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Where Mud Matters

Towards a Mud Balance for the Trilateral Wadden Sea Area: Mud supply, transport and deposition

Report

PROGRAMMA NAAR EEN RIJKE WADDENZEE

Deltares

waddenacademie

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Towards a Mud Balance for the Trilateral Wadden Sea Area: Mud supply, transport and deposition

Report

Colophon

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FOREWORD

Muddy sediments are a vital element for the Trilateral Wadden Sea ecosystem and mud, both in the form of suspended particles in the water column as well as substrate on shoals, tidal flats and salt marshes, plays an important role in providing and developing ecosystem-services. For many centuries the import and deposition of mud has significantly contributed to the silting up and evolution of tidal basins in the Wadden Sea in response to tidal processes and long-term sea level rise. Mud accumulates in the high intertidal and supra-tidal zone and contributes to the growth of tidal flats and salt marshes. Likewise, mud dynamics and deposition plays an important role in the development of major estuaries in the Wadden Sea region. Mud has various impacts on the food web of the Wadden Sea. High concentration of fine-grained suspended matter, for example, may become a limiting factor for primary production of phytoplankton (pelagic microalgae) by increasing turbidity levels and reducing the penetration of light in the water column. High densities of microphytobenthos (benthic microalgae) are, however, generally found on the more muddy parts of the tidal flats, amongst others due to higher concentration of nutrients in the pore waters of finer sediments. Fine suspended sediment in the water column may hamper the uptake of food for suspension-feeders such as mussels and cockles, whilst deposit-feeding benthos such as mudsnails prefer muddy substrates.

For already a long time, mud dynamics in the Wadden Sea is heavily affected by human activities and interventions such as land reclamation, channel deepening for navigation, maintenance dredging and more recent attempts to locally extract or demobilize mud in tidal basins and estuaries to reduce turbidity. Surprisingly though a more or less comprehensive overview of mud dynamics in the Trilateral Wadden Sea is lacking. This omission has inspired both the Wadden Academy and "Programma naar een Rijke Wadden Zee" to invite Deltares to launch a study to identify the major sources, sediment pathways and sinks of mud in the Trilateral Wadden Sea. This report provides the first mud balance for the Trilateral Wadden Sea, making use of a range of data sources such as existing literature, bathymetric charts, sediment distribution maps and measurd deposition rates.

We are confident that the report is highly informative and may act as a kind of benchmark study for future work. We wish you pleasant reading!

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Summary

The Trilateral Wadden Sea is an extensive barrier-lagoon system composed of three main estuaries and a series of tidal basins, covering Dutch, German, and Danish territory. Although being an important nature reserve, the area also provides important economic services (through fisheries, tourism, and shipping). Because of these economic services, resulting in deepening, land reclamations and flood defences, the area is strongly influenced by human interventions – especially in the three main estuaries (the Elbe, Weser and Ems). The sedimentary processes in tidal basins are dominated by sandy and muddy sediments, with the largest mud content in the shallow tidal flats on the landward side and on the tidal divides. Most of the mud supplied to the Wadden Sea originates from the Straits of Dover, via the so-called North Sea Continental Flow. Additional but smaller contributions are from the IJsselmeer, the Ems, Weser and the Elbe Rivers, local sources and aeolian deposition.

This report provides the first mud balance for the Trilateral Wadden Sea, providing detailed estimates for mud sinks, sources, and transport using a combination of existing literature, bathymetric charts, sediment distribution maps, observed deposition rates, and dredging information. The total mud supply to the Trilateral Wadden Sea is estimated at 12.1 to 16.5 million ton/yr. Mud is mainly deposited on the upper tidal flats connected to the mainland of the Trilateral Wadden Sea, in the tidal marshes, and in the sheltered embayments, providing a sink of sediments. An additional sediment sink is sediment extraction, whereby sediment is dredged and placed on land. The total amount of mud deposition and extraction is estimated at 10.8 to 11.3 million ton/yr. This implies that currently, the mud sources are larger than the mud sinks, but not much larger.

Sand-mud mixtures are either sand-dominated or mud-dominated, resulting in spatial segregation of sand and mud. Especially the inland embayments such as the Dollard, the Leybucht and the Jade Bay are characterised by high mud contents. This segregation is an important characteristic of the system, especially when evaluating the response of the system to sea-level rise and local anthropogenic disturbances. At present, the (mud-dominated) upper tidal flats and salt marshes are accreting at a faster rate than sea-level rise, while some subtidal sections are eroding, especially in the German Wadden Sea. It remains unclear to what extent this redistribution is the result of the observed increase in tidal amplitude or mean sea-level, and therefore related to local human interventions or global sea-level rise.

The most important human interventions influencing mud dynamics are land reclamations and channel deepening. Historic land reclamations resulted in a major loss of sediment sinks where fine sediments naturally accumulate. This loss in sediment accommodation space resulted in more sediment remaining in suspension and therefore higher sediment concentration and more eastward transport of sediment. Both land reclamations and channel deepening (for navigation purposes) lead to amplification and asymmetry of the tides, promoting landward transport of sediments in the estuaries.

How long-term sea-level rise will impact deposition of mud is at present difficult to predict. On the short-term, the basins will probably keep pace with sea-level rise, resulting in an increased sediment deposition. This would imply that progressively more mud would be deposited in the western Wadden Sea. The total amount of mud transported within the system is limited, and therefore mud availability may become limited in the Eastern Wadden Sea. At higher rates of sea-level rise, the system may partly drown, which may accelerate as a result of sand-mud interactions. For instance, disappearance of sandy shoals sheltering the mudflats may lead to erosion of previously aggrading mudflats, resulting in a decreasing mud deposition over time. However, these predictions are limited by our present-day understanding of the system response over the full extent of the tri-lateral Wadden Sea.

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1 INTRODUCTION

1.1 BACKGROUND

Recent estimates (Colina Alonso et al., 2021) suggest that ~30% of the sediment deposited in the Western Wadden Sea since closure of the Zuiderzee basin is mud (<63 micron, consisting of clays, silts and organic matter). Fine sediments mainly deposit on intertidal mudflats fringing the coastline or tidal divides, providing important habitats for specific benthic organisms. Mud further deposits on the salt marshes, contributing to the important ecological services provided by these systems, but also protect the dikes and therefore the hinterland against flooding. Too much sediment in suspension has adverse effects, as it reduces visibility and therefore reduces primary production, but also hampers food uptake by filter feeders.

With a contribution of up to 30% in volume, mud plays a crucial role in the sedimentary development of the Wadden Sea. Muddy deposits may therefore substantially contribute to the basin's ability to keep up with Sea-level Rise (SLR), which means that fine sediments may become an important commodity. However, it is not known how much sediment annually deposits in the Wadden Sea or is extracted through anthropogenic processes, and how much is annually supplied through its various fluvial and marine sediment sources. Moreover, it is poorly known to what extent present-day depositional processes are the result of various human interventions, ranging from land reclamations, construction of dikes to channel deepening for navigation purposes and associated maintenance dredging.

In order to increase our understanding of the mud dynamics of the Wadden Sea, Deltares was assigned by the Wadden Academy and 'Programma naar een Rijke Waddenzee' (PRW) to provide an overview of the processes and issues related to mud dynamics in the trilateral Wadden Sea, and extend quantitative analyses on the mud content previously done for the Western Wadden Sea to the whole trilateral Wadden Sea. A draft version of this report was sent to an international group of experts for suggestions and omissions. We have received valuable input for, and/or feedback on the report from Theo Gerkema, Eelke Former, Julia Vroom, Andreas Wurpts, Yoeri Dijkstra, Matias Duran-Matute, Frank Kösters, Maarten Kleinhans, Bas Borsje, Hans Burchard, Emil Stanev and Peter Milbradt. The report has been reviewed by Thijs van Kessel, Piet Hoekstra, Michiel Firet, and Hein Sas. Financial support was provided by the Wadden Academy, the Ministry of Agriculture, Nature and Food Quality, and Deltares.

1.2 RESEARCH QUESTIONS

To better understand the role of mud and to assess the potential impact of human interventions, climate change and sea-level rise on the behaviour of mud in the Wadden Sea, we aim at producing an overview based on existing knowledge. This literature review has been performed with a system-based approach, with the following research goals in mind:

1. Provide an overview of the mud budget in the Trilateral Wadden Sea, based on existing literature and data.
2. Provide a brief overview of the existing knowledge on the mud dynamics in the Trilateral Wadden Sea.
3. Provide an overview of the areas in the Trilateral Wadden Sea where the current mud concentration levels negatively impact ecology and deposition rates threaten safe navigability, resulting in high maintenance dredging.
4. Evaluate current and future management strategies and interventions to tackle mud-related problems, such as increased turbidity values or deposition in harbours and navigation channels.
5. Identify the main knowledge gaps.

To this end, we have formulated the following research questions:

1. What are at present the main sources for the input of mud in the Trilateral Wadden Sea, and how much mud is annually imported (gross and net) and subsequently deposited?
2. What are the main hydrodynamic processes and sediment transport mechanisms relevant for the import, transport and deposition of mud in the Wadden Sea and How important is the exchange of mud between individual tidal basins?
3. What is the natural range of mud concentrations as a function of local environmental conditions and how have these concentrations changed in response to human interventions?
4. How have these concentrations been influenced due to large-scale interventions which have been structural over time (land reclamation, closure works, substantial landfill with dredged materials)? Are there alternatives to deal with mud-related problems?
5. What is the spatial distribution of mud in surface deposits on shoals, tidal flats and salt marshes?
6. What kind of management strategies, interventions and tools have been used so far to deal with mud-related problems in the Wadden Sea? How were their effects measured in terms of physical and ecological changes? How cost-efficient were the measures?
7. Are there other options (not yet explored) to deal with mud-related problems and, if so, what would be the efficiency of these measures (in reducing the problem and with respect to the costs)?
8. What has been the impact of long-term sea-level rise on the supply and deposition of mud and how will climate change and (accelerated) sea-level rise alter these processes?
9. Who is presently working on which mud-related research question in the trilateral Wadden Sea and what is the type of projected outcome of this research (e.g. dose-effect field studies, model scenario's)?
10. Analytical and numerical models play an important role in understanding, hindcasting and predicting mud behaviour in the Wadden Sea. How reliable and accurate are these models? What kind of improvements are necessary in terms of process knowledge and implementation, model calibration and validation?

Many of the research questions above have not yet been addressed on the scale of the Wadden Sea, and available data and literature is insufficient to provide conclusive answers. This report therefore primarily serves as a starting point on large-scale mud dynamics and management, rather than providing final answers. More specifically, we aim to test the following hypotheses:

i. Sand and mud deposits are spatially segregated, which influences not only their distribution but also their response to human interventions and sea-level rise.
ii. The contribution of mud to total sedimentation rates in the whole trilateral Wadden Sea is substantial.
iii. The sources and the sinks of mud are closely balanced.
iv. Sea-level rise may lead to a shortage of mud.
v. Anthropogenic sediment extraction may lead to a shortage of mud.

1.3 STUDY AREA

The area which is considered is the Danish, German and Dutch Wadden Sea area including the three big estuaries Ems, Weser and Elbe. As the available data are not very detailed, we decided to study the developments in the following larger regions:

1. Dutch Wadden Sea area: From the Marsdiep Inlet up to the watershed under Schiermonnikoog;
2. Ems estuary: the Dutch area east of the watershed of Schiermonnikoog, the estuary proper (up to the weir at Herbrum), the Dollard area and the German Wadden area up to the watershed of Borkum (so excluding the Eastern Ems channel channel which has become more typical for the lower Saxonian Wadden Sea since infilling of the connection with the Western Ems channel);
3. The Lower Saxonian Wadden Sea area: from the watershed of Borkum to east of the Minskeneroog barrier island and the Jade embayment.
4. Weser: The estuary up to the weir and the area east of it up to the Elbe;
5. Elbe: the estuary up to the weir and the area north of it up to the watershed of Trischen;
6. The Wadden Sea area of Schleswig Holstein: from the watershed of Trischen up to the dam of Sylt;
7. The Danish Wadden Sea area: from the dam of Sylt up to the northernmost part of the Wadden area.

Figure 1.1: Satellite image of the Wadden Sea during low tide showing the numbered sub-areas. (albedo39 Satellitenbildwerkstatt e.K., image processing; Brockmann Consult GmbH, scientific consulting; raw data: U.S. Geological Survey).

1.4 REPORT OUTLINE

The report set-up is as follows: First, we provide a general description of the study areas in which we discuss the main characteristics including main hydrodynamic drivers, the geology and the bed sediments (Chapter 2). Next, we discuss the main hydrodynamic processes and sediment transport mechanisms relevant for the import, transport and deposition of mud in the Wadden Sea (Chapter 3). In Chapter 4, we provide an overview of the natural range of suspended mud concentrations (mud availability in the water column) and in Chapter 5 we elaborate on the mud availability in the sediment bed. A first version of a mud budget for the Trilateral Wadden Sea is presented in Chapter 6. This mud budget is based on literature and data on the sources, import of mud, dredging activities and remaining sedimentation in the basins. Subsequently, we elaborate on the impact of human interventions (Chapter 7) and potential effects of sea-level rise on this mud budget (Chapter 8). In Chapter 9 we elaborate on (numerical) modelling practices, focusing on mud. Lastly, a discussion on the results and conclusions are presented in Chapter 10.

2 A GENERAL DESCRIPTION OF THE STUDY AREAS

In order to study the mud balance and the functioning of mud in the trilateral Wadden Sea of Denmark, Germany and the Netherlands it was decided to split the Wadden area into seven larger regions, being (from west to east) the Dutch Wadden Sea, the Ems estuary, the Lower Saxony Wadden Sea, the Weser estuary, the Elbe estuary, the Schleswig-Holstein Wadden Sea and the Danish Wadden Sea. The present-day topography and prevailing hydrodynamic conditions will to a large extent determine where mud is deposited (see chapter 6.1-6.3). The geological built-up and (pre-)historic development determine mud availability in the subsurface which is expected form an internal source of mud (see chapter 6.4). For this reason, both are discussed relatively extensively, based on available literature, for each area.

2.1 THE DUTCH WADDEN SEA AREA

2.1.1 Characteristics

The west to east trending Wadden area of the Netherlands has a total surface area of 4155 km² within the Bird or Habitat framework directives. The back-barrier Wadden Sea itself has a total area of some 2710 km^2 and consists of tidal salt marshes (both intertidal and supratidal), inter and subtidal flats and tidal channels (Figure 2.1).

The area consists of 6 inlet systems, namely, from west to east: Marsdiep, Eijerlandse Gat, Zeegat van het Vlie, Borndiep, Pinkegat, Zoutkamperlaag, and Eilanderbalg (Figure 2.1). Several freshwater streams are entering the back-barrier, the major ones are the ones via IJsselmeer and Lauwersmeer, and the Ems. The inlets have islands at either side and clearly developed ebb-tidal deltas.

Observations over the period 1890-2008 show that MSL increase in the Dutch Wadden Sea is 1.3-1.9 mm/yr (Dillingh et al., 2010). Vermeersen et al. (2018) showed that the large interannual variability of mean sea-levels hinders the detection of a present-day acceleration in sea-level rise at local scales. Their results on sea-level rise rates agree with previous findings by Dillingh et al. (2010). Gerkema and Duran-Matute (2017) showed that the interannual variability of mean sea-level (up to 10 cm) can be largely explained by the west–east component of the net wind energy vector. This interannual variability is increasing, with 100 year long sea-level records revealing that MSL is increasing consistently faster in winter than summer (with the MSL in the station of Harlingen rising two times faster in winter than in summer) – see Gerkema and Duran-Matute (2017).

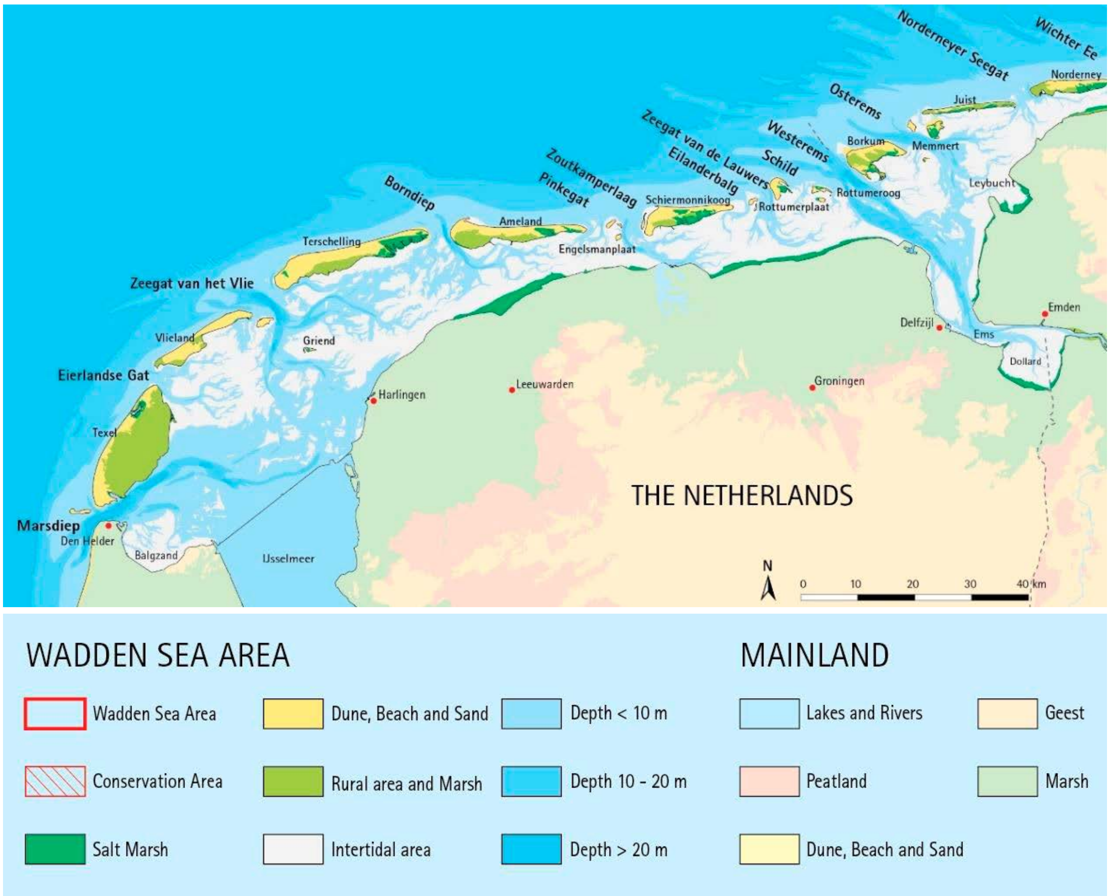


Figure 2.1 The inlet systems of the Wadden area of the Netherlands (Courtesy Wadden Sea Secretariat).

The tidal amplitude increases from west to east from 1.4 m at Marsdiep up to 2.1 m in the Westerems. The mean significant wave height offshore is around 1.3 m (Coast Dat data). Along the North Sea coast of the Dutch Wadden Sea littoral drift of primarily sandy sediment is directed to the east, calculated to be 0-0.1 to 0.6×10^6 m^3/yr (Figure 2.2; 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 20th century, decreased towards the mid-century and increased until the beginning of the 1990ies, 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 to be significant (Smits et al., 2005; Sluijter, 2008). For the period 1948-2007 the share of westerly winds increased in the late winter and early spring, the number of north- to north-westerly winds remained more or less constant (Van Oldenborgh et al., 2009).

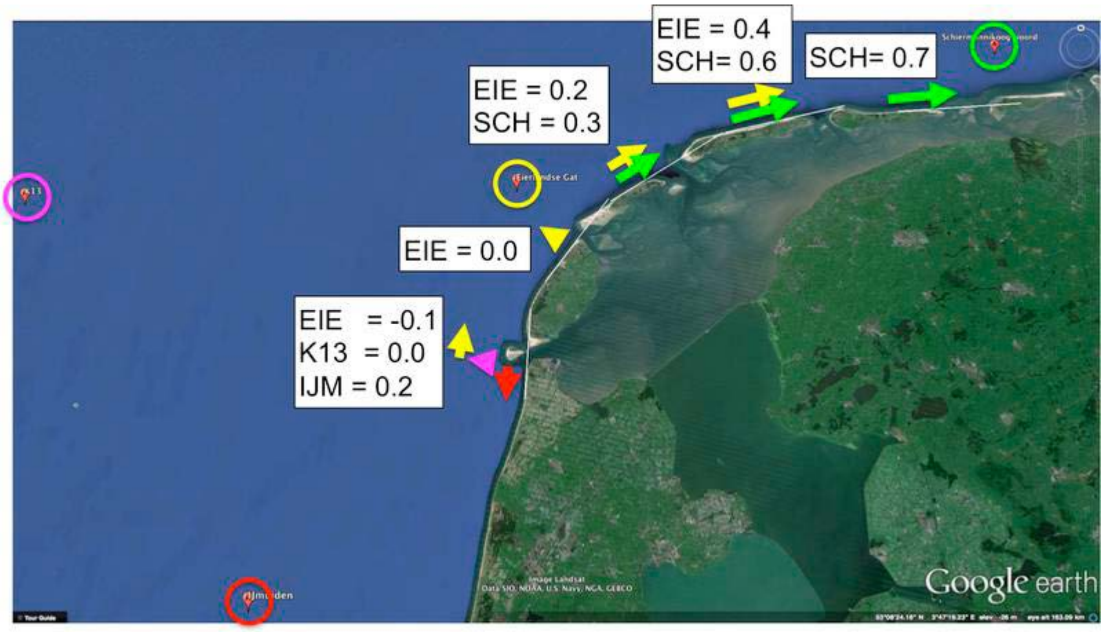


Figure 2.2 Littoral sand drift along the Dutch Wadden coast, computed using wave data from stations IJmuiden (IJM, red arrows), Eierland (EIE, yellow arrows), K13 (magenta arrows), and Schiermonnikoog (SCH, green arrows), in 10^6 m^3/yr (From: Ridderinkhof, 2016).

Several large engineering interventions have been carried out in the area. The most important are the damming of the Zuiderzee in 1932 and the Lauwers Sea 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. Furthermore, 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 1930s (until the 80's). On the barrier islands, only the inhabited areas are surrounded by a closed chain of sand drift dikes and back-barrier dikes.

2.1.2 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 2.2; Kiden et al., 2002, Gehrels et al., 2006; Busschers et al., 2007; Vink et al., 2007; Kiden et al., 2008; Pedersen et al., 2009; Baeteman et al., 2011). In close association with the relative sea-level rise, the tidal range increased from initially microtidal conditions everywhere to the more differentiated ranges presently observed (Jelgersma, 1979; Franken, 1987; Van der Molen and De Swart, 2001).

At 8000 a BP sea-level was still around 20 m below its present MSL (Figure 2.3) 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 and Van Kesteren, 2000). The rising sea-level followed and modified the mostly gentle Pleistocene relief and determined the initial position of the Wadden Sea.

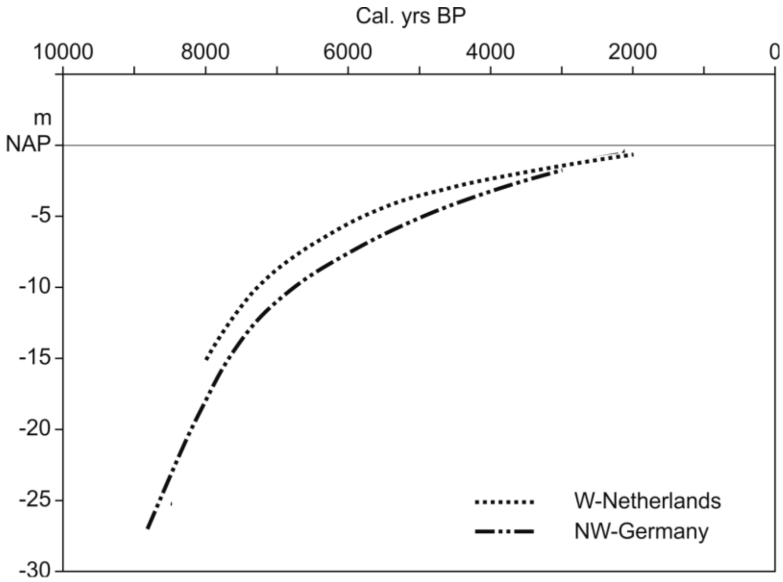


Figure 2.3 Differences in Holocene relative mean sea-level rise for the Dutch and NW German North Sea coast, making clear the differences on a regional scale. Sea-level rise in NW Germany has been larger than in the Western Netherlands. The differences are mainly caused by relative glacio-isostatic subsidence (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., 2012).

Some of the areas were partially filled with peat and could be incised relatively easily and be converted into back-barrier embayments (e.g. Zuiderzee and Lauwerszee), thereby enlarging the tidal volume of the estuaries or back-barrier basins of which they were part. In the western Wadden Sea area, the deepest river valleys were flooded around 8000 a BP (Beets and 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), but most inlets seem to have “drifted” from their original locations. Especially in the western part of the Dutch Wadden Sea 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 and 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 2.4) and intertidal sand flats expanded (Van Heteren and 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 was insufficient to fill the basins everywhere despite a decelerating absolute sea-level rise (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 and 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 northward in comparison with their 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/yr, and a large part of the sediment was deposit-ed into the back-barrier areas (Oost, 1995).

The situation of the West Frisian Wadden area at 1,200 a BP is given in Figure 2.4. 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 and Knol, 2015). Tidally influenced rivers and streams were in open connection with the Wadden Sea.

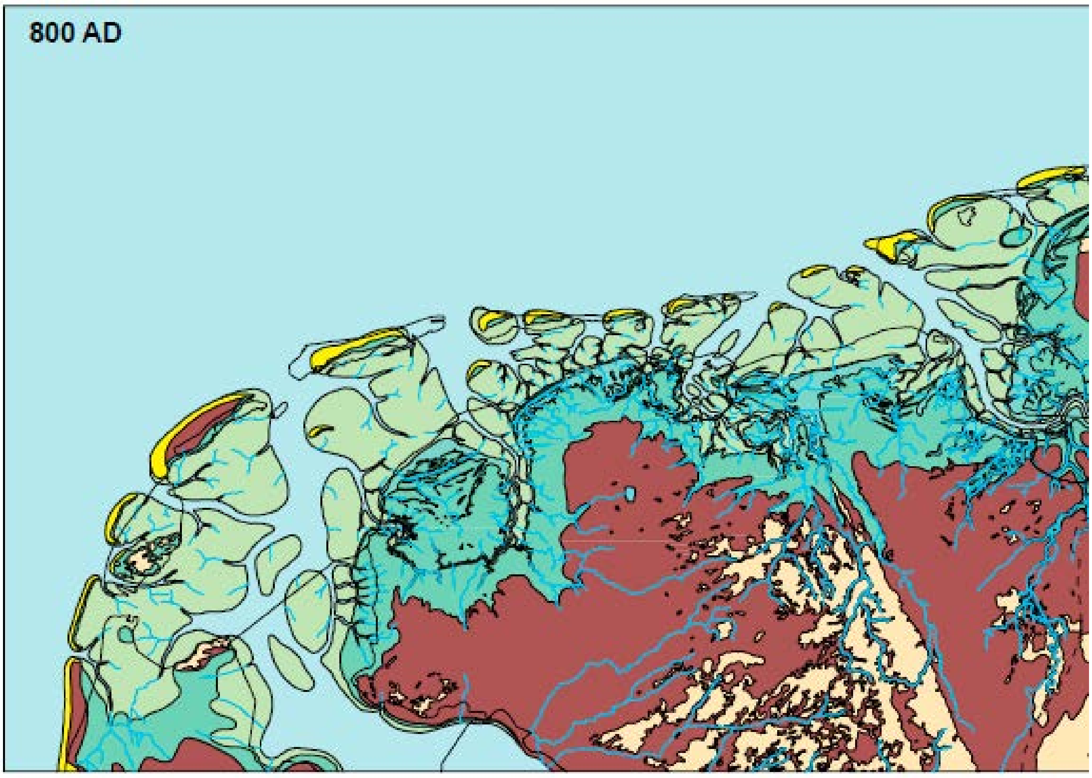


Figure 2.4 Situation around AD 800. Orange = higher sand grounds; brown -= peats; yellow = coastal dunes ;dark green = tidal marshes; light green = tidal flats; blue is subtidal area; contours of present day coasts are given (Oost et al., 2015).

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).

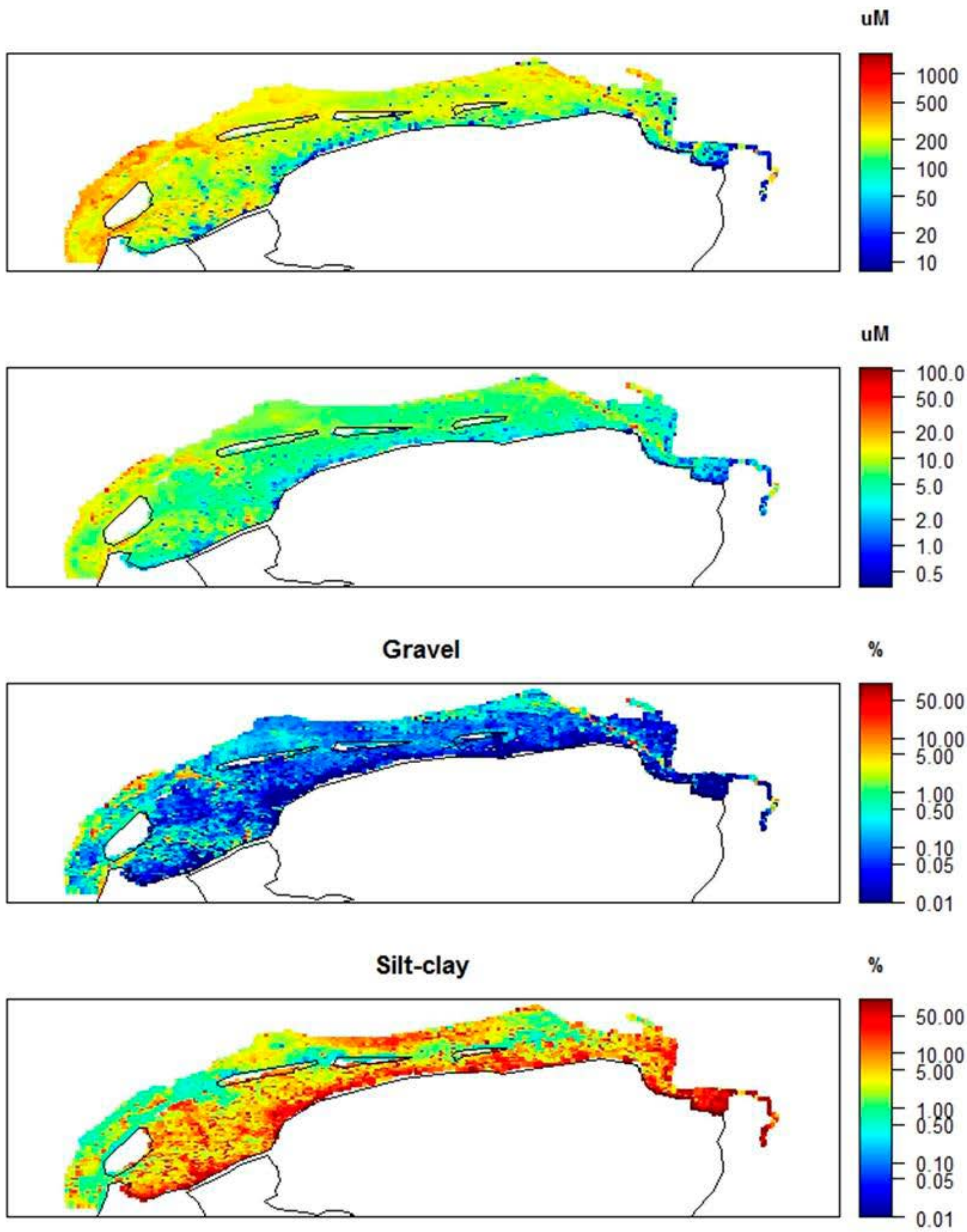


Figure 2.5 Sediment characteristics in the Dutch Wadden Sea area. From top to bottom: median and mean grain size in µm, gravel content (relatively high around Texel) and mud content (high north of Ameland and near the mainland. Based on sediment atlas Rijkswaterstaat. Data source: http://opendap.deltares.nl/thredds/catalog/opendatap/rijkswaterstaat/sedimentatlas_waddenzee/Karline Soetaert

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 flooding 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 had silted up to such a level that they could successfully be embanked and extensive areas of land (Middelzee, Lauwerszee, Fivelboezem) were reclaimed (van der Spek, 1994; Oost, 1995; Vollmer et al., 2001; Van Heteren and van der Spek, 2003). The land reclamations reduced the surface area of the tidal basins, creating smaller tidal prisms which in turn resulted in smaller tidal inlet systems. Because the mainland coast was prograding seaward and the barriers were retreating landward, the tidal basins became smaller.

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 2.5).

2.2 THE EMS ESTUARY

2.2.1 Characteristics

The Ems estuary is located between the Netherlands, province of Groningen and Germany, Lower Saxony, and between the barrier island Rottumeroog in the west and Borkum in the east. For the purpose of this study we have added the eastern Wadden Sea with the smaller tidal inlets (Zeegat van de Lauwers, and Schild – see Figure 2.1) geographically to the Ems estuary. The Ems estuary consists of an outer estuary and a connected tidal river, the lower Ems river. The length of the estuary between the barrier islands and the weir at Herbrum is 105 km (Figure 2.6). The tidal river is approximately 40 km long, and the outer estuary 65 km. The outer estuary consists of tidal channels and flats, which become increasingly muddy in the landward direction. The most seaward section is composed of deep channels with a depth locally limited by Pleistocene substrate (Pierik et al., 2018) and sandy shoals. The outer area has two main outlets: a western channel and an eastern channel. At present, the western channel is the main outlet. The middle reach is a two-channel system with a main channel (the 'Friesche Gaatje') and an abandoned tidal channel (the 'Bocht van Watum'). The outer estuary terminates in a muddy tidal embayment known as the Dollard.

For the local meteorology, the reader is referred to the chapter on the Dutch Wadden Sea.

Land reclamations carried out in the past 500 years have greatly reduced the intertidal area. Since 1650, the size of the Ems Estuary (the subtidal, intertidal and supratidal area) up to Eemshaven decreased by 40% from 435 to 258 km^2 (Herrling and Niemeyer, 2007). The combined intertidal and supratidal area decreased by 45% from 285 to 156 km^2. Human interferences in the estuary have accelerated in the past 50 years, with the construction/extension of three ports (Eemshaven, Delfzijl and Emden), a large shipyard (Papenburg), and the deepening of the shipping lanes.

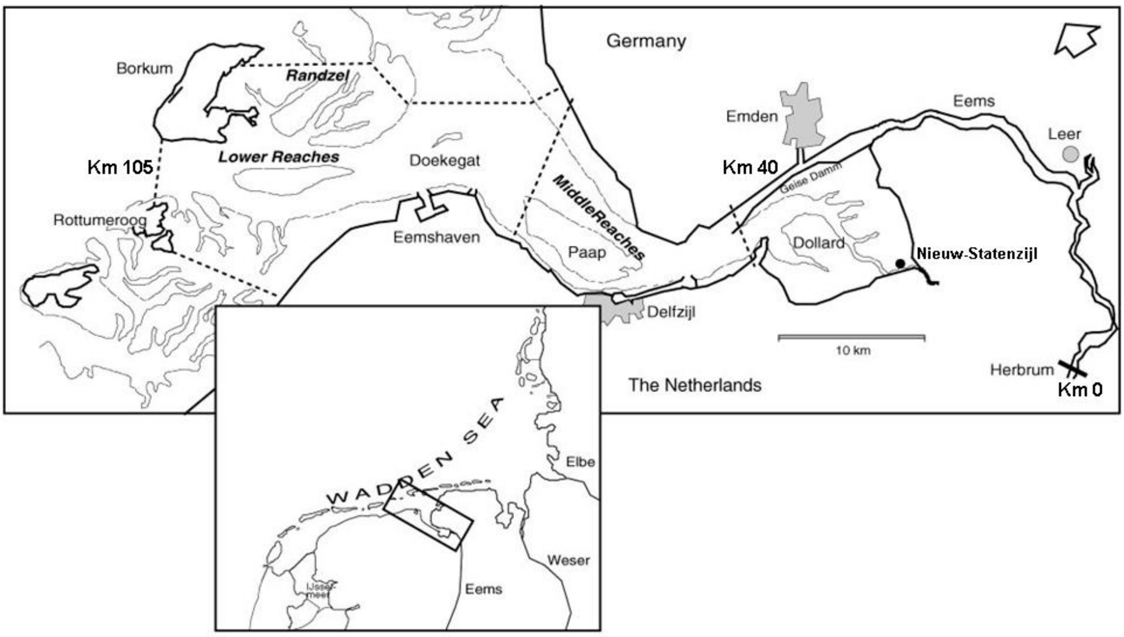


Figure 2.6 Map of the Ems estuary (including the lower reaches, the middle Reaches, and the Dollard estuary) and lower Ems River (between km 0 and 40). Adapted from De Jonge (2000).

The present-day approximate maintenance depths of the approach channels to the ports are 12 m (Eemshaven), 10 m (Delfzijl) and 11 m (Emden), requiring regular maintenance dredging. The lower Ems River was deepened from a water depth of ~4 m below HW to ~8 m below HW between the 1930s and 1994 (van Maren et al., 2015b). This deepening has led to strong tidal amplification, possibly amplified by the presence of the weir at Herbrum constructed in 1899 (Schuttelaars et al., 2013). The tidal range at Papenburg (km 0) has increased from 1.6 m in 1950 to 3.6 m in 2010, with a major lowering of the tidal low water level (Krebs and Weilbeer, 2008). Until 1990, the tidal range peaked at Emden (42 km downstream of the weir at Herbrum), because the tide was dampened further in the upstream direction. Since then, however, the Lower Ems has been deepened further, and the tide amplified upstreams of Emden, and nowadays the tidal range at Papenburg exceeds the tidal range at Emden by 50%.

2.2.2 Geology

For the general local geology, the reader is referred to the chapter on the Dutch Wadden Sea.

The paleo-valley 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). It was filled early during the rise of the sea. Originally, large peatlands surrounded this drowned river valley. Some land areas have opened to the sea in an early stage. They were flooded, filled up with fine-grained sediment and became land again. Other areas, such as the Dollard and the Leybucht were breached during medieval times. Peat was partially eroded. Another part was compressed under the weight of new sedimentary deposits which gradually filled up the large part of the areas. During the formation of the Dollard the estuary widened considerably in the direction of Emden.

2.3 The Lower Saxony Wadden Sea

2.3.1 Characteristics

The west to east trending Wadden area of Lower Saxony has a total surface area of 2.777 km² within the Nationalpark Niedersächsisches Wattenmeer. The back-barrier Wadden Sea consists of tidal marshes, supra- inter and subtidal flats and tidal channels (Figure 2.7).

The described area consists of (Figure 2.7):

1. Inlet systems in the mesotidal area, from west to east: Westerems, Osterems, Norderneyer Seegat, Wichter Ee, Accumer Ee, Otzumer Balje, Harle and Blaue Balje;
2. A more eastern coast with few islands in the supratidal area, from west to east: Jade, Weser, Robinbalje and Westertill / Nordertill.

In general, this area resembles strongly the Dutch Wadden area, both for its appearance and the morphogenesis. Several freshwater streams are entering the back-barrier, the major one is the river Ems, whereas the more eastern half is also strongly influenced by the Weser and Elbe estuaries. Most of the inlets have islands at either side and clearly developed ebb-tidal deltas, but east of Minseneroog the increasing tidal range results in small supratidal shoals instead of islands. 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 west to east, 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 Lower Saxony North Sea coast, the littoral drift of sandy sediments is directed to the east and calculated to be $0.3\text{-}1.9\times10^6$ m^3/yr (Figure 2.8; Ridderinkhof, 2016). For windiness, storminess, wave conditions and related storm-surge conditions along the Wadden Sea the reader is referred to the Dutch Wadden Sea paragraph 2.1. Wave conditions and related ocean responses in the area of East Frisian Wadden Sea and Southern North Sea are addressed by Grashorn et al (2015) and Schloen et al. (2017), respectively.

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 and the deepening of the Westerems, the Weser and the Elbe, which led to increases in tidal amplitude in a large part of each estuary. Another important feature 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 constructed on many places resulting in foreland salt marshes. On the barrier islands, only the inhabited areas are surrounded by a closed chain of sand drift dikes and back-barrier dikes.

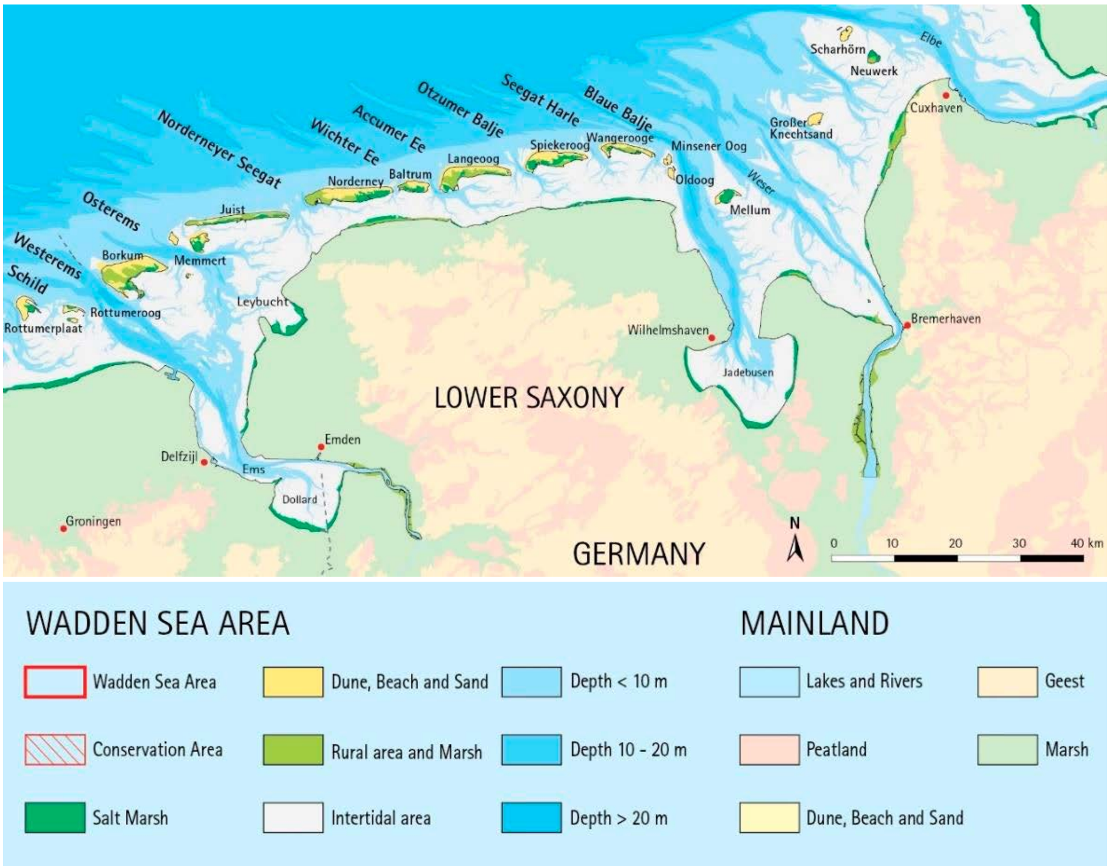


Figure 2.7 The inlet systems of the Wadden area of Lower Saxony (Courtesy, Wadden Sea Secretariat).

