneby 0.8 Esbjerg	2003	1			
MLW (m to DVR90)	-0.82 Havneby -0.91 Esbjerg	1970	1	-0.93 Havneby -0.77 Esbjerg	2003	1			
MTR (m)	1.71 Havneby 1.52 Esbjerg	1970	1	1.84 Havneby 1.61 Esbjerg	2003	1			
$L_{ebbdelta}$ (km)	5	2012	-6 m	6.5	2012	-10m			
Surge height (m to MSL)	20 y 3.76 (+/-0.31)	2000-2012	Mandø; 4	50 y 4.03 (+/-0.44)	2000-2012	Mandø; 4	100 y 4.24(+/-0.54)	2000-2012	Mandø; 4
Mean annual max surge height (m to AOD)	2.27		CoastDat						
A_{MHW} (km^2)	175	1966	4	175	2003	4			
A_{MLW} (km^2)	46.4	1966	4	52.3	2003	4			
A_{cross} (m^2)	11,054	1966	4	11,873	2003	4	1		
V_{MHW} (10^6 m^3)									
P (10^6 m^3)	143.3	1970	4	153.3	2003	4			
$SV_{ebbdelta}$ (10^6 m^3)									
$AS_{backbarrier}$ (10^6 m^3/yr)	-0.1	1966-2003	4 enlargement of channels						
$AS_{ebbdelta}$ (10^6 m^3/yr)									
Longshore drift (10^6 m^3/yr)	0	2006-2009 & 1998-2007	2 (stations Sylt & Fanø)	-0.5 to -1.3 Fanø	2006-2009 & 1998-2007	2 (stations Sylt & Fanø)	-0.3 to +0.8 Koresand	2006-2009 & 1998-2007	2 (stations Sylt & Fanø)
Change ebb-delta?	Hardly, some seaward expansión at the NW side (Fanø) and erosion at the SW side	1966-2003	4						
Sediment	N								

transport direction?									
Development island coasts	Growth of S/ Fanø; Slight growth of NW Koresand								

1 = Kystdirektoratet, 2012; 2 = Ridderinkhof, 2016; 3 = Wang & van der Weck, 2002; 4 = Kystdirektoratet, 2008

Extended Table 8.4: Facts and figures Grådyb

Parameter	Obs.	Year	Reference	Obs.	Year	Reference	Obs.	Year	Reference
MSLR (mm/yr)	1.35 mm/yr	1889-2006	1 (station Esbjerg)						
Hs (m)	1.39		CoastDat	1.04	1998-2007	2 (station Fanø Bugt)	1.04 & 1.02	1998-2007 & 2006-2009	2 (stations Fanø Bugt & Sylt)
Tp (s)	5.65		CoastDat	5.65	1998-2007	2 (station Fanø Bugt)	5.65 & 6.04	1998-2007 & 2006-2009	2 (stations Fanø Bugt & Sylt)
Tf/Te	0.9	1902-2002	3						
MHW (m to DVR90)	0.73	1967	3	0.79	2002	3			
MLW (m to DVR90)	-0.77	1967	3	-0.78	2002	3			
MTR (m)	1.5	1967	3	1.57	2002	3			
$L_{ebbdelta}$ (km)	5.5	2012	-6 m	8,5	2012	-10m			
Surge height (m to MSL)	20 y 3.62 (+/- 0.11)		1 (station Esbjerg)	50 y 3.88 (+/- 0.13)		1 (station Esbjerg)	100 y 4.05 (+/- 0.16)		1 (station Esbjerg)
Mean annual max surge height (m to AOD)	2.27		CoastDat						
A_{MHW} (km^2)	131	1967	3	129	2002	3			
A_{MLW} (km^2)	68	1967	3	69	2002	3			
A_{cross} (m^2)									
V_{MHW} ($10^6 m^3$)									
P ($10^6 m^3$)	157	1967	3	165	2002	3			
$SV_{backbarrier}$ ($10^6 m^3$)									
$SV_{ebbdelta}$ ($10^6 m^3$)	44	1967	3	37	2002	3			
$AS_{backbarrier}$ ($10^6 m^3$/yr)	-0.4 (-0.9_+0.2)	1967-2002	3 Sedimentation above 0 m DVR90 and enlargement of channels						
$AS_{ebbdelta}$ ($10^6 m^3$/yr)									
Longshore drift ($10^6 m^3$/yr)	-0.6		2 (based on 4)	-1.5 to -1.6	2006-2009 & 1998-2007	2 (stations Sylt & Fanø)			
Change ebb-delta?									
Sediment transport direction?	Attachment S at Fanø Skallingen to deliver ca. $0.4*10^6 m^3$/yr	1989-2013	2						
Development island coasts	Sedimentation Fanø; Erosion of Skallingen		5						

1 = Kystdirektoratet, 2012; 2 = Ridderinkhof, 2016; 3 = Kystdirektoratet, 2006; 4 = Aagaard & Sørensen, 2013; 5 = Kystdirektoratet, 2008.

Appendix II: Local projections climate change & sea-level rise

The Royal Netherlands Meteorological Institute developed four national scenarios of climate change (Table I.1) composed of a moderate (G) and high (W) temperature increase and a changing (H) and non-changing circulation (L) pattern (Lenderink et al., 2007, KNMI, 2014). Next to that, projections have been made for sea-level rise. It can be seen that uncertainties for temperature changes are much smaller than for wind and sea-level rise (compare also: Kabat et al., 2009; Oost et al., 2009).