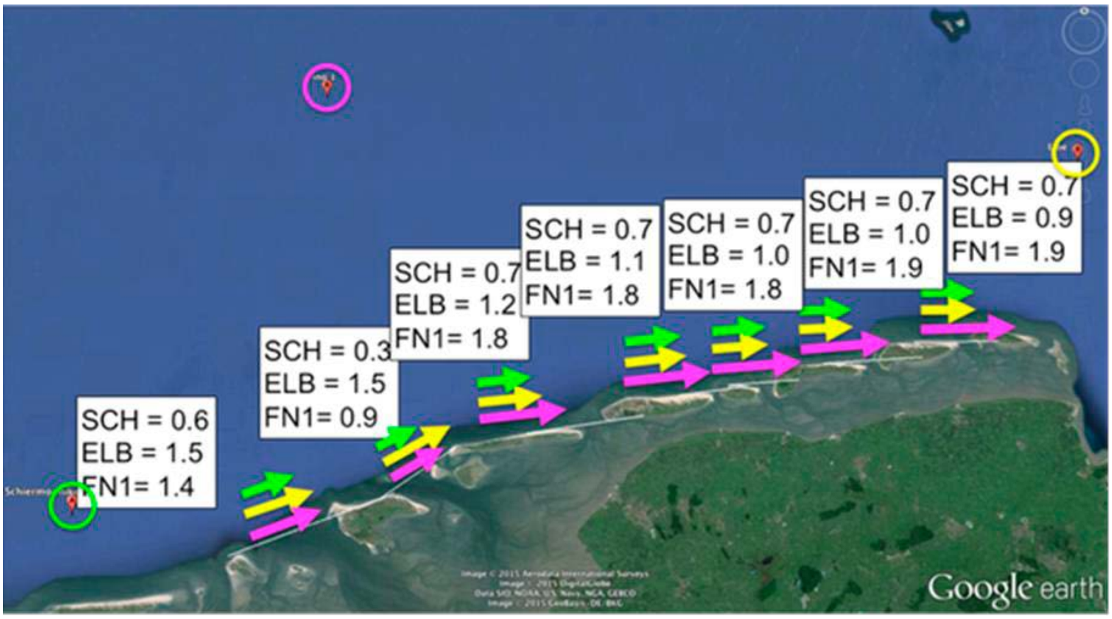


Figure 2.8 Littoral drift along the North Sea coast of Lower Saxony, computed using wave data from stations Schiermonnikoog (SCH, green arrows), Elbe (ELB, yellow arrows) and Fino1 (FN1, magenta arrows), in 10^6 m^3/yr (From: Ridderinkhof, 2016).

2.3.2 Geology

After the last Ice Age relative sea-level rise was initially rapid but decreased over time (see Figure 2.3). 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 back-barrier embayments (e.g. Harle- and Jade-embayments) thereby enlarging the tidal volume of the estuaries or back-barrier basins of which they were part. In the East Frisian Wadden Sea area, the deepest river valleys were flooded around 8000 a BP (Beets and 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 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 and 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).

In the following millennia after 5000 BP subsidence of the bottom in the East Frisian Wadden Sea, was relatively large, 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 (Vos et al., 2011). In other places the Wadden Sea silted up locally, and 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 back-barrier areas.

The situation of the East Frisian Wadden area at 1,200 a BP is given in Figure 2.9. 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.

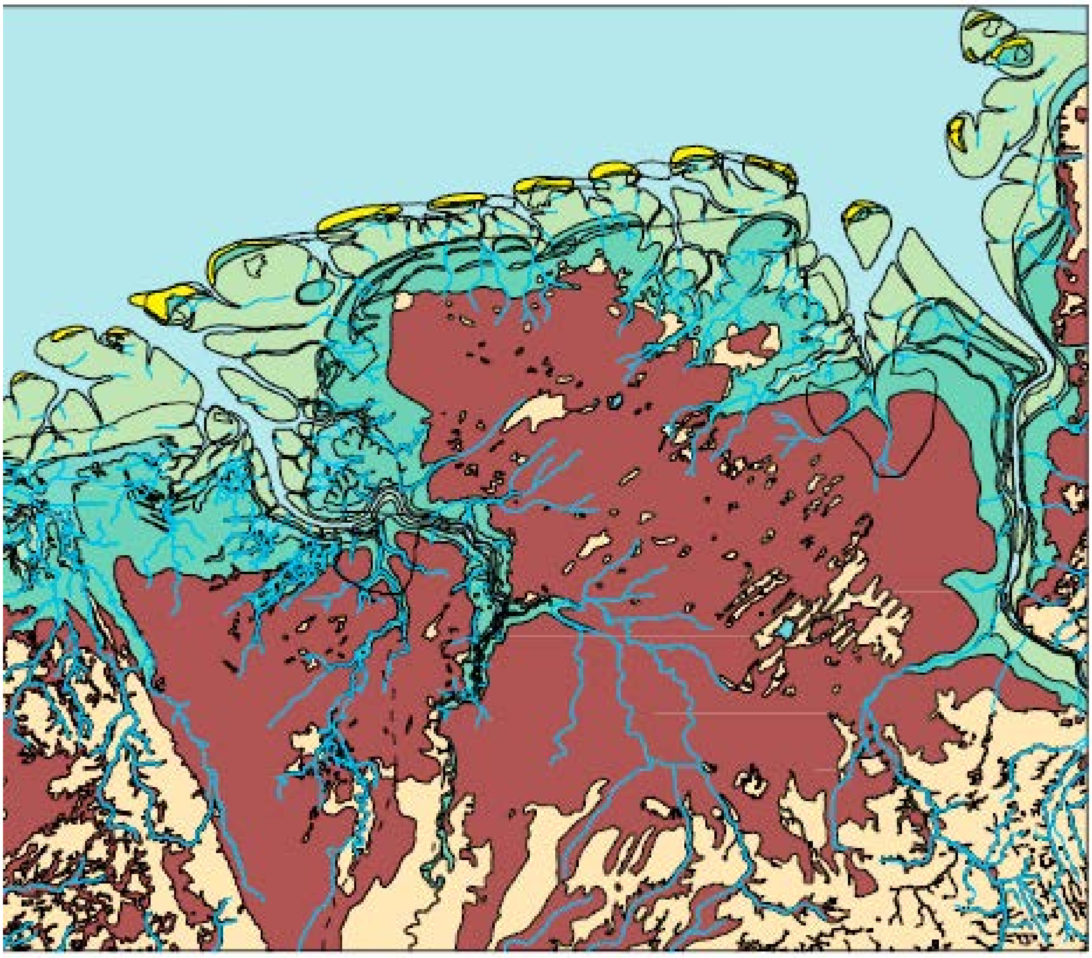


Figure 2.9 Situation around 800 AD. Orange = higher sand grounds; brown -= peats; yellow = coastal dunes ;dark green = tidal marshes; light green = tidal flats; blue is subtidal area; contours of present-day coasts are given (Oost et al., 2017).

The first local dikes surrounding small areas to safeguard arable fields against typical 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 as a result of 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 (Leybucht, Maade Einbruch, Schwarzes Brack, Harlebucht) has been reclaimed (Vollmer et al., 2001; Van Heteren and 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. As technology up to the end of the 19th century 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 on the tidal flats, whereas medium to coarse grained sediments are present in most of the inlets and around the islands (Figure 2.10). Along the mainland coasts and in the estuaries (especially more upstream) and in the Jade Busen, fine-grained sediments are dominant resulting in large mud-rich areas.

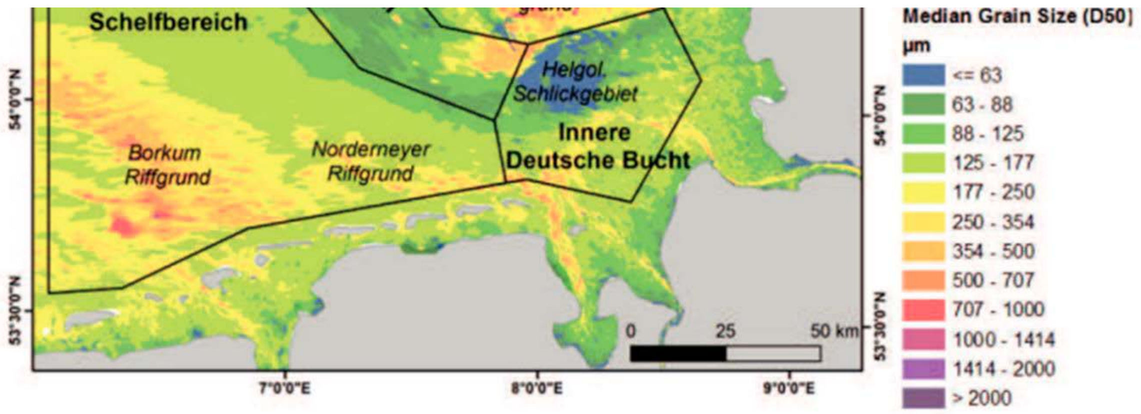


Figure 2.10 Median grain size distribution in µm-classes of the Lower Saxonian area as given in the functional bottom model (Milbradt et al. 2015).

2.4 THE WESER ESTUARY

2.4.1 Characteristics

The Weser is the second-largest river in Germany discharging into the North Sea. The length of the estuary from the tidal weir is approximately 130 km (Figure 2.11). The Weser estuary consists of the Lower Weser between the weir and the city of Bremerhaven and the Outer Weser seaward of Bremerhaven. The tide influenced tributaries are those of the Ochtum, Lesum, Hunte and Geeste. The Outer Weser has a funnel shape oriented to the north-west.

The tidal range has increased in Bremen since the first deepening from approx. 0.2 m to a current level of 4.1 m due to the deepening of the Lower and Outer Weser. Nowadays, mean tidal range rises from 2.9 m at the lighthouse Alte Weser (approx. km 115) to 3.8 m at Bremerhaven (approx. km 66) and to 4.1 m at Bremen-Oslebshausen (approx. km 8). Between 1973 and 1978 the Lower Weser was deepened to -9 m chart datum. In the period 1998-1999 the Outer Weser was deepened to -14 m chart datum.

Bottom sediments of the Lower and Outer Weser consist mainly of medium and fine sands. In the Lower Weser large pronounced bed forms (dunes superimposed by ripples) are present due to currents. They have average crest heights of 2 m at mean lengths of 60 m, while maximum heights of 4.5 m can be found. Seawards of Nordenham, these bedforms disappear. There, the so-called "Nordenham mud section" (km 55–58) is present. This is the turbidity maximum zone, where muddy sediments dominate, containing up to 25% silt and clay and 5% organic matter (Grabemann and Krause, 2001; Müller, 2002). Near-bed concentrations exceed 0.25 g/l (Fanger et al., 1985; Riethmüller et al.1988; Grabemann and Krause 1989, 2001). The turbidity maximum zone is formed due to the combined effects of tidal asymmetry (Grabemann et al., 1997; Lang et al., 1989) and non-tidal estuarine gravitational circulation (Riethmüller et al., 1988).

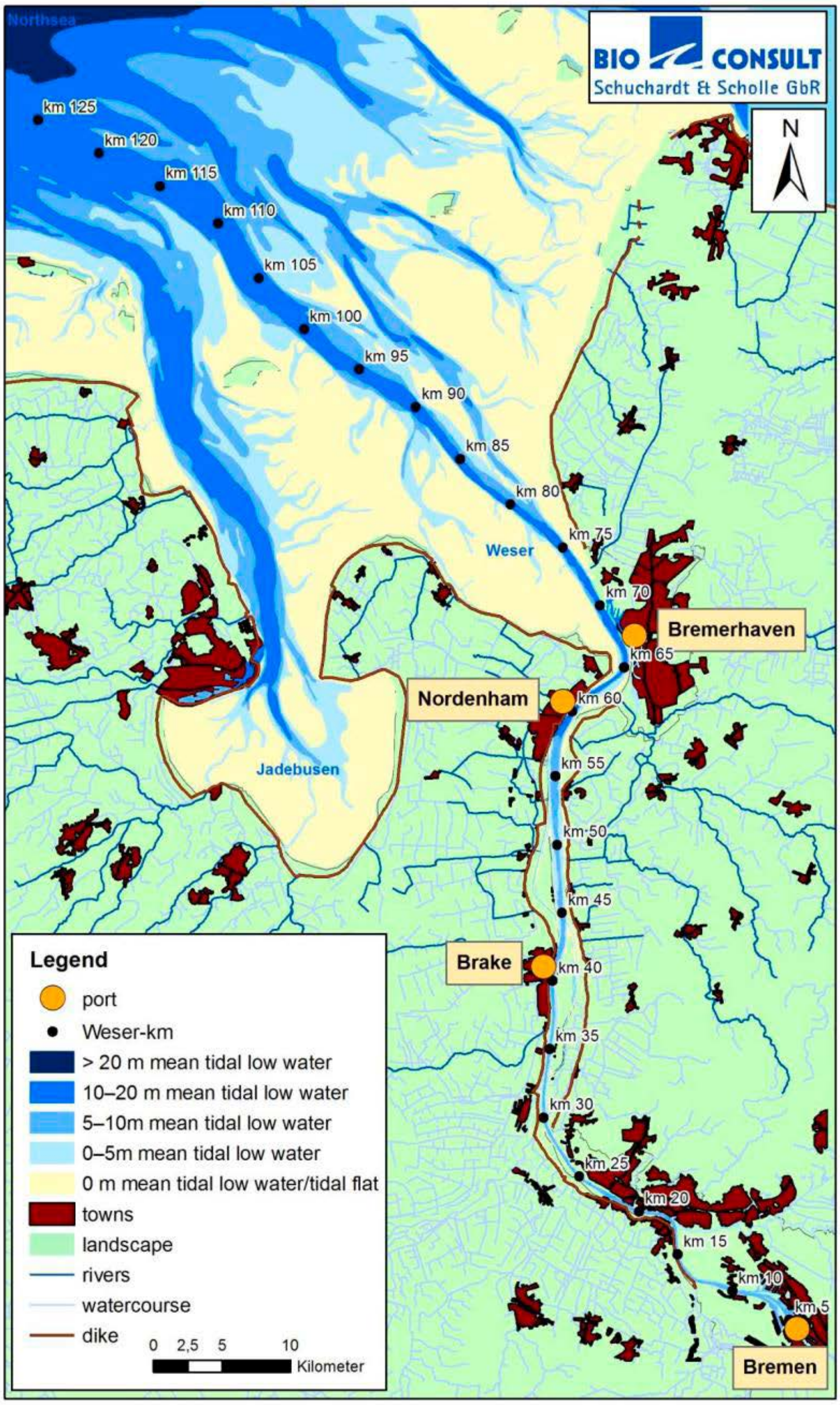


Figure 2.11 An overview of the Weser estuary (BIOCONSULT and NLWKN, 2012)

The funnel-shaped Outer Weser has two main channels, several secondary channels, tidal gullies and extensive tidal flats (Lange et al., 2008). In this sandy area the topography changes continuously due to the strong hydrodynamics. Before the main navigation channel in the inner estuary was established and groynes and training walls were fixating the main channels (early 20th century), cyclic variations led to an alternating preference of the western (Fedderwarder Arm) or eastern (Wurster Arm) channel (Lange et al., 2008). Sediments of the channels of the Outer Weser are mainly fine and medium sands. On the bottom of the navigation channel extensive flat sections alternate with scoured areas or stretches with sand waves having crest heights up to 5 m and lengths of up to 480 m. Depending on the location, tidal flats and gullies consist of sand, silt and all other sediment mixtures.

Dikes were first built on the lower reaches of the Weser River about 1000 AD. Large areas of the floodplain were thus separated from the estuary. The Weser estuary got its present shape in the Middle Ages. Thereafter, fortified embankments and dikes were built (Grabemann, 1999). In the period 1887-1895 the first regulation of the river course was undertaken, in order to guarantee passage for sea-going vessels with a draft of less than 5 m. As a result, the tidal wave could penetrate almost unimpeded till Bremen. In the 20th century additional changes and improvements were made to adapt to increasing ship sizes and to counter the reaction of the estuarine system (Table 2.1). Training works and walls, jetties and groynes were built, to stabilize the course and protect the embankments and shorelines (Hovers, 1973). Due to the penetration of the tide, LW levels were falling resulting in lower ground water tables upstream of Bremen. In the period 1906-1911 a weir was built in Hemelingen to stop this development. In the 1970s, the storm surge barriers were built at the mouth of the tributaries Hunte, Lesum und Ochtum.

For meteorological conditions the reader is referred to the section in the description of Lower Saxony.

Table 2.1 Overview of river deepening and correction measures in the Lower and Outer Weser (SKN = nautical chart datum; from Lange et al., 2008)

1887–1895	1. Unterweser-Korrektion for vessels with 5 m draft (5 m-correction) according to a plan of Ludwig Franzius
1913–1916	Upgrading of the Lower Weser for vessels of 7.0 m draft
1921–1924	Upgrading of the Lower Weser for vessels with a draft of 7.0 m when leaving Bremen (extended 7.0 m-correction of the UW)
1922–1926	Upgrading of ‚Fedderwarder Arm' in Outer Weser to SKN – 10 m
1925–1929	Upgrading of the Lower Weser for vessels with a draft of 8.0 m
1953–1958	Upgrading of the Lower Weser for vessels with a draft of 8.7 m, levelling of the bottom sill at Brake (Braker Buckel)
1969–1971	Upgrading of the Outer Weser to a depth of SKN – 12 m (dredging works for deepening)
1973–1978	Upgrading of the Lower Weser between Brake and Bremen to SKN – 9 m
1973–1974	Deepening of the Lower Weser between Bremerhaven and Nordenham to SKN – 11m and dredging of the turning circles
1998–1999	Upgrading of the Outer Weser to SKN – 14 m

2.4.2 Geology

For the general overview of the development of the Weser area the reader is referred to the chapter on the geology of the Lower Saxony area. Radiocarbon measurements and pollen analysis indicates that the North Sea reached the Weser area around 4200 BC.

2.5 THE ELBE ESTUARY

2.5.1 Characteristics

The Elbe is the largest river in Germany discharging into the North Sea. From the weir at Geesthacht until it flows into the North Sea, the 140 km long estuary is dominated by tides. From the Geesthacht Weir the Elbe is tide-influenced and known as the inner Elbe (Innenelbe) up to Cuxhaven; from thereon it is known as the Outer Elbe (Aussenelbe). The inner Elbe consists of a Low Elbe (Unterelbe) starting at the weir at Geesthacht and the Lower Elbe (Niederelbe) ending at Cuxhaven. Within Hamburg the Unterelbe has a number of branches, such as Dove Elbe, Gose Elbe, Köhlbrand, Northern Elbe (Norderelbe), Reiherstieg, Southern Elbe (Süderelbe), some of which have been disconnected by dikes.

The Elbe's two main branches Northern Elbe and the Köhlbrand reunite south of Altona-Altstadt in Hamburg city. At kilometer 634 (see bottom of Figure 2.12), the Northern and the Southern Elbe used to reunite, which is why the bay there is seen as the starting point of the Lower Elbe (Niederelbe). At Cuxhaven the Lower Elbe flows into the Aussenelbe which connects to the North Sea. The National Park Hamburgisches Wattenmeer exists since 1990 and has a surface area of ca. 11,700 ha. It is part of the Elbe estuary and includes the islands Neuwerk, Scharhoern and Nigehoern.

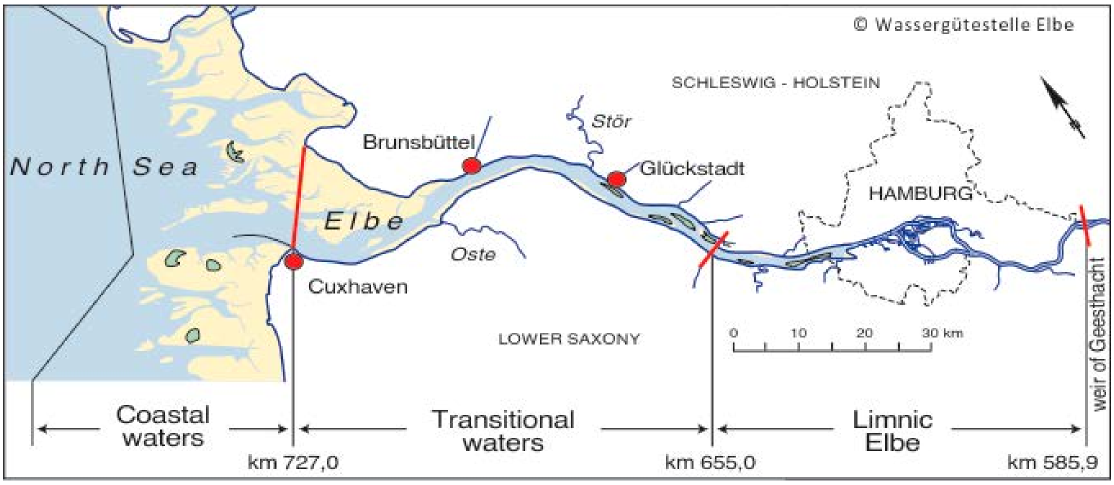


Figure 2.12 Overview of the Elbe estuary. TIDE factsheet

In the early 19th century, the estuary was still relatively natural (Figure 2.13 and Figure 2.14). At that time, the Elbe estuary near Hamburg was still relatively shallow with a water depth of about 4 m. A lot of small islands formed a delta close to Hamburg. Since then, the Elbe has been deepened 7 times and is now passable up to Hamburg for ships that need a depth of 13.5 m.

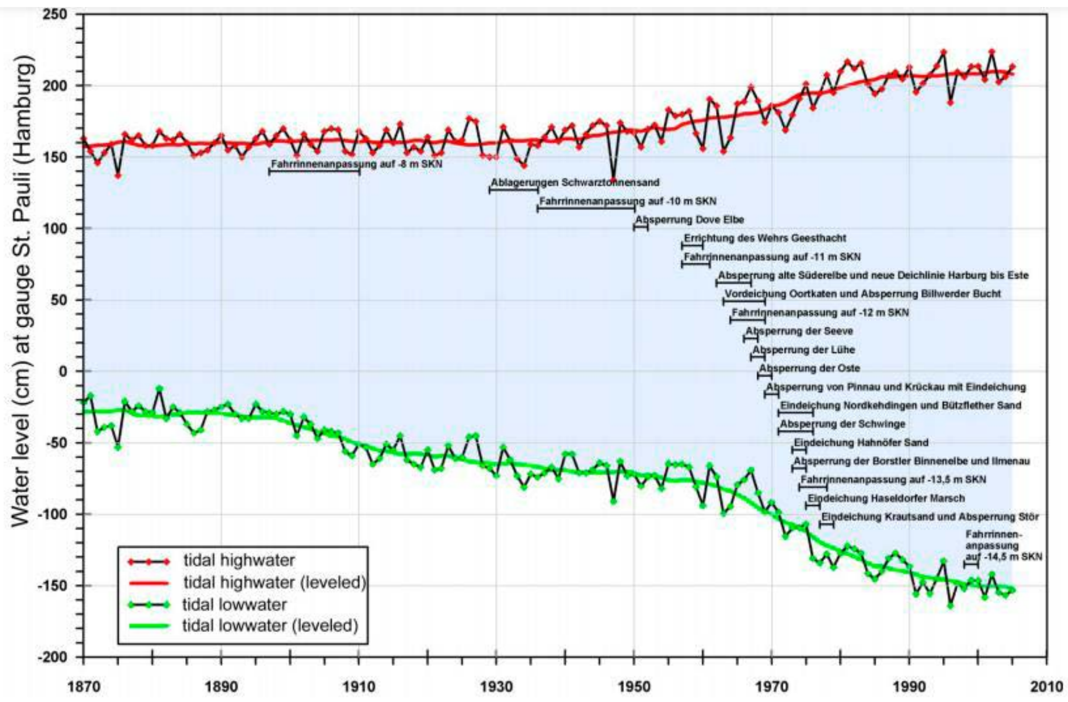


Figure 2.13 Development of high water and low water levels at St. Pauli station with running mean and the various management measures in the Elbe estuary (Meine, 2011).

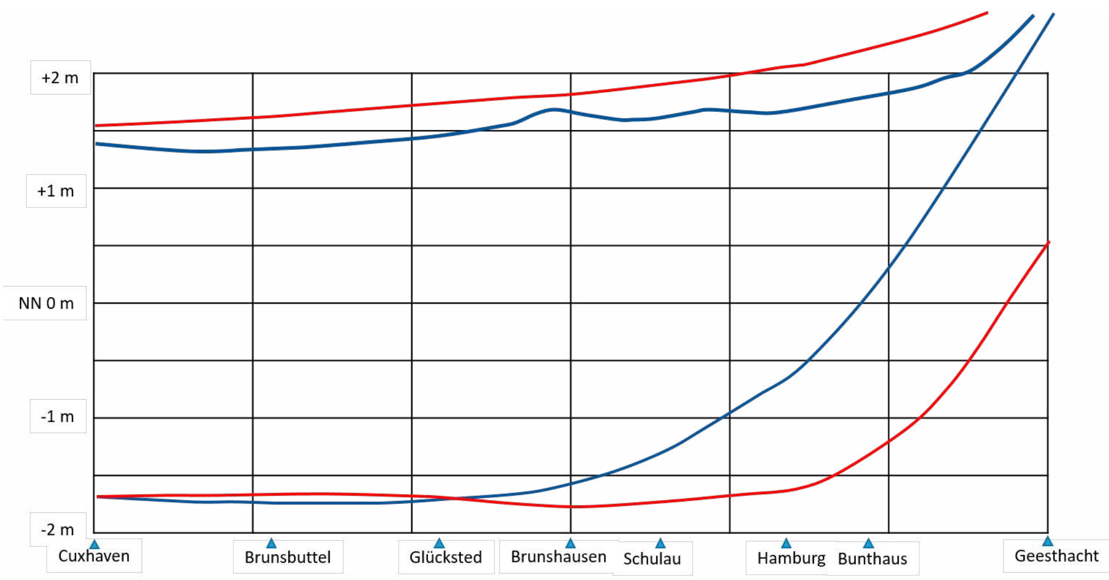


Figure 2.14 High water and low water levels along the estuary in 1900 (blue) and 2010 (red) (after Meine, 2011).

In 1890, the tidal amplitude was still some 1.9 m at Hamburg (Figure 2.13). At the mouth of the Elbe estuary tidal ranges are circa 3 m (Cuxhaven). From there it increases up to Hamburg Saint Pauli to 4 m, after which it decreases to some 2.5 m in the direction of the weir at Geesthacht. The flood period is shorter than the ebb period, a process associated with a flood-dominated asymmetry in tidal currents which causes tidal pumping and upstream sediment transport.

For meteorological conditions the reader is referred to the chapter on Schleswig Holstein.

2.5.2 Geology

For the general overview of the geology the reader is referred to the chapter on Schleswig Holstein.

During the Elster Ice Age (400,000-320,000 years ago) melt water eroded channels up to 400 m deep, which were later filled with sands. During the Saale Ice Age (300,000 – 126,000 years ago) land ice reached the area. Sands, pebbles and boulder clay were deposited at both sides of the Elbe valley and formed a height between mainly 20 to 60 m above present-day sea-level. In the lower areas north of the Elbe up to 8 m thick peatlands were formed (a.o. Liether Moor, Himmelmoor, Holmmoor, Ohmoor, Glasmoor, Wittmoor and Eppendorfer Moor).

During the Weichsel Ice Age (115,000 – 11,600 years ago) glaciers ended Northeast of the Elbe. In these days the river flow was diverted to the Northwest and the Elbe acted as a marginal glacial meltwater system flowing parallel to the Weichselian icefront. Deep valleys were formed such as those of the Alster, Bille, Wandse and Pinnau. Together with the paleo valley of the Elbe they determine the present-day landscape of the Hamburg region. After the Weichsel Ice Age sea-level rose once more and tidal water could enter the Elbe valley and turn the valley into a broad estuary. This led to the generation of river shifts and island formation. The mud flats near the Elbe estuary are believed to have been above sea-level during Roman history and to have been inundated when the shoreline sank during the 13th century.

2.6 THE SCHLESWIG HOLSTEIN WADDEN SEA AREA

2.6.1 Characteristics

The south-north oriented World Heritage Wadden area of Schleswig Holstein has a total surface area of 4,367 km^2 and ranges from the mouth of the river Elbe up to the Danish border by the island Sylt. The Wadden Sea of Schleswig Holstein itself has a total area of some 2.350 km^2 and consists of small islands which may or may not be inhabited, the so-called Halligen (12% of the area, for further explanation see Chapter 6), tidal marshes (4%), tidal flats (51%) and tidal channels (33%; Figure 2.15; MELUR, 2013).

Figure 2.15 The inlet systems of the Wadden area of Schleswig Holstein: Norderhever-Heverstrom to Hörnum Tief (Courtesy, Wadden Sea Secretariat).

The area consists of fourteen inlet systems, from south to north: 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 and Norderaue), Hörnum Tief and Lister Tief (Lister Dyb; Figure 2.16).

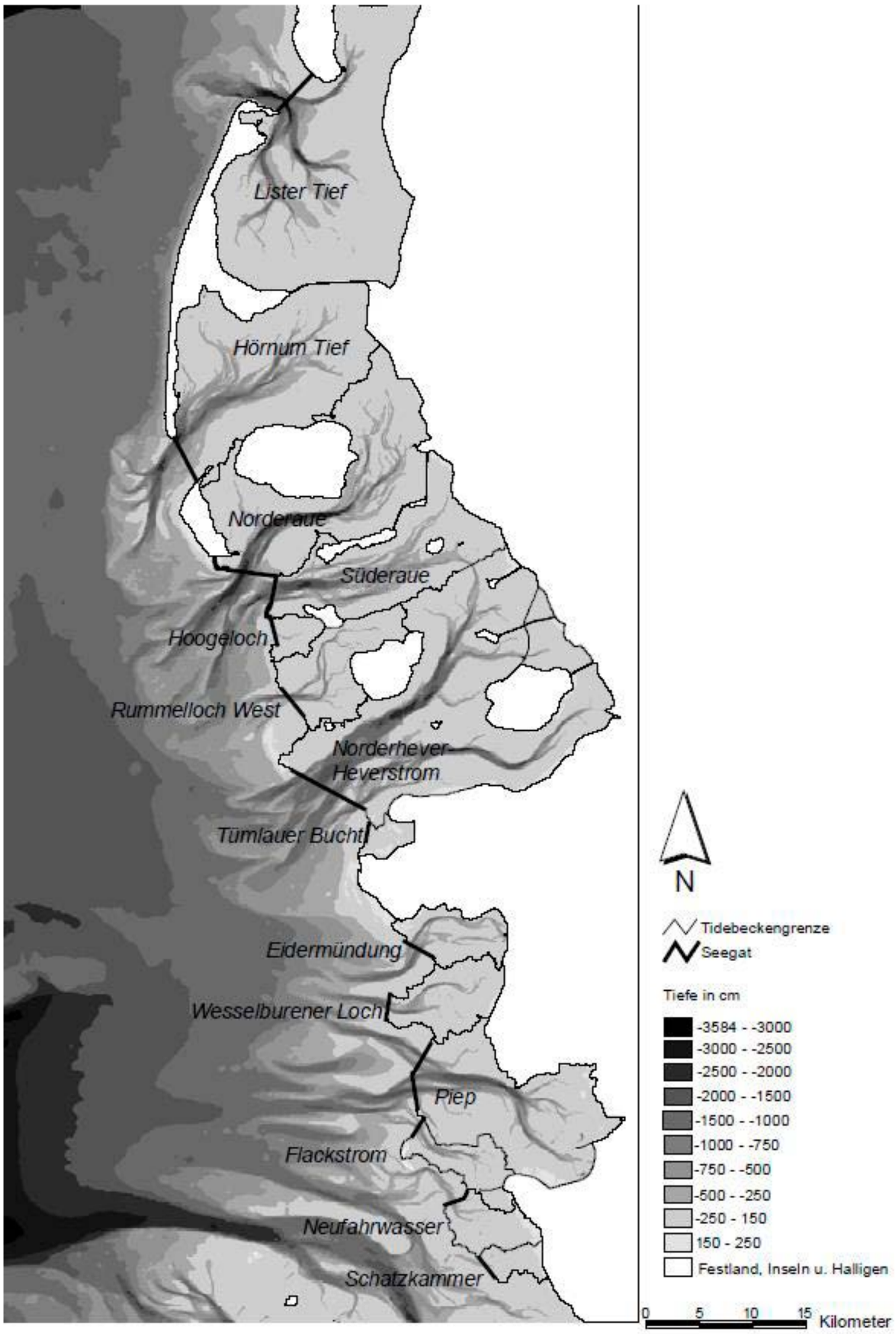


Figure 2.16 Detailed overview of the inlet systems of Schleswig Holstein.

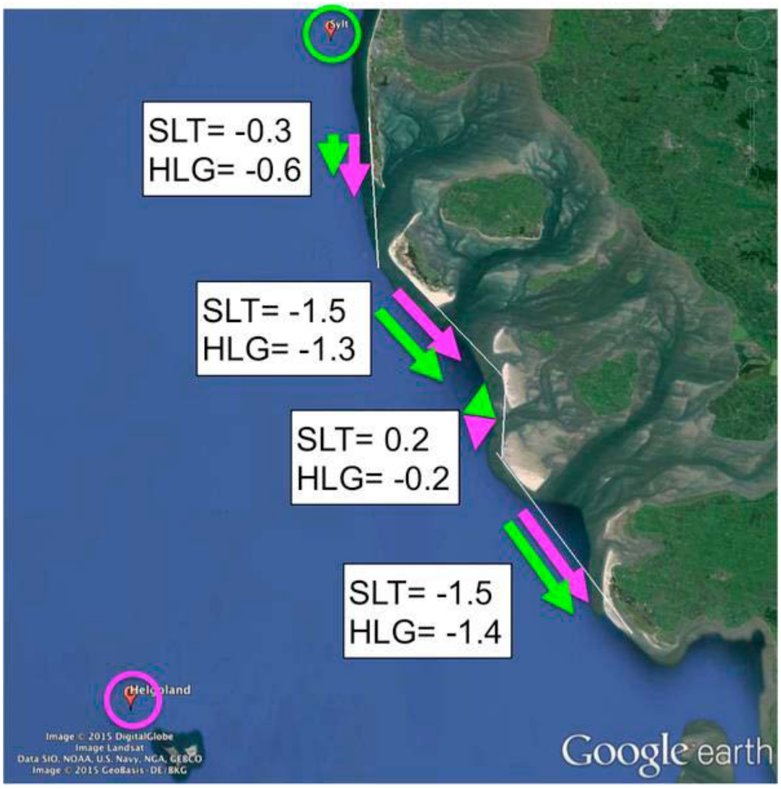


Figure 2.17 Littoral drift along the Schleswig Holstein coastline, computed using wave data from stations Helgoland (HLG, magenta arrows) and Sylt (SLT, green arrows), in 10^6 m^3/yr (From: Ridderinkhof, 2016).

Several small rivers enter the back-barrier; the major ones are the Eider and Aue. Five of the inlets have islands at both sides and clearly distinguishable ebb-tidal deltas, namely Norder-hever-Heverstrom, Rummelloch-West, Aue, and Lister Tief.

Tidal amplitude increases from north to south 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 south, calculated to be 0.2-1.5×10^6 m^3/yr (Figure 2.17; 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 the significant wave height may reach 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 mid-water level increase of 1.8 mm/yr (Figure 2.18; 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 2.19; MELUR, 2013). Also, the annual cumulative duration of storm surges has increased since 1900 (Figure 2.20). Figure 2.19 and Figure 2.20 show a strong increase in storm surge intensity from the early 1960's up to the early 1990's. Afterwards, storm surge climate became less energetic.

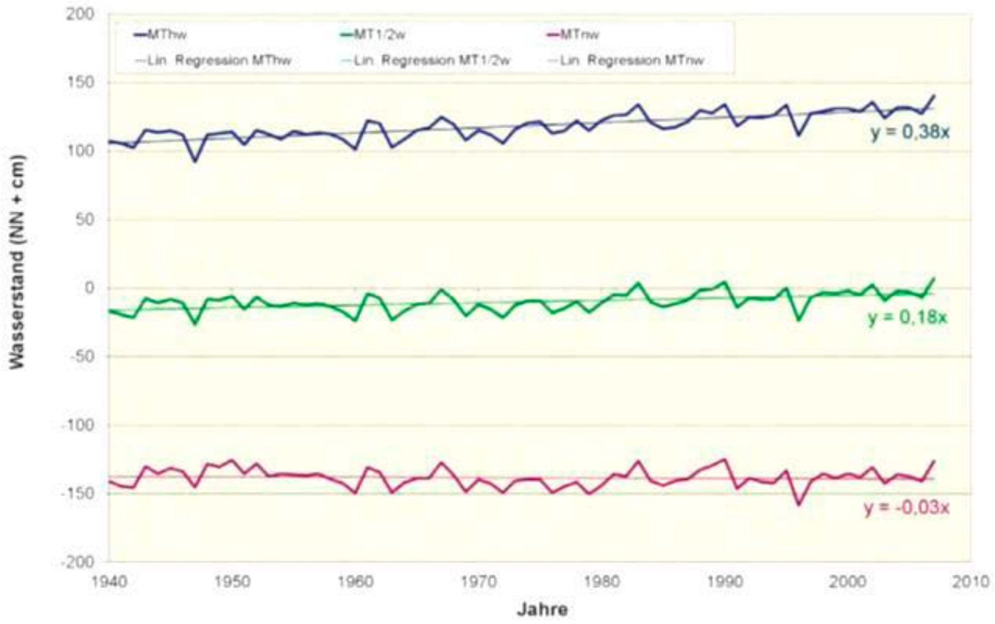


Figure 2.18 Development of the MHW, mid-tide and MLW over the period 1940-2007 as a mean of the stations: List, Hörnum, Wittdünn, Dagebüll, Husum, Büsum and Helgoland (MELUR, 2013).

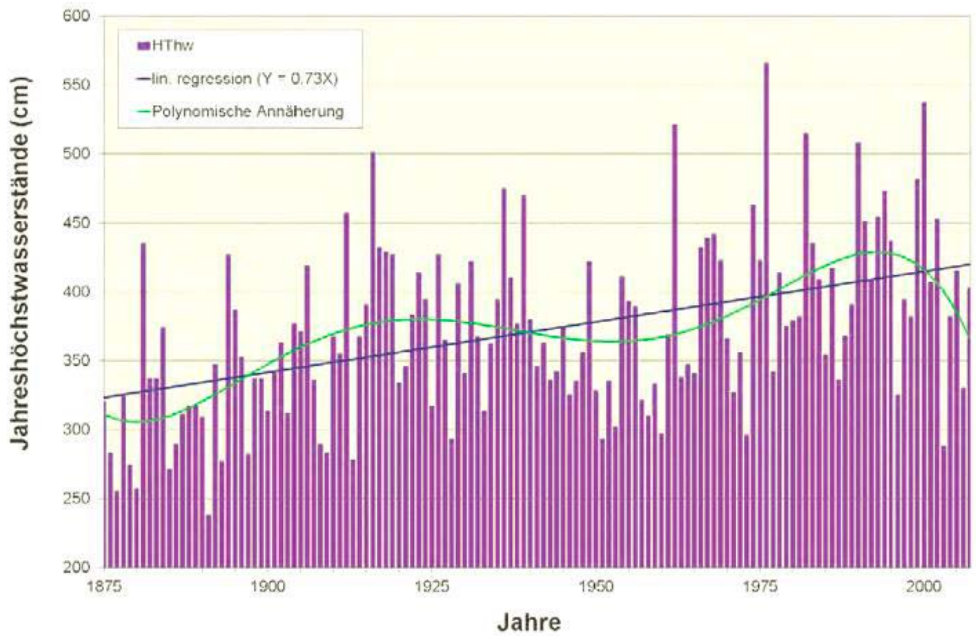


Figure 2.19 Observations of the annual highest storm surges at Husum gauge (MELUR, 2013)

Several large engineering interventions have been carried out in the area. The most important are the Eider Sperrwerk (a storm surge barrier in the mouth of the Eider estuary), the dams to Sylt and the diking of some parts of the back-barrier 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 tidal water volume between MHW and MLW decreases, whereas the data on the subtidal water volume of the area below MLW show a less clear trend (using the data of van Riesen and Winskowsky, 2007). This suggests sedimentation in the intertidal reach and erosion or sedimentation stillstand in the subtidal areas.

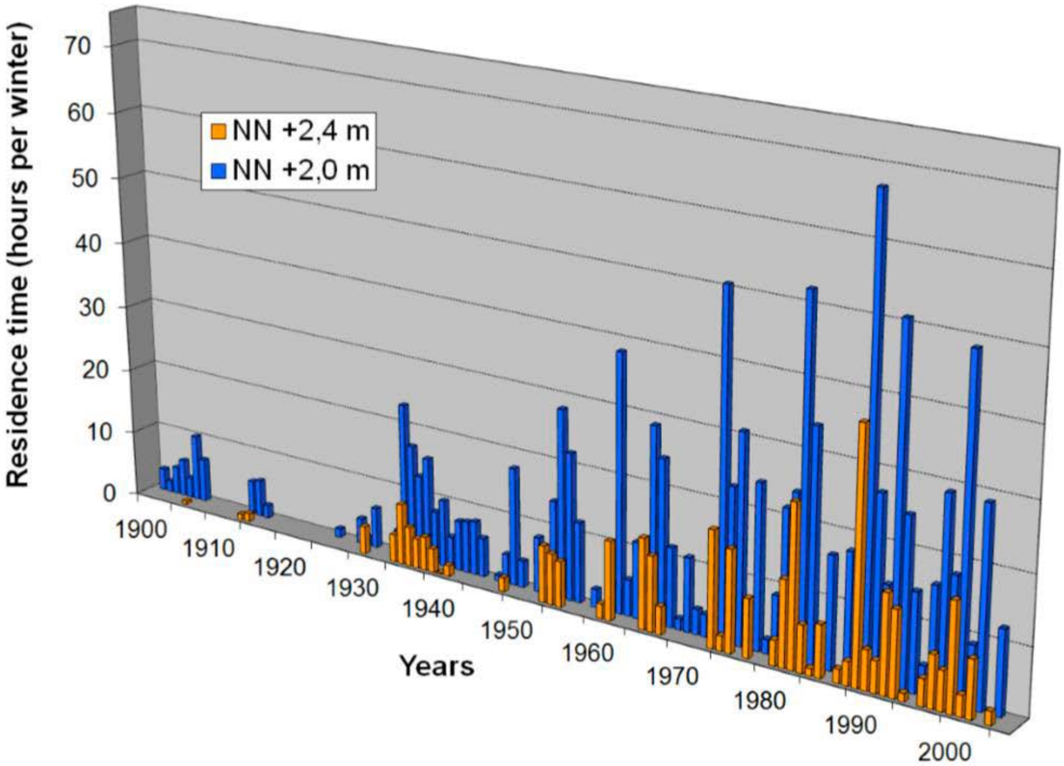


Figure 2.20 Annual hours of storm surges higher than +2.0 and 2.4 m NN at tidal gauge station List on Sylt over the period 1900-2004 (MELUR data, courtesy of Hofstede). NN is the reference level in the German Ordnance system, and is identical to Dutch NAP (both approximately corresponding to MSL).

2.6.2 Geology

A large part of the geomorphology of Schleswig-Holstein was created during the Saale glaciation, when 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-level was some 110 m lower than today and rivers scoured valleys into the Saalian deposits and later on the landscape was modified by the sandy meltwater deposits of the Weichselian ice sheet further towards the East filling up depressions and former valleys. In addition, aeolian 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 (partly displayed in Figure 2.21). 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, formed the North Frisian Wadden area (Bartholdy and Pejrup, 1994; Lindhorst, 2007). Nordfriesland can be considered as the remnant of an area west 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 sources of the sediments were the Saalian Geestland sediments, west of today's Geest islands Sylt, Föhr and Amrum. Southward coast-parallel transport of these sediments resulted in the formation of a more or less closed barrier spit, behind which a landscape developed of swamps, bogs and forests (Bantelmann, 1966).

Around AD 1,000, the land was cultivated by people who 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 AD 800 onwards, dwelling mounds were once more constructed in the North Frisian region (Vollmer et al., 2001) as had been done before. Between AD 1,000-1,100, 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. Those 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 both intertidal and subtidal areas (Schmidtke, 1995, Higelke, 1998). In 1634 a severe 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.

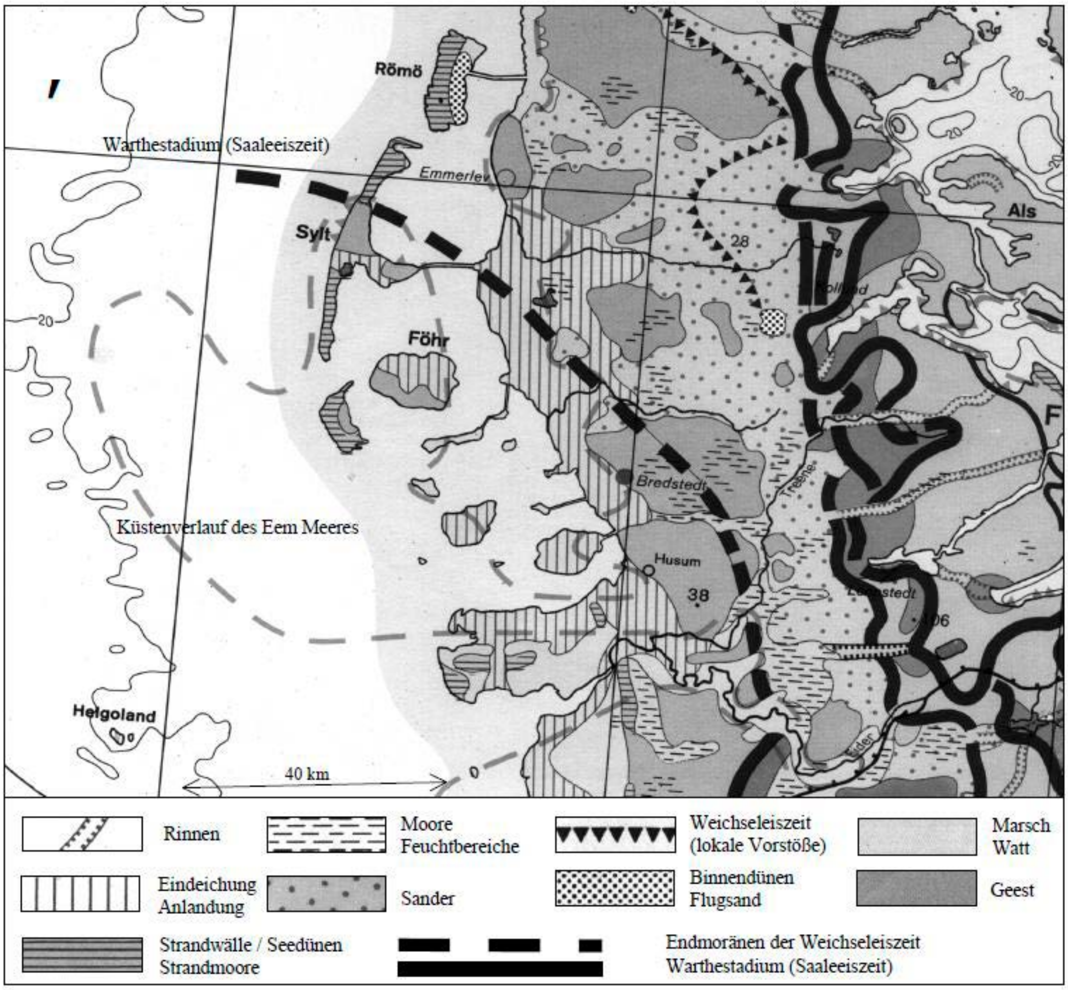


Figure 2.21 Geological map of the Schleswig Holstein Wadden Sea area (Falk, 2001).

The larger part of the sediments of the tidal area consists of medium-sized quartz sands. But it is clearly visible on Figure 2.22 that the channels of Hever, Aue, and especially Hörnum Tief and Lister Tief are characterized by coarse-grained sediments (indicating erosion into the Pleistocene moraine deposits or transport of coarser materials in meltwater of the continental ice sheets), the sturdy boulder clays. This might be an explanation to the general lack of meandering in the deeper inlet channels. The sand is mainly originating 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).

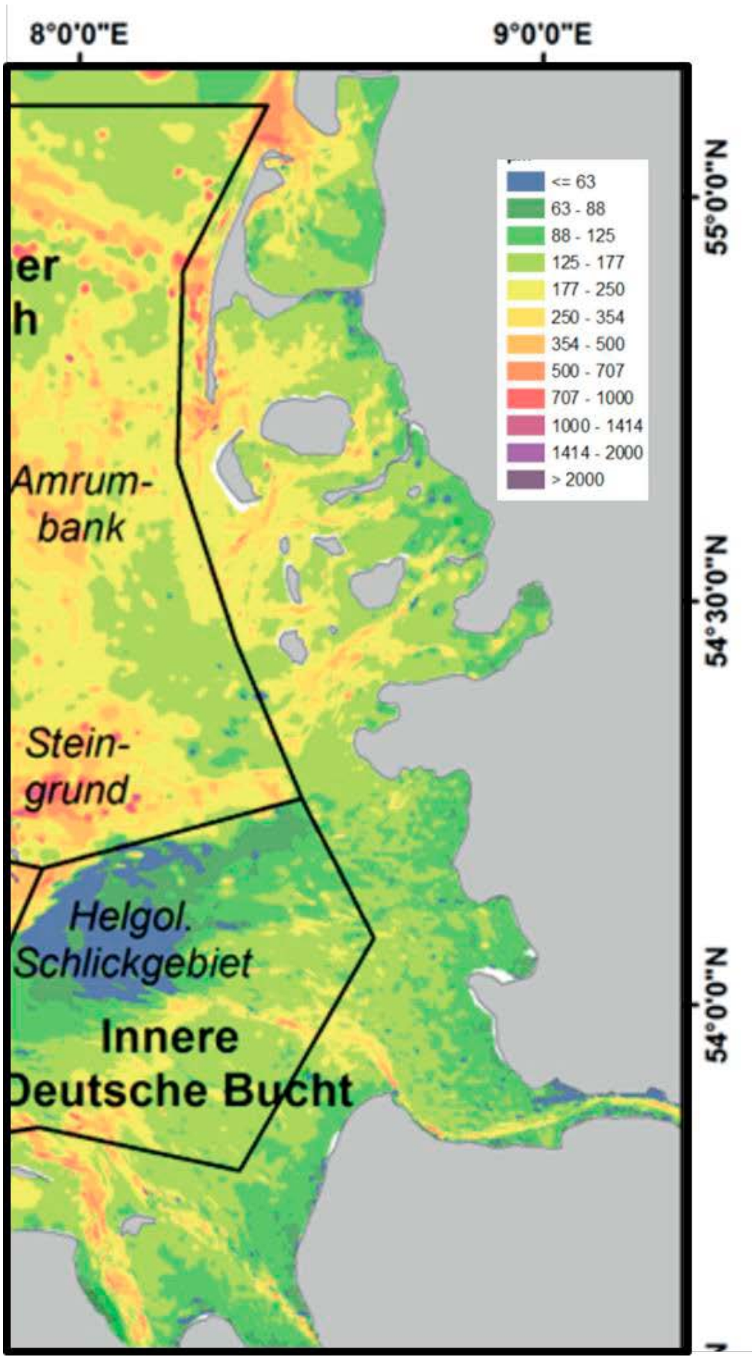


Figure 2.22 Median grain size distribution in µm-classes of the Schleswig Holstein Wadden Sea area as given in the functional bottom model (Milbradt et al. 2015).

2.7 THE DANISH WADDEN SEA

2.7.1 Characteristics

The south-north oriented Danish Wadden Sea area has a total area of some 1.500 km^2 (Figure 2.23: Laursen and Frikke, 2016). It consists of four inlet systems, from south to north: Lister Dyb (Lister Tief), Juvre Dyb, Knude Dyb and Grådyb, situated between Sylt, Rømø, Mandø, Fanø and the Skallingen peninsula (Figure 2.23). Several small (compared to German and Dutch Wadden area) freshwater rivers are entering the back-barrier. 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).

Figure 2.23 The inlet systems of the Wadden area of Denmark: Lister Dyb to Grådyb (Courtesy, Wadden Sea Secretariat).

Tidal amplitude is 1.5-2 m (Kystdirektoratet, 1999; Laursen and Frikke, 2016). The mean significant wave height decreases from Lister Dyb (ca. 1.5 m) to Grådyb (ca. 1.4 m) (Coast Dat data). Along the west coast of Jutland littoral drift is directed to the south, amounting to 0.3-1.6×10^6 m^3/yr (Figure 2.24; 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 south-wards (DHI and 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 south of the new ebb channel and transported towards the coast by waves (Bartholdy and Pejrup, 1994).

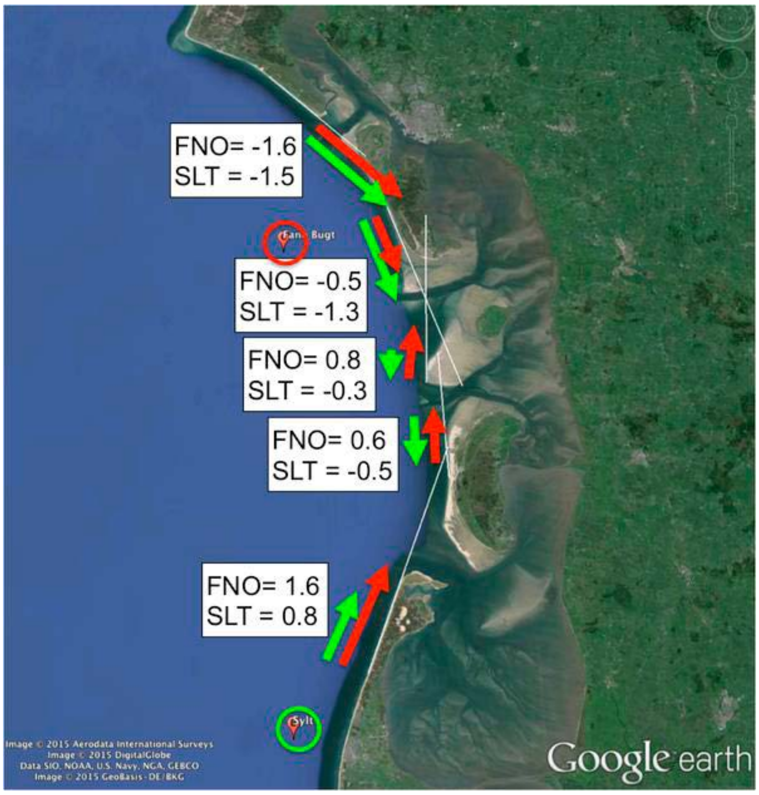


Figure 2.24 Littoral drift along the Danish coastline, computed using wave data from stations Fanø (FNO, red arrows) and Sylt (SLT, green arrows), in 10^6 m^3/yr (From: Ridderinkhof, 2016).

Observations indicate that MSLR in the Danish Wadden Sea is 1.35 mm/yr in the period 1889-2007. Comparison to the average rate of sea-level rise of 1.3 mm/yr in the 20^{th} 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 indicate 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 salt marsh works are present. Along the Grådyb mainland coast the harbour town of Esbjerg has been developed. The waterway to the harbour of Esbjerg has been deepened and is maintained by dredging.

2.7.2 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 east of the present-day Wadden Sea. Melt waters drained to the west 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 2.25; Jacobsen, 1993; Bartholdy and Pejrup, 1994).

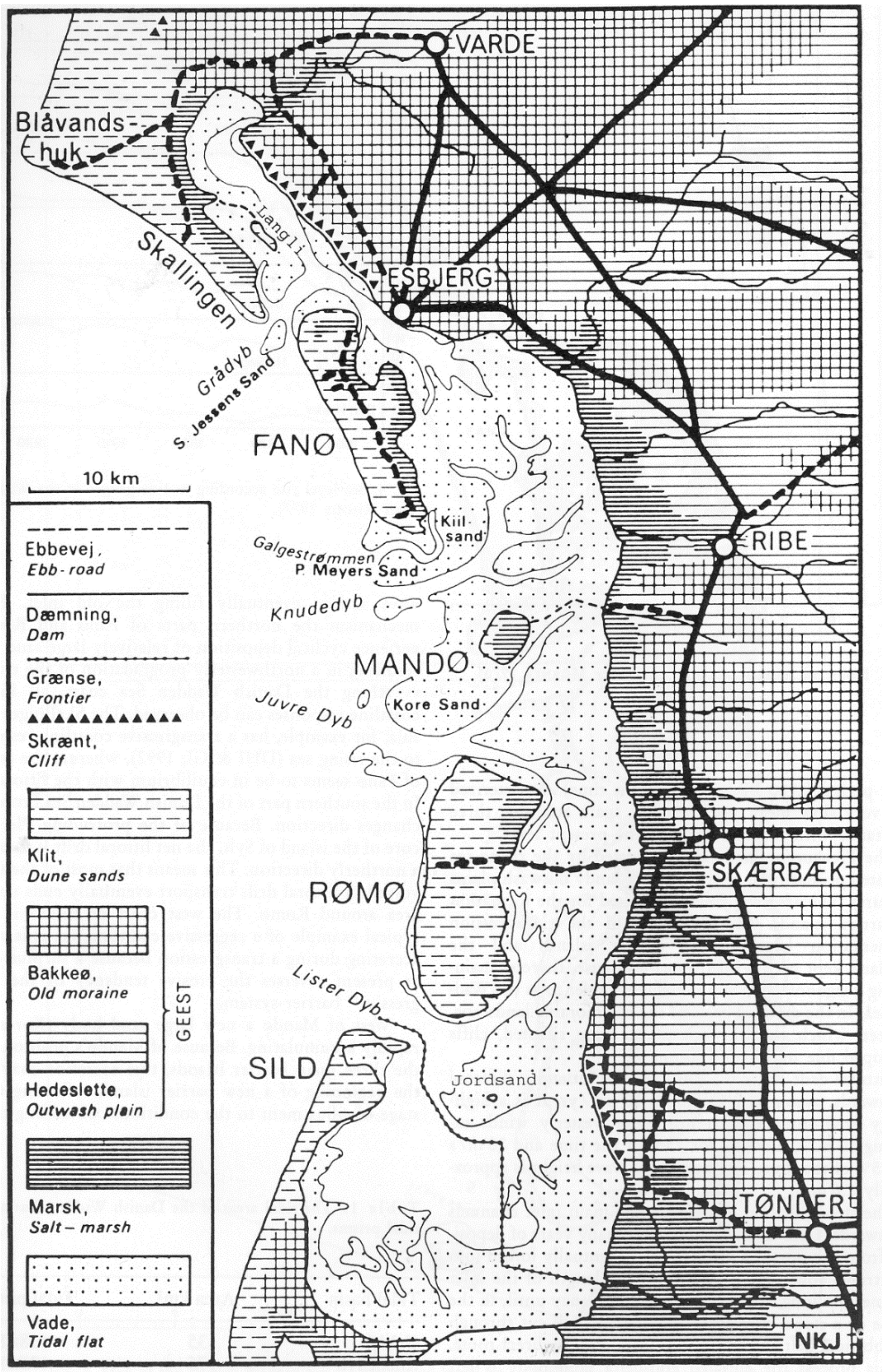


Figure 2.25 Geological map of the Danish Wadden Sea (Jacobsen, 1993)

The east and north 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 and 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 sea-level rise velocity was high, but gradually slowed. 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) from the updrift ebb-tidal delta between Sylt and Rømø. 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 were formed. It is thought that Langli, the eastern part of Fanø, Mandø, and Jordsand formed a system of old barrier islands (Bartholdy and 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 (the most recent barrier island), Fanø, (Koresand) and Rømø (Kystin-spektoratet, 1999). Sylt is an eroding Pleisto-Pliocene core (Rotes Kliff and surroundings) which has an even more western position than the Danish islands more to the north.

The larger part of the Danish Wadden Sea consists of fine to coarse sand. The area of mudflats, mixed flats and tidal marshes with a high mud content is rather small.

3 A BRIEF OVERVIEW OF MAIN PROCESSES

In this chapter we discuss the main hydrodynamic processes and sediment transport mechanisms relevant for the import, transport and deposition of mud in the Wadden Sea. Besides, we discuss the residence time of mud inside the basins, and the exchange of mud between individual tidal basins and between the sub-parts of the Trilateral Wadden Sea system.

3.1 DETERMINING FACTORS AND TIMESCALES

Herman et al. (2018) recognized three important factors and three important time scales where processes operate that determine both the SPM (suspended particulate matter) in the water column and the mud content of sediments in the Wadden Sea (see Figure 3.1).

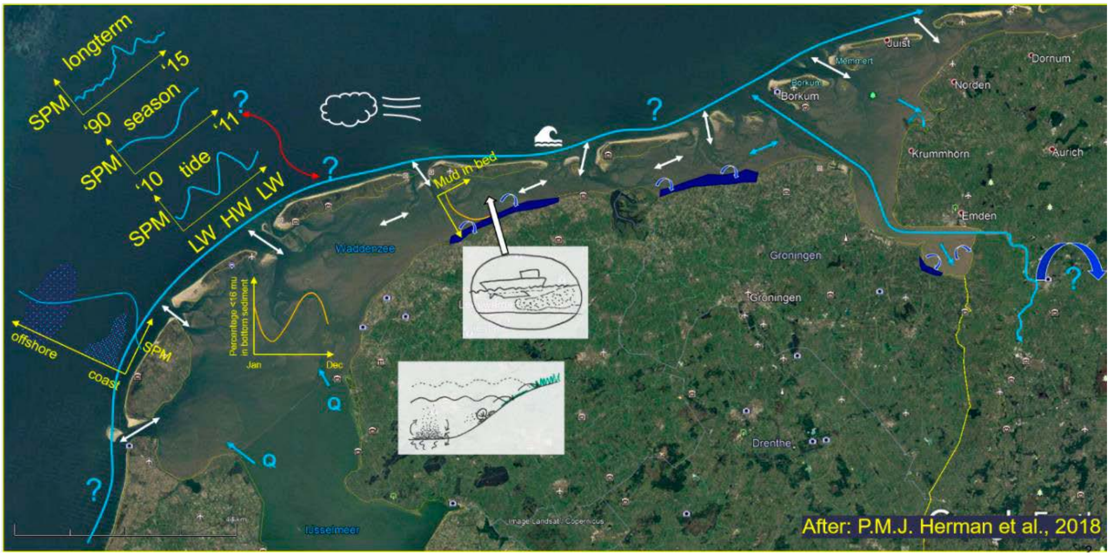


Figure 3.1 Schematic diagram of the most important processes affecting mud dynamics in the Wadden Sea. After: Herman et al. (2018). The light blue arrows indicate the mud sources, the dark blue arrows show mud extraction, by salt marshes and landfills and the white arrows show mud transport between the basins and the North Sea and between the individual basins.

The factors are:

- The *quantity of mud*, some of which is in suspension but most of which is stored in the seabed, in an either easy or difficult to erode state;
- The *properties of mud* which determine both horizontal and vertical transport (i.e. sedimentation, erosion and transport), mainly characterized by settling velocity, critical shear stress for erosion and the erosion rate;
- The *hydrodynamic forces* acting on mud, steered by the tide, wind, waves and freshwater discharge (see also Figure 3.2).

The time scales are: 1) Short: tidal to spring/neap tidal (0.5 - 14 days), 2) intermediate: seasonal to multi-year, and 3) long: > 5 years, i.e. morphological time scale.

At the short time scale, most processes related to deposition, resuspension and transport exchange between the Wadden Sea and North Sea of suspended material take place. At the very long timescale (decadal) we observe interactions between major hydrological changes (e.g. changes in tidal volume because of land reclamations, closures of Zuiderzee and Lauwerszee, migrations of tidal divides) and mud content of the sediments. However, the observations also point to a third time scale, which ranges from seasonal to multi-year, where the surprisingly long 'memory' of the system resides. There are year-to-year variations both in mud content of the sediment and SPM concentrations, which have autocorrelations up to more than one year, and where, because of this, average SPM fluctuations may diverge from the long-time average for a number of successive years. This time scale is often neglected in conceptualizations of mud dynamics, but it appears to play an important role in the time dynamics of the observation series.

Note that this does not exclude other factors that can be important from a management point of view, such as influence of biota, fisheries and dredging. Herman et al. (2018) explain that these influences operate mainly through changes in the main factors mentioned above (see also Figure 3.2).

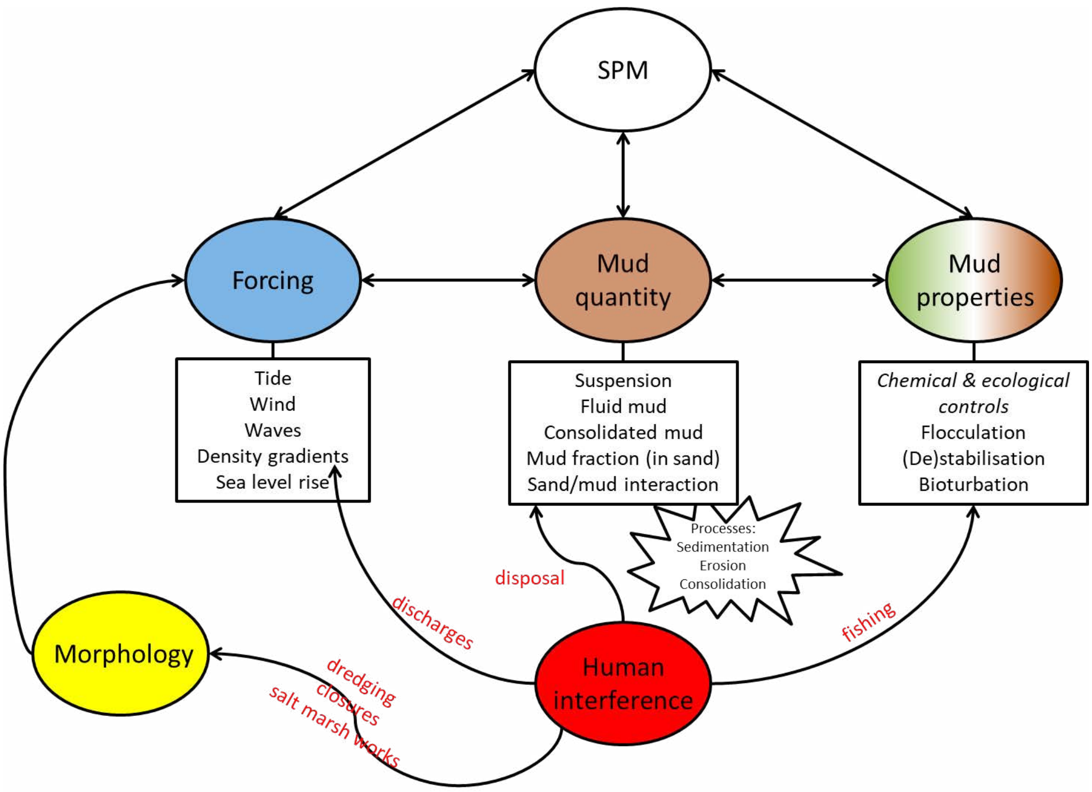


Figure 3.2 Schematic and generic diagram of the most important processes affecting SPM levels. By: Herman et al. (2018).

3.2 GROSS AND NET FLUXES

In multiple-inlet systems like the Wadden Sea, large amounts of sediment are exchanged with the adjacent sea during ebb and flood. For any inlet, the amount entering with flood is generally unequal to the amount leaving with ebb, giving a residual flux of suspended sediment over a tidal period. The residual flux is very small compared to the gross flux and is highly variable in space and in time (Gerkema et al., 2014; Sassi et al., 2015). Exchange processes between the Wadden Sea and surrounding systems include the North Sea coastal zone and freshwater discharge. Gross exchange rates between the North Sea and each of the tidal basins are in the order of 50 10^6 ton/yr, and net import rates are roughly 1 to 5% of the gross exchange rate (Herman, et al., 2018).

The residual flux of water and sediment in the Wadden Sea is in the eastward-direction, generating a residual transport over the tidal divides. The Marsdiep inlet is the first inlet encountered by the northward SPM plume along the Dutch coast and is hence a favourable location for import (Nauw et al., 2014; Gerkema et al. 2014). Most of this sediment will not be exported again in the downdrift tidal inlet, but rather be transported eastward across the watershed (Duran-Matute et al., 2014). The large contribution of wind to residual transport over tidal divides was first established using numerical models (Stanev et al., 2003; 2019, Duran-Matute et al., 2014; Sassi et al., 2015; Burchard et al., 2015; Herrling and Winter, 2015). Its importance was corroborated through observational data by van Weerdenburg (2019) in the Western Wadden Sea. The contribution of the wind to residual flow and transport over intertidal areas of the Western Wadden Sea was analysed in detail by Colosimo et al. (2020), who showed that a single and even moderately strong wind event may transport the same amount of sediment transported during weeks of tide-dominated conditions. As a result of the dependence of residual transport of sediment on storms, sediment is mostly deposited in the (eastward) German Bight during periods with high wind velocities (Kösters et al., 2016).

Representative estimates of overall transports are still lacking, because of the high (short- and long-term) variability induced by the wind, and the logistic difficulties in measuring continues fluxes over a tidal divide. Residual fluxes therefore need to be computed using numerical models. However, numerical models themselves introduce uncertainties, especially in residual quantities as net transport is often a small difference between two much larger gross sediment fluxes (Sassi et al., 2015; Smits et al., 2020). As will be elaborated in more detail in Chapter 0, important sources of uncertainties in net sediment transport arise from (1) the meteorological conditions (definition of wind climate /variability; schematization of wave-driven transport/resuspension), (2) geometry of the basins (including model resolution), and (3) sediment parameter settings. Determining average residual fluxes therefore requires running a large amount of meteorological years and model parameter settings, which is challenging from a computational point of view. In order to improve our knowledge on the net exchange between basins, more long-term measurements in combination with dedicated modelling is needed.

3.3 RESIDENCE TIME OF MUD

While advective exchange of water between the Wadden Sea and the North Sea has a time scale of weeks only (Ridderinkhof, 1990) advective exchange of mud can have much longer time scales, because large quantities of mud are stored within the bed and can be resuspended in the future (Herman et al., 2018). Based on tracer studies, it is estimated that the residence time of mud in the Dutch coastal zone (in the water column and the sediment bed combined) is multiple years (Van Kessel et al., 2012).

The residence time of mud has not been quantified in a similar way for the Wadden Sea. However, as large parts of the system are depositional, the residence time of mud in the bed must be much longer in the Wadden Sea than in the fairly energetic North Sea. Mud has been depositing here for millennia, forming substantial mud buffers within the Wadden Sea area. A large part of these deposits is now closed off from the sea through construction of dikes. Nevertheless, within the Wadden Sea area substantial volumes of mud are still present, of which a part can be eroded during energetic conditions (e.g. heavy storms).

Eisma et al. (1989) estimated the time scales of transport and deposition of mud in the Wadden Sea using an unstable isotope of lead (Pb-210) measured in suspended and bed sediments. The transfer time (the average time needed for dissolved Pb-210 to become adsorbed onto particles) is 2.15 days, the removal time (the average time needed to remove particulate Pb-210 from the water column) is 41.1 days and the residence time (the average time during which Pb-210 remains in the Wadden-sea) is 43.0 days. This is relatively short, reflecting the rapid exchange of water and suspended matter between the analysed flats in the Wadden Sea and the coastal North Sea and the frequent settling and resuspension of suspended matter.

Smits et al. (2020) explain that the residence time of mud within the Wadden Sea determines at which timescale the dynamic amount of mud will substantially vary. They estimated the residence time based on model simulations, by comparing mud transport fluxes (net and gross) and mud availability in the bed. They showed that the residence time largely depends on the fall velocity of the mud particles (especially related to the density and size of flocs), being significantly larger for particles with a large settling velocity (on average 257 days) compared to particles with a small settling velocity (on average 61 days), since the fast-settling particles interact more with the sediment bed. Based on their results, they estimated an average lower limit of the residence time of 166 days and an upper limit of 20 years. The lower limit (in the order of half a year) will probably be a better indication for relatively dynamic areas close to the inlets, while the upper limit (in the order of a decade) represents the residence time in low-dynamic areas, such as the salt marshes along the mainland coast.

There is also an assumed transport of SPM from west to the east in the Wadden Sea (Laane et al., 2013). Using a physical mixing model of the Dutch Wadden Sea, Verhagen (1990) calculated the adaptation time of the sediment quality in various parts of the Wadden Sea. By using the inter-annual trend of lead concentration in the surface sediments, he could quantify the time an SPM particle needs to travel from the western to the eastern parts of the Dutch Wadden Sea. According to the results, it takes about 26 years for SPM and associated contaminants to travel through the Dutch Wadden Sea from the west to the east.

4 SUSPENDED SEDIMENT CONCENTRATION

Suspended mud concentrations show a very wide natural range, both spatially and temporally. Mid-term variations can have natural and anthropogenic causes. Examples of natural causes are the wave climate, meteorological variation (wind, air pressure), effects by microphytobenthos, water salinity and temperature variations, vertical mixing and changing properties of fine sediments by for instance flocculation. On the other hand, human interventions have an impact by carrying out dredging activities and regulating freshwater output into the basins. Human activities such as land reclamations and extraction of mud can also influence the long-term variation of suspended mud concentrations. In this chapter we briefly discuss observed spatial and temporal variations of suspended mud concentrations brought about by natural factors. In chapter 7 the human interventions are discussed.

4.1 SPATIAL VARIATIONS

4.1.1 Introduction

The development of suspended mud concentrations is complicated, because settling velocity and critical shear stress for erosion are not directly linked to particle size. Flocculation-processes influence settling velocity, whereas consolidation and diatom covers of bed sediment influence erosion properties.

4.1.2 The larger picture

Analysis of SPM data (Herman et al., 2018) collected as part of the Dutch national water monitoring programme (MWTL) revealed that SPM within the North Sea transects (off Zeeland, off Noordwijk and off Terschelling) is primarily determined by the water depth: the time-averaged concentration depends linearly on the logarithm of depth (Eleveld et al., 2008). However, most Wadden Sea stations have a mean concentration well above that of the North Sea-levels, and a direct correlation with the depth does not exist. The SPM in e.g. a channel station is also influenced by processes in the intertidal (Stanev et al., 2007), thereby obscuring any depth-dependency in the observations. A multi-year trend analysis of SPM did reveal the existence of multi-year variability in SPM (i.e. SPM values may be lower or higher for a period of multiple years) over larger spatial domains (such as the Wadden Sea, North Sea Northern part, North Sea Southern part, etc.). However, this multi-annual variability may differ per spatial domain (i.e. a period of several years with elevated concentrations in one area does not correspond with multi-year trends in another area) without any autocorrelation between areas.

4.1.3 Basin variations

Grain-size fractions in tidal basins are sorted according to an energy gradient (see e.g., Nyandwi, 1998; Flemming and Ziegler, 1995). The general trend shows a decrease with both tidal and wave energy and, hence, in grain size from the inlet to the landward side of the basin. Mud (d<0.063 mm, $\phi > 4$, where $\phi = -2\log d$) is thus dominant in the water column in the lowest-energy parts of the tidal basin.

Grain sizes < ca. 0.16 mm (diameter) are sometimes called the suspension population, as the differences between current velocities needed for entrainment of a grain or to suspend them in the water are very low (van Rijn, 2008). Thus, a distinction can be made between finer sediments which are almost totally transported in suspension (the 'suspension population') and a so-called 'bed load population' of coarser grains. The latter group is partly transported over the bottom and will only be suspended at fairly high current velocities (>0.4 m/s). Under normal conditions, such current velocities can occur for longer periods during the tidal cycle in the deeper channels, but only occur for a short period in the shallower channels, gullies, shoals, marshes, creeks, etc. Near the inlet and in some parts of the main channel the current velocities are sufficiently high that even coarse sand will be picked up.

Moving from the inlet towards the end of the channel systems, under normal conditions, the grain size of particles suspended in the water column decreases (Postma, 1961). The two main sediment populations (suspension population and bed load population) are clearly separated here. The coarser sands of the bed load population are mainly to be found near the inlet and show a quick decrease towards the back-barrier. From channel lags (the shells and stones which are left behind after the washing out of sands) down to sand of ca. 0.16 mm, the distribution is clearly determined by the current velocities in the channel. The suspension population in the channel increases in concentration with increasing distance from the inlet; highest concentrations are found closer to the end of the channels (Figure 4.1).

Within this suspension population, there is also a very clear decrease in the median grain size towards the end of the channels. The same is also true for the median grain size and the clay content at the sediment surface of the channels (Eysink, 1993). The observations strongly suggest that the suspension transport in channels functions to sort the various grain size fractions. Although tidal currents dominate the bigger channels, wave- and wind-generated turbulence does influence the smaller channels (Postma, 1961). It is important to realize that also the shoals become muddier in the direction of the mainland by settling lag and scour lag effects. A part of this material will be brought back from the shoals towards the channels. This implies that the concentrations of suspended matter do not have to correlate completely with the local current velocities in the channels (Eysink, 1993).

In this report, we argue that the sorting of mud is determined by the currents and waves both in the smaller channels and on the shoals, because:

1. Selection to grain size is clearly visible in the water column of the channels;
2. In the channels parallel to the mainland in Figure 4.1 (stations 5, 6 and 7), the grain size clearly decreases towards the end. At the same time the intertidal to supratidal coast is very rich in mud. This can only be explained by deposition of the coarser suspended material of the mud rich water and transporting the finer material to the end of the channel;
3. Model studies show that in subtidal areas the concentrations of mud are low near the inlet due to tidally driven bed shear stress. Also, mud concentrations are high towards the end of the channels due to a combination of tidal and wave-driven shear stress. This is in good accordance with field data. In general it is observed (Nieuwenhuis, 2001) and predicted (Van Prooijen and Wang, 2013) that mud will be encountered some 10 km

distance from the inlet in the case of the Ameland inlet (Figure 4.2; Nieuwenhuis, 2001; Van Prooijen and Wang, 2013).

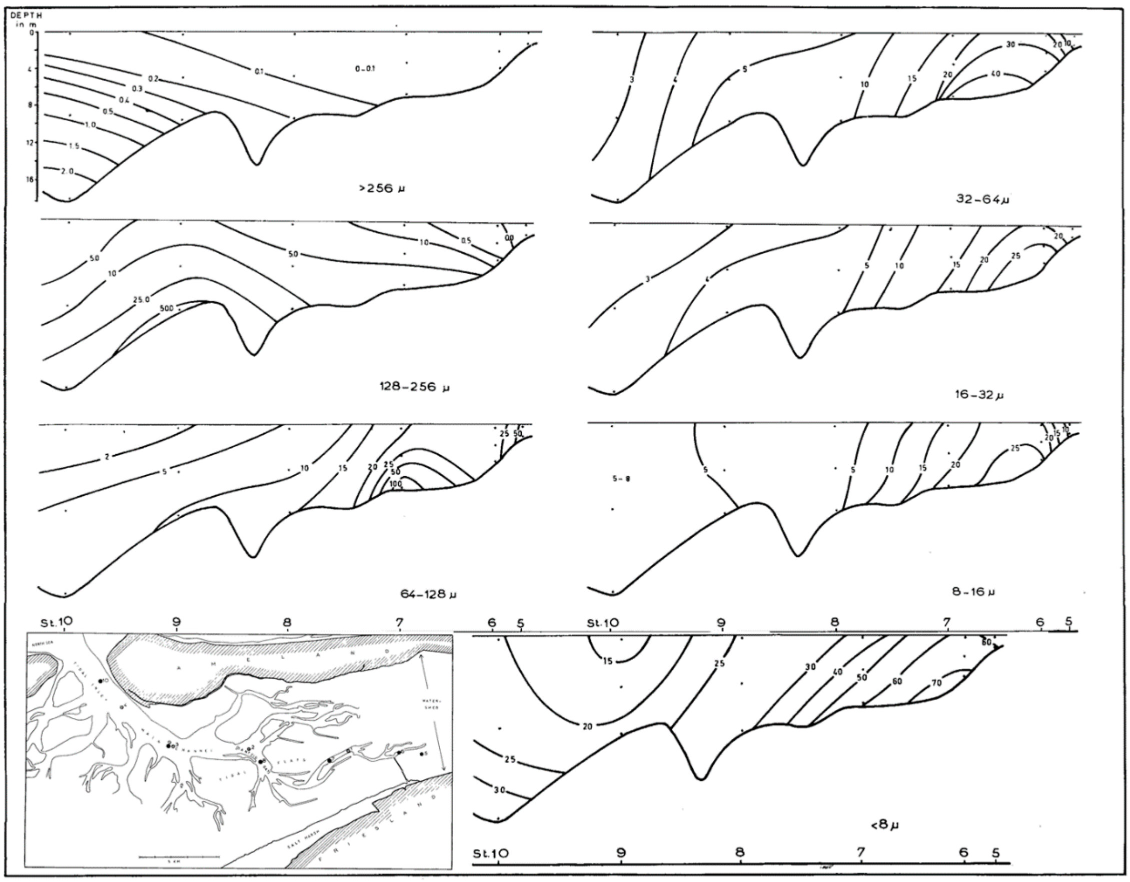


Figure 4.1 Suspended sediment concentrations of various grain sizes in the Borndiep channels as measured in September 1958 (Postma, 1961).

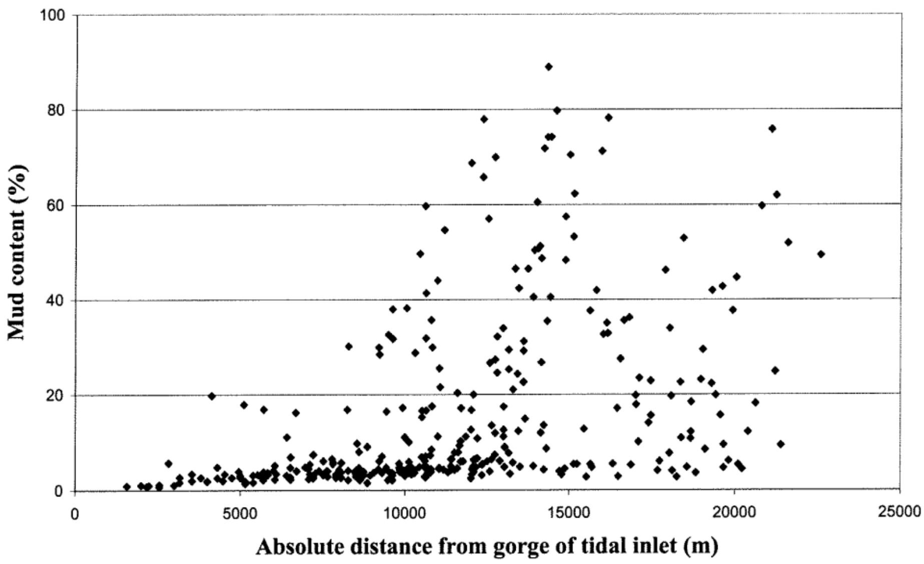


Figure 4.2 Mud content of the sediment versus distance from the gorge (Nieuwenhuis, 2001).