Table II.1a: Overview projection effects of climate change for the Wadden Sea around 2030/2035.

Variable	**Indicator (change)**	**Climate 1981_2010 (KNMI) or 1961_1990 (DMI, 2014)**	**Scenario climate change around 2030/2035**			**Natural variation average 30 yrs**
			Dutch 2016_2045, relative to 1981_2010 (KNMI, 2014)	**Danish 2021_2050, relative to 1986_2005 Unless stated differently (DMI, 2014)**	**German 2016_2045, relative to 1961_1990 (Wadden Sea Region CLIMATE ATLAS)**	
Increase world temperature	Mean **(in ^{0}C)**					
Atmospheric temperature	Mean (in ^{0}C)	10.1	1	+1.2 ± 0.2 relative to 1961_1990	+1.2 (0.5_2.2)	±0.16
Wind	Mean speed			+1_+3%	+1% (-3_+3%)	
	Mean speed in winter	6.9 m/s				±3.6%
	Highest daily mean in winter	15 m/s				±3.9%
	Number of days between south and west	49				±6.4%
Storms	Storm intensity				0% (-3_+4%)	
KNMI (2014)	Tropical cyclone in North Sea Basin					
	Stormy days (number)				1 (-9_12)	
Storm surges (Weisse et al., 2012)	Heights					
Wave climate (Weisse et al., 2012)	Wave heights					
Sea level	Absolute level (cm)	+3 cm DOD	10_25	5_6		±1.4
	SLR velocity (mm/yr)	2	1_6			±1.4

Table II.1b: Overview projection effects of climate change for the Wadden Sea around 2050.

Variable	**Indicator (change)**	**Climate 1981_2010 (KNMI) or 1961_1990 (DMI, 2014)**	**Scenario climate change halfway this century**			**Natural variation average 30 yrs**
			Dutch 2036_2065, relative to 1981_2010 (KNMI, 2014)		**German 2036_2065, relative to 1961_1990 (Wadden Sea Region CLIMATE ATLAS)**	
			G_L_G_H	**W_L_W_H**		
Increase world temperature	Mean **(in ^{0}C)**		1 _2			
Atmospheric temperature	Mean (in ^{0}C)	10.1	+1_1.4	+2_2.3	+1.7 (0.8-3)	±0.16
Wind	Mean speed				0% (-3_+4%)	
	Mean speed in winter	6.9 m/s	-1.1_ 0.5%	-2.5_+0.9%		±3.6%
	Highest daily mean in winter	15 m/s	-3_ - 1.4%	-3_0%		±3.9%
	Number of days between south and west	49	-1.4_ +3.0%	-1.7_4.5%		±6.4%
Storms	Storm intensity				0% (-3_+5%)	
KNMI (2014)	Tropical cyclone in North Sea Basin					
	Stormy days (number)				0 (-9_14)	
Sea level	Absolute level (cm)	+3 cm DOL	15_30	20_40	24_25 (DW, 2016) 20_30 Schleswig Holstein	±1.4
	SLR velocity (mm/yr)	2	1_5.5	3.5_7.5		±1.4

Table II.1c: Overview projection effects of climate change for the Wadden Sea near the end of the century.

Variable	**Indicator (change)**	**Climate 1981_2010 (KNMI) or 1961_1990 (DMI, 2014)**	**Scenario climate change end of the century**				**Natural variation average 30 yrs**
			Dutch 2071_2100, relative to 1981_2010 (KNMI, 2014)		**Danish 2071_2100, relative to 1986 to 2005 (DMI, 2014)**	**German 2071_2100, relative to 1961_1990 Wadden Sea Region CLIMATE ATLAS**	
			G_L_G_H	**W_L_W_H**			
Increase world temperature	Mean **(in ^{0}C)**		1.5 _ 3.5				
Atmospheric temperature	Mean (in ^{0}C)	10.1	+1.3_1.7	+3.3_3.7	+1.2 ± 0,5 _ +3.7 ± 1.0	+2.6 (0.9-4,8)	±0.16
Wind	Mean speed					0% (-4_+6%)	
	Mean speed in winter	6.9 m/s	-2.0_+0.5%	-2.5_+2.2%			±3.6%
	Highest daily mean in winter	15 m/s	-2.0_-0.9%	-1.8_+2%			±3.9%
	Number of days between south and west	49	-1.6_+6.5%	-6.5_+4.0%			±6.4%
Storms	Storm intensity					0% (-4_+4%)	
KNMI (2014)	Tropical cyclone in North Sea Basin					Might increase?	
	Stormy days (number)					0 (-11_13)	
Storm surges (Weisse et al., 2012)	Heights					Uncertain tendency to increase	
Wave climate (Weisse et al., 2012)	Wave heights					Uncertain: tendency to increase,	
Sea level	Absolute level (cm) Schleswig Holstein (flood protection)				50_150		
	Absolute level (cm) Schleswig Holstein (general strategies)				50_80		
	Absolute level (cm)	+3 cm DOL	25_60	45_80	34 (10_60) _ 61 (30_90)	105 (Katsman)	±1.4
	SLR velocity (mm/yr)	2	1_7.5	4_10.5			±1.4