On the tidal flats, current velocities are generally low. As soon as the tidal flat is flooded, current velocities drop sharply. The coarser grains are deposited near the channel edge, forming the channel levees. During the ebb-phase, the highest current velocities occur when the flats are (almost) dry. Consequently, suspension transport dominates on the intertidal shoals, with the exception of the levees. Eysink and Biegel (1992) agreed with Postma (1961) that wave action on the tidal flats dominated and that currents were not important. However, observations show that currents also play an important role:

1 The grain size decreases in general, going from the islands towards the mainland (Postma, 1954; Kamps, 1962; Flemming and Nyandwi, 1994; Flemming and Ziegler, 1995; sediment atlas RWS). This suggests that also currents must be of influence, otherwise the sheltered areas near the islands would probably be muddier. The decrease in grain size towards the mainland (see Flemming and Nyandwi, 1994) can partially be explained from the settling lag and scour lag effects (Postma, 1954; Van Straaten and Kuenen, 1958), and partially by the sorting in the tidal channels, as discussed before.
2 In comparable sub environments, the median grain size decreases from west to east (Eysink, 1994). Since the tidal flats east of Schiermonnikoog are far less sheltered than the ones south of Ameland or Schiermonnikoog, this cannot be explained by wave effects alone (only waves would lead to highest mud content directly south of the islands. This suggests that currents, likely in combination with storm-induced setup / setdown, lead to eastward transport of fines (such as the prevalent eastward wind-driven transport coinciding with storm setup during winds from the SW to NW.
3 Kamps (1962) found that during storm surges, the tide and wind-driven currents determine the direction of sediment transport on the shoals. Model studies indicate that areas where mud deposition occurs are mainly determined by the tide. Even though in shallow water depths waves determine how much and how fast mud can be suspended, the tidal currents determine the actual transport (Nieuwenhuis, 2001).

All in all, it can be concluded that grain size fractions in tidal basins are deposited according to an energy gradient (Flemming and Ziegler, 1995; Nyandwi, 1998).

4.1.4 Influence of hydrodynamic conditions in the wider area

Suspended sediment concentrations are not simply a factor of entrainment and deposition, i.e. the water-bed exchange (as discussed above). Also processes in the water column (settling versus vertical mixing) play an important role. This is quite evident in estuaries where estuarine turbidity maxima are determined by many hydrodynamic and sediment dynamic processes (Burchard et al., 2018; Stanev et al., 2019).

Horizontal salinity gradients generate horizontal gradients in the near-bed hydrostatic pressure (driving a near-bed flow directed to areas with low salinity) and a sloping free water surface (driving a seaward directed current near the surface). In most estuaries, this gives rise to a vertical gravitational circulation with landward-directed currents near the bed, and seaward-directed currents near the water surface. With sediment concentrations typically higher close to the bed, this gravitational circulation leads to net landward transport of sediment.

This salinity-driven circulation increases non-linearly with the water depth. In water depths of several meters (pristine conditions in many natural estuaries) such a salinity-driven circulation is not important. At water depths exceeding 10 m, a pronounced salinity-driven circulation often develops in the transition zone of salt and fresh water. At water depths exceeding 20 m, it often becomes a dominant mechanism for sediment transport.

In summary, the relative importance of these processes for SPM trapping is determined by topography, fluvial and tidal forcing — because the interaction determines the degree of mixing and stratification — and SPM composition. Mud transport is steered by hydrodynamic conditions in the wider area and with important memory effects. Typically, mud transport is driven by supply (sinks and sources) rather than by transport capacity as is the case with sand.

4.1.5 Fluid mud layers

During the past decades, the accumulation of flocculated cohesive sediments and the formation of weakly consolidated mud deposits, including fluid mud, gained attention. Fluid mud is deposited in depressions, in troughs of subaqueous dunes, in the form of mud drapes during slack water, or as large-scale bed covers in areas with abundant mud supply. Entrainment is controlled by local production of turbulence, which is, in turn, influenced by local morphology.

Fluid mud may develop in areas where the deposition rate is very high, as mud consolidation times scale quadratically with the thickness of the deposit. This occurs for instance in coastal systems where mud transport converges in energetic areas (resulting in regular resuspension of the mud). Mud particles in the water column are kept in suspension by turbulent mixing, and therefore the strong turbulence damping at the interface between the fluid mud and the water column promotes settling of mud into the fluid mud. This leads to positive feedback mechanisms in which muddy, fluid mud-dominated areas become progressively muddier.

In the Wadden Sea, fluid mud is primarily confined to the estuaries (most prominent in the lower Ems River) and various harbours. However, fluid mud may also develop in navigation routes in the tidal basins. Regular infilling of the access channel to the ferry platform at Holwerd has led to a rapid increase in dredging quantities in the last 20 years.

4.2 TEMPORAL VARIATIONS

4.2.1 Tidal variations

During slack tide in subtidal areas, mud deposits on the bed as a thin (several mm thick) layer, resulting in low SPM concentrations around the turn of the tide. During the flood and ebb phase resuspension occurs and mud concentrations in the water increase (Figure 3.1 and Figure 4.3). Due to the asymmetry of the tides, current velocities in a channel may be either characterized by a shorter duration of the flood or ebb period which results in higher current velocities and a higher chance of erosion (Visser, 1989; De Boer and Oost, 1991). In addition, asymmetries in slack water duration can largely influence the import of fine sediment, since this duration may determine the opportunity for settling of SPM. During flood an extra factor is that the intertidal flats are flooded leading to –on average- a smaller water depth in the areas which are covered by water, resulting in a more complete sedimentation of mud (under quiet wave conditions). Furthermore, North Sea water is brought into the basin which is likely to have lower suspended sediment concentrations thus reducing the SPM concentrations in the water.

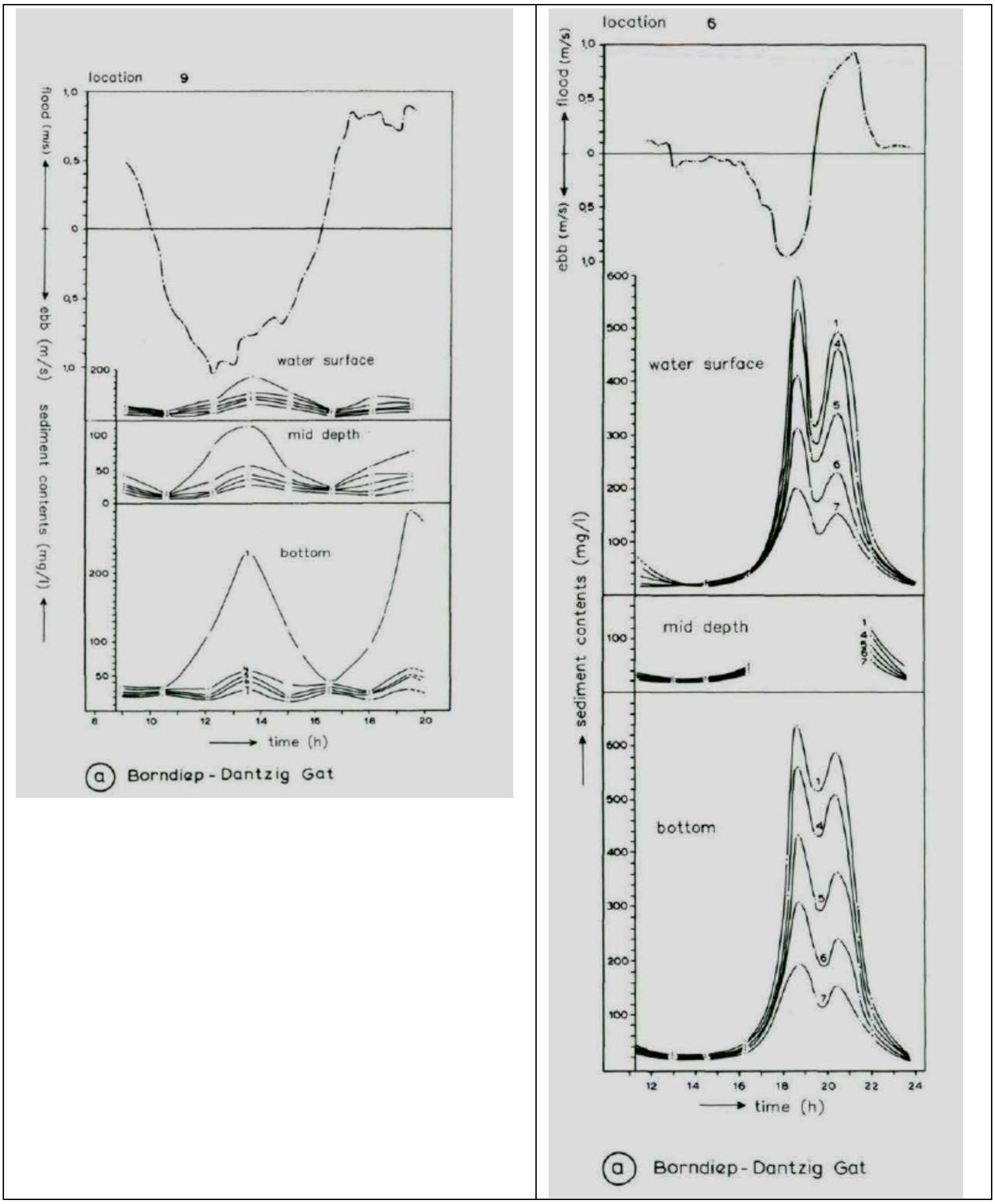


Figure 4.3 Sediment concentrations during the tide on the locations 9 (large channel Borndiep) and 6 (small channel eastward of Veerdam, for the different fractions (from: Postma, 1961). The numbers at the lines correspond to the fractions: 1: total suspended matter; 4: fraction < 63 μm; 5: Fraction < 32 μm; 6: Fraction < 16 μm; 7: Fraction < 8 μm.

4.2.2 Seasonal variations

Suspended matter concentrations are characterized by a seasonality, with higher values in winter than in summer (Philippart, et al., 2013). Herman et al. (2018) found that when expressed relative to the overall mean, the monthly multiplication factors of the different series (ranging from high-concentration inner estuary sites to low-concentration sites far offshore) strongly coincide. Most of the common variation could even be represented by a single simple periodic function (see Figure 4.4). Seasonal variation with spatially homogeneous high and low concentrations is also described based on remote sensing images (Gemein et al., 2006; Eleveld et al., 2008).

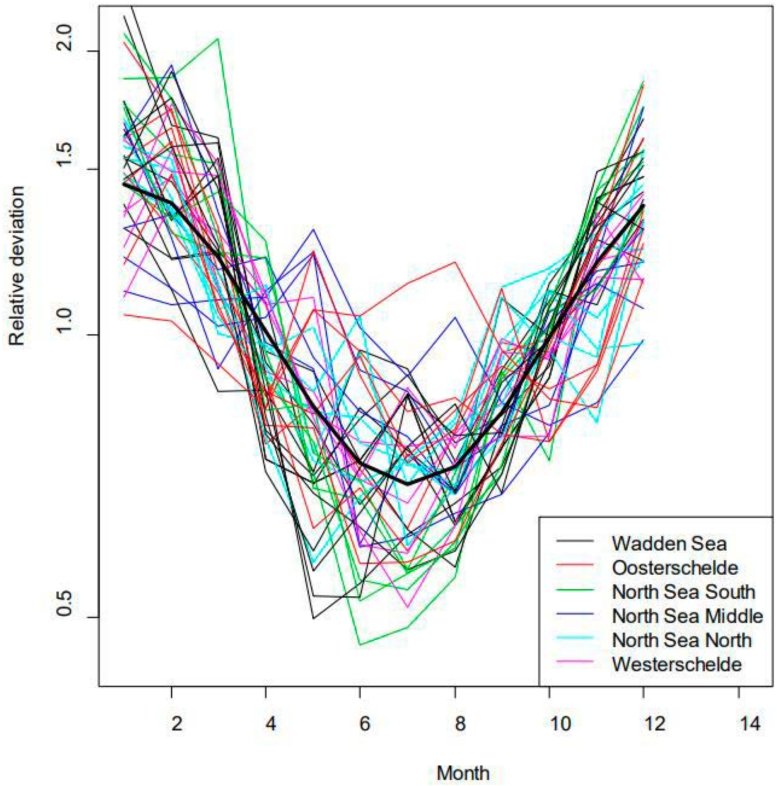


Figure 4.4 Monthly relative deviation from the long-time average concentration of SPM in the different systems of the Netherlands continental shelf. From: Herman, et al. (2018).

In shallow coastal systems, the seasonal pattern can be ascribed to a seasonally shifting balance of mud exchange with the sediment, because of shifting wave activity (Figure 4.5) and probably also biological activity. This cannot explain, however, the similar seasonal pattern in the offshore deeper stations, where direct resuspension from the sediments can be assumed to be rare. However, as the samples are taken near the surface, it is possible that the seasonality in the series is caused by sinking of particles in stratified deep-water columns and remixing upon termination of the stratification. This could also be partly biologically mediated, as algae can be agents in the flocculation/sinking of mud particles. Whereas the increasing autocorrelation and importance of trend with distance offshore could be explained by advection, the seasonal components are in opposition to this mechanism. Therefore, it is concluded that relatively local processes are dominant over advection processes for the seasonal cycle. (Herman et al., 2018).

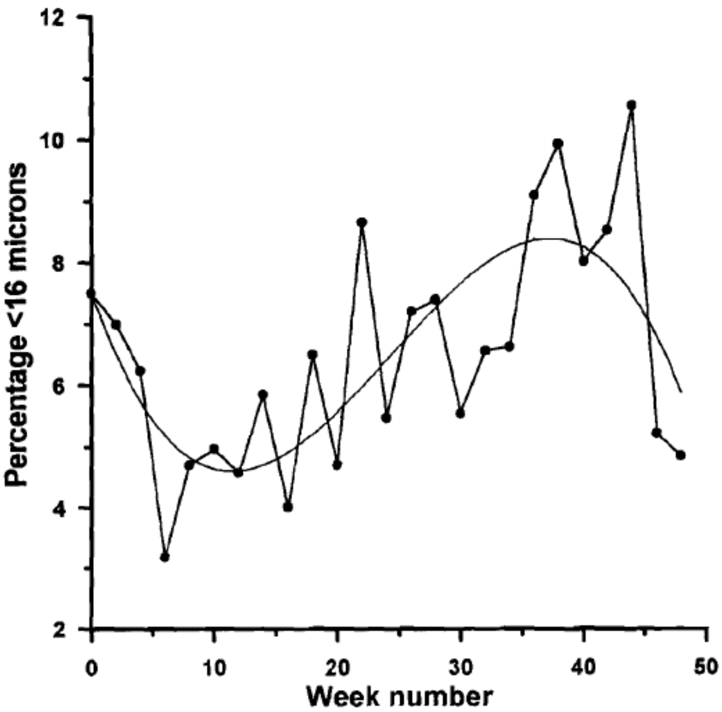


Figure 4.5 Annual variation of the percentage of sediment <16 micron in the top 0.5 cm of the intertidal flats near the mainland (average of 15 separate observations). The smooth line is a third order polynomial fit (Oost, 1995; data from Kamps, 1956).

4.2.3 Annual variations

Variations of the yearly mean SPM between the years are in the order of 50-200 %. In a long-term perspective, again the patterns show a correlation between several stations within a system (such as the Dutch Wadden Sea), but the temporal patterns in the multi-year trend qualitatively differ between the Wadden Sea and the adjacent North Sea. This suggests that the explanation of multiyear SPM trends in the Wadden Sea by external advection is not very likely. There are no clear signs of 'clouds of elevated SPM' drifting into the Wadden Sea (Herman et al, 2018), in line with the timescales governing mud transport (section 3.3), estimated at 26 years for transport from the west to the east of the Wadden Sea.

4.2.4 Long-term variations developments

Over longer periods, however, SSC observations are not available. The main source of historic observations approximating the suspended sediment concentration is light attenuation, For the Western Dutch Wadden Sea these were compiled by Giesen et al. (1990) for the period 1920-1980 and calculated into light attenuation coefficients which increase with increasing turbidity (Figure 4.6), The increase was attributed to changed hydrology (following the closure of the Zuiderzee in 1932), and loss of sea grass beds (decreased mud trapping; after 1932), according to Giesen et al. (1990). In contrast, Philippart et al. (2013) analysed the variability of Secchi disk measurements recorded at one location in the westernmost part of the Wadden Sea during almost four decades (from 1974 to 2010). They conclude that the turbidity in the Western Wadden Sea has not changed, which might be attributed to observations on a single station close to open sea in contrast to the more landward observations of Giessen (1990).

Furthermore, the filling up of basins where intertidal areas change into supratidal areas which allow for less and less mud deposition (often followed by poldering) results in a smaller inter-to subtidal area which restricts mud deposition. For the Ems estuary it has been shown that such decrease in sedimentation space for fines results over the course of several decades the SSC may increase considerably (van Maren et al., 2016). Given the historic development over the past millennia, where many embayments and tidal flats silted up and were diked it can be expected that turbidity may have increased considerably within the remaining Wadden Sea and its estuaries. However, direct proof is not available.

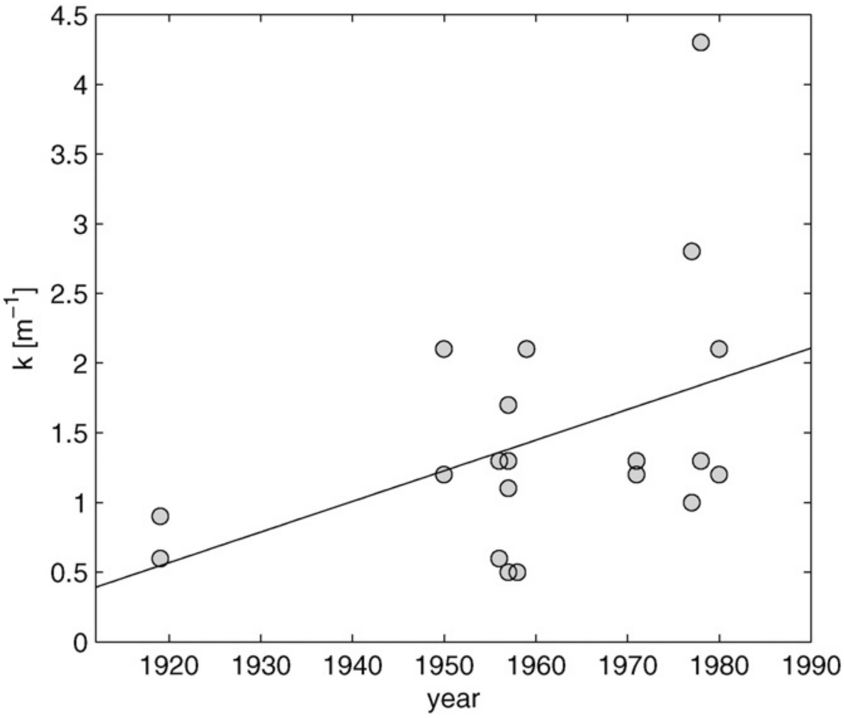


Figure 4.6 Light attenuation coefficient k in the Western Wadden Sea, using data of Giesen et al. (1990), suggesting a decreasing visibility from 1920 to 1990. The R2 correlation coefficient is only 0.18 because of the large scatter in the k-values (van Maren et al., 2016).

5 MUD AVAILABILITY IN THE SEDIMENT BED

In this chapter we describe the spatial distribution of mud in surface deposits on shoals, tidal flats and salt marshes in tidal basins and estuaries of the Wadden Sea.

5.1 DUTCH WADDEN SEA

Rijkswaterstaat collected an extensive set of sea-bed samples from the Wadden Sea, including tidal basins, inlets and barrier-island coasts (Rijkswaterstaat, 1998). Mud is almost completely absent in samples from the North Sea beach, the ebb-tidal delta and the main tidal channels. The mud content increases in samples from the lee side of the barrier islands and in the direction of the mainland.

The overall sediment distribution in the Western Dutch Wadden Sea is characterized by a strong sand-mud segregation, which has also been observed and described in various earlier studies (e.g. Postma, 1954; van Straaten and Kuenen, 1957; de Glopper, 1967; van Ledden, 2003; Zwarts, 2004). We observe distinct differences in the mud deposits between the Western part (corresponding to the Marsdiep, Eijerlandse Gat and Vlie inlets) and the Eastern part (up to the Ems-Dollard estuary). In the Western part, shoals are mainly subtidal and consist of fine sand (with a D_{50} of about 160 µm). The central parts of the basins mainly consist of sandy channels with low (<10%) mud content. Surface mud deposits can be found along the mainland coastline, where surface sediments have a typical mud content of up to 40-50%. In addition, abandoned channels rapidly filled in with fine sediments after the closure of the Zuiderzee in 1932, and these mud deposits are still present in the upper bed (Colina Alonso et al., 2021).

In the Eastern Dutch basins, more (mud rich) intertidal and subtidal shoals are present. Near the coastlines and the watersheds, the mud content suddenly increases to high values (> 50%) over a limited distance. For the back-barrier area S of Ameland it was observed that mud content is higher in the eastern part of the Ameland tidal basin than in the western part (Nieuwenhuis, 2001). This might be related to the distance from the inlet (van Prooijen and Wang, 2014) and to maximum bed shear stress during the tidal cycle which is higher in the western back-barrier area (Nieuwenhuis, 2001). Furthermore, where filterfeeders are present, local patches with high mud content are observed in areas with otherwise relatively low mud content (Oost, 1995). By closing off the tidal basin Lauwerszee in 1969, an important mud sink was removed. As a consequence, the watershed between Schiermonnikoog and the mainland became muddier in the years (Colina Alonso, 2020). Folmer et al. (2017) showed that the intertidal flats in the Dutch Wadden Sea have become slightly sandier in the period 2009-2015; the median grain size of the sediment has increased (with an average yearly increase in mean grain size of 0.89 µm) and the mud fraction has decreased (with an average reduction of 0.24% per year).

5.2 Ems-Dollard estuary

In the Ems-Dollard, the mud content is relatively high in:

1. The tidal flats of the Dollard (typical mud content is >70%);
2. The main channel of the Dollard (the Groote Gat). This difference is most pronounced when comparing the mud content in the Groote Gat with the Heringsplaat located southwest of the Groote Gat;
3. The lower Ems River and the Emden navigation channel (Vroom, et al., 2014).

Vroom, et al. (2014) showed that both finer and coarser sediments are present (a PSD analysis showed two peaks, around 10 µm and 100 µm). In the Middle Reaches (Fig. 2.6), the median grain size is larger in the deeper areas; in both the Dollard and the lower Ems River this difference is less pronounced.

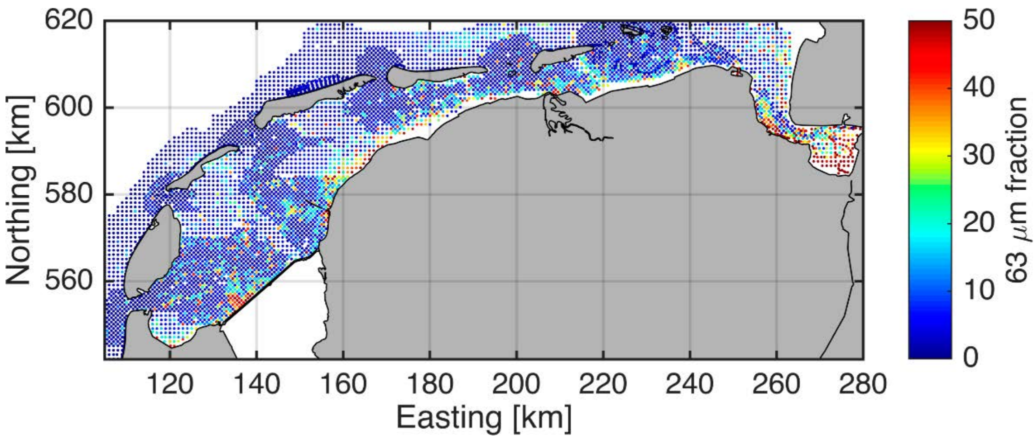


Figure 5.1: Mud content in the upper bed. Based on Sediment Atlas data (1989-1996, all measurements were carried out in summer).

A qualitative comparison of the mud content of 1989 with the mud content of 2013 revealed the following:

- The mud content on the tidal flats of the Dollard Bay seems to have decreased.
- The bed of the main tidal channel in the Dollard (the Groote Gat) appears to have become muddier.
- Most of the lower Ems River shows an increase in mud content.

Even though the 1989 and 2013 samples were collected in a similar period (Sept – Dec and Aug – Oct in 1989 and 2013), some of the observed changes (between 1989 and 2013) may have to be attributed to seasonal fluctuations (Vroom et al., 2014).

5.3 Lower Saxony Wadden Sea

As explained in Section 2.3.2, the tidal flats in the Lower Saxony Wadden area mainly consist of fine sand with medium low percentages of mud (10-20%). However, along the mainland coasts and in the Leybucht and Jade Bay, mud content in the upper bed ranges up to 90% and fine-grained sediments are dominant (see also Figure 5.2).

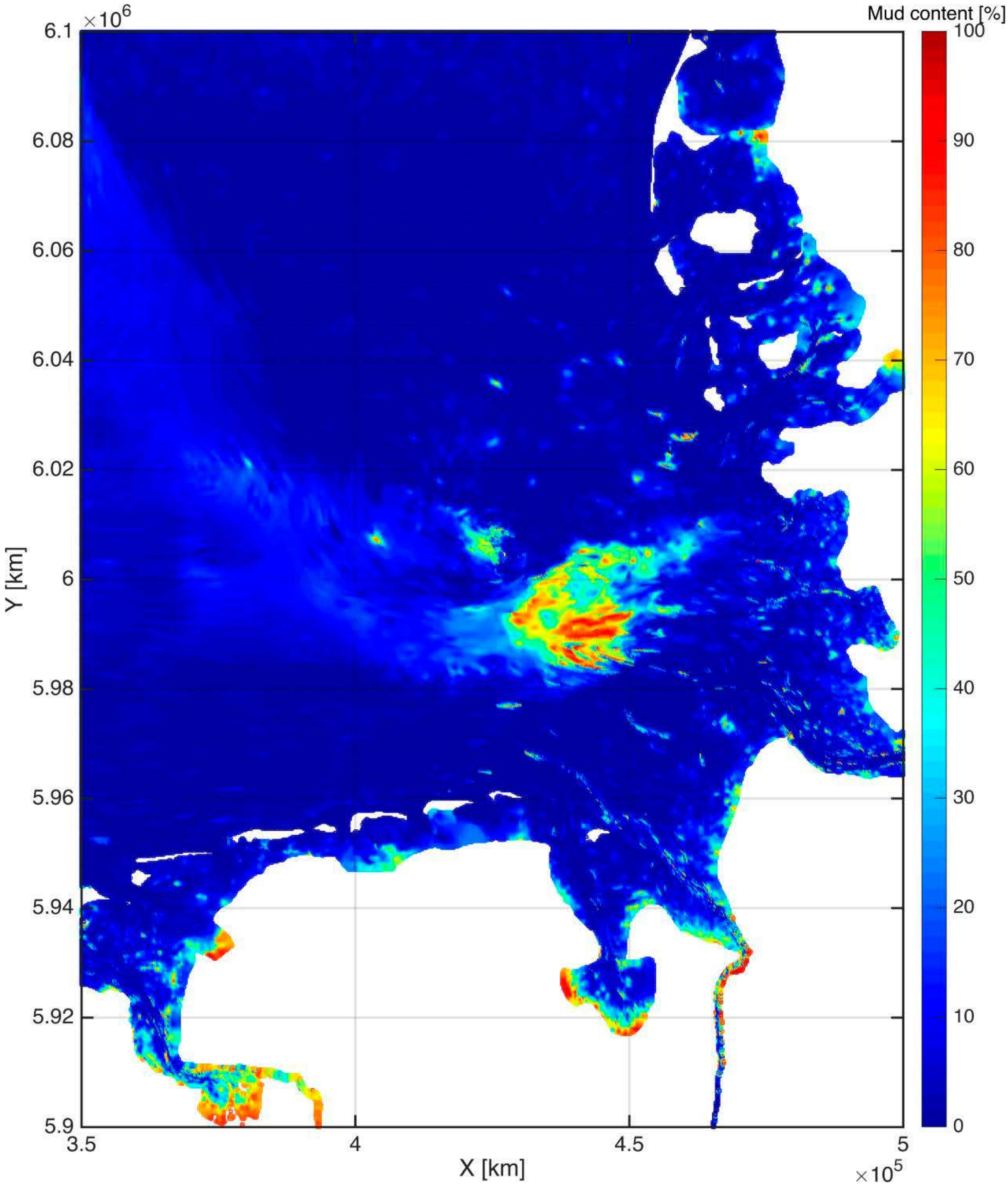


Figure 5.2 Mud content in the bed sediments of the German Bight. Raw data retrieved from: www.geoseaportal.de/mapapps/resources/yrpps/projekt_aufmod/

Also here, grain-size fractions are deposited according to an energy gradient (Flemming and Ziegler, 1995; Nyandwi, 1998). The general trend shows a decrease in both tidal and wave energy and, hence, in grain size from the inlet to the landward side of the basin and from W to E (see **Figure 5.3**). Local morphology determines second-order variations on top of this general trend, such as coarser grains in the channels and finer grains on tidal flats. Flemming and Nyandwi (1988) made a case that, nowadays, the natural gradient has been truncated at the mainland side due to the presence of dikes and that in the past the natural mud gradient stretched over a much larger distance than at present.

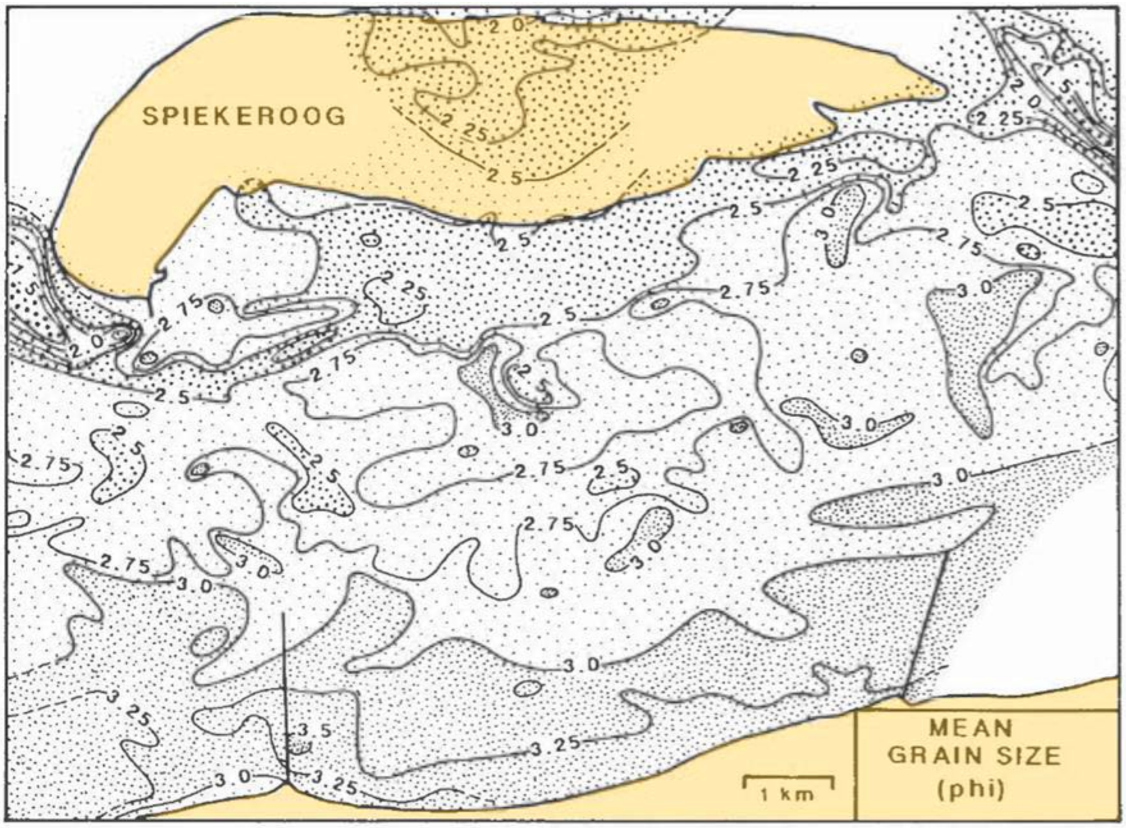


Figure 5.3 Spatial pattern of the mean sediment grain-size in the back-barrier area of Spiekeroog Island. Note the landward-fining trend. Sediment grain sizes are indicated in phi classes. The phi unit (ø) is a logarithmic transformation of millimetres into dimensionless numbers, according to the formula: ø =2log-d, where d = grain diameter in millimeters. The grain size decreases with increasing phi number. (From Flemming and Ziegler, 1995).

5.4 WESER ESTUARY

The bed of the Lower Weser has a relatively high mud-content (see Figure 5.2), especially around the Nordenham mud section, where the turbidity maximum (ETM) is located and where bed sediments are dominated by fine sand and mud.

The channel beds of the Outer Weser mainly consist of sandy sediments. However, the mud content shows a sharp gradient on the shoals, especially on the south-western flats where the mud content is typically around 50% and shows a landward-directed increase.

5.5 ELBE ESTUARY

Compared to the other estuaries, the sediment bed of Elbe estuary has a much lower mud content. The flats of the Outer Elbe are dominated by sand, with a few distinct local patches where the mud content ranges to approximately 30%.

In Meldorf Bight, however, only 15 km northwards, the mud content is higher, and bed sediments are even predominantly muddy in the southern border of the Bight.

5.6 SCHLESWIG HOLSTEIN WADDEN SEA

The channel beds are characterized by medium-sized to coarse-grained sand, whereas the mud content increases (>40%) on the flats close to the mainland. These mud-rich areas are relatively large compared to the basins southward of Norderhever-Heverstrom. The mud content is especially high on the watershed behind Sylt, where locally, bed sediments can contain over 90% mud.

5.7 DANISH WADDEN SEA

The larger part of the Danish Wadden Sea consists of fine to coarse sand. Of the Danish Wadden Sea 36% is permanently water-covered and 64% consist of tidal flats and salt marshes. Of the flats, 11% are mud flats, 20% muddy or mixed flats, 30% wet or moist sand flats, 25% dry sand flats and 14% high sands. Sandy tidal flats tend to have a maximum of 4% of mud (Bartholdy and Folving,1986). Figure 5.4 gives an overview of the sediment types on the flats of the Danish Wadden Sea. High mud contents are mainly found along the mainland coastline and on the mudflats fringing the salt marshes along the islands.

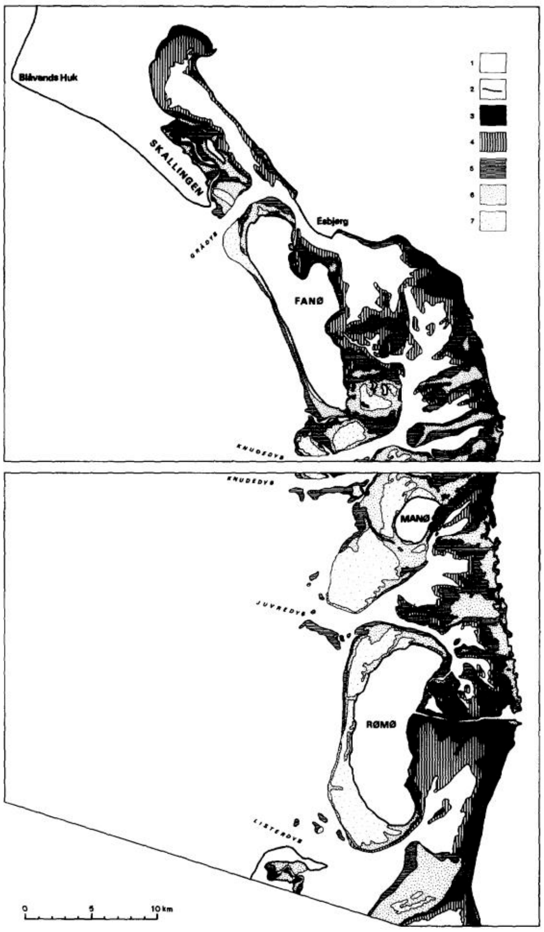


Figure 5.4 Map of the Danish Wadden Sea (at low water) according to a classification by means of remote sensing: 1. Land and ocean. 2. Coastline. 3. Mudflat. 4. Muddy or mixed flat. 5. Wet or moist sand flat. 6. Dry sand flat. 7. High sand. Retrieved from: Bartholdy and Folving (1986).

5.8 Sand-mud segregation

As explained in Section 5.1, many researches have observed an overall strong sand-mud segregation in the sediment bed of the Dutch Wadden Sea. This segregation is not only explained by the bathymetry (with for instance sandy channels and muddy intertidal flats): Herman et al. (2018) found that the intertidal areas tend to be either sand-dominated or mud-dominated, with sharp transitions in between. This was shown by plotting a histogram of the mud availability in the upper part (top 10 cm) of the sediment bed, see also Figure 5.5. It is important to note that this bimodality was found for datapoints with equal spatial and temporal distributions (SIBES dataset, littoral zone 2008-2013). In addition, they showed that stations with a mean close to the modes of the statistical distribution (either low or high) are relatively stable in time, whereas the rarer observations with a mean in between the modes tend to have a higher standard deviation. They suggest that this reflects the stability of the different states, where both modes can be characterized as stable conditions, whereas in between the modes instability is more likely. A comparison with data of the Sediment Atlas Wadden Sea showed that this bimodality has remained relatively stable over the past decades for the Dutch Wadden Sea basins (Colina Alonso, 2020).

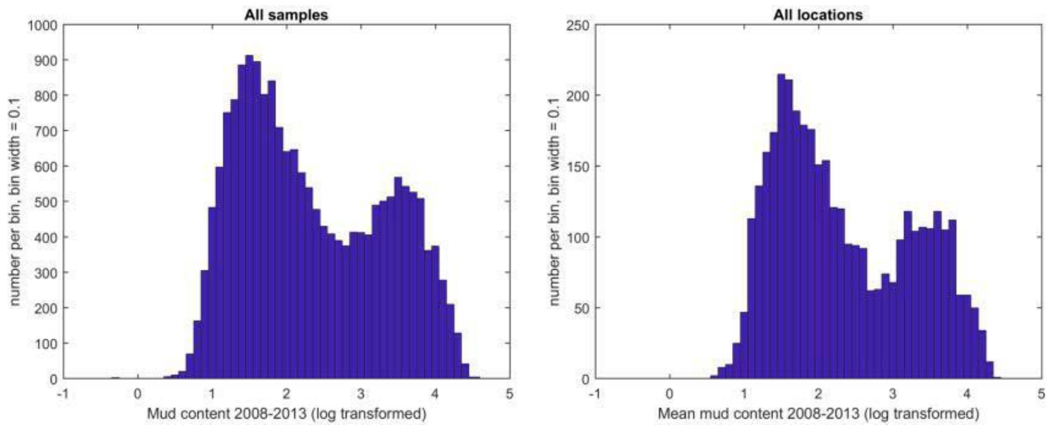


Figure 5.5 Statistical distribution of the observed values of sediment mud content in the SIBES data base (left) and of the station means over the period 2008-2013 (right). Values (%) were natural log-transformed. Very low observations close to detection limit (< 0.1%) were discarded. From: Herman, et al. (2018).

The existence of the bimodality in the German Wadden Sea could not be studied in this project because the available data (AUFMOD) consists of interpolated data and the original datasets were not available. Analysis of the probability of occurrence of certain mud contents would therefore be largely steered by the interpolation method, rather than providing realistic information. In case the original datasets become available in the future, it is recommended to perform this analysis to determine whether the bimodal distribution is observed in the entire Wadden Sea, and to which extent this distribution differs for the sub-systems.

5.9 Sand and mud in the Wadden Sea: two different worlds?

From Chapters 4 and 5 it appears that there is a bimodality (Figure 4.2; Figure 5.5), which effectively leads to a mud-rich sediment and sandy sediments with hardly any mud. Mud sedimentation is important in abandoned channels, at mudflats at a distance of 10 km or more from the inlets, in tidal marshes and in quiet embayments. In the estuaries mud accumulates around the turbidity maximum and in fairways and harbours with overdepth.

The relatively strong separation of both types of sediments is attributed to their strongly differing sedimentary behaviour in terms of entrainment, transport and settling (Postma, 1961). Furthermore, it appears that mud settles preferentially in mud fields, which are often remarkably stable over the course of a century or more (Colina Alonso et al., 2020). A factor might be that mud has a relatively large surface area with much organic matter attached to the sediment. This stimulates the development of benthic diatoms which may “glue” the grains to the surface once they have settled, thus increasing entrainment velocity.

Thus, as a first approximation, one might think of the back-barrier area as consisting of two separate “worlds”: one of mud-rich sediments that are generally cohesive and one of sand-rich sediments that are non-cohesive. The implication is that it is no longer sufficient to consider just the resilience of the sedimentary back-barrier system, but that both mud and sand budgets should be considered. For instance, we know that in the western part of the Dutch Wadden Sea after the closure of the Zuiderzee, sand transport from the coast was insufficient to immediately bring the system to a new dynamic equilibrium and over the past century sand sedimentation followed a saturation curve. In the same area, however, mud sedimentation followed a straight line (Colina Alonso et al., 2021).

Of course, the idea of two separate worlds is an over-simplification and it should be noted that in both worlds (cohesive and non-cohesive) the bed sediments exist of both sand and mud. Moreover, these two worlds interact: the shelter which is provided by the sandy shoals enables the settlement of fines further away from the inlet. Thus, if sandy shoals are becoming lower relative to mean high water, or if channels orient towards a mudflat, erosion may be expected. Indeed, erosion of mudflats due to channel migration and subsequent wind-wave erosion has been observed (e.g. Janssen-Stelder, 2000). Reversely, if sand supply is not sufficient or energies are too low to transport sand into a quiet area, only mud can fill up the basin and so reduce the tidal prism, which on its turn will lead to reduction of the dimensions of the sandy channels. Thus, the two worlds clearly interact and cannot be treated separately if we want to understand morphodynamic behaviour.

Mud budgets are mainly governed by the influx from rivers, and coast parallel transport, whereas sand is mainly eroded from the North Sea side of the Wadden system and transported into the Wadden Sea. In the next chapter the mud budget of the trilateral Wadden Sea is discussed.

6 TOWARDS A MUD BUDGET

In this chapter we work towards a first indication of a mud budget for the Trilateral Wadden Sea. This sediment budget is based on observed mud sedimentation volumes in the tidal basins (section 6.1) and salt marshes (section 6.2), dredging volumes and anthropogenic sediment extraction (section 6.3) and reworking of older deposits (section 6.4). Combined with a balance for sediment fluxes in the North Sea (section 6.5) we derive an integrated mud budget for the Wadden Sea and adjacent North Sea (section 6.6).

6.1 MUD SEDIMENTATION IN THE BASINS

6.1.1 Dutch Wadden Sea basins

A large-scale sand and mud budget of the Dutch Wadden Sea has been presented by Colina Alonso et al. (2021) in which an estimate was given for the volume changes by both mud and sand fractions for the past 80 years. The sediment budgets were calculated by multiplying the bed level changes with the measured (volumetric) mud content in the bed (RIKZ, 1998). A formula by van Rijn (2019) was used to estimate the bulk density of the sand-mud mixture, which depends on the local sediment composition. The findings were validated against sediment cores.

Figure 6.1 and Table 6.1 show the calculated volume budgets and the spatial sedimentation/erosion patterns. In the Western Dutch Wadden Sea, a more or less linear infilling of mud has been observed since the closure of the Zuiderzee. Large mud sinks are abandoned channels as a result of the closure, and tidal flats near the mainland coast. In the Eastern Dutch Wadden Sea, a sudden increase of import of mud was observed after 1970 (following the closure of the Lauwerszee in 1969). Volume changes in Groninger Wad have been much smaller compared to the other basins (Figure 6.2, Table 6.1).

Mud sedimentation seems to be largely constant in space and in time: we observe a spatial sedimentation-erosion pattern that is quite persistent in time. Consequently, it is likely that compaction has played an important role. Therefore, we assume a mean mud dry density of 700 kg/m^3 (representing slightly consolidated mud typical for surface deposits). With this, the Dutch Wadden Sea basins currently act as a mud sink of 1.2×10^6 ton/yr (excluding salt marshes).

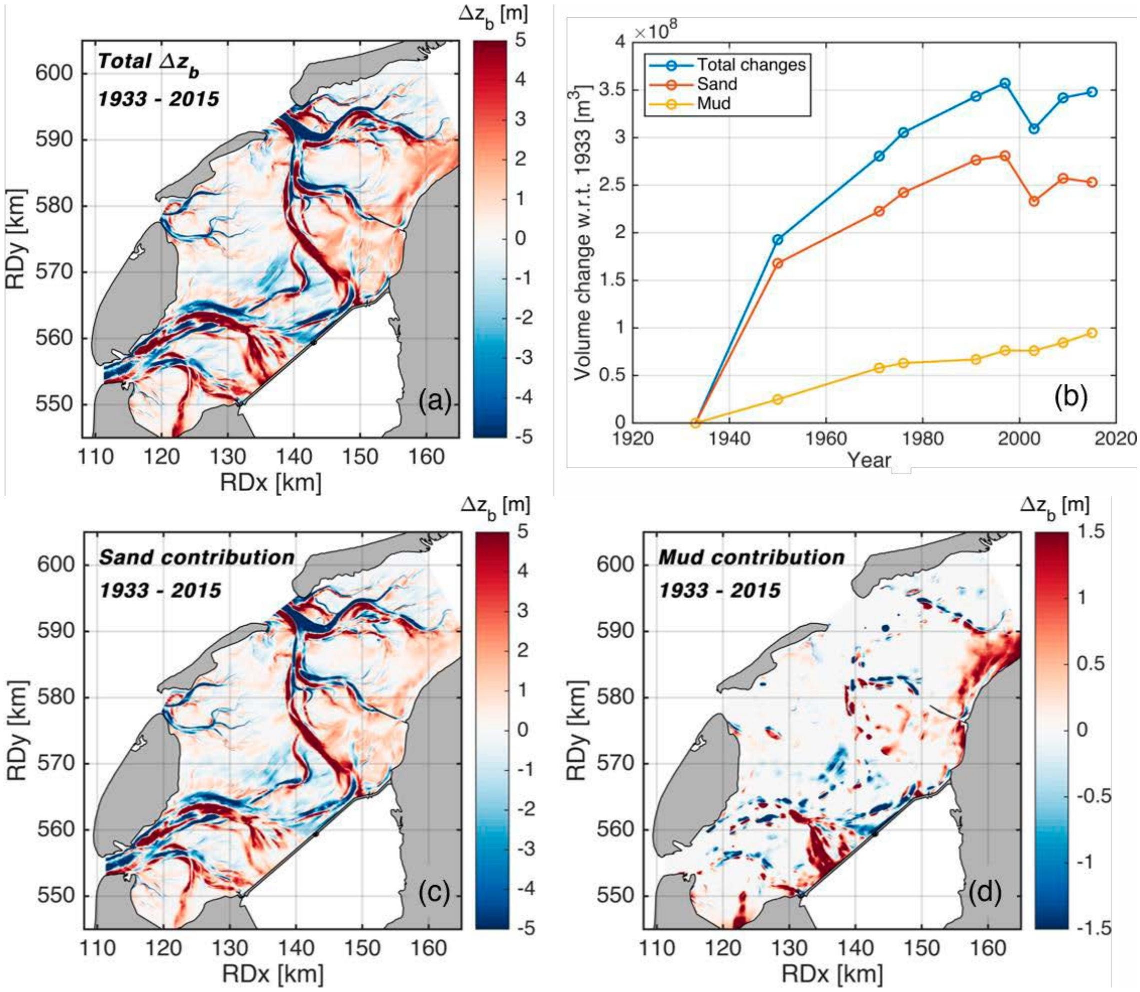


Figure 6.1 Volume budget of the Western Dutch Wadden Sea: a) bathymetry changes based on Vaklodingen data, b) calculated volume changes in the basins, c) estimated sand contribution to the bathymetry changes d) estimated mud contribution to the bathymetry changes. From: Colina Alonso et al. (2021).

Table 6.1 Calculated volume changes in the Dutch Wadden Sea basins (Colina Alonso, 2020)

	Total volume changes [$\times 10^6$ m^3]	Sand volume changes [$\times 10^6$ m^3]	Mud volume changes [$\times 10^6$ m^3]
Western Dutch Wadden Sea (1932-2015)	348.1	253.2	**94.9**
Inlets of Ameland and Schiermonninkoog (1971-2011)	105.2	81.7	**23.5**
Groninger Wad (1985-2011)	8.84	8.32	**0.52**

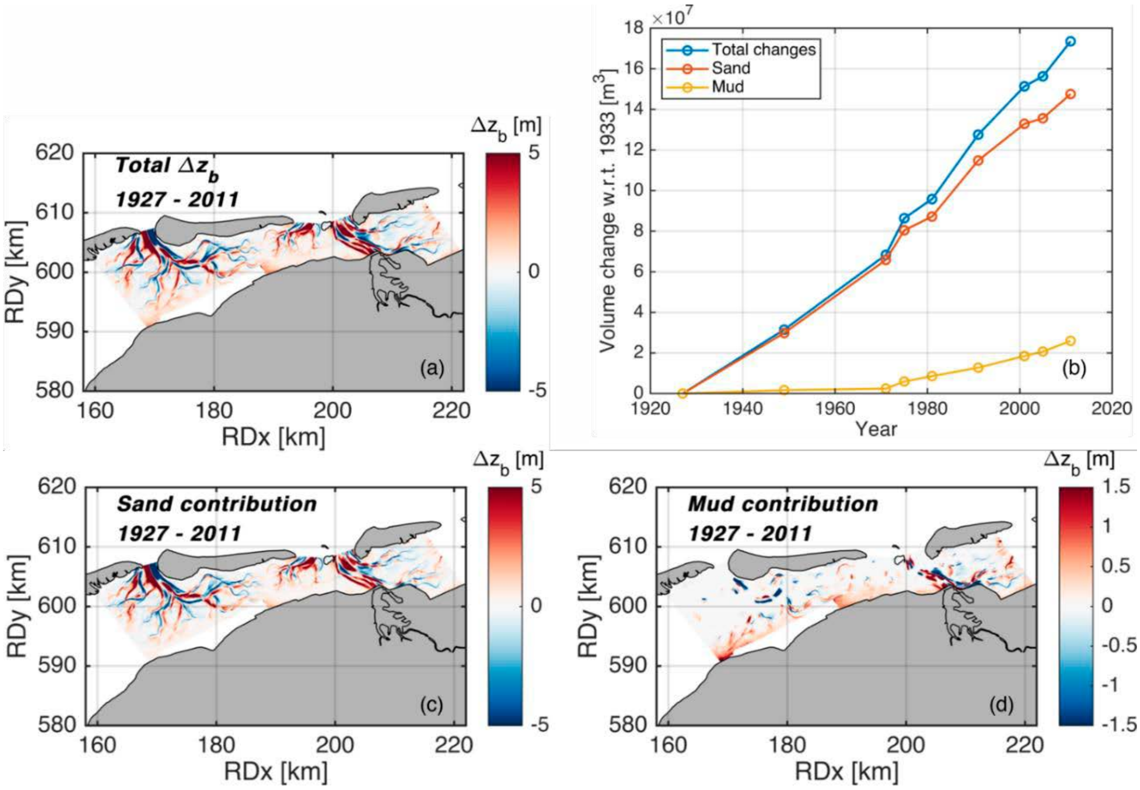


Figure 6.2 Volume budget of the Eastern Dutch Wadden Sea: a) bathymetry changes based on Vaklodingen data, b) calculated volume changes in the basins, c) estimated sand contribution to the bathymetry changes d) estimated mud contribution to the bathymetry changes. From: Colina Alonso (2020).

6.1.2 Ems Estuary

Bed level changes

The net volume changes in the Ems estuary also contribute to the net sediment budget and have been established by Elias and van Maren (2020). The largest gross volumetric changes in the Ems estuary occur in the tidal channels connecting the Ems estuary with the North Sea. The two outlet channels in the west of the estuary are laterally migrating, resulting in large volume changes but small net volume changes. Also, one of these two outlet channels (Westereems) is deepening while the other channel (Huibertgat) is degenerating. Additionally, the flood-tidal delta is accreting with 1.25×10^6 m^3/yr with primarily sandy sediment.

The two largest areas with net bed level changes within the estuary are a degenerating tidal channel (the Bocht van Watum) and the Eemshoornplaat. This latter is now an extensive shallow area but used to be a channel connecting the Eastern part of the estuary with the western part. In the past 25 years 78×10^6 m^3 was deposited here, corresponding to ~3×10^6 m^3/yr. The part of the Eemshoornplaat with largest net bed level changes is primarily muddy, and it is estimated (Elias and van Maren, 2020) that with 20-50% mud, the annual mud deposition here is 0.6 - 1.5×10^6 m^3. With a mud dry density of 500 kg/m^3 (which we assume as an average value representative for the estuaries), this sink constitutes ~ 0.3 – 0.8×10^6 ton of mud. The sand volume (50-80% with a density of 1600 kg/m^3) is equivalent to 2.4 – 3.8×10^6 ton of sand. The annual sedimentation in the Bocht van Watum is 1.6×10^6 m^3 of almost completely muddy sediment, therefore corresponding to 0.8×10^6 ton/yr. The major sediment source in the area is the channel (~2×10^6 m^3/yr of primarily sandy sediment), partly from natural processes but also because of dredging. Correcting the channel volume changes for sand mining (1.1×10^6 m^3/yr, see above), a source of 0.9×10^6 m^3/yr sand remains (1.4×10^6 ton/yr). Note that sediment is no longer extracted in the past 25 years for other purposes than sand mining.

Overall, the net sedimentation of mud within the estuary is therefore 1.1 – 1.6×10^6 ton/yr, and the net sedimentation of sand is 1 – 2.4×10^6 ton/yr. No detailed information is available for the period before 1985 because sufficiently accurate maps are not available. However, it is likely that sedimentation was considerable also before 1985 (with both the connection to the Oostereems and the infilling of the Bocht van Watum already taking place).

The sediment budget

The Ems estuary is a major sink of sediment, with estimates for mud around 2×10^6 ton/yr since 1960 (see summary in Table 6.2). Probably the actual sink was larger before 1960 because infilling of degenerate channels before 1985 is not accounted for (whereas infilling did take place, as topographic maps show). The estuary provides an even greater sink for sand in terms of sediment mass (around 6×10^6 ton/yr since 1960). However, with a three times greater density of sand deposits compared to mud deposits, the volumetric changes are comparable (both sand and mud 4×10^6 m^3/yr since 1960).

The Ems Estuary has been a sediment sink for much longer time than elaborated on here. The sedimentation of mud in the Dollard in the period 1550-1800 has been estimated at 2.4×10^6 ton/yr (van Maren et al., 2016), gradually decreasing until the early 20th century (at present, volume changes in the Dollard are very small – see Elias and van Maren, 2020). And in the period 1830-1960 on average 2.9×10^6 m^3/yr of mainly sandy sediment annually deposited in the main channels of the Ems estuary (Pierik et al, 2018). However, this latter analysis excluded the Eemshoornplaat which was probably the biggest net sediment sink.

Table 6.2 Sediment sinks in the Ems estuary [10^6 ton/yr], with a sink defined as net accretion, extraction during maintenance dredging, and sand mining, over the approximate period 1960-1990 and 1990 - 2011

	1960-1990	1990-2011
Lower Ems River (mud)	0	0.8 (extraction)
Outer Ems estuary (mud)	>1.8 (extraction)	1.1-1.6 (accretion)
Total Ems(mud)	*>1.8 (extraction)*	*1.9-2.4*
Total Ems (sand)	>4.3 (2.4 by extraction and 1.9 by mining, from 1970 onwards)	2.9 – 4.3 (1-2.4 by accretion and 1.9 by mining)
Total Ems (sand + mud)	*>6.1*	*4.8-6.7*

6.1.3 Lower Saxony

To provide a first estimate of the current mud sedimentation rates in the basins of Lower Saxony, we have performed a similar calculation as Colina Alonso (2020) did for the Dutch Wadden Sea. With use of bathymetry and sediment composition data of the project Aufmod (see for data: https://www.geoseaportal.de/mapapps/), the net bed level changes have been multiplied with the local mud content in the bed. Sediment mass fractions have been converted to volume fractions by using the approximation for the mixed dry bed density of Mulder (1995) based on the local sediment composition. The approximation of van Rijn (2019) (as used for the Dutch basins, see Colina Alonso (2020)), could not be used, since detailed data on the clay and the silt contents was not available. This analysis is performed for the period 2000-2010.

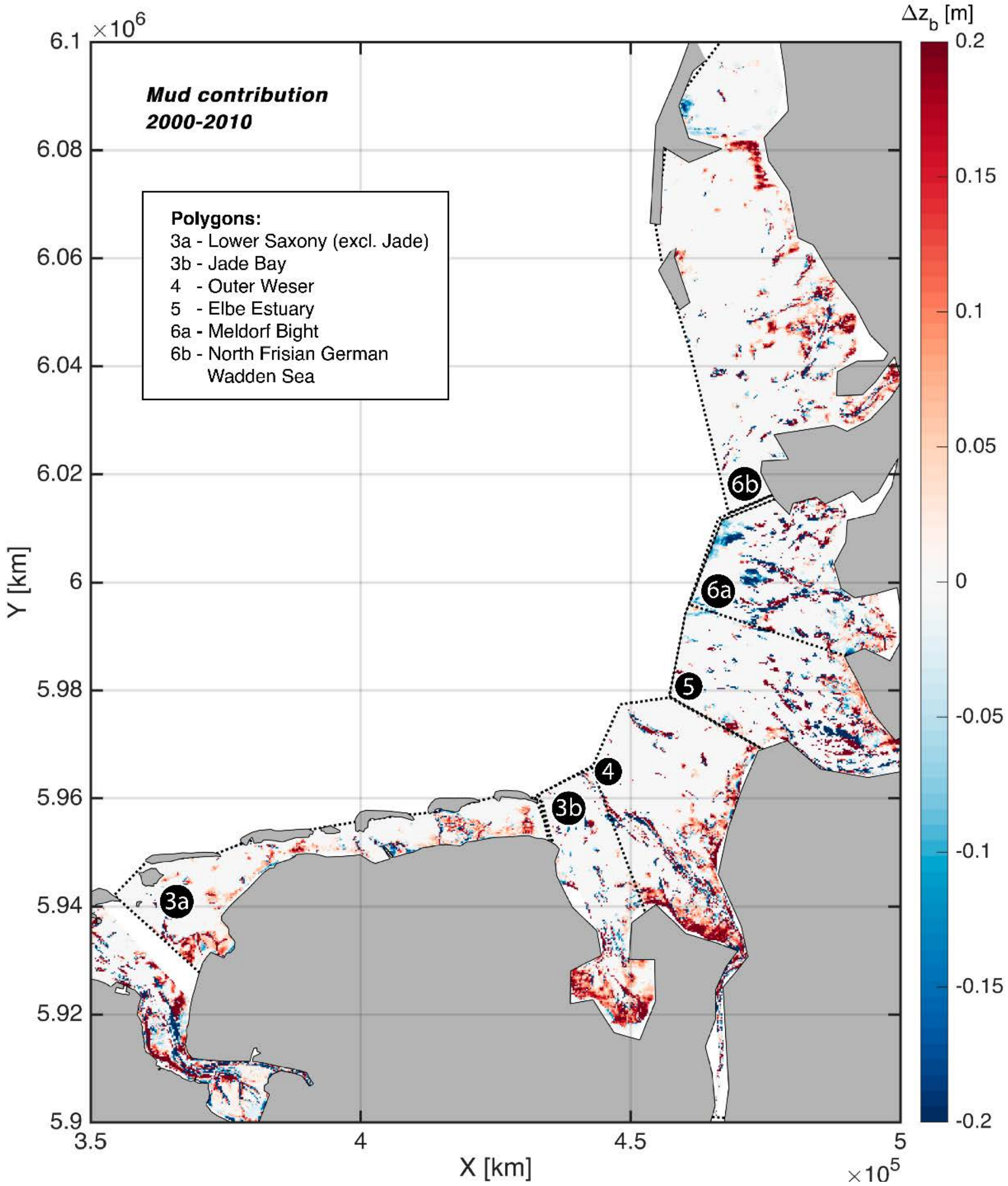


Figure 6.3 Calculated mud contribution to the bed level changes in the Wadden Sea basins of the German Bight, for the period 2000-2010.

The results of the analysis are presented in Table 6.3. In the basins of the Wadden area of Lower Saxony (up to east of the Minskeneroog barrier island, excluding the Jade Bay) an average total mud mass of 0.6×10^6 ton is deposited yearly. The spatial patterns of this mud deposition are presented in Figure 6.3. The largest deposition occurred near the mainland and in the lee area of embayments such as the Leybucht. In the Jade Bay, we have performed a similar calculation. This analysis is also performed for the period 2000-2010 and gives a net sedimentation of 0.9×10^6 ton/yr (Table 6.3).

Table 6.3 Calculated mud sedimentation in Lower Saxony, Jade Bay and the Weser estuary (excl. extraction)

	Total mass changes (2000-2010) [$\times10^6$ ton/yr]	**Sand mass changes (2000-2010) [$\times10^6$ ton/yr]**	**Mud mass changes (2000-2010) [$\times10^6$ ton/yr]**
Lower Saxony excl. Jade Bay	**12.3**	**11.7**	**0.6**
Jade Bay			**0.9**
Outer Weser	**22.1**	**20.8 ***	**1.3**

* The mass changes of sand are predominantly a result of the morphodynamic changes at the northern boundary of the polygon (bordering the North Sea), where the bed is highly dynamic because of channel migration. Therefore, the calculated volume changes of sand depend greatly on the polygon definition, and these should be interpreted with care.

6.1.4 Weser Estuary

Via the river Weser an average of 0.43×10^6 ton/yr (or 0.9×10^6 m^3/yr) fluvial, mainly muddy sediment is imported into the estuary (based on an average discharge of 323 m^3/s and a sediment concentration of 40 mg/l; Grabemann and Krause, 2001). Most fluvial sediments are trapped in the estuary (Irion et al. 1987), but little is known about the influx of marine sediment into the estuary (Grabemann and Krause, 2001). Extraction of mud from harbours on land is nowadays estimated to be some 0.41×10^6 m^3/yr. Using a specific density of 500 kg/m^3 (which we assume as an average value representative for the estuaries), this is approximately 0.2×10^6 ton/yr.

In the period 1998-2008 the annual extraction of sand from the estuary has varied between 0 to 9.1×10^6 m^3 depending on infrastructural needs. It is unclear if sand mining in the estuary is still allowed at present. Sand mining from the harbours varies between 0.1 and 0.2×10^6 m^3/yr.

Total dredging including harbours has increased. For the period 2014-2018 it amounted on average 10.3×10^6 m^3/yr. Thus, extraction of mud is of the order of ca 4% of the total dredging.

Following the calculations for the German Wadden Sea basins the mud sedimentation rate in the Outer Weser is given in Table 6.3. It appears that in total some 1.25×10^6 ton/yr of mud is deposited. The amount of mud which is extracted, should be added to this amount, leading to a total of 1.45×10^6 ton/yr of mud deposition.

6.1.5 Elbe Estuary

Heavy metals and contaminations which are strongly absorbed to fine sediments can be used as a tracer to calculate the import from mud from the sea, if the import via the river is known. Puls et al. (1997a) used the lead content in the fraction < 20 microns as a tracer for the fine sediment balance in the years 1990 and 1991 (i.e. before the 1999 deepening). The fluvial mud import via the Geesthachter Weir was 340,000 ton/yr, of which 250,000 ton/yr deposited in the Elbe estuary and 90,000 ton/yr reached the German Bight. Fluvial sediment from the Elbe river is transported all the way up to Sylt (Zeiler et al., 2004. Furthermore, 300,000 ton/yr of North Sea mud was deposited in the Elbe estuary. In the following section, we apply the ratio of sediment import/export/deposition as found by Puls et al. (1997a) to longer records of sediment loads, including the situation after deepening.

After the deepening of 1999 marine suspended material could travel all the way upstream to Bunthaus, demonstrated using natural Zn as tracer material (Ackermann and Schubert, 2007). Their studies showed that during the period 1987-2005 the average fluvial mud supply from the Middle Elbe River (<20 µm) amounted to 660,000 ton/yr. We estimate that 320,000 ton/yr of these fluvial sediments deposit in the port of Hamburg (based on an annual sediment deposition of 0.8 million ton in 2005 of which 40% is fluvial mud), which is subsequently removed from the system either by landfill or via dumping at Buoy E3. The remaining fluvial mud (340.000 ton/yr) will reach the estuary seaward of Hamburg. If we extrapolate the ratio of estuarine sediment deposition / offshore transport as observed by Puls et al. (1997a) in 1990-1991, the amount of fluvial mud from the Elbe which reaches the North Sea averaged over 1987-2005 is ~175.000 ton/yr. That leaves 165.000 ton of fluvial sediment annually depositing in the Elbe Estuary (see Table 6.4).

Before deepening, 300.000 ton of marine mud deposited in the estuary. Based on a similar approach as for the fluvial sediments it furthermore can be calculated that some 641.000 ton/yr of marine mud is imported after closure in the estuary of which a large part is removed annually since at least 2005. For the 2005 situation this brings the total net sedimentation of mud in the Elbe estuary on average to be some 326,000 ton/yr (Table 6.4). This is here considered to be an estimate for the current situation.

Table 6.4 Overview of the average import from the Elbe river and the North Sea of mud, the removal by dredging and the net result in ×10^6 ton/yr

Source	**Weights Ton/yr**
Import of fluvial mud from the Elbe river	+0.66
Permanently dredged and stored outside estuary	-0.32
Transported into the open North Sea	-0.175
Net sedimentation of fluvial mud in the Elbe estuary	*+0.165*
Import of marine mud from the North Sea	+0.641
Permanently dredged and stored outside estuary	-0.480
Net sedimentation of marine mud in the Elbe estuary	*+0.161*
Net total sedimentation of mud in the Elbe estuary	***+0.326***

6.1.6 The Wadden Sea area of Schleswig Holstein

In our calculations we have separated the Wadden Sea area of Schleswig Holstein into two subareas: Meldorf Bight area and the North Frisian German Wadden Sea, as shown in Figure 6.3. For the Meldorf Bight area, following the same systematics as for the Lower Saxony area, the mud weight changes are calculated on 0.2×10^6 ton/yr (Table 6.5).

Table 6.5 Calculated mud sedimentation in the Meldorf Bight

	Mud mass changes (2000-2010) $\times 10^6$ ton/yr]	Sand mass changes (2000-2010) [$\times 10^6$ ton/yr]
Meldorf Bight area	**0.2**	*****
North Frisian German Wadden Sea	**1.4**	**22.2**
Total Wadden Sea area of Schleswig Holstein	**1.6**	

* The volume changes of sand have been excluded for Meldorf Bight area, since these are a result of the morphodynamic changes at the western boundary of the polygon (bordering the North Sea), where the bed is highly dynamic because of channel migration. Therefore, the calculated volume changes of sand depend fully on the polygon definition.

Note that the data does not cover the entire area; data is for instance missing in a part of Meldorf Bight which contains high mud contents (see also Figure 5.2). Therefore, we expect that these results might underestimate the total mud sedimentation.

For the German part of the North Frisian Wadden area, following the same systematics as for the Lower Saxony area, the mud mass changes are calculated on 1.5×10^6 ton/yr (Table 6.5).

6.1.7 Danish Wadden Sea basins

Pedersen and Bartholdy (2006), constructed a sediment budget for the northern and central part of the Danish Wadden Sea, consisting of three tidal areas belonging to the tidal inlets (from north to south) Grådyb, Knudedyb and Juvre Dyb. They found a net mud deposition of 0.173×10^6 ton/yr distributed over an accumulation area of 90.3 km^2 consisting of 5.5 km^2 mudflat, 26.9 km^2 mixed flat and 53.9 km^2 of salt marsh. Dredging is regularly performed in Esbjerg harbour, but as the material is dumped within the Grådyb tidal area, the activity is regarded as neutral in relation to the mud sediment budget.

The largest contribution to the accumulation is input from the North Sea, which adds up to 64% of the total accumulated fine-grained sediment. Accumulation varies considerably between the three areas: The northernmost tidal area (Grådyb) receives 50% while the others receive only 21% and 29%, respectively. The import variations are suggested to be a consequence of three factors:

1. An assumed increasing availability of fine-grained sediment from south to north on the shelf adjacent to the Danish Wadden Sea;
2. A smaller trapping efficiency in the open tidal area of Knudedyb compared to the two other areas, equipped with large closed embayments;
3. A larger combined salt-marsh area in the Grådyb tidal area compared to the two other areas, where large reclaimed salt-marsh areas are protected by dikes.

The tidal basin of the Lister Dyb between Sylt and Romo was not in the study by Pedersen and Bartholdy (2006). Although erosion dominates in the Lister Dyb, there was a marked net sedimentation over the period 1968-1994 between +1 and +2 m MSL (MHW = ca +1 m) of 0.077×10^6 m^3/yr (Kystinspektoratet, 1999). If this is all mud with a dry density of 700 kg/m^3 (which we assume as an average value representative for the basins), this would result in an extra 0.054×10^6 ton/yr, bringing total mud sedimentation to maximal 0.227×10^6 ton/yr.

6.2 MUD SEDIMENTATION IN SALTMARSHES

6.2.1 Introduction

Salt marshes form the upper part of the intertidal zone. They may extend vertically from well below the mean high-tide level up to the highest water mark. Salt marshes reach their greatest extent along low-energy coasts where wave action is limited, and mud can accumulate. Salt-marsh deposits generally have a more fine-grained sediment than the seaward fringing intertidal flats and the intertidal-flat deposits where a salt marsh is built up on (Mueller et al. 2019).

This section provides an estimate of the total amount of mud that is annually deposited in these marshes. For this purpose, the Wadden Sea is subdivided into seven sections for each of which a mud budget will be computed. The seven sections are (from southwest to northeast, Figure 6.4):

1) NL- Dutch sector except the Ems estuary
2) Ems Ems estuary (Dutch plus German part)
3) LS- Sectors of Lower Saxony and Hamburg except the parts in the major estuaries, including the Jade Bay
4) Weser Weser estuary
5) Elbe Elbe estuary
6) SH- Schleswig-Holstein sector minus the Elbe estuary
7) DK Danish sector.

6.2.2 Methods

In order to assess the amount of mud that is annually deposited in the salt marshes of the Wadden Sea, the following input is required:

a) the size of the salt marshes
b) the sedimentation rates in these marshes, and
c) the grain-size distribution of the marsh deposits to correct for the sand fraction

The size of salt marshes was derived from the overview of Esselink et al. (2017) based on surveys carried out between 2004 and 2014. For sedimentation, the terminology of Nolte et al. (2013a) is followed, where sedimentation is expressed as the amount of sediment which is deposited in the marsh per unit area and time, e.g. kg/m^2/yr. Studies on sedimentation in salt marshes are on the increase, but stay relatively scarce in comparison with studies and regular monitoring of marsh surface elevation and surface-elevation change (SEC, mostly expressed in mm/yr). Because of the much wider availability of SEC data, it was decided to assess sedimentation indirectly via SEC data, volume increase and estimates for the bulk dry density (BDD) of salt-marsh deposits.

Figure 6.4 Overview of the subdivision of the Wadden Sea into seven sections in which the annual mud deposition is estimated.

In order to distinguish the amounts of mud and sand in the total sediment import by the salt marshes, grain-size distributions are required. Grain-size distributions were available either as mass or volume fractions of sand, silt and clay (i.e. the mineral portion of the sediment). In case of mass fractions, the mud mass was acquired by firstly estimating the sand mass in the sediment by multiplying the sand fraction by the specific weight for sand (2650 kg/m^3) and subsequently by subtracting the mass of sand from the total mass of sediment:

$$\text{Mud BDD} = \text{Total Sediment BDD}(1 - \text{Sand}_{\mathit{MASS\ FRACTION}})$$

In case the grain-size distributions were volumetric, the amount of mud was calculated by the multiplying the total amount of sediment by the combined volumetric fraction of silt and clay:

$$\text{Mud BDD} = \text{Total Sediment BDD} \times (\text{Clay} + \text{Silt})_{\mathit{VOLUME\ FRACTION}} \times \text{ specific weight (Clay + Silt)}$$

No adjustments were made for organic matter. Wadden Sea salt marshes are generally minerogenic, and thereby low in organic matter. Salt-marsh vegetation contributes to an enrichment of organic matter in the upper sediment layers of the marsh bed, but this organic matter appears to be lost at greater depth when it is buried by new sediment layers (Mueller et al. 2019).

6.2.3 Results

Total area

Based on the most recent trilateral overview, salt marshes in the Wadden Sea cover almost 40,000 ha (Table 6.6). From a morphological point of view, three main types of salt marsh may be distinguished in the Wadden Sea, viz.: (a) barrier marshes, (b) foreland marshes and (c) hallig salt marshes. A hallig salt marsh is a salt-marsh island which in the past has been part of the mainland. Hallig salt marsh thus accreted on low-lying old land. The reported extent of salt marshes in Table 6.6, however, is not based on geomorphology, but on vegetation and habitat mapping (Petersen et al. 2014). Green beaches for example, are not mentioned in Table 6.6, but halophytic vegetation in the foreshore area has been merged with the back-barrier marshes into one group of barrier-connected marshes. Salt marshes on small sandy islands located in the inner parts of the Wadden Sea in the lee of the barrier system, such as Griend, Mellum and Langli have also been merged into the group of barrier-connected salt marshes.

Table 6.6 Overview of tidal marsh types in the Wadden Sea in ha (Esselink et al. 2017).

Landform	Netherlands	Lower Saxony	Hamburg	Schleswig-Holstein	Denmark	Total
Year of survey	2008/2012	2004	2009/2014	2011/2012	2010/2012	
Island salt marsh						
Barrier connected (foreland incl.)	4,640	3,670	310	1,700	3,280	**13,600**
De-embanked (summer) polder	90	150	40			**280**
Mainland salt marsh						
Barrier connected				780	1,340	**2,120**
Foreland type	4,000	5,460		8,580	2,520	**20,560**
De-embanked summer polder	360	380				**740**
Hallig salt marsh						
	50			2,180		**2,230**
Total	**9,140**	**9,660**	**350**	**13,240**	**7,140**	**39,530**

Foreland salt marshes make up about half of the salt-marsh area in the Wadden Sea. These marshes have largely been developed by coastal engineering. Recently, natural expansion of foreland salt marshes contributed to their total extent.

Surface-elevation change (SEC)

SECs clearly differ among different types of salt marsh in the Wadden Sea (Figure 6.5). Esselink et al. (2017) carried out a survey of published and unpublished studies on salt-marsh accretion in the Wadden Sea (Table 6.7). On average SEC of foreland salt marshes show three times higher values than barrier-connected marshes (9.6 mm/yr versus 3.2 mm/yr). Hallig salt marshes show on average the lowest SEC (2.2 mm/yr). Hallig marshes are largely formed by high salt marsh, which indicates a low flooding frequency and duration, and hence a low potential for sediment import. At the same time, however, the majority of the halligen are surrounded by raised revetments or constructed low banks, and these structures may impede flooding of these marshes, and hence curtail import of sediment onto these marshes.

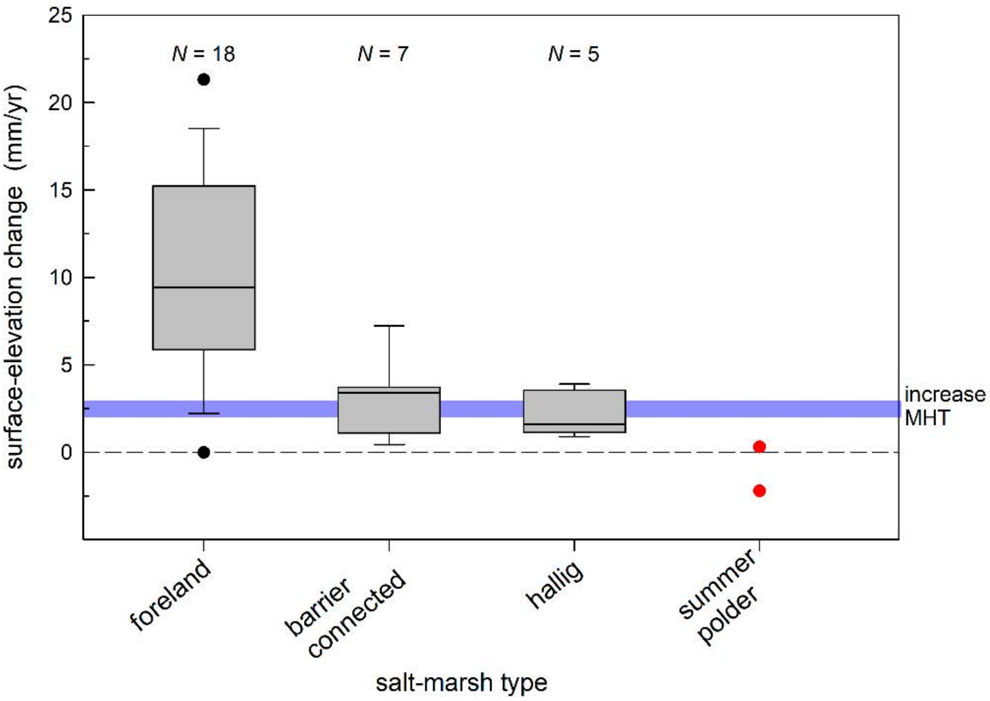


Figure 6.5 Comparison of SEC and vertical accretion rates in Wadden Sea salt marshes and summer polders. The graph is a compilation of studies based on both SEC from levelling and accretion data from studies which used SEB and marker-horizon techniques including clay-layer thickness measurements (Nolte et al. 2013a). SECs are based on overlapping and varying periods in time, mostly starting around 1990 or a more recent date. The graph presents a boxplot with median and 25 and 75 percentiles (grey). The vertical lines give the minimum and maximum values or 1.5 times the interquartile range of the data. Black dots show outliers. The horizontal blue bar gives the range of the long-term increase of MHT level since about 1900 (figure from Esselink et al. 2017).

SEC shows also regional differences (Table 6.7; Suchrow et al. 2012). For foreland marshes, a different value was assigned to each of the seven sections in Figure 6.4. Differences in SEC among barrier marshes were much smaller, with a SEC of 7.2 mm/yr on the Island of Vlieland as an exception. All values are of relatively recent date. SECs older than about 1985 were discarded.

Grain-size distribution and bulk dry densities

Salt marsh deposits have generally a more fine-grained sediment than the intertidal flats in front of the marshes, or the sediment of the former intertidal flat where a salt marsh developed on (Mueller et al. 2019) as salt marshes provide a very low-energy environment where also the finest sediment fraction can settle In order to exclude possible coarser sediment from the intertidal-flat layer underneath the salt-marsh deposits, only grain sizes from a shallow depth were selected from literature. Furthermore, grain size distributions in the deeper layers of the foreland salt marshes, may have been disturbed by the regular upkeep of the artificial drainage, which has been common practice up to the 1980s.

Table 6.7 Overview of SEC and vertical accretion rates in Wadden Sea salt marshes. The table presents data that were selected for the boxplot in Figure 6.5.

Sector	Site	Period	SEC / accretion (mm/yr)	Method	References
Foreland					
NL	Friesland_West (B' pollen)	1992-2014	21.3	Levelling	van Duin et al. 2016
NL	Friesland_mid	1992-2014	15.3	Levelling	van Duin et al. 2016
NL	Friesland_East	1992-2014	15.2	Levelling	van Duin et al. 2016
NL	Peazemerlannen	2007-2015	10.5	SEB	van Duin and Sonneveld 2016
NL	Groningen_West	1992-2014	8.5	Levelling	van Duin et al. 2016
NL	Groningen_Mid	1992-2014	9.8	Levelling	van Duin et al. 2016
NL	Groningen_East	1992-2014	10.2	Levelling	van Duin et al. 2016
NL	Dollard	1984-2012	6.5	Levelling	Esselink et al. 1998, 2013
LS	Leybucht	1989-1994	18.2	Sedimentation plates	Erchinger et al. 1994, 1996
LS	Wûrster Kûste	1960-1997	16.0	Levelling	Michaelis 2008
SH	Reg_Marien	1988/90-2009	7.0	Levelling	Suchrow et al. 2012
SH	Reg_NissHH	1988/90-2009	7.0	Levelling	Suchrow et al. 2012
SH	Reg_NordBu	1988/90-2009	9.1	Levelling	Suchrow et al. 2012
SH	Reg_EiderN	1988/90-2009	9.7	Levelling	Suchrow et al. 2012
SH	Reg_Tümlau	1988/90-2009	0.0	Levelling	Suchrow et al. 2012
SH	Reg_Ehsten	1988/90-2009	2.5	Levelling	Suchrow et al. 2012
SH	Reg_Hering	1988/90-2009	4.1	Levelling	Suchrow et al. 2012
SH	Reg_DiekKo	1988/90-2009	2.6	Levelling	Suchrow et al. 2012
Barrier-connected					
NL	Vlieland	2002-2008	7.2	SEB	Esselink unpubl.
NL	Terschelling	1992-20xx	1.1	SEB	de Groot, pers.comm.
NL	Schiermonnikoog	1994-20xx	3.4	SEB	de Groot, pers.comm.
HH	Scharhörn/Nigehörn	2011-2015	3.5	SEB	Hellwig, pers. comm.
SH	Trischen	2004-2013	3.7	SEB	Stock et al. 2014
DK	Langli	2001-2009	0.4	SEB	Kuijper and Bakker 2012
DK	Skallingen	1992-1997	2.8	clay thickness, SEB	Van Wijnen and Bakker 2001
Hallig					
SH	Hamburger Hallig	1995-2010	0.9	SET/SEB	Stock 2011
SH	(Nordmarsh-)Langeneß	1986-2011	1.6	Cs-137 and Pb-210	Schindler 2014
SH	Süderoog	1963-2007	3.9	sediment traps, Cs-137, SEB	Deicke et al 2009
SH	Nordstrandischmoor	1986-2011	3.2	Cs-137 and Pb-210	Schindler 2014
SH	Hooge	1986-2011	1.4	Cs-137/Pb-210	Schindler 2014

BDD generally increases with depth due to the load of the overlying sediment. BDD in the top layer of the salt-marsh bed is, however, easily affected by management, especially by livestock grazing (Nolte et al. 2013b; Elschot et al. 2015, Esselink et al. 2015). BDD of fine-grained sediments with only little sand may reach up to about 1000 kg/m^3, also at very shallow depth due to grazing (Marijnissen et al. 2020). BDD of coarser sediments may easily amount to values well above 1000 kg/m^3 as a consequence of the sand fraction (Table 6.8).

6.2.4 Mud sedimentation

The information above has been assigned for input estimates for each of the sections (see Table 6.9). Multiplying the salt-marsh area with the SEC gives the increase of sediment volume of the salt marshes. The BDD gives the input value that was applied. If available, BDD of the compacted deeper layers were preferred. Barrier-connected marshes often have only a thin layer of salt-marsh sediment, and a reliable estimate for the BDD of a deeper layer that was not affected by the former sand flat underneath could not be found. This implies that mud sedimentation in the barrier marshes may have been somewhat underestimated.

Table 6.8 Grain-size distributions and bulk dry densities in Wadden Sea salt marshes. Grain-size distribution in italics and shaded cells refer to volumetric distributions; other values are mass percentages (100×g/g). Bulk dry densities either refer to the same depth as the grain-size distribution, or to the compacted salt marsh sediment at greater depth.

Sector	Site	Depth (cm)	Mineral fraction (%)			Bulk dry density (kg/m^3)		No. of cores	Source
			Sand	Silt	Clay	upper layer	deeper layer		
Foreland									
NL	Noord-Friesland	0-30	*27.2*	*68.1*	*4.7*		c. 1000	4	Nolte 2014
NL	Dollard	0-100	7.4	48.3	42.9		915	4	Wiertsema and Partners 2016
LS	Leybucht	0-45	1.8	55.9	42.3		769	5	Erchinger et al. 1994
LS	Leybucht-Buscherheller	0-30	52.4	31.2	16.4		1233	2	Erchinger et al. 1994
LS	Neßmerheller	0-35	65.2	31.2	3.7		1343	1	Erchinger et al. 1994
SH	Dieksanderkoog	0-35	19.1	61.1	19.8		1325	2	Mueller et al. 2019
SH	Westerhever	0-75	9.1	56.4	34.5		1000	2	Mueller et al. 2019
SH	Hamburger Hallig	0-30	*34.5*	*56.7*	*8.8*				Nolte 2014
SH	SankeNissenKoog	0-60	9.3	63.7	27.0		1000	2	Mueller et al. 2019
DK	Juvre Dyb	upper l.	25.6	74.4	n.a.	692		4	Pederson and Bartholdy 2006
DK	Knudedyb	upper l.	48.8	51.2	n.a.	1030		3	Pederson and Bartholdy 2006
DK	Grådyb	upper l.	8.6	91.4	n.a.	584		8	Pederson and Bartholdy 2006
Barrier-connected									
NL	Ameland	0-10	*52.7*	*47.3*	*4.3*	-		14	Elschot pers. comm.
NL	Schiermonnikoog	0-10	*56.8*	*43.2*	*n.a.*	460		108	Elschot et al. 2015 and pers comm
SH	Föhr	0-10	*35.9*	*56.7*	*7.4*			6	Schuerch et al. 2018
DK	Fano	upper l.	1.0	99.0		483		4	Pederson and Bartholdy 2006
DK	Skallingen	0-20	c. 10	c. 50	c.40	600		-	Bartholdy et al. 2004
DK	Langli	upper l.	9.2	90.8		600		2	Pederson and Bartholdy 2006

In the Ems estuary, information on SEC and other sediment characteristics were not available for the small hallig salt marsh Punt van Reide (50 ha). SEC was set at about 50% of the Dollard salt marshes, because of the high surface elevation of this marsh with respect to the tidal frame. For the BDD and grain-size distribution, values from the Dollard salt marshes were used.

The total amount of mud that is annually deposited in the marshes is estimated at approximately 1.9 x 10^6 tons, of which nearly 16% occurs in eastern part of the Dutch Wadden Sea. This is in agreement with the findings by Cleveringa (2018). The estimate for the Danish Wadden Sea may be compared with the study of Pedersen and Bartholdy (2006) on the budget of fine-grained sediments in the Danish Wadden Sea. According to these authors, the mud accumulation in Danish salt marshes amount to nearly 100,000 tons per year, i.e. about 50% of the value in Table 6.9. To a large extent, the difference may be explained by the difference between the salt-marsh area used by Pedersen and Bartholdy (2006) and in Table 6.9 (5,390 ha compared to 7,140 ha).

Table 6.9 Mud sedimentation in the Wadden Sea salt marshes, specified for seven sections (Figure 6.4), and the three main salt-marsh types. QSRarea refers to the subdivision of the Wadden Sea into 23 tidal areas in Fig. 5 of Esselink et al. (2017). For further explanation, see text.

QSRarea	Section	Marsh type	Area	SEC	Sediment increase	BDD	Sand fraction		Mud	Mud	Total Mud
			(ha)	(mm/yr)	(m^3/yr)	(kg/m^3)	(w. %)	(vol.%)	(kg/m^3)	(ton/yr)	(ton/yr)
21-23	1 NL-	barrier	4355	3.2	139360	460		55	207	28848	
21-23		foreland	2235	17.0	379950	1000		27	730	277364	
Total	1 NL-										**306211**
18	2 Ems	barrier	285	2.8	7923	460		55	207	1640	
20		foreland	1393	9.7	135121	1000		27	730	98638	
19		foreland	905	6.5	58554	915	7		851	49827	
19		hallig	50	3.0	1500	915	7		851	1277	
Total	2 Ems										**151382**
15-18	3a LS-	barrier	3350	2.8	93130	460		55	207	19278	
		foreland	2455	18.2	446810	835	2		818	365625	
Total	3a LS-										**384903**
14	3b Jade	foreland	1795	17.0	305150	835	10		752	229320	
Total	3b Jade										**229320**
12-13	4 Weser	barrier	665	3.5	23275	460		55	207	4818	
12-13		foreland	1215	16.0	194400	1000	10		900	174960	
Total	4 Weser										**179778**
9-11	5 Elbe	barrier	125	3.7	4650	460		55	207	963	
9-11		foreland	3785	2.6	99546	1325	19		1073	106838	
Total	5 Elbe										**107801**
5-8	6 SH-	barrier	2355	2.8	65940	460		55	207	13650	
5-8		foreland	5090	5.6	286567	1000	9		910	260776	
5-8		hallig	2175	2.2	47763	715	10		644	30735	
Total	6 SH-										**3051618**
1-4	7 DK	barrier	4620	2.8	130746	600	10		540	70603	
1-4		foreland	2520	5.6	141876	1000	9		910	129107	
Total	7 DK										**199710**
Grand total											**1864263**

6.3 DREDGING ACTIVITIES

6.3.1 Dutch Wadden Sea

In the period of 1989-2017 an average amount of 1.6×10^6 m^3/yr was dredged in the Dutch Wadden Sea (excluding the Ems estuary), of which approximately 56% mud and 44% sand (Mulder, H., 2016). Currently, about 3×10^6 m^3/yr sediment is being dredged, of which 1.7×10^6 m^3/yr consists of mud. The dredged sediment is subsequently disposed within the Wadden Sea. Therefore, this is considered as redistribution of the sediment within the system, instead of a sediment sink.

6.3.2 Ems Estuary

Between 1960 and 1994, 5.1×10^6 m^3/yr was dredged from the port of Emden (1.5×10^6 m^3/yr) and fairway (3.6×10^6 m^3/yr) and brought on land (sediment extraction in Figure 6.6). Another 5×10^6 m^3 of sediment was dredged from the estuarine approach channels and ports, and subsequently dispersed within the estuary (data from Mulder, 2013). Approximately 1.5×10^6

m^3 of the extracted sediment was sand: the remaining 3.6×10^6 m^3/yr is mud. Since 1994, sediment is no longer dredged from the port of Emden, but regularly re-aerated, thereby preventing consolidation. The resulting poorly consolidated bed remains navigable, and consequently the port no longer requires maintenance dredging (Wurpts and Torn, 2005). At the same time, sediment dredged from the approach channel to Emden is no longer extracted but dispersed in the estuary. No dredged sediment is disposed in marine waters outside of the estuary.

The density of the poorly consolidated sediment currently dredged from the approach channels to Emden is 500 kg/m^3 (Mulder, 2013), providing a measure to convert historic extracted sediment volumes to mass. Using this density, on average 1.8×10^6 ton of fine-grained sediment was annually extracted from the port of Emden and its access channel between 1960 and 1994. The annually averaged sand volume extracted as maintenance dredging (of 1.5×10^6 m^3/yr) corresponds to a mass of 2.4×10^6ton/yr (using a density of 1600 kg/m^3, typical for sand). The average amount of sand mining in the period 1970-2011 is 1.1×10^6 m^3/yr (corresponding to 1.8×10^6 ton/yr). Sediment was also extracted before 1960, but these quantities are not exactly known. Köthe et al (2003) estimate that on average 1×10^6 ton/yr was extracted from the estuary between 1924 and 1960 to raise the surface level of polders. It is not clear to what extent these numbers overlap with dispersal data from de Jonge (1983), and therefore have not been added to Figure 6.6. Since its last major deepening in 1994, the lower Ems River requires regular dredging. Around 1.5×10^6 m^3 (0.8×10^6 ton) of fine sediment are extracted annually from the lower Ems River (Krebs and Weilbeer, 2008) and brought on land.

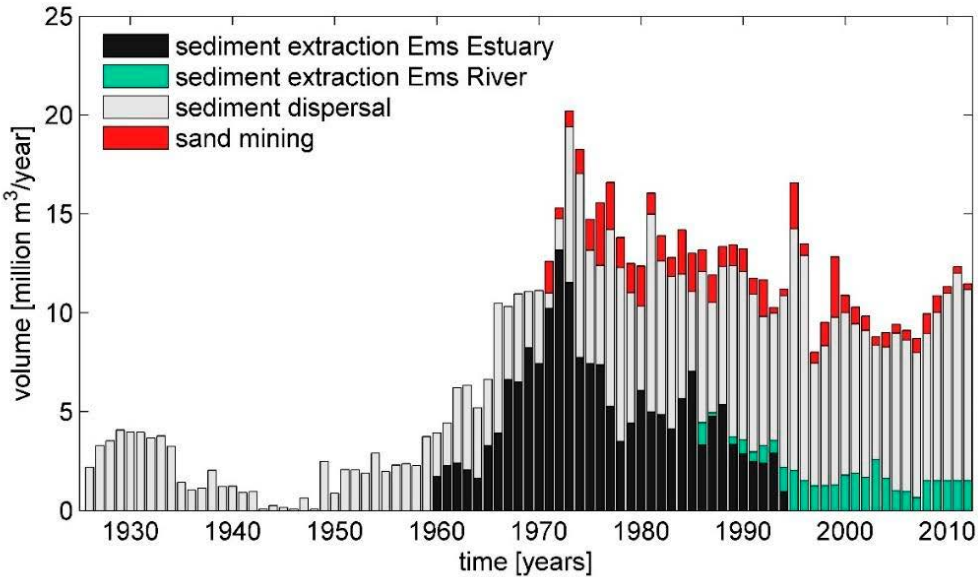


Figure 6.6 Dredging volumes for the Ems estuary since 1925: sediment extraction (mainly mud) in the Ems estuary and the lower Ems River, sediment dispersal, and sand mining (from van Maren et al. (2016). Total dredging volumes before 1960 are from de Jonge (1983); dredging volumes after 1960 are from Mulder (2013) for the Ems estuary and from Krebs (2006) in the lower Ems River (until 2006; after 2006 a constant value of 1.5×10^6 m^3 is assumed).

In terms of sediment sinks, sediment extraction from the outer estuary (port of Emden and approach channel) increased up to the mid 1970's, but became close to 0 in the early 1990's. On average 1.8×10^6 ton was annually extracted in the period 1960-1994. After that, extraction shifted to the lower Ems River, from which around 1×10^6 ton is annually extracted. On top of mud extraction, 2.4×10^6 ton was extracted in the period 1960-1994 for navigability, and 1.8×10^6 ton of sand was mined in the period 1970-2011.

6.3.3 Weser Estuary

Dredging

In the Weser estuary dredged maintenance volumes have decreased after the 9 m deepening from 7.5×10^6 m^3 in 1979 (mainly in the Lower Weser) successively to 1.7 ×10^6 m^3 in 1986 (Wetzel, 1987). However, data over the period 1998-2010 give an average maintenance dredging (including Water Injection Dredging) of 5.4×10^6 m^3/yr for the fairway (Figure 6.7). Data over the period 2007-2018 give an average maintenance dredging (including Water Injection Dredging) of 8.9×10^6 m^3/yr; a clear increase. From the fairway mainly sand is dredged which is relocated within the estuary and in the adjacent North Sea (where it is partially influenced by coast parallel sediment transport).

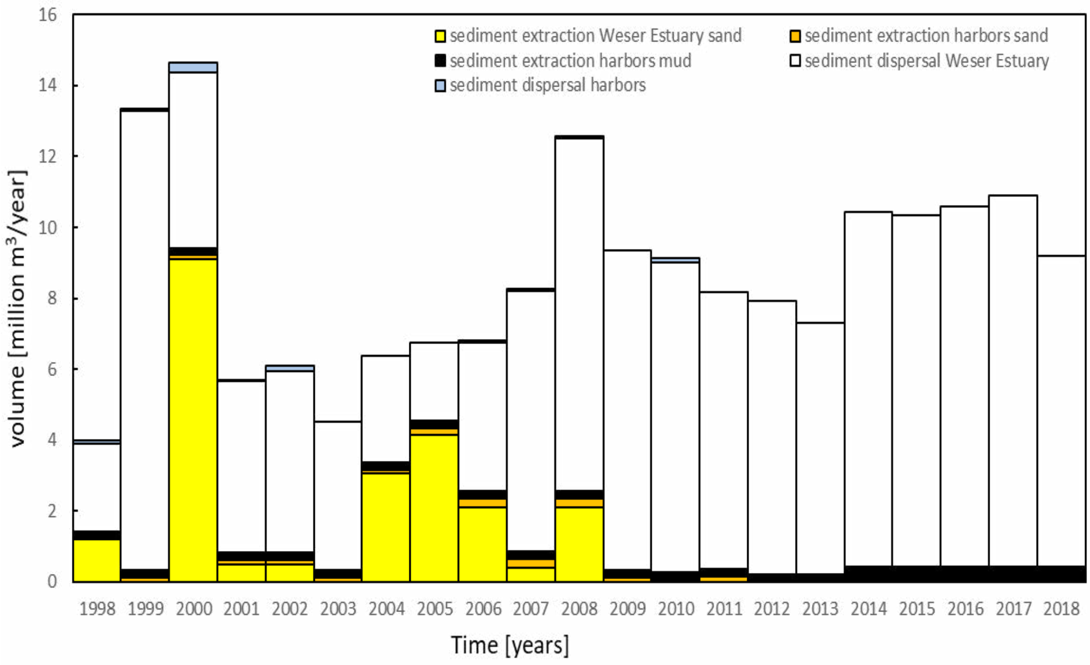


Figure 6.7 Overview of data on dredging. Data 1998-2010 based on BIOCONSULT and NLWKN (2012); data 2007-2018 WSV data für dritten. Differences in overlap most likely due to exclusion of sand mining in latter series.

Sand mining

Sand is mined from the estuary and the harbours. Over the period 1998-2007 an average of at least 2.1×10^6 m^3/yr was removed from the fairway. Mining was mainly done for building purposes near to the Weser. No data could be found for the period after 2007. Over the period 1999-2010 on average some 0.14×10^6 m^3/yr of sand is dredged from the harbours.

Permanent storage of mud outside the estuary

The muddy sediments dredged from the harbours are brought on land because of contamination with harmful substances. Before 1994 contaminated fine-grained material from the harbours was deposited on disposal sites on land and on a placement site in the Wurster Arm (Outer Weser). Since 1994 Bremen stored dredged material on land at the integrated dredged material disposal site in Bremen-Seehausen. Since 2001 also Bremerhaven used this site. Depending on the source, storage figures differ somewhat from 0.17 to 0.200×10^6 m^3/yr (BIOCONSULT and NLWKN, 2012; BIOCONSULT, 2018). More was removed in the period 2006–2008 and 2011 when sediments were transported to the Lower Rhine. Furthermore, since 2011 more material can be removed because it can be stored in the Slufter deposal site at Rotterdam. In 2015 the total need for permanent deposition has been estimated to be some 0.41×10^6 m^3/yr due to the enlargement of the Kaiserschleuse and the more intense use of the Fischereihafenschleuse (BIOCONSULT, 2018). This figure was used for permanent storage on land (including Rotterdam deposition) since 2014.

6.3.4 Elbe Estuary

The tidal Elbe has 4 major players involved in dredging of the area: the Water and Shipping Authorities of Brunsbüttel, Cuxhaven and of Hamburg and the Hamburg Port Authority. In total dredging volumes have been growing up to more than 15-34×10^6 m^3 since the deepening of 1999.

Until 1999, before the last Elbe shipping lane depth increase, some 2-3×10^6 m^3 sediments were dredged annually in the Elbe and the Hamburg harbour. Given a specific density of 550 kg/m^3 (Sjenitzer and van der Star, 2018) this amounts to an annual dredging of 1.1-1.7×10^6 ton/yr. The amount of dredging material produced in the Elbe and the Port of Hamburg has increased from 4.2 million m^3 in 2000, up to 8.2×10^6 m^3 by 2004 (Nix, 2005). Since the beginning of the years 2000 on average some 9×10^6 m^3 is dredged (Hamburg Port Authority, 2017).

In combination with all other dredging and mining some 15-34×10^6 m^3 is annually dredged in the entire Elbe Estuary in the period 2000-2016. On average some 11.5% of the dredged sediment is removed from the system. Removal of the mud is as follows:

1) Mud deposited on land

1.4×10^6 m^3 or 0.8×10^6 ton/yr is treated on land (Netzband et al., 2002). Traditionally, the dredging material from the Port of Hamburg is stored on land, to heighten areas. At the end of the 1970s, the environmental impacts of this practice became clear. To reduce these effects a dredging material treatment was developed and implemented in the 1980s, the so-called METHA-Anlage (Arbeitsgemeinschaft für die Reinhaltung der Elbe, 1996). The METHA-Anlage treats some 1×10^6 m^3 per year of the most contaminated dredging sludge. It is separated in sand, fine sand and a silt/clay fraction. The contaminated fines are deposited in special depots on land. The uncontaminated fine fraction is used as a clay layer on top of dikes. Total permanent deposition is 1.2×10^6 m^3 (Nix, 2005). This is mainly mud.

2) Mud deposited at Buoy E3

It was decided to place part of the lightly- to uncontaminated sediments even more seaward. The dumping location is at 30 m depth NW of Scharhörn and SE of Helgoland near Buoy E3. A part of the finer material can be resuspended (Weilbeer and Uliczka, 2019). In 2005 some 0.8×10^6 m^3 were dumped, in 2006 and 2007 1.5×10^6 m^3 and in 2008 0.7×10^6 m^3 (Nix, 2005; HPA, 2017). After 2008 it was allowed to dump another 6.5×10^6 m^3. Up to June 2016 5.6×10^6 m^3 was dumped of this new location. For the period 2016-2021 an additional 10×10^6 m^3 are allowed to dump (HPA, 2017).

Dispersal of remaining dredged sediment: deposition in the seaward part of the estuary

Near Wedel (Island Neßsand), the relatively uncontaminated part of the dredged sediment is deposited at the seaward border of Hamburg in the Elbe. This occurs mainly during the ebb-phase (Nix, 2005; Hamburg Port Authority, 2017). This became possible due to the improvement in sediment quality (HPA, 2017). In 1994 and 1996 some 0.7 and 0.5×10^6 m^3 of dredging material was put back into the stream as an experiment. This was increased to $7\text{x}10^6$ m^3 in 2004. The hypothesis was that the sediment could be transported seawards. However, part might be deposited on the tidal flats. Comparison of the depth soundings shows that between 1998 and 2003 the surface elevation of the flats along the Unterelbe increased by 0.5 m (Nix, 2005).

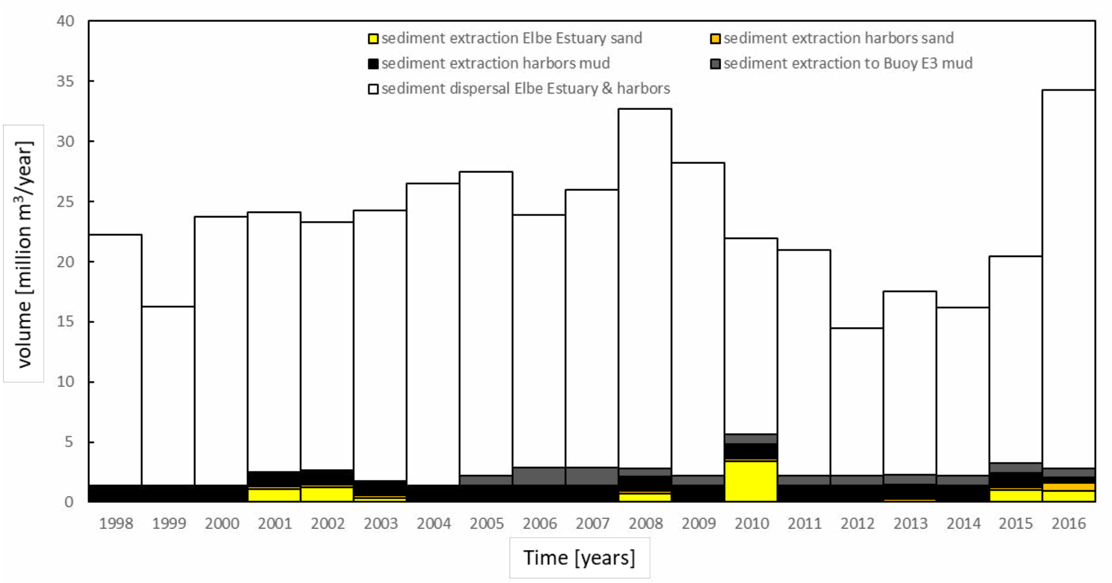


Figure 6.8 Dredging volumes for the Elbe Estuary since 1998: (mainly) sand extraction in the Estuary, sand extraction from the harbours; mud extraction from the Estuary plus harbours and sediment dispersal by various means in the Estuary and the harbours. Data WSA and Hamburg Port Authority

6.4 INTERNAL REWORKING

In theory, it might be possible that the observed mud sedimentation in the Wadden Sea is caused by release of fines during reworking of sand or erosion of older Pleistocene or Holocene clay-rich deposits such as boulder clays. Furthermore, on a short time scale, local mud stocks can make up the difference. The role of local redistribution of mud will be addressed below.

Outwash of fines during reworking of sand

A large part of the reworking of sandy deposits occurs near to the inlets, where channels displace relatively strongly. Gross movements of sand over a few years are easily 10-20 times larger than the net sedimentation. Percentages of mud resting in the interstitial pores are in general low: of the order of a few percent. However, the sediments near the inlets mostly consist of channel deposits. It is therefore likely that deposited sediments will have an equal sand-mud ratio compared to the eroded sediments and therefore reworking of sand will not provide substantial amounts of mud for the Wadden Sea. This also holds for sediment release resulting from the migration of island or islets. The only net sources of mud are tidal marsh deposits which are eroded due to e.g. channel migration. The contribution of eroding old salt marsh deposits is unknown but estimated to be small as most islands are nowadays fixated by human actions. Overall, reworking of sand seems not to be a large source of mud.

Pleistocene deposits

Boulder clay from the penultimate Ice Age is often very poorly sorted, which implies that next to fine clay particles stones can be present up to a few meters in size and everything in between. Locally these deposits are present at or near the surface on and adjacent to the barrier islands (for instance Amrum, Sylt, Borkum, Texel, Wieringen and along parts of the mainland of Denmark). It can be expected to be incised locally by channels, as has for instance been observed in the Ems, or at cliffs (Cliff of Sylt). Other possible sources of mud (although rare) are the overconsolidated clay from the penultimate Ice Age (e.g. in the Ems Estuary) or clay deposited during the Eemien (the previous warm period).

Holocene clay-rich deposits

During the early Holocene, clay layers have been deposited in lacustrine and other conditions. Mud deposition was fairly dominant during the Wadden Sea stage (which probably started some 5000-6000 years ago for the West Frisian and East Frisian area and the estuaries and ca 1000 years ago for a large part of the North Frisian and westernmost part of the Dutch Wadden Sea). However, a large part of these muddy deposits was reclaimed. Before the construction of dikes, the landscape was characterized by valley-like depressions. These were usually, but not necessarily, formed by local brooks and rivers, which were present between higher sand ridges. The valleys and the lower areas around it became initially filled up with peat, which was partly eroded in later stages. The valleys changed into tidal embayments as a result of Sea-level Rise (see e.g., van der Spek, 1994). Hence, the basins have orientations perpendicular to the coastline. In time, as the landward parts of these basins filled up with mud, they were reclaimed (Figure 6.9). These reclaimed tidal basins were sheltered from wave action and probably also experienced mild tidal conditions. Therefore, their reclamation resulted (1) in a reduction of the surface area were mud can settle (see van Maren et al., 2016) and (2) in an overall increase in the average energy level in the basin (see Flemming and Nyandwi (1994) and Mai and Bartholomä (2000) for details). In most of the present-day basins, pure muddy intertidal flats account for only a small percentage of the total basin area: the coastal squeeze has reduced the accommodation space for fine-grained sediment.

In general Pleistocene and early Holocene clay rich deposits will be near to the surface where Pleistocene deposits were pushed up by the land ice. On top of these, early Holocene deposits may be present. Locally, this may be a source of mud when eroded, as is for instance shown (indirectly) by the Pleistocene pebble concentrations in the outer Ems channels. However, areas with such deposits are generally limited in extent and will most likely not deliver substantial amounts of mud (Hijma pers. comm.). That it cannot be a substantial source is also shown by the sheer volumes of mud which are being deposited. If clay-deposits would be eroded in channels and filled up with sand, it would result in a higher sand import from the North Sea.

Furthermore, we know that the hydrodynamic conditions in the North Sea and Wadden Sea may vary over the years. During years and periods with quiet conditions this will result in deposition of fines in both the North Sea and the Wadden Sea. As hydrodynamic conditions vary strongly going from the North Sea to the Wadden Sea, it is imaginable that if mud supply is insufficient, it may still be delivered by depletion of the near-coast mud buffers in the North Sea. On a seasonal scale this has been observed in Blavands Huk (see 6.1.8). Due to this mechanism, the mud fluxes in the Wadden Sea and North Sea minus the calculated amounts of deposition in the various areas won't add up exactly. How large this discrepancy is, is unknown and might be a subject of further research.

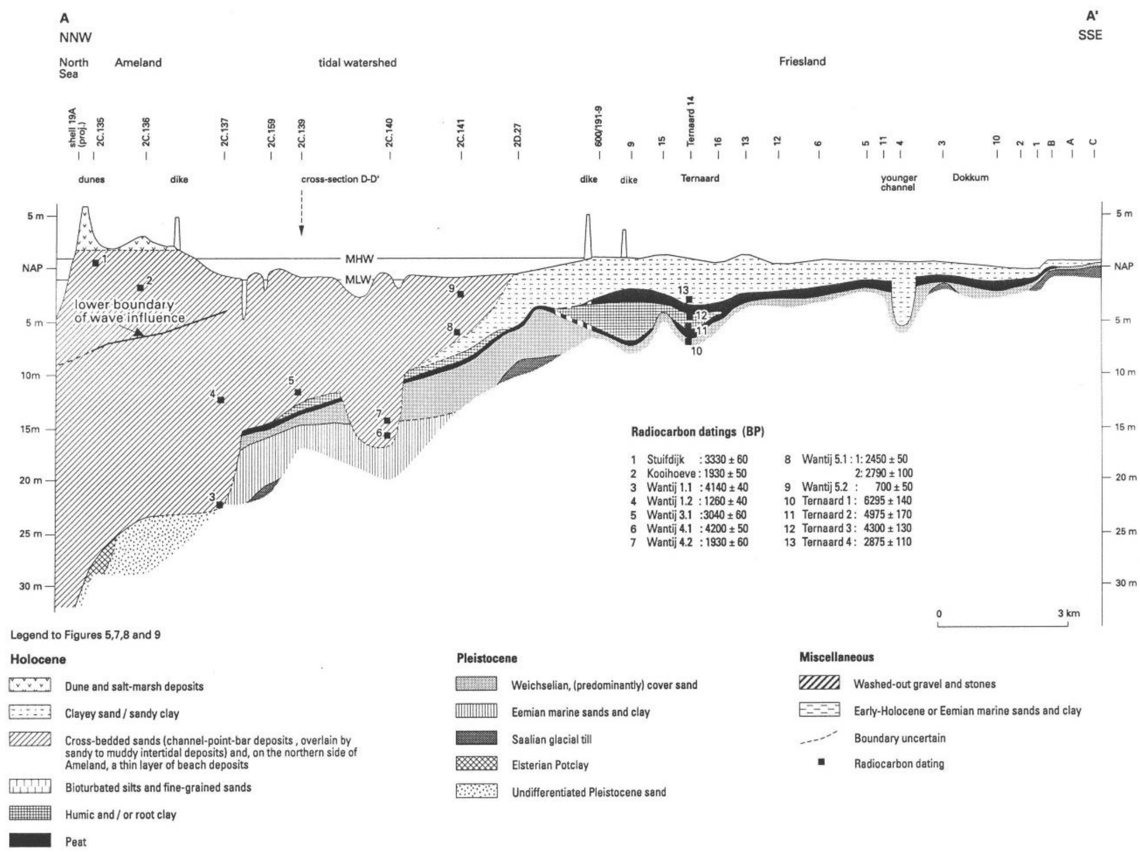


Figure 6.9 Cross-section running from the North Sea coast of Ameland, through the Wadden Sea onto the mainland of Friesland, showing the distribution of fine-grained deposits. Note the decrease in basin length of the original basin versus the present-day basin bounded by dikes (Van der Spek, 1994).

6.5 THE NORTH SEA

The main source of mud transported into the Wadden Sea is the North Sea. In this section, we provide a sediment budget for the North Sea, constructed from data and model results reported in literature, but also findings related to net sediment deposition and sediment extraction (sections above).

6.5.1 Major sediment sources

Most sediment enters the North Sea from the North Atlantic between Scotland and Norway (characteristic settling velocity 2×10^{-3} mm/s) and through the Strait of Dover (characteristic settling velocity 0.1 to several mm/s; Eisma and Kalf, 1987; Puls et al., 1997). Sediment composition suggests that SPM which is transported along the Belgian and Dutch coasts is largely supplied by sediment eroded from the French and British cliff coasts (Irion and Zöllmer, 1999; Fettweis and van den Eynde, 2003). The annual input shows large interannual variability which probably reflect differences in frequency and duration of storms (van Alphen, 1990).

Another important source are the fresh water inputs, such as Elbe, Weser, Ems, Rhine, Thames, Welland, Humber, Tees, Tyne, Forth, IJssel and the Noordzeekanaal (Huthnance et al., 2016). River input of SPM shows a strong interannual variability due to the interannual changes in discharge, in relation to climate variability. Also, strong variations occur over the year, with maxima coinciding with peak discharges. Furhermore, suspended matter is entering the North Sea from the Baltic Sea, erosion of the bottom and coasts, atmospheric deposition and, mainly in the summer half year biologic primary production[1] (Kappenberg and Fanger, 2007; Table 6.10).

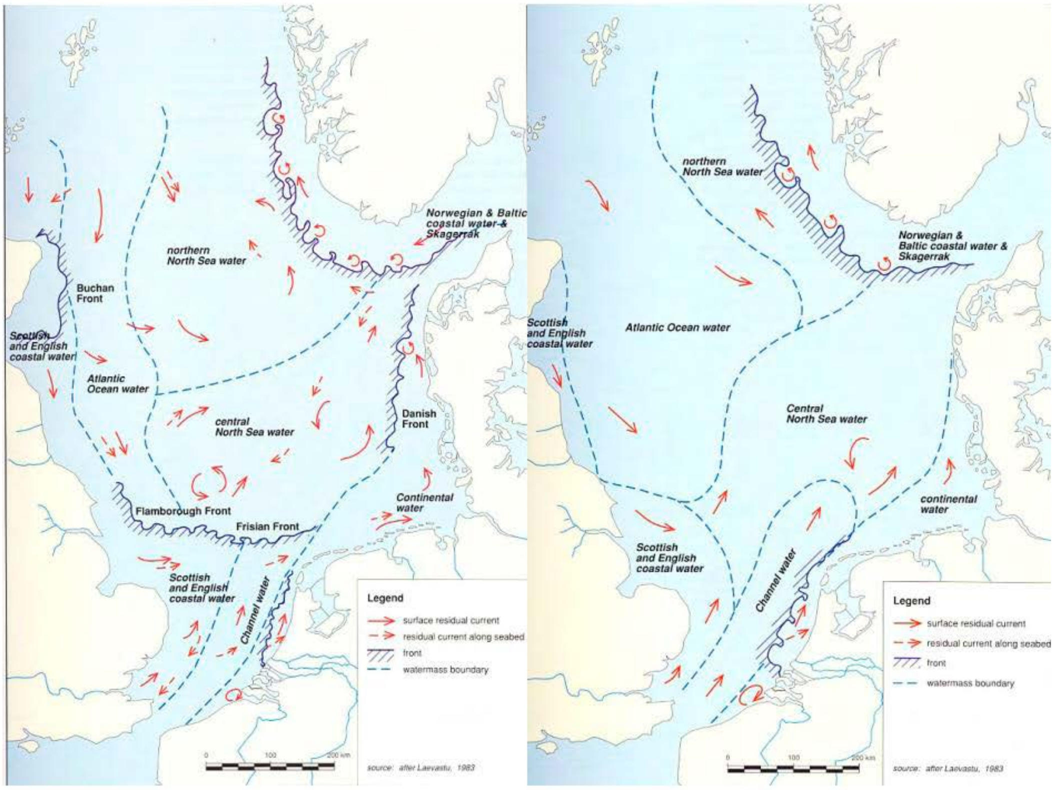
Table 6.10 Overview of the estimates of the various sources of SPM input in the North Sea basin. Values vary due to differences in measurement techniques and natural fluctuations. Total input in the tidally influenced realm is given irrespective of deposition or dredging; data for landfill are added as negatives. It should be noted that Eisma and Irion (1988) made calculations for <63 mu, whereas Puls (1997) and Schubert (2006) looked at <20 mu which constitutes some 85% of all fines. The estimates of Puls (1997) being in general higher than those of Eisma and Irion (1988).

Source of SPM	Input (10^6 ton/yr)	Source
North Atlantic	13; 10	Puls (1997); Eisma and Irion (1988)
Dover Strait	44 (22-58); 21.6 ± 2.1; 14; 19.2; 10.6; 10	McManus and Prandle (1997) Velegrakis et al (1997); Puls (1997); Lafite et al. (1993); Van Alphen (1990); Eisma and Irion (1988)
Balthic	0.5	Eisma and Irion (1988)
Erosion of sea bed	12.4; 6-7.5	Van Alphen (1990) + ICONA (1992); Eisma and Irion (1988)
English Cliff erosion	4; >2	Puls (1997); Eisma and Irion (1988)
All rivers	4.8; 4.4-4.8	Eisma and Irion (1988); McCave (1987)
Atmospheric deposition	1.6	Eisma and Irion (1988)
Primary production	1	Eisma and Irion (1988)
Extraction Elbe	-0,2	
Extraction Ems	-1	
Land storage mud Rotterdam harbour	-1.4	Van Alphen (1990)
Total input SPM matter in the North Sea Basin	**44.8 – 95.3**	

[1] It is assumed that all studies addressed the suspended mineral matter.

6.5.2 Residual transport patterns

The main mud transport towards the Wadden Sea area follows the long-year residual current patterns in the North Sea (Eisma, 1971; Eisma and Irion, 1988; Eleveld et al., 2008; Figure 6.10 and Figure 6.11). The SPM concentration in the open North Sea is mainly determined by the distance to the coast, water depth, sediment composition of the seabed, meteorology and the amount of plankton. The variability is up to two orders of magnitude (Kappenberg and Fanger, 2007). Using remote sensing images Pietrzak et al. (2011) characterized the water types, relating the suspended matter to stratification in the southern North Sea area (Figure 1.2). They showed strong seasonal and neap-spring variability and highlighted the important role of tides and winds in controlling stratification and SPM distribution.



a b

Figure 6.10 Fronts and residual currents in the North Sea during a) summer and b) winter (ICONA, 1992).

Two important paths, relevant to the Wadden Sea suspended matter import, are recognized: one which we will refer to as the North Sea Continental Flow (NSCF) and the other being the East Anglia plume. Both transport plumes are separated by clearer waters originating from the Straits of Dover. We will quantify the transport rates in both these plumes in more detail in the following sections from their source to their terminus.

6.5.3 The North Sea Continental Flow

The NSCF is the residual current from the Dover Strait along the French, Belgian and Holland coast which reaches Texel Inlet and subsequently moves along the Wadden Sea coast (Tabel 6.11; Figure 6.10). Along the Holland coast its northward motion is strengthened by the Rhine

ROFI (region of fresh water influence) through deflection of fresh water masses by the Coriolis Force. The density differences generate a vertical circulation current with landward-directed bottom currents and seaward directed surface currents. As sediment particles settle, they are transported landward by these bottom currents, effectively keeping the turbid waters close to the coast.

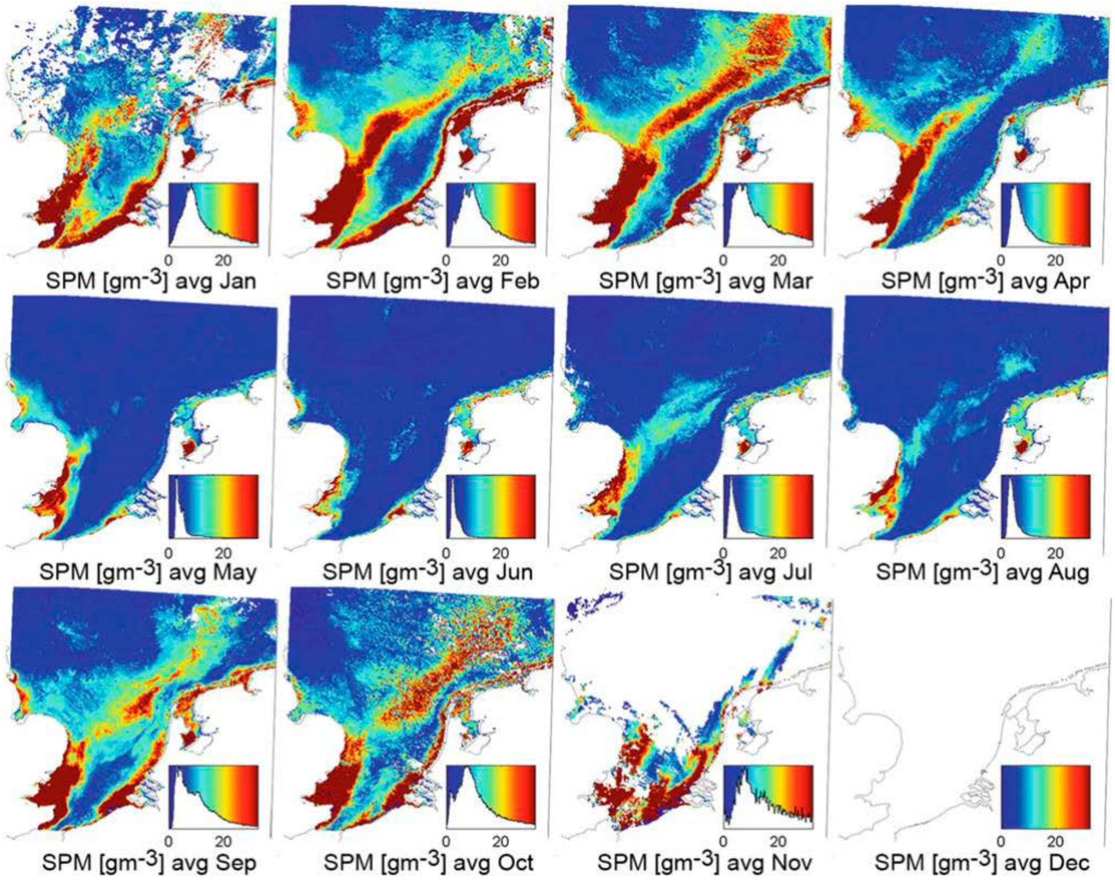


Figure 6.11 Monthly average surface SPM based on SeaWiF's data 1998. Insets show histograms of the pixel values, with x-axis giving the SPM pixel value and y-axis relative frequency distribution (Pietrzak et al., 2011).

Dover Straits

The largest contribution of mud originates from the Dover Straits which import some 44.4×10^6 ton/yr, half of which flows along the UK coast and half into the NSCF (22.2 with a range of 11.9-28.9 × 10^6 ton/yr); see McManus and Prandle, 1997). Fettweis et al. (2007) estimated the flux from the Dover Strait (using a combination of satellite images and a numerical model) at 22-32 million ton/yr of which 60% (13.4 – 19.0 million ton) enters the NSCF (see also Table 6.11).

Belgium

High SPM concentrations are measured along the Belgian coast during almost all months of the year, but especially in September to March (average monthly concentrations may be as high as 80 mg/l (Raaphorst et al., 1998). It forms a turbidity maximum in front of Zeebrugge. The high turbidity near Zeebrugge has been explained with a combination of salinity and sediment-induced sediment convergence mechanisms and local erosion of the muddy substrate (van Maren et al., 2020); the decreasing magnitude of residual transport and the shallowness of the area (Fettweis and van den Eynde, 2003); erosion of the Flemish Banks; and dumping of harbour sludge (Fettweis and van den Eynde, 2003; Raaphorst et al., 1998). Bed scour resulting from the extension of the port of Zeebrugge (1975) eroded 50 million m^3 in a 37-year period (or 1.4 million m^3/yr) (van Maren et al., 2020). Given the temporal character of this sediment source, the sediment eroded from the Zeebrugge coastal zone is not accounted for in our budget.

Table 6.11 Overview of the estimates for the SPM flux in the NSCF from France to the Marsdiep Inlet. Sediment sources are positive, sediment sinks (landfill or net deposition) are negative. Underlined rows give local transport in transects perpendicular to the coast (eastward positive).

Source of suspended matter	Input (10^6 ton/yr)	Source
Transport Dover Strait via France	**13-19; 22.2 (11.9-28.9); 8.5**	Fetweis et al. (2007); McManus and Prandle (1997); Van Wielsma (2009)
Erosion of Flemish Banks (mainly in winter)	3-2.4	Fetweis et al. (2007); Van Alphen (1990)
Transport from France to Belgium	**15.4-15.6**	Fetweis and van den Eynde (2003)
Transport from Belgium to SW Netherlands	**12.8-14.5; 20**	Fetweis and van den Eynde (2003); Salden [2] (1993)
Sink in the Western Scheldt	-0.1 ± 0.2; -0,5	Van Maldegem and Vroon (1995); van Alphen (1990)
Sink in the Eastern Scheldt	-1	Van Alphen (1990)
Loswal Noord deposition	-0,5; -0.7 - -1.4	De Kok (2004); Van Alphen (1990)
Land storage river mud Rotterdam harbour	-0.7	Van Alphen (1990)
Land storage marine mud Rotterdam harbour	-0,3; -0.7	De Kok (2004); Van Alphen (1990)
Rhine (Maasmond)	1.2; 0.7-1.5	De Kok (2004); Van Alphen (1990)
Transport N of Rotterdam	**10.5 to 13.6**	Table 6.12
Transport in front of appr. Noordwijk = also Marsdiep	**10; 12.6-14.3; 6.8**	Nauw and Ridderinkhof (2009); after De Kok [3] (2004); Van Alphen (1990)[4]

Table 6.12 Sediment flux in the NSCF North of Rotterdam

	Min	Max	Source used
Transport from Belgium to SW Netherlands	12.8	14.5	Fetweis and van den Eynde (2003)
Sink in the Western Scheldt	-0.5	0.1	Van Maldegem and Vroon (1995); van Alphen (1990)
Sink in the Eastern Scheldt	-1.0	-1.0	Van Alphen (1990)
Loswal Noord deposition	-0.5	-0.5	De Kok (2004)
Land storage river mud Rotterdam harbour	-0.7	-0.7	Van Alphen (1990)
Land storage marine mud Rotterdam harbour	-0.3	-0.3	De Kok (2004)
Rhine (Maasmond)	0.7	1.5	De Kok (2004); Van Alphen (1990)
TOTAL	10.5	13.6	

[2] Transport through a 70 km long cross section at the border between Belgium and Netherlands
[3] Calculations based on loss of 0.2 million ton as calculated by de Kok (2014) along southern Holland which is subtracted from the outcome of Fetweis and van den Eynde (2013) which is giving a more coast-near SPM transport.
[4] Transport through a 70 km long cross section at Noordwijk (1985-1988); huge uncertainties as gales can increase the amount with 100%;

Netherlands, Holland coast

The Western Scheldt basin is most likely a net sink for North Sea mud. North of Rotterdam the SPM concentrations decrease after the Rhine delta has been passed. This pattern is abrupt in winter and more gradual during the summer. SPM concentrations go down to less than 5 mg/l a few km from the Holland coast from May to September. Along the Holland coast the Rhine ROFI controls transports of SPM towards the north (Dronkers et al., 1990; de Kok, 1992; de Ruijter et al., 1992; McCandliss et al., 2002), with a local SPM minimum some 30 km offshore (Suijlen and Duin, 2001, 2002). Transport flux of SPM along the northern Dutch coast is strongly increased by acceleration by geostrophic effects and by wind stress (De Kok, 1994). As a result, the residence time of SPM along the northern Dutch coast is reduced and concentrations become much lower than in the coastal area south of the Rhine (Raaphorst et al., 1998). Based on ship-board measurements it was shown that along the coast of North Holland, a turbidity maximum zone is present at a distance between 0.5 and 3 km from the coast along 30 km of the coastline as a result of landward directed near-bed currents (van der Hout, 2015). De Kok (2004) states that in total a zone of only some 5 km perpendicular to the coast is important for mud transport.

Dutch Wadden Sea

The annual SPM transports in the NSCF at Den Helder (near the Marsdiep which is the westernmost inlet of the Wadden Sea) cited in literature are relatively high (19.8×10^6 ton/yr by De Kok, 2004, and $22 \pm 10 \times10^6$ ton/yr by van der Hout et al., 2015). However, the estimates of van der Hout et al. are based McManus and Prandle (1997) and not their own observations. It seems more accurate to use the more recent calculated transports at Noordwijk of 10 and 14.3×10^6 ton/yr, which are based, respectively, on Nauw (2010), and on the De Kok (2004) using the calculations of Fetweis and van den Eynde (2003). This range agrees with the findings of Cronin and Blaas (2015), who calculated SPM fluxes of approximately 12×10^6 ton/yr at Callantsoog.

The sediment flux into the Wadden Sea through the Marsdiep (Texel) inlet is estimated at 7 – 11 million ton/yr using long timeseries of ADCP transect data (Nauw et al., 2014). However, model-based sediment fluxes (Sassi et al., 2015) are much lower (~1 million ton/year). This large discrepancies between model and observations is at least partly the result of the temporal and spatial limitations inherent to the ferry-borne ADCP measurements (Sassi et al., 2015; 2016). A residual flux in-between Nauw's and Sassi's estimates therefore seems most likely. Nevertheless, using the lower bound of the sediment transport estimates along the Holland coast (10 million ton/yr) and Nauw et al. (2014)'s estimate for the Marsdiep flux would result in a very small residual transport (0-3.4 million ton/yr) the North Sea coast of Texel. This seems unrealistic but is not impossible. Numerical model results by Sassi et al. (2015) suggest that the residual flux in the Eierlandsche Gat (in-between Texel and Ameland) is directed seaward, and comparable in magnitude to the landward flux through the Marsdiep. Therefore a large part of the total sediment flux entering the Wadden Sea south of Texel may join the coastal flux again east of Texel. The data or modelling results are at present insufficient to verify this.

The NSCF becomes narrow (some 10 km, but with variations over the seasons) in the North Sea bordering the Wadden Sea. Very high concentrations have been observed in the upper 10 m of the water column in the North Sea near the Frisian Inlet where the Wadden Sea area is relatively narrow (ca. 10 km) and sediments are muddy (Raaphorst et al., 1998). The transport of particulate matter from the North Sea into the Wadden Sea is assumed to occur largely in bottom currents which have a landward component (Postma, 1954; Visser, 1993). The Wadden Sea is filling in with fine sediments resulting from (1) a net residual landward but annually varying residual flow driven by the dominantly westward-directed winds (Buijsman and Ridderinkhof, 2007) and (2) the low energy conditions in the Wadden Sea compared to the North Sea result in higher SSC during the flood than during ebb, generating residual transport from the North Sea to the Wadden Sea (Nauw et al., 2014). During more energetic storm conditions, wave-driven sediment remobilisation may lead to export of sediment. The exchange between the North Sea and Wadden Sea can be simplified as follows:

1. The Wadden Sea is an area of net long-term SPM sedimentation (see especially section 6.1), trapping part of the mud provided by the North Sea.
2. Sediment in the Wadden Sea is resuspended during storm conditions. Depending onto the storm characteristics and the tide this resuspended mud can be deposited on the tidal marshes (Kamps, 1962), be transported to the North Sea, or remain in the Wadden Sea inter- and subtidal area. During storm periods the Wadden Sea may therefore function as a temporal source of mud for the North Sea.

It is difficult to quantify the eastward change of the sediment flux in the NSCF based on data, given constraints in spatial coverage, duration and frequency of observations. As an alternative, we start with our best estimate for sediment transport along the Holland Coast (10.0-14.3 million m^3/yr – see Table 6.11) and correct this for sinks and sources in the eastward direction; resulting sediment fluxes are verified with existing numerical model results.

Subtracting the estimated sedimentation in the Dutch Wadden Sea (-1.6×10^6 ton/yr – see section 6.1) and adding mud deliverance through the Afsluitdijk (0.4×10^6 ton/yr) this results in an eastward transport of 8.8-13.1×10^6 ton/yr at the transect over Schiermonnikoog. One of the few comprehensive model studies shows that over a 210 km long S-N profile at the east side of the barrier island Schiermonnikoog the eastward transport of suspended sediment (in both the NSCF and the East Anglia Plume combined) is in the order of 11.7×10^6 ton/yr (Putzar and Malcherek, 2015) which is comparable in magnitude to the calculated transports at Marsdiep.

Wadden Sea of Lower Saxony

Given the losses due to retrieval and sedimentation in the Ems (1×10^6 ton/yr) and in the Wadden Sea area of Lower Saxony (1.5×10^6 ton/yr) the sediment transport towards the Weser area can be estimated to be some 6.3-11.6×10^6 ton/yr of mud (Table 6.13). Near to the East Frisian barrier islands sediment transport follows the coast and proceeds all the way up to the Jade (Figure 6.12). More seaward west of Helgoland the paths change towards a S-N trajectory (Putzar and Malcherek, 2015).

Table 6.13 Overview of the estimates for the SPM flux in the NSCF from Marsdiep Inlet to Denmark. Sediment sources are positive, sediment sinks (landfill or net deposition) are negative. Underlined rows give local transport in transects perpendicular to the coast (eastward positive).

Source of suspended matter	Input (10^6 ton/yr)	Source
Transport in front of appr. Noordwijk = also Marsdiep	**10; 12.6-14.3**	Nauw and Ridderinkhof (2009); after De Kok[5] (2004)
Supply via Afsluitdijk	0.4	De Kok (2004)
Sedimentation mud Dutch Wadden Sea	-1.6	This study (section 6.1)
Transport to a transect N of Schiermonnikoog	**8.8-13.1**	This study (section 6.5)
Calculated transport over a 210 km long S-N cross section at E Schiermonnikoog	11.7	Putzar and Malcherek (2015)[6]
Supply Ems	0.0975; 0.03	De Jonge (1994); Puls et al. (1997)
Extraction Ems	-1	This study (section 6.3)
Sedimentation mud Lower Saxony Wadden Sea	-1,5	This study (section 6.1 and 6.2)
Transport over a transect near Langenoog	**6.3-11.6**	Calculation
Calculated eastward transport over a 100 km long S-N section at Langenoog	13.5	Rick et al. (1998)
Supply Weser	0.532	Grabemann and Krause (1998)
Extraction Weser	-0,2	See 6.2
Supply Elbe	0.660	Schubert (2006)
Extraction Elbe	-0.8	See 6.2
Erosion of the Elbe Urstromtal deposits	unknown	Figge (1981)
Atmospheric deposition in Wadden Sea	0.03	Estimate based on relative surface area
Primary production Wadden	0.5	Estimate
Calculated northward transport over a 160 km long E-W cross section Knudediep	1.9	Putzar and Malcherek (2015)

The Elbe-Weser-Helgoland triangle

In the Elbe-Weser-Helgoland triangle the sediment transport patterns do not show clear patterns (Putzar and Malcherek, 2015). A mud patch exists on the seabed between the Elbe estuary and the Weser estuary and Helgoland (Figure 5.2, Figure 6.13) which may be generated by the NSCF and/or from mud discharged by the Elbe and Weser estuaries. Although it is a net long-term sedimentation area, strong storms may occasionally result in erosion. This is also confirmed by observations of the sedimentary structure of the bed (partially consisting of mud layers alternating with sandy storm-surge layers), which are indicative of erosion (Reineck et al., 1967 Aigner, 1985). Thus, the area is a long-term sink but intermittent source for mud.

Wadden Sea of Schleswig Holstein

Along the North Frisian coast, the highest values of SPM can be found between the 8 degrees East-line and the mainland coast over a 30 km broad zone of higher turbidity. The zone in which SPM values are high is broader than the one along the East Frisian coast (Kappenberg and Fanger, 2007). Depth-averaged SPM concentrations are 4 mg/L in the summer and 18.5 mg/L in the winter (Heinrich, 1993). There is a waning gradient from the Elbe estuary mouth to the north. A good explanation for this is given by the model study of Putzar and Malcherek

[5] Calculations based on loss of 0.2 million ton as calculated by de Kok (2014) along southern Holland which is subtracted from the outcome of Fetweis and van den Eynde (2013) which is giving a more coast near SPM transport.

[6] Assuming an s.d. of 0.8 ton/m^3

(2015) who show a break-up of the coast parallel NSCF in the Weser-Elbe-Helgoland triangle (see above). North of it mud might be delivered by remnants of the NSCF suspended sediments and the Elbe (see also Weigelt-Krenz et al., 2014), by the East Anglia Plume and by local erosion.

Finally, in front of Sylt sediment transport paths become once more coast parallel (Figure 6.12; Putzar and Malcherek, 2015). There, Pleistocene deposits are present in front of the island which might be a (small) local source of mud (Figure 6.13).

Wadden Sea of Denmark

Coast parallel currents are present in the Danish part of the coast. It has been noticed that mud accumulates during quiet weather conditions at the southside of Blavands Huk. During storm surges the mud can be entrained and transported in a few weeks into the Wadden Sea area. The northernmost basin Grådyb receives a major part of this mud followed by Knude Dyb, Juvre Dyb and Lyster Dyb (Bartholdy pers. com.)

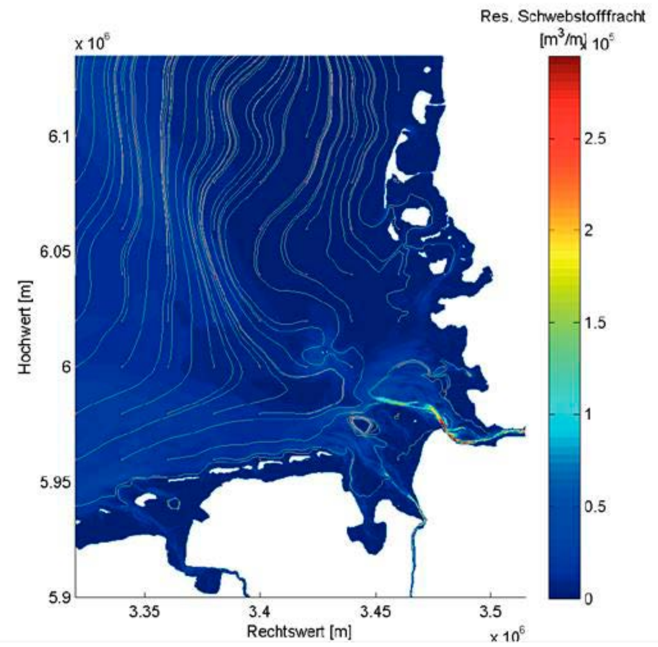


Figure 6.12 Residual suspension transport paths for the scenario 2006 (Putzar and Malcherek, 2015).

Total gross availability of mud

Based on these observations an estimate can be made how much suspended sediment becomes potentially available on a yearly basis from the North Sea Continental Flow for the Wadden Sea, in combination with local factors. As a first approximation the NSCF transport at Marsdiep in combination with the local rivers, local atmospheric deposition and primary production totals a gross influx of 12.1-16.5 × 10^6 ton/yr, (Table 6.11). Due to extraction from the three estuaries the gross availability of mud is reduced to 10.3-15.2 ×10^6 ton/yr.

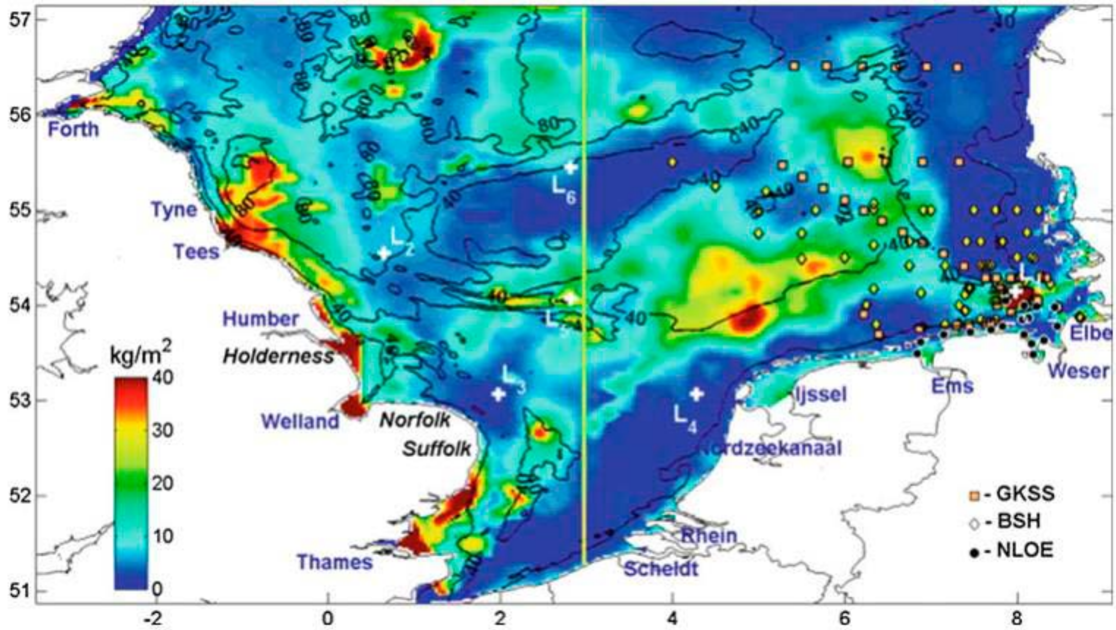


Figure 6.13 Sea-bed (upper 20 cm) fine sediment (<20 micron). Bathymetry given in black lines; depth in m. Distribution determined by combination of grain-size analysis, satellite data during storms and numerical model results (Dobyrnin et al., 2010).

6.5.4 East Anglia Plume

Another current transports suspended matter derived from the Dover Strait, the Thames estuary and cliff erosion to the NE along the southern English coast (Table 6.14). In front of the East Anglia coast it is transported in an eastward direction, and subsequently transported coast parallel towards the Skagerrak. The East Anglia Plume is an almost permanent phenomenon of SPM distribution in the southern North Sea, more pronounced in winter than in summer (Pietrzak et al., 2011; see Figure 6.11). A frontal boundary is formed which separates well-mixed water in the southern Bight from seasonally stratified North Sea waters, especially in summer (Flamborough Head and Frisian Front; Figures 1.1 and 1.2; Huthnance et al., 2016).

On its way to the East mud is intermittently deposited and resuspended many times, especially below the -40 m contour (Huthnance et al., 2016). The mud area Oyster Grounds and a nameless mud area far west of Blavands Huk near Denmark, are the result. They are depocenters during the spring and summer, but can get eroded during severe storms, occurring mainly in autumn and winter (Raaphorst et al., 1998). The exact net deposition volumes are still under debate. The German Bight is a net sedimentation area for mainly suspended sediment. Models indicate that it enters the area from western directions (some 11.7×10^6 ton/yr; Putzar and Malcherek, 2015[7]). Only some 1.9×10^6 ton/yr goes out through the northern boundary and some 9.8×10^6 ton/yr must thus be deposited in the German Bight (Putzar and Malcherek, 2015). Eisma and Irion (1988) give 3 to 7.5×10^6 ton/yr of sedimentation).

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[7] Using a S.D. of 700 kg/m^3

Table 6.14 Overview of the estimates of the SPM availability of the East Anglia Plume. Total input in the tidally influenced realm is given irrespective of deposition or dredging; data for permanent deposition are added as negatives. Underlined rows give local transport in transects perpendicular to the coast.

Source of suspended matter	Input (10^6 ton/yr)	Authors
Transport Dover Strait via UK	22.2 (11.9-28.9); 5,5	Fetweis and van den Eynde (2003); Van Wielsma (2009)
English Cliff erosion	4; >2	Puls (1997); Eisma and Irion (1988)
UK rivers and dumping of dredged sediments	0.6; 0.2	Puls (1997); Eisma and Irion (1988)
Erosion of East Anglia Seabed	10; 5.1	ICONA (1992); Eisma and Irion (1988) - Van Alphen (1990)
Losses along English coast	-1_-4	Eisma and Irion (1988)
SPM transport from East Anglia	8.8-35.8	Calculation
EAP transport near East Anglia	6.6	Sündermann (1993)
Losses to North Sea of East Anglia Plume during flow to German Wadden	-2 - -3	Eisma and Irion (1988) and McCave 1987
East Anglia Plume input to German area	5.8-33.8	Calculation
Losses in the German Bight	>-9.8; -3 - -7.5	Putzar and Malcherek (2015); Eisma and Irion (1988)

So far, it is unclear how much of the suspended matter travelling with the East Anglia Plume can reach the Wadden area coast. During most of the year, but especially during wintertime, water from the Dover Strait is separating the East Anglia Plume from the Continental Flow. In the Netherlands there is no influence of the EAP on coast-nearby mud transport (De Kok, 2004). Twenty years of in situ observations (Raaphorst et al., 1998) and modelling studies (Sündermann, 1993) indicate that most of the SPM from the EAP does not enter the inner German Bight, but is transported via the Oyster Grounds directly to the Skagerrak and the Norwegian Channel. Another sign of separation is the observation that seabed grain sizes show that the mud deposition of the plume is separated from the fine-grained deposits along the Wadden Sea area (Figure 6.13; Dobyrnin et al., 2010), suggesting a near complete separation of both SPM transports. The long-year average input from the West over the line from Langeoog to the N up to the height of southern Amrum (thus far seaward of the (NSCF) is calculated to be some 13.5 $\times 10^6$ ton/yr (Rick et al., 1998)[8]. This line is approximately east of the EAP. The amount calculated is more than the 6.3-11.6 $\times 10^6$ ton/yr calculated for the total SPM transport of the NSCF plus local rivers (Table 6.14). It suggests that a small part of the EAP SPM may enter the inner German Bight (see also Dyer and Moffat, 1998). Given the far seaward-extending calculation-line used by Rick et al., (1998) it is not clear if EAP SPM can be transported all the way to the Wadden Sea, thus into the NSCF. Eisma (pers. com.) thought EAP SPM could only migrate landward during storms due to resuspension of the deposited

[8] That the influence of storms on SPM load is important is illustrated by Puls et al. (1997). For a line from Borkum up to halfway the EAP, Puls and co-workers determined an SPM inflow from the W of 29.9 ± 6.4 $\times 10^6$ ton/yr and an outflow to the North amounts to 27.3 ± 6.3 $\times 10^6$ ton/yr, leaving a net input for the inner German Bight sedimentation of 1.3 ± 6.3 $\times 10^6$ ton/yr. This was on the basis of the TUVAS measurements (1989-1992), with two out of four measurement campaigns after major storms. The observations also suggest that storms may contribute to net SPM loss from the inner German Bight.

mud further offshore. Raaphorst et al. (1998) state that EAP SPM may reach the inner German Bight particularly under favourable wind conditions and that, furthermore, transverse circulations along the bottom may transport SPM towards the Wadden Sea area. If there is a net influx of SPM from the EAP into the NSCF, the chance that this happens will probably increase with increasing distance to the east and, along the North Frisian coast, to the North. From Raaphorst et al. (1998) it appears that the separation between the EAP and the NSCF may occasionally be broken in front of the east Frisian Wadden Sea area.

6.6 SYNTHESIS: A MUD BALANCE FOR THE WADDEN SEA AND NORTH SEA

In this paragraph, first the mud balances of the Ems, Elbe and Weser estuaries are intercompared. Then, we elaborate on the mud balance for the Trilateral Wadden Sea.

The mass of sand annually depositing in the Ems and Weser estuary is larger than the mass of mud (Table 6.15) This is probably also the case for the Elbe estuary as the larger part of the area consists of sand (but data is not available). The Ems estuary has relatively large extraction rates and therefore the total mud sink (extraction + sedimentation) is larger than the total sand sink. More mud deposits in the Ems Estuary compared to the other two estuaries, despite its negligible fluvial mud import. Likely, the Ems estuary is an efficient sediment sink in its current conditions (resulting from the present-day bathymetry, hydrodynamics, and prevailing suspended sediment concentrations) and is adapting more rapidly than the Weser and Elbe estuary.

Table 6.15 Overview of net mud and sand sedimentation/yr in terms of million ton/yr and million m^3/yr in the three major estuaries. Metric tons were recalculated into m^3 (and vice versa) by using a sediment density of 1600 kg/m^3 for sand and 500 kg/m^3 for mud, based on the average experiences within the estuaries.

		Sedimentation in 10^6 ton/yr					Sedimentation in 10^6 m^3/yr	
Area	**Period**	**Net sedimentation sink (= net sedimentation basins and salt marshes + extraction)**	**Net mud extraction**	**Net mud import from river**	**Net mud import from North Sea**	**Net sedimentation sand**	**Net sedimentation mud (excl. salt marshes)**	**Net sedimentation sand (excl. salt marshes)**
Ems Estuary	1990-2011	**2.1 - 2.6**	0.8	≤0.03	≥1.9-2.4	2.9 - 4.3	3.8 - 4.8	1.8 - 2.7
Weser Estuary	2000-2010	**1.7**	0.2	≤0.5		20.8*	2.9	13.0*
Elbe Estuary	1999-2016	**1.3**	1.0	0.7	0.6	unknown	2.6	unknown
Total main estuaries	**1999-2011**	**5.1-5.6**	**2.0**	**1.4**	**2.5-3.0**		9.2-10.2	

* The mass and volume changes of sand are predominantly a result of the morphodynamic changes at the northern boundary of the polygon (bordering the North Sea), where the bed is highly dynamic because of channel migration. Therefore, the calculated volume changes of sand depend greatly on the polygon definition, and these should be interpreted with care.

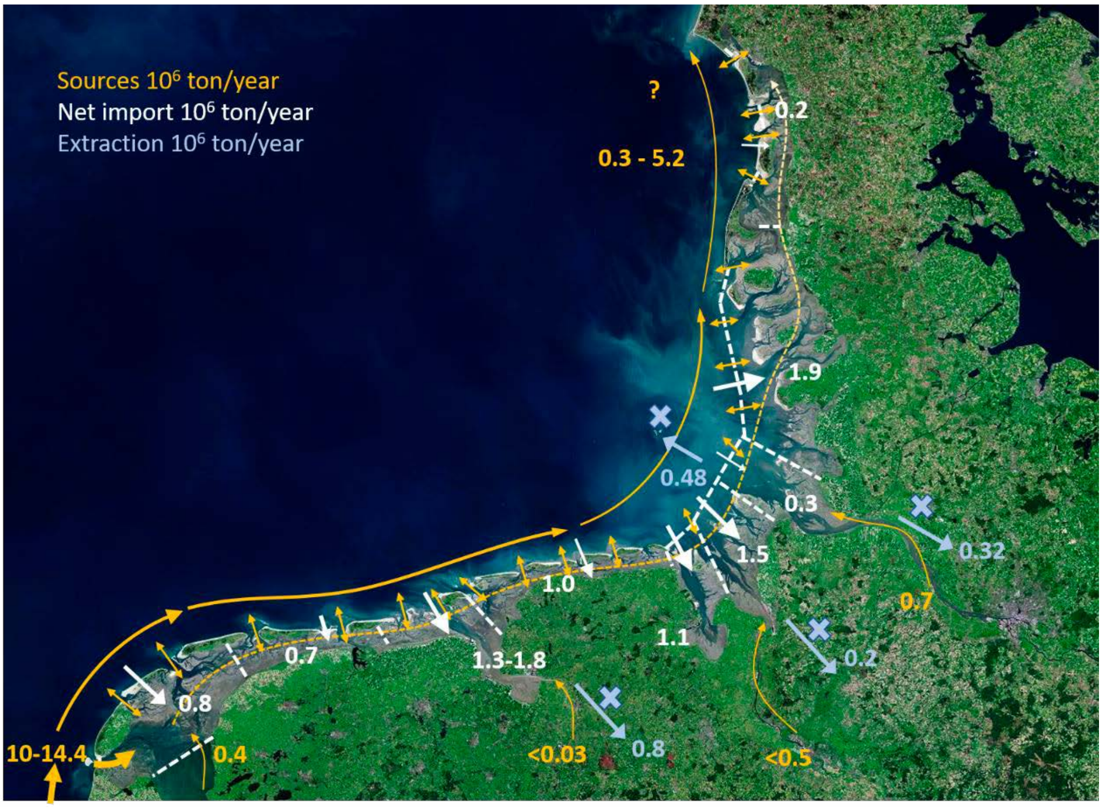

Figure 6.14 Visual presentation of the estimated mud budget for the trilateral Wadden Sea. Yellow numbers indicate annual mud transport fluxes, white numbers annual deposited mass of mud, and blue number anthropogenic extraction rates (all in million ton/yr). Local storage during quiet periods in the near coastal part of the North Sea could not be quantified.

The mud budget for the Trilateral Wadden Sea is summarized in Figure 6.14, with details in Table 6.16. This sediment budget reveals the following main points:

- Mud sedimentation is large in the estuaries.
- Mud sedimentation in terms of volume is several tens of percentage points of the total net sedimentation in the estuaries. It can be expected that such large volumes play an important role in the morphological and ecological functioning of the estuarine systems.
- Mud sedimentation is largest in the Ems estuary which has the smallest riverine input. This highlights the important contribution of marine sediment supply. It is not yet known why these sedimentation rates are so much larger than the other estuaries. This may be the result of hydrodynamics more suitable for sediment trapping, or a higher mud supply (compared to the Weser and Elbe). Mud trapping rates in the Jade Bay are very large as well, which may be one of the reasons deposition rates in the adjacent Weser estuary is relatively small.
- Net extraction is relatively high in the Ems estuary and the Elbe estuary. In the Elbe and Weser, the riverine mud is strongly contaminated, and therefore has to be treated and stored on land. from the sediments extracted from the Ems tidal river are of marine origin and therefore largely uncontaminated.

- Total extraction of mud is of the order of circa 2×10^6 ton/yr in all estuaries combined. This is a large mass compared to the estimated annual suspended sediment transports in the NSCF current and can be estimated to amount to some 10-15% of the total transport. In addition, also the current sedimentation rates are large compared to the magnitude of the sources.
- In addition, the current net sedimentation rates in the Trilateral Wadden Sea are large compared to the magnitude of the sources of mud (~15×10^6 ton/yr).
- Sedimentation in the Danish Wadden Sea basins seems much smaller than in the Dutch and German parts. The reason for this is not yet known, but might be attributed to the flow of mud with the NSCF from W to E and S to N, during which the availability of mud from this flow gradually decreases. Other reasons might be the differing mud deliverance during storm surges from the mud accumulation at Blavands Huk, and the fresh water discharge, which is likely much lower in the Danish part, since mud import is very sensitive to salinity gradients (Smits et al., 2020).
- At a long timescale, the fluxes shown in Figure 6.14 add up. However, at a short timescale, local mud stocks could make up the difference in case of a mud shortage: if mud supply is insufficient, a high sediment demand from the Wadden Sea may still be delivered by depletion of the mud buffer in the seabed North of the Wadden Sea at the time scale of a few years.

Table 6.16 Overview of sediment sinks (net mud sedimentation per year in the Trilateral Wadden Sea.

		Sediment sinks (in 10^6 ton/yr)	
Area	**Period**	**Total sinks (net sedimentation + extraction)**	**Of which extraction**
Dutch Wadden Sea basins	1927-2015	1.5	- (only redistribution)
Ems Estuary	1990-2011	2.1 - 2.6	0.8
Lower Saxony	2000-2010	1.0	
Jade Bay	2000-2010	1.1	
Weser Estuary	1998-2016	1.7	0.2
Elbe Estuary	1999-2016	1.3	0.8
Schleswig Holstein (incl. Meldorf Bight)	2000-2010	1.9	
Danish Wadden Sea basins	Mainly: 1980–2003	0.2	- (only redistribution)
Total Trilateral Wadden Sea		**10.8-11.3**	

6.7 DISCUSSION: UNCERTAINTIES

As this is a first reconnaissance study, we are aware that the many assumptions and different methods which have been applied to establish these mud balances introduce uncertainties (see the chapters on the estuaries). However, our compilation of data does provide first ballpark estimates for the various estuaries and tidal basins in the trilateral Wadden Sea and the adjacent North Sea, which is important for establishing a relation between the impact of human interventions in the estuaries and the overall sediment availability. The main uncertainties involved with the presented mud balance are:

- Transports along the North Sea coasts are not well known, thus leading to uncertainties in the influx of mud. Our best estimate is around 10-14.4 million ton/yr, with the higher value probably being more realistic. A large part of this flux enters the Wadden Sea through the Marsdiep inlet and may partly re-join the North Sea coastal flux by exchange through downdrift inlets.
- Sedimentation over the period 2000-2010 in the German area might be dominated by the reaction to the ending of a stormy period, so that sedimentation rates are relatively high. The measurements of Benninghoff and Winter (2019) show in several tidal inlet basins a saturation curve in the sedimentation rate, suggesting adaptation to new conditions on the tidal flat. Thus, mud deposition could be higher than average.
- Variations in annual mud sedimentation and erosion in the NSCF coastal zone and the more energetic parts of the Wadden Sea might be of importance but could as yet not be quantified. The example of the Blavandshuk accumulation which feeds the Danish Wadden Sea indicates that such influences might be locally important.
- For the Dutch part of the Wadden Sea, several datasets are available that together show the historical evolution of the sediment composition. With this, it is possible to analyse the mud budgets for different periods and to validate the results against observations of deep sediment cores. The results of the German Wadden Sea are however based on one sediment composition map only, which was previously generated out of combined datasets. It is strongly advised to analyse the original datasets in the future, and to see whether an analysis is possible on how the bed composition may have changed locally. This would be a valuable addition and validation to the mud balance.
- No bathymetry data was available in several areas with high mud contents (such as mudflats bordering the salt marshes in Meldorf Bight). These areas are likely to be accreting, and therefore we expect the local mud budgets in these areas to be underestimated in our calculations. However, it is unlikely that this will have large effects on the overall mud balance.
- The results on the mud sedimentation in the German Bight are based on analysis of a (recent) short period (2000-2010), which is too short to pose conclusions on the long-term mud budgets of the Wadden Sea. Our results show that recently, mud sinks were similar in magnitude to the mud sources. However, it is possible that the analysed period coincided with a period with sedimentation rates that are above average. We strongly advise to analyse the mud budgets for longer periods if possible, since this will give a better representation of the long-term mud budgets, as well as of the potential of the Wadden Sea to act as a mud buffer after sedimentation periods.
- The dry density of mud remains an uncertainty, since this will vary largely spatially and over time (e.g., because of consolidation). The dry bed density is important for interrelating volumetric sources of sediment with different densities (e.g. bed level changes, dredging data). We have used a simplified approach in which we assume that in the three estuaries, mud has an average dry mud density of 500 kg/m^3 and in the remaining basins, the density is larger (700 kg/m^3) because sediments are more consolidated.

7 HUMAN INTERVENTIONS

7.1 INTRODUCTION

A reduction in accommodation space for mud sedimentation will in general increase the mud concentration in the water column as sediment has nowhere to permanently settle (van Maren et al., 2016). This is true as long as (1) the large-scale hydrodynamics have not changed (for instance, reclamation of a certain sheltered location has created an equally low-energy location elsewhere) and (2) the marine sediment supply has remained unchanged. Under these assumptions we can estimate the effect of large-scale interventions which have been structural over time on mud concentrations.

7.2 POLDERING AND CLOSURE WORKS

In the past, areas where the net sedimentation exceeded sea-level rise and tidal marshes heightened to a middle or upper marsh elevation were reclaimed ('poldered'). Such strong sedimentation followed by poldering, was normal in the embayments and former river valleys, where low-energy conditions generally prevailed. Huge areas were thus reclaimed, e.g. Middelzee, part of Lauwerszee, Dollard, Leybucht. Jadebusen, Harlebucht. Next to that, measures in foreland tidal marsh also enhanced sedimentation. In this way large areas along, for instance, the Groningen coast could be reclaimed.

Land reclamations carried out in the past 500 years have greatly reduced the intertidal area of the Ems estuary. Since 1650, the size of the Ems Estuary (the subtidal, intertidal and supratidal area) up to Eemshaven decreased by 40% from 435 to 258 km^2 (Herrling and Niemeyer, 2007). The combined intertidal and supratidal area decreased by 45% from 285 to 156 km^2. Dikes were first built on the lower reaches of the Weser River about 1000 AD. Large areas of the floodplain were thus separated from the estuary. The Weser estuary got its present shape in the Middle Ages. Thereafter, fortified embankments and dikes were built (Grabemann, 1999). Over 2000 km^2 of land was reclaimed from the Elbe estuary before 1500. Around 235 km^2 of land was reclaimed between 1500 and 1955, accelerating again to 206 km^2 after 1955 (Schuchardt and Scholle, 2017). As the historic reclamations were probably mainly supratidal, and the more recent reclamations include intertidal areas, the total tidal volume lost after 1955 equals the loss in tidal volume before 1955.

With poldering, large areas where fines could have settled under natural conditions can no longer sequester sediments. This may in turn also lead to an increase in the suspended sediment concentration (van Maren et al., 2016). A reasonable but conservative first-order estimate for the poldered area size is ca 15.000 km^2. A sedimentation rate of1 mm/yr (which is less than the present-day salt marsh areas) would lead to a sedimentation rate of 10.5 10^6 tons/yr.

On top of that, closure works in deeper water courses (Leda, Aa) and embayments (Lauwerszee, Zuiderzee) have been separating these from the open water, leading to reduced possibilities for fines to settle. Thus, with the closure of large basins such as the Zuiderzee and the Lauwerszee and the gradual diking of the tidal marshes it may be expected that less sedimentation space was available (see also van der Spek and van der Valk, 1994; Flemming and Nyandwi, 1994 and Mai and Bartholomä, 2000) and concentrations in the Wadden Sea will have increased (van Maren et al. 2016).

7.3 DEEPENING AND PORT CONSTRUCTION

7.3.1 Historic developments

The Ems estuary provides access to three ports (Eemshaven, Delfzijl and Emden) and a large shipyard (Papenburg). The present-day approximate maintenance depths (all depths below local ordnance levels; NAP in Dutch ports and Normal Null in Germany) of the approach channels to the ports are 15 m (Eemshaven), 10 m (Delfzijl) and 11 m (Emden), requiring regular maintenance dredging. The lower Ems River was deepened from a water depth of ~4 m below HW to ~8 m below HW between the 1930's and 1994 (van Maren et al., 2015b).

The first regulation of the Weser river course occurred in the period 1887-1895 in order to reach a minimum depth for sea-going vessels with a draft of less than 5 m. As a result, the tidal wave could penetrate almost unimpeded till Bremen. In the 20th century additional changes and improvements were made to adapt to increasing ship sizes and to counter the response of the estuarine system. Training works and walls, jetties and groynes were built, to stabilize the course and protect the embankments and shorelines (Hovers, 1973). Due to the penetration of the tide, LW levels were falling resulting in lower ground water tables upstream of Bremen. In the period 1906-1911 a weir was built in Hemelingen to stop this development. In the 1970s, the storm surge barriers were built at the mouth of the tributaries Hunte, Lesum und Ochtum. Between 1973 and 1978 the Lower Weser was deepened to -9 m chart datum. In the period 1998-1999 the Outer Weser was deepened to -14 m chart datum.

In the early 19th century, the Elbe estuary was still relative natural. At that time, the Elbe estuary near Hamburg was relatively shallow with a water depth of about 4 m. A lot of small islands formed a delta close to Hamburg. Since then, the Elbe has been deepened 7 times and is now passable up to Hamburg for ships with a depth of 13.5 m, transforming the estuary from a shallow multi-channel system to a single, deep channel system. Major deepening projects were executed in 1965 (from 11 to 12 m) and 1975 (13.5 m)

7.3.2 Impact on tidal propagation

Deepening and loss of intertidal area (land reclamations) influence the tidal propagation. Alluvial estuaries in equilibrium are funnel-shaped: their size decreases exponentially in the landward direction. This funnel shape leads to an increase in the tidal range due to convergence of tidal energy – therefore many estuaries are characterized by an initially increasing tidal range in landward direction. The tidal range decreases by friction from the seabed, and water storage in intertidal areas. Friction though decreases with increasing water depth, and therefore channel deepening leads to an increase in the tidal range and an increase in propagation velocity of the tidal wave. Loss of intertidal areas reduces water storage, and therefore land reclamations may lead to tidal amplification. In most estuaries channels are deepened and intertidal areas reclaimed, resulting in an increase of the tidal range in many estuaries in the past 50 to 100 years. The change in tidal dynamics is often well documented in heavily influenced estuaries, including the Elbe, Ems and Weser. Tidal changes in these systems will be summarized in the following sections.

Until 1950, the tidal range in the Ems estuary and Ems river increased from 2.2 m at the mouth to 2.9 m at Emden, after which the tidal range decreased in the landward direction. The tidal range in the outer Ems estuary (up to Emden) has not changed much since then, with the largest change being the increase from 2.7 m to 3 m at Delfzijl in the period 1950-1980. Deepening of the lower Ems River, however, has led to strong tidal amplification, possibly strengthened by the presence of the weir at Herbrum constructed in 1899 (Schuttelaars et al., 2013) and a positive feedback mechanism associated with the import of fine-grained sediment (Winterwerp et al., 2013). The tidal range at Papenburg (km 0) has increased from 1.6 m in 1950 to 3.6 m in 2010, with a major lowering of the tidal low water level (Krebs and Weilbeer, 2008). Until 1990, the tidal range peaked at Emden (42 km seaward of Papenburg), because the tide was damped further in the up-estuary direction. Since then, the tide is amplified upstream of Emden, and within 20 years the tidal range at Papenburg has become 50% larger than the tidal range at Emden.

Before deepening, the tidal range of the Weser estuary decreased in the landward direction, from about 3 m on the seaward entrance with a tidal limit near Bremen. The tidal range in Bremen increased from approx. 0.2 m since the first deepening to a present level of 4.1 m due to the deepening of the Lower and Outer Weser (Schuchard and Scholle, 2019). Nowadays, the mean tidal range increases from 2.9 m at the lighthouse Alte Weser (approx. km 115) to 3.8 m at Bremerhaven (approx. km 66) and to 4.1 m at Bremen-Oslebshausen (approx. km 8).

Also, the tidal range in the Elbe estuary used to decrease in the landward direction, from nearly 3 m at the mouth of the Elbe estuary (Cuxhaven) to 1 m (Zollenspieker, upstream of the port of Hamburg) in 1911. The tidal range at the mouth remained fairly constant in time, increasing approximately 30 cm between 1911 and 2005 (Winterwerp et al., 2013). In-between the mouth and the port of Hamburg (stations Kollmar and Schulau) the tidal range increased with 30 and 60 cm (respectively) between 1965 and 1978 following the deepenings of 1965 and 1975. The tidal range at Hamburg increased with 1 m, and since 1971 the highest tidal range is observed at the Port of Hamburg (nowadays 3.7 m). The tidal range of the Inner Elbe (Zollenspieker) has been steadily increasing, exceeding 2.5 m in 1995 (Niemeyer, 1998). The increasing range in the Inner Elbe does not display a clear correlation in time with human interventions (in contrast to interventions in the outer estuary, where deepening directly resulted in an increase in tidal range).

What these three systems have in common is that their tidal range decreased in the landward direction before deepening due to friction and energy loss of the tidal wave, but switched to a landward increase as a result of channel deepening. It is also noteworthy that changes in the tidal range of the outer estuary show abrupt changes related to deepening, whereas the tides in the inner estuaries respond much more gradually.

7.3.3 Impact on estuarine circulation

A second modification of the hydrodynamics is related to a salinity-driven circulation. In Section 4.1.4 we explained that salinity-driven circulation (or gravitational circulation) increases non-linearly with the water depth: In water depths of several meters (pristine conditions in many natural estuaries) such a salinity-driven circulation is not important. At water depths exceeding 10 m, a pronounced salinity-driven circulation often develops in the transition zone of salt and fresh water. At water depths exceeding 20 m, it often becomes a dominant mechanism for sediment transport.

The change in salinity-driven circulation resulting from a modified water depth can only be established through model-based hindcasts. Only for the Ems estuary such a hindcast has been done (van Maren et al., 2015a), and only for a fairly small change in water depth. In both the Elbe, Ems, and Weser salinity-driven flows are currently important for sediment transport (see also next section). It can therefore be assumed that deepening resulted in (enhanced) salinity-driven circulations that became important due to channel deepening.

7.3.4 Impact on sediment dynamics

The sediment concentration increases from several 10’s of mg/l in the outer estuary to 10’s of g/l in the lower Ems River. The outer Ems estuary has become more turbid in the past decades (de Jonge et al., 2014). Estimates for this increase are typically up to a factor 2 higher (at least in the Dollard; van Maren et al, 2015a) but possibly also in wider sections of the outer estuary (de Jonge et al., 2014). This increase was probably the result of a loss of sediment sinks (van Maren et al., 2015a, 2016) and interaction with the lower Ems River (de Jonge et al., 2013). Deepening of the fairways and maintenance dredging probably contributed less to the increase in turbidity. The high concentration in the outer estuary are the result of tidal pumping but also of salinity-driven gravitational circulation (van Maren et al., 2015a). The sediment concentration in the lower Ems River has increased much more, presently being several orders of magnitude larger than in the 1950’s (de Jonge et al., 2014). This increase most likely results from deepening of the river channel, resulting in a feedback mechanism with deepening leading to deformation of the tides in turn leading to more sediment import, which further deforms tides and therefore strengthens sediment import (Winterwerp et al., 2013) – see also Figure 7.1. Deformation of the tides is in the form of amplification and change in asymmetry (towards a more flood dominant tide), with van Maren et al. (2015b) stressing the importance of the increase in amplification and Dijkstra (2019) the role of changing tidal asymmetry.

The Elbe estuary has two ETM’s (estuarine turbidity maxima): one at the tip of the salt wedge (50 km land inward) and one further landward in the tidal freshwater zone of the Elbe (Kappenberg et al., 1995, Burchard et al., 2004; Stanev et al., 2019). The outer ETM is the result of salinity-induced residual flows, the inner ETM from tidal pumping. Over interannual timescales, the position of the ETM in the Elbe estuary depends on the fresh water discharge (Kappenberg and Grabemann, 2001). The outer estuary of the Elbe is dominantly depositional while the inner estuary is erosional, resulting from tidal pumping (Li et al., 2014). Deposition primarily takes place on the tidal flats, whereas erosion dominates in tidal channels. The sediment concentration in the Elbe has increased in the period 1999-2002 relative to 1996-

1998 around the port of Hamburg (20%) but even more in the freshwater part landward of the port (120%) (Kerner, 2007). There are no specific studies relating the change in sediment concentration to detailed interventions as established for the Ems estuary. Winterwerp et al. (2013) argue that changes in SSC around the port of Hamburg are quite limited because of the dredging strategies around the port of Hamburg (a large amount of sediment is dredged and disposed on land or at sea).

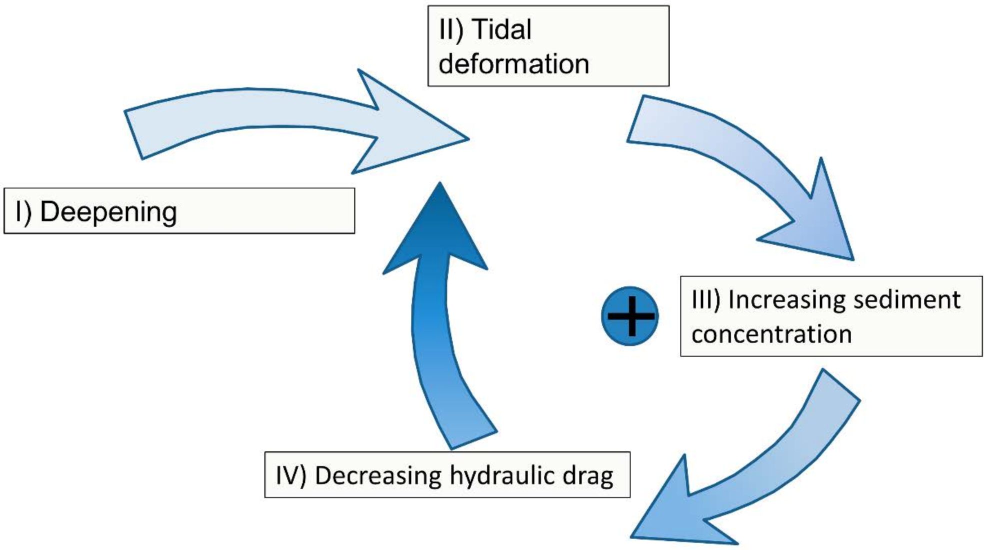

Figure 7.1 Graphical presentation of the conceptual model of Winterwerp et al. (2013) relating tidal deformation to channel deepening. The initial increase in tidal range as a result of deepening leads to more sediment import, hence higher sediment concentrations and a reduction in the apparent hydraulic drag, which in turn further strengthens tidal deformation.

The formation of the ETM in the Weser estuary is also the combined result of estuarine circulation and asymmetries in mixing. Mainly fine sediments deposit in the main channel, often as a fluid mud, at a location which varies seasonally (Hesse et al., 2019). There is no information on historic changes in the sediment concentration in the Weser estuary, or on the impact of human interventions on SSC. However, as for the Elbe estuary, the location of the ETM varies over years resulting from variability in fresh water discharge (Kappenberg and Grabemann, 2001).

For all three estuaries, the location with high turbidity (the ETM) is formed by landward transport by tidal pumping and by salinity-driven circulation, balanced by seaward transport governed by freshwater flow. Especially the ETM of the Elbe and Weser is susceptible to the river discharge. In the Elbe two ETM’s exist, one formed by salinity-driven flows and one by tidal pumping. For all three estuaries the sediment concentrations have increased during a period in which intertidal areas were reclaimed and channels were deepened. The increase may have been partly mitigated by sediment extraction as a maintenance dredging strategy. However, only for the Ems estuary historic hindcasts have been carried out revealing how human interventions lead to higher suspended sediment concentrations. More research is needed to relate mechanisms responsible for the increase in sediment concentrations in the Elbe and Weser to the various human interventions.

7.3.5 Maintenance dredging

Disposal of sediments primarily leads to a redistribution of sediment, rather than an increase in suspended sediment concentrations (van Maren et al., 2015a), because the estuarine sediment concentrations effectively decrease when sediment settles in the ports or fairways. Subsequent disposal restores the sediment concentration to a level comparable with a situation without settling in ports and fairways, at least on large time and spatial scales. Close to disposal sites, the sediment concentrations increase. On top of this (as a secondary effect) maintenance dredging can be considered as an episodic stirring mechanism, leading to temporally higher suspended sediment concentrations compared to a situation without dredging (i.e. comparable to a storm event). Averaged over time, this effect constitutes an increase in the suspended sediment concentration.

High sediment concentrations negatively impact biota through loss of visibility (especially pelagic primary production) or burial / smothering (especially impacting benthic organisms but also vegetation). Dredging therefore negatively impacts ecology close to disposal sites, where a mud layer is deposited on the bed and the turbidity temporally increased. Its impact over larger spatial scales remains unknown. There are indications, for instance, that the sediment concentrations around the port of Hamburg (Elbe) are relatively low because of the dredging works carried out by the port of Hamburg (Winterwerp et al., 2013). For the Ems estuary the large-scale effect of dredging and disposal on turbidity are probably limited (van Maren et al., 2015a) – the observed gradual increase in turbidity (negatively impacting primary production) is probably not directly related to other factors.

7.4 LANDFILLS AND SEDIMENT EXTRACTION

Landfills imply a retrieval of sediment from the estuary and should be considered an artificial sink in which sediment is permanently extracted from the Wadden Sea system. If volumes which are thus stored are significant, the influence on the suspended mud concentrations may be noticeable.

Starting in the late 19th century landfills with mud have taken a flight in the 20th century as harbours were extended and fairways were deepened. Firstly, sediment had to be dredged to deepen the areas. Secondly, maintenance dredging was needed to keep the depths. This is especially true for the three big estuaries of the Ems, Weser and Elbe, each showing their own developments. An estimated 370×10^6 m^3 of mud has been stored on land along the Ems in the past 100 years (2 million m^3/yr between 1924 and 1960 and since 1993 and 3.6 million m^3/yr between 1960 and 1993; see van Maren et al., (2016) and references therein). This is comparable in magnitude to the total net sedimentation (of sand and mud) in the western part of the Dutch Wadden Sea area in the same period. For the Weser and Elbe these figures are not well known.

Figure 7.2 The Niederung Eden Riepe is being filled via a 13 km long pipe transporting the dredging sludge over the Ems-Jade channel (period 1946-1989). (Source: Creative Commons Attribution 4.0 International License Photo HB01395.jpg)

Sediment dredged from the Ems and Elbe (and probably for the Weser as well) were partially used in landfills to heighten areas. Sediment storage began as early as the beginning of the 20th century. Already in the 1930's substantial amounts of mud were stored in landfills along the Ems. Quantities of sediment extracted before 1960 are not exactly known. Between 1960 and 1994, 5.1×10^6 m^3/yr was dredged from the port of Emden and fairway and brought on land (see Figure 7.2 for an illustration of transport). On many sites east of the Ems landfills were developed to heighten the land and improving the agricultural quality of the soil. Furthermore, sediment was used to heighten tidal marshlands which were formed behind dams, such as the Rysumer Nacken over the period 1949-1995. Nowadays dredging in combination with landfill has largely ceased in the Elbe and Weser estuary, with exception of contaminated sediments (Arbeitsgemeinschaft für die Reinhaltung der Elbe 1996; BIOCONSULT and NLWKN 2012: BIOCONSULT, Schuchardt and Scholle GbR 2018). Since its last major deepening in 1994, the lower Ems River requires regular dredging. Around 1.5×10^6 m^3/yr (0.8×10^6 ton/y) of fine sediment are extracted annually from the lower Ems River and brought on land. These are clean sediments used for landfills.

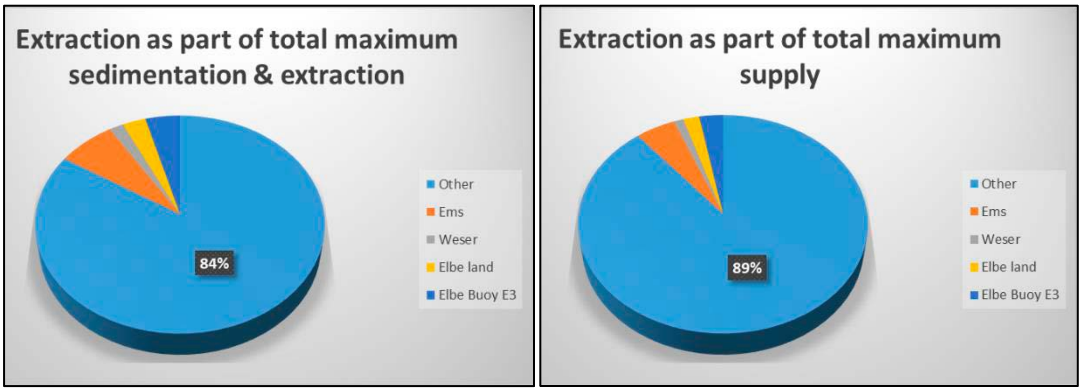

Figure 7.3 Comparison of volumes of retrieved mud as part of total sedimentation (left) and total maximum influx of suspended matter (right; excluding supply by the East Anglia Plume, since this is most likely largely insignificant)

Figure 7.3 shows the current significance of the retrieval of mud from the system (between 11 and 16% of the total, depending on the definition). Extracting mud lowers the suspended sediment concentration of the adjacent estuary (Figure 7.4) – this was numerically investigated for the Ems estuary by van Maren et al. (2016). Extraction may also have a downdrift impact (depending on the scale of extraction), potentially influencing a larger part of the Wadden Sea East of the extraction, as less mud is available for natural sedimentation in the downdrift area of the sediment extraction. Any impact of large-scale extraction may remain unnoticed for a prolonged period because the sediment stock within the Wadden Sea is large. At the moment, it is unclear whether such extraction influences the sedimentary and ecological development of the Wadden Sea area more to the east of the estuary, and what associated response timescales are.

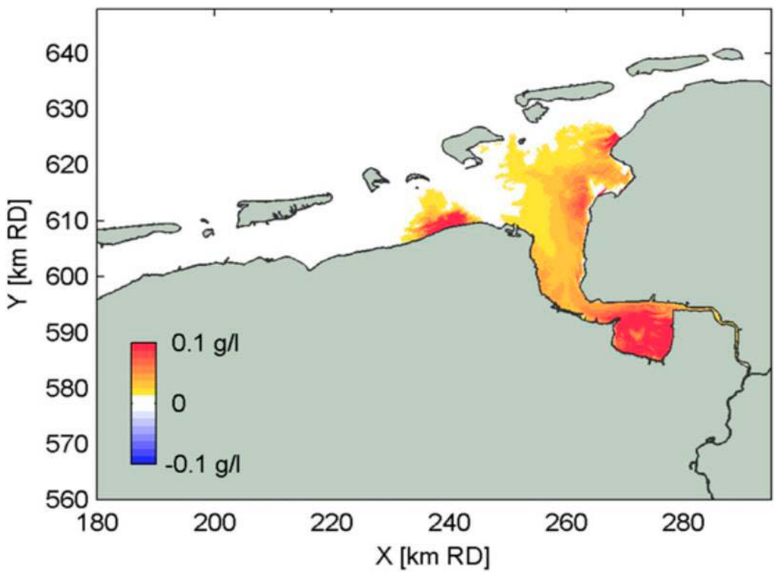

Figure 7.4 Effect of sediment extraction (from all ports and fairways) on SSC in the Ems Estuary. From van Maren et al. (2016).

The results of this research indicate that the annual supply of mud (which does not all settle in the Wadden Sea) is only 1.1 to 1.7 times larger than the annual deposition including extraction. This would imply that with an increase in extraction or mud deposition rates, mud availability may become limiting on the scale of the trilateral Wadden Sea in the longer run. Over a shorter period, the influence would probably be limited because the gross influx is at least 1-2 orders of magnitude larger than the net annual fluxes. Unknown is however, what the cumulative effects of multiple extraction sites will be, especially in combination with the anticipated increase in mud deposition rates resulting from SLR. For instance, it might be possible that the extent of the mud areas would gradually diminish as the mud is transported to those places where it can still be deposited. Potential shortages in mud would become manifest in the more (north) eastern parts of the trilateral Wadden Sea, not the western Wadden Sea. Mud may therefore become a scarce commodity which should become an integral part of sustainable long-term sediment management. Measures aiming at using / extracting mud should account for its impact on the large-scale sediment budget on the level of the trilateral Wadden Sea. Continuous, long term observations of suspended sediments and bed sediments are essential to quantify local and large-scale impacts of sediment management.

7.5 MANAGED REALIGNMENT AND DEPOLDERING

An important estuarine and tidal habitat restoration measure is to connect embanked coastal areas with the coastal system, thereby creating new sedimentation space via managed realignment (Legget et al., 2004; ComCoast, 2006; Linham and Nichols, 2010). Over many centuries, continuing far into the 20th century, poldering has resulted in the loss of extensive areas of salt marshes. Often, poldering proceeded in a two-step fashion by first building summer dikes resulting in summer polders which were occasionally flooded, after which they were diked more definitely to form polders. Especially along the mainland, poldering rates exceeded the development of new salt marsh, despite the artificial enhancement. Consequently, the size of the current mainland salt marshes is much smaller than the historic reference (Dijkema, 1987), and salt marsh restoration was called for, especially now nature conservation and coastal defence issues have become increasingly important (Esselink, 2000).

Since 1973 over 30 realignment projects have been implemented in the Wadden Sea Area and the estuaries: a surface area of more than 1800 ha (Figure 7.5). However, a large part of these projects consists of summer polders previously reclaimed from artificial salt marshes, former beach plains and dune slacks. In some projects the whole dike was removed whereas the dike was only partly opened in others, occasionally using (storm-surge) sluices, culverts or dams were installed. Sites with regulated tidal access (Polder Breebaart and Lütetsburger Sommerpolder) have a limited tidal range and high sedimentation rates in the sublittoral / lower intertidal zone. The Polder Breebaart must be regularly dredged to maintain natural values. As a result of these restrained tidal dynamics, the ecological value of these depoldered sites is less than for sites with unrestricted tidal inundation. Also the size of the realised project remains limited: in total 18 km^2 has so far been depoldered throughout the Wadden Sea (Figure 7.5). And although 1800 ha constitutes a substantial effort, the resulting sedimentation volumes are limited. If we assume an average sedimentation rate of 10 mm/yr (which is quite high, requiring maintenance dredging of the various sites to maintain sedimentation), the sedimentation volume is only 0.18×10^6 m^3/yr. Compared to the net influx and sedimentation in the Wadden Sea, the effects of such a sediment volume is negligible. More substantial sediment sinks can be realised by gradually letting the larger part of east Groningen accrete by alternatingly allow large areas to be inundated (Figure 7.6). Such large-scale measures form an important sink for mud which would result in pronounced local effects on suspended sediment concentrations, but also substantially influence the large-scale mud balance.

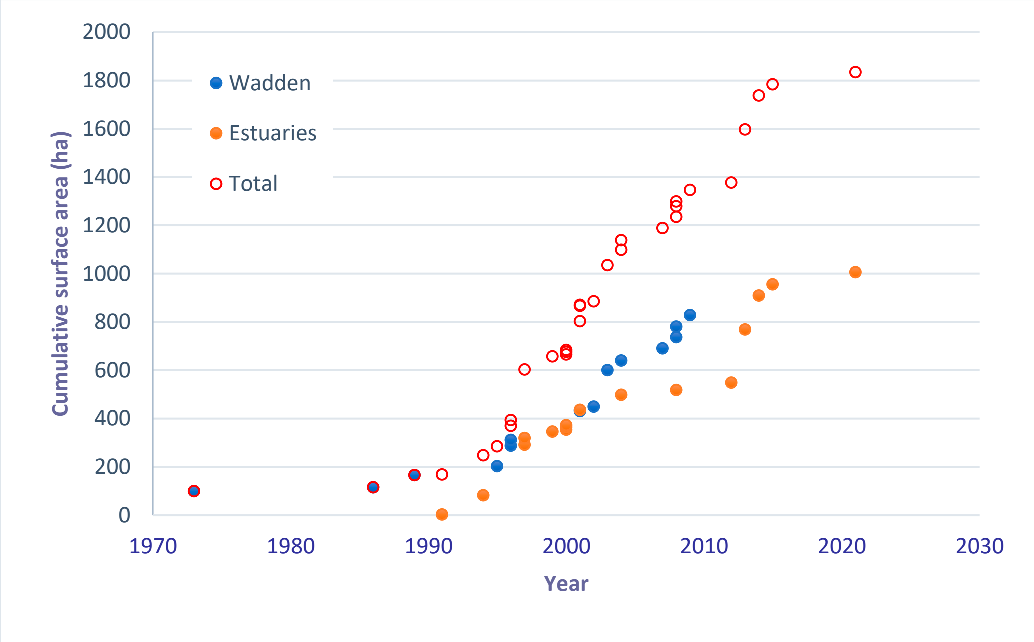

Figure 7.5 Realignment projects and cumulative area in the estuaries (Ems + Weser + Elbe) and the Wadden Sea outside the estuaries (data mainly Esselink et al., 2017, APA, 2013 and several other sources).

Sites which have become reconnected to the tides of the Wadden Sea will have developed an elevation deficit in respect to sea-level rise during their polder period. A relative low elevation may provoke a higher sedimentation in the first period after de-embankment (Wolters et al., 2005), but in the longer term sedimentation will be comparable to values in nearby reference sites. Mostly the areas are still quite sheltered, due to the land-near location and the (partial) presence of dikes. Where storm surge barriers are present, the natural erosion is largely halted. Often sedimentation rates in these areas are slightly higher or comparable to averages found in the near tidal marshes (Spadenländer Spitze: 8.8 mm/yr; Holwerder summerpolder: 10 mm/yr). However, sometimes sedimentation rates are very high, especially in estuaries, e.g. the Kleinsieler Plate in the Weser: 500 mm/yr. To lower sedimentation rates, an adaptation of the sill in the entrance was made. Occasionally, sedimentation rates may be very low such as in the Bildtpollen (1.2 mm/yr). This was explained by the high surface level of the de-embanked site (Bakker et al., 2014). The reasons for differences in sedimentation rates are the following (Rupp and Nicholls, 2002; APA, 2003):

- Inner-dike or outer-dike realignment. Outer-dike realignment allows full tidal action and relatively natural sediment transports, whereas inner-dike realignment implies connection via a sill or smaller entrance leading to a smaller tidal range with less sediment transport.
- Suspended Particulate Matter concentrations. In general, sedimentation rates are higher at sites with a high SPM concentration. Basically, most realigned areas form a basin where most mud entering the area deposits in the high-water turn of the tides.
- Hydrodynamics of the area. Sedimentation and erosion are strongly determined by the exposure of the area. Wave-exposed sites (resulting from a large nearby tidal channel, or proximity to the North Sea) will experience lower sedimentation rates (or even erosion, depending on sediment supply). In some areas ship-generated waves lead to erosion. Such effects can be dampened by the design of the realignment

measure, for instance by using brushwood groins which allow tide-induced siltation while preventing wave-induced erosion.

- Elevation and inundation of the site. Differences in elevation will influence the spatial patterns of accretion and salt marsh vegetation development. There is an inverse relation between elevation and vertical accretion. Vegetation may only develop if the area is or has accreted to a few decimetres below mean high water. The vegetation will enhance the sedimentation rates especially during the pioneer and low marsh succession stages.
- Slope of the terrain. It has been observed that a shift from sedimentation to erosion occurs once the slope grade becomes higher than 2.5%.
- The number of breaches. If one breach is present, the area functions as a basin in which most of the sediment which enters will be deposited. If several openings are present water may flow through and sedimentation rates are reduced or even erosion may occur. This was for instance the case in the Wrauster Bogen in the Elbe, where one site of a creek was closed to stop erosion and enhance habitat development (Rupp and Nichols, 2002; Wolters et al., 2007; Linham and Nichols, 2010; APA, 2013)

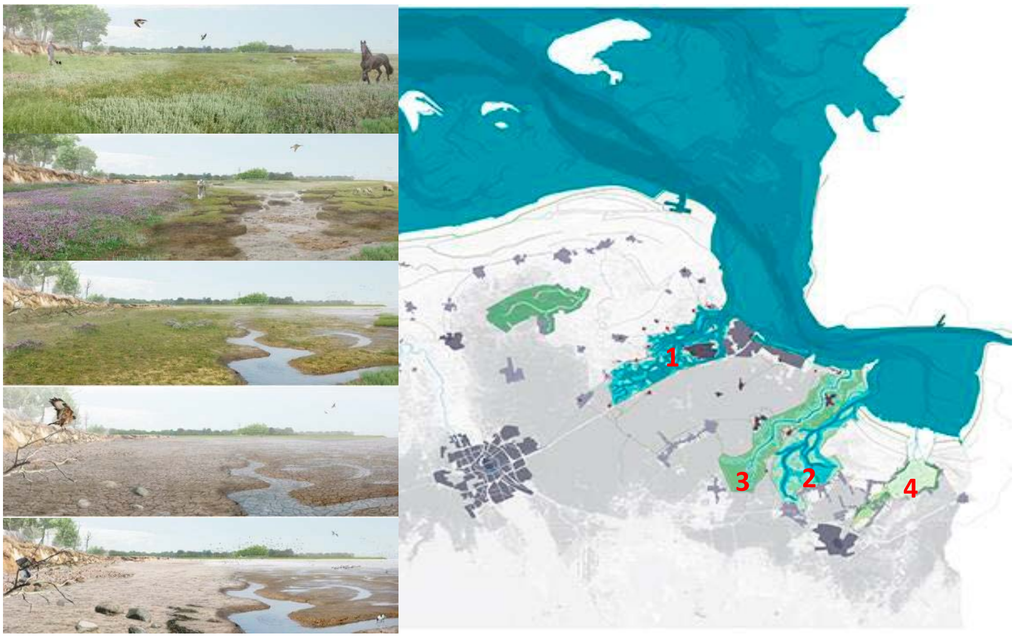

Figure 7.6 Artist impression of alternative ways to heighten the low-lying land of East Groningen by sequential flooding of large areas. ("Rijzend Land" of Bureau Lamaland, see http://www.lamaland.eu/projects/rijzend-land/)

7.6 Foreland marsh development

A belt of fertile marshland, from Denmark to the Netherlands stretches along the mainland shores of the Wadden Sea. Based on the most recent data, some 20.000 ha of foreland salt marshes is present (Arens and Götting, 2008; Bakker, 2014; Esselink et al., 2017). During the past 2 to 3 decades this area has extended. Along the Wadden Sea, man-made tidal marsh formation started several centuries BC, when small mud ridges were built on the lower tidal marshes, apparently to enhance sedimentation (Figure 7.7). From at least the late medieval times onwards, salt marsh works were common, as shown by maps and descriptions from halfway the 16th century. Enhancing marsh development was mainly done by means of systems of ditches and earthen dams (so-called "farmer's method"). Since the 20th century upkeep of drainage and brushwood groins were combined (so-called "Schleswig-Holstein method") to establish foreland salt marshes.

The brushwood screens and the drainage system form an extra sink for mud, as wave action and currents are reduced (Suchrow et al., 2012). As a consequence, a substantial amount of mud is annually deposited (see section 6.2).

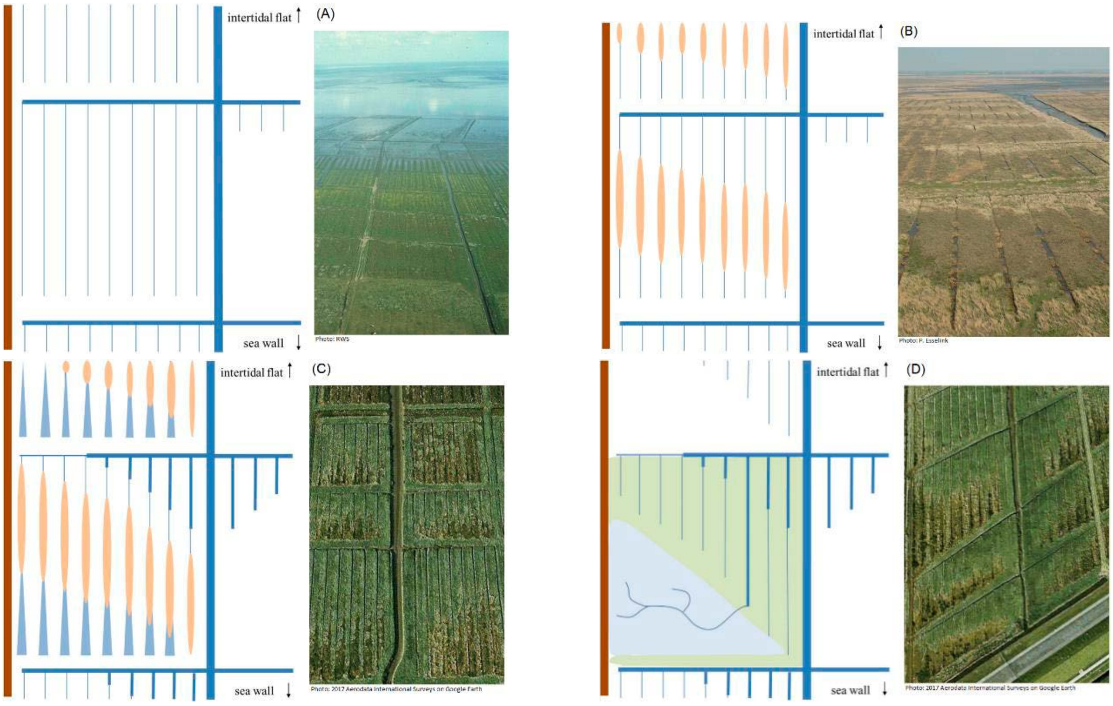

Figure 7.7 Schematic overview of changes in the artificial drainage system after the traditional maintenance was discontinued (examples from sites in the Netherlands and Germany). (A) Starting situation. (B) Central parts of the ditches or field drains have silted up. (C) Upstream drainage is blocked, downstream drains deepen and de-crease in width. (D) The resulting soil-waterlogging causes local replacement of vegetation by secondary pioneer vegetation and low-marsh vegetation. (Esselink et al., 2016; modified from van Weesenbeeck et al., 2014).

8 SEA-LEVEL RISE

One of the research questions was: *"What has been the impact of long-term sea-level rise on the supply and deposition of mud and how will climate change and (accelerated) sea-level rise alter these processes to your opinion?"* Here we shortly discuss this question by comparing the past, present and future situations.

8.1 PAST MUD SEDIMENTATION

A large part of the response to long-term sea-level rise in the Holocene has already been discussed in Chapter 2. Here, we will focus on the changes in sedimentation rates through time in the Wadden Sea. Before humans started to influence the development of the mainland coastal zone, a large part of the Wadden Sea area was a vegetated tidal landscape intermittently flooded during high tides or storms. Tidal marshes and tidal mudflats were up to several tens of kilometres wide (Figure 8.1). Until dikes were constructed on a large scale during the Middle Ages, these tidal marshes formed about the half of the Wadden Sea (Reise, 2005).

Mud brought in during high water conditions probably largely deposited on the extensive tidal areas, providing an extensive sink for fine sediments. Flemming and Nyandwi (1988) argue that the original natural mud gradient stretched over a larger distance than at present (Figure 8.2), resulting in an overall coarsening of the bed of the Wadden Sea.

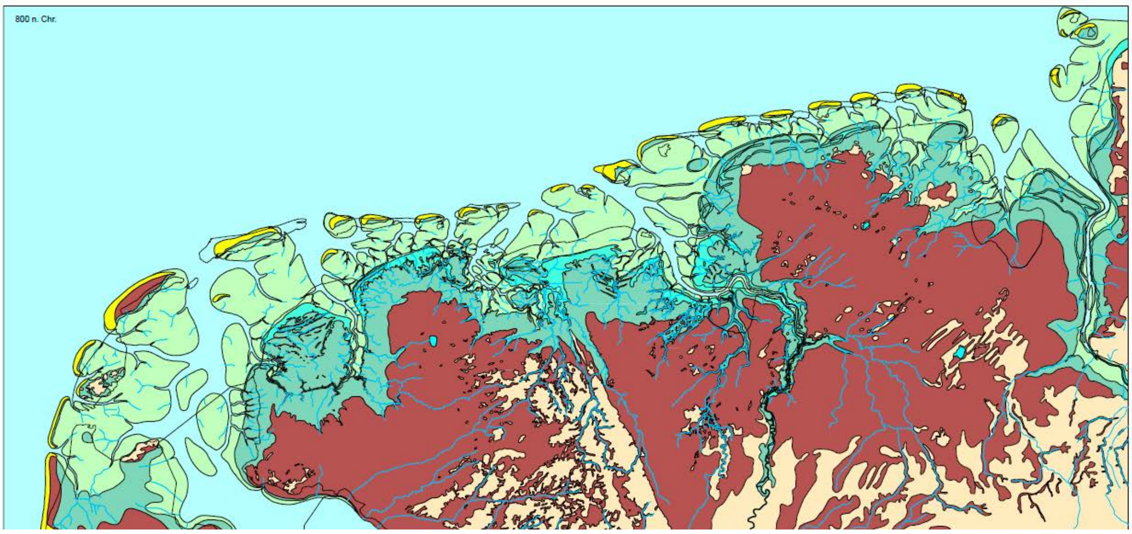

Figure 8.1 Reconstruction of the East and West Frisian Wadden Sea landscape around AD 800. Orange = Higher Pleistocene grounds; brown = peat; dark green = salt marsh; light green = intertidal sand and mudflats; blue green = high salt marsh (levees and ridges); yellow = dunes and beach ridges (Vos and Knol, 2015).

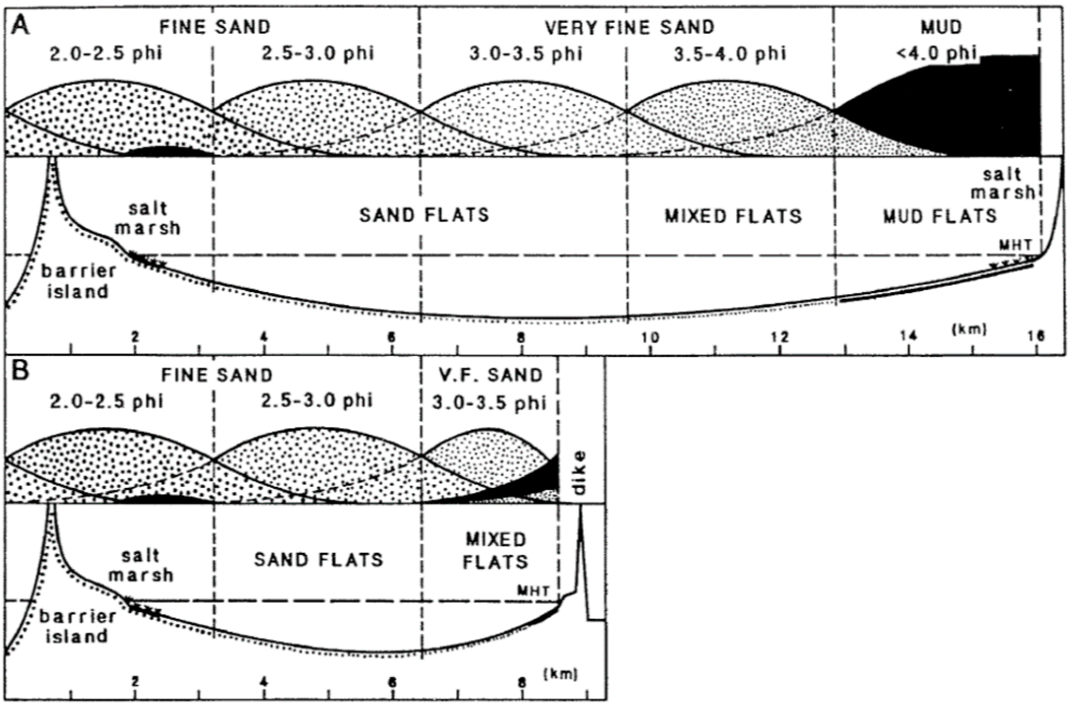

Figure 8.2 A: Hypothetical shoreward-fining grain size model for a natural back-barrier depositional system. B: Actual shoreward-fining grain size sequence observed in the back-barrier region of Spiekeroog Island. (From Flemming and Nyandwi, 1994).

Formation and infill of valleys: mud fills

When valleys or peat areas were flooded, the peat was eroded or compacted, and strong sedimentation of mud occurred (Figure 8.3). After the initial incursion of the sea, the area silted up and became land once again. The rapid infill of embayments such as the Dollard, the Middelzee and the Harlebay point to a very large availability of mud. For the Holocene deposits in the Dutch Wadden Sea it has been calculated that in total some 18,178×10^6 m^3 of mud was deposited (van der Spek and Beets, 1994). If it is assumed that the major part has been deposited during the past 5000 years, corresponding to an average deposition volume of some 2.5 ×10^6 m^3/yr for the Dutch Wadden Sea area up to Groningen. This is about twice as high as present-day values. The explanation is most likely two-fold:

1) The Wadden Sea area was much larger with incised valleys and embayments which provided large areas with very quiet conditions for muds to be deposited.
2) The supply of mud might have been higher. Forests were cleared by humans, leading to stronger erosion and the sea bottom was still reacting on the rapid flooding after the last Ice Age, locally eroding the bottom. Also, coastal retreat has occurred over the past 5000 years in the West and East Frisian Wadden area and over the past 1000 years along the Holland coast and parts of the North Frisian Wadden area.

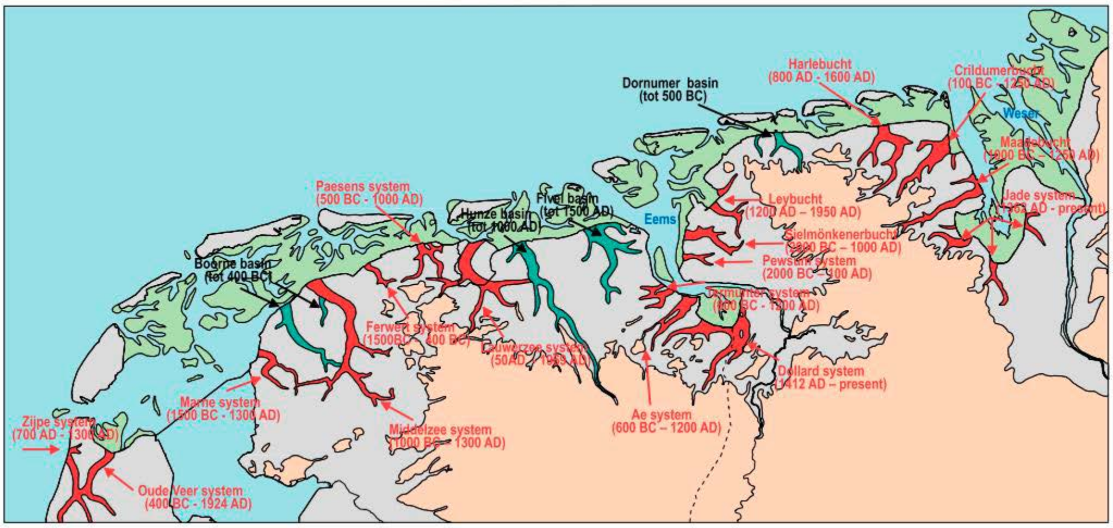

Figure 8.3 Locations of active tidal systems during the past 2400 years. Green: tidal channels of older tidal basins which were still active; red channels new ingressions (Vos and Knol, 2005).

8.2 PRESENT-DAY MUD SEDIMENTATION: EFFECT OF TIDAL AMPLITUDE AND STORMS

For present-day conditions, the natural landward net sediment flux allows for the tidal flats to keep pace with sea-level rise. Even more, Benninghoff and Winter (2019) concluded that most of the German Wadden Sea basins were accreting over the period 1998 – 2016 with rates higher than the observed mean sea-level rise in the German Bight, while simultaneously the subtidal mean depth increases. For the period of investigation this Wadden Sea steepening is quantified to averaged values of +7.9 mm/yr for the tidal flats and −20.0 mm/yr for the channels.

Sedimentation rates increase with increasing tidal amplitude (Figure 8.4). For the mesotidal flat areas behind barriers the linear fit of the positive correlation between the mean tidal range and sedimentation rates has an R^2 of 0.79 (Figure 8.4). This suggests that tidal amplitude may influence the rate of sedimentation on a tidal flat (as also suggested by Benninghoff and Winter, 2019). However, for the estuaries and Jade Bay observations are less clear. With increasing tidal amplitude, the velocity of the water increases and brings larger amounts of sediments in suspension which are transported from the channels towards the shoals. Above the shoals the mean settling distance with respect to MHW is rather constant (Hofstede, 2015), resulting in faster sedimentation rates with increasing tidal range.

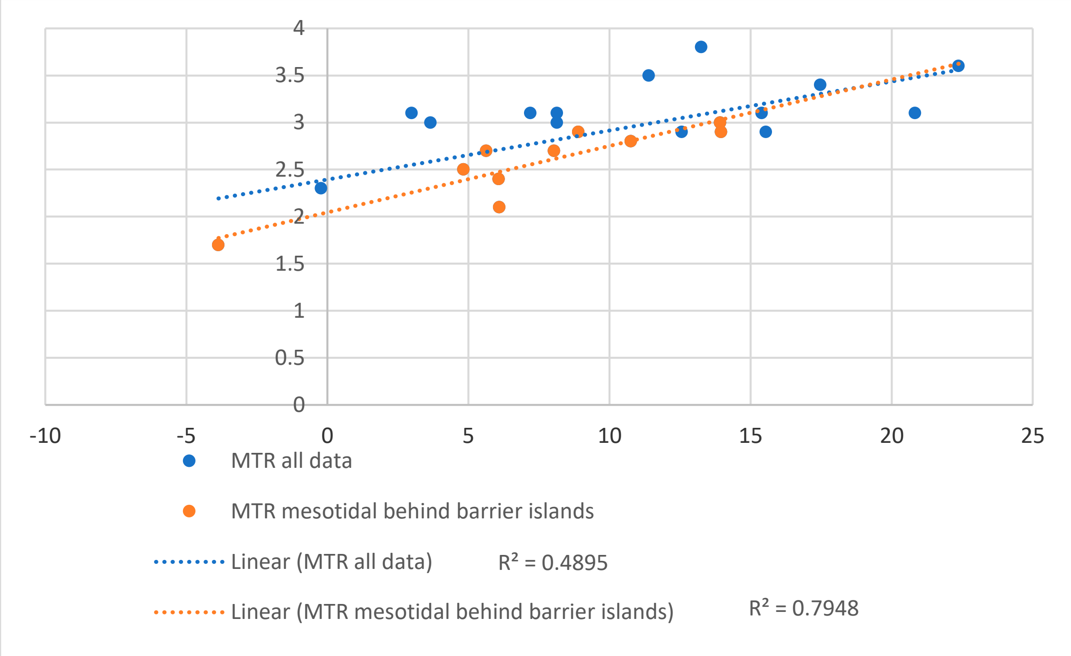

Figure 8.4 Comparison of mean intertidal bed elevation change in mm/yr (X-axis; data Benninghoff and Winter, 2019) and tidal range in m (Y-axis; this study)

It is known that an increase of wave action decreases the sedimentation on mudflats or may even result in erosion (Janssen-Stelder, 2000). The decline of the storm index from 1998 to 2007, a situation which may have continued up to 2012 or later (compare Gerber et al., 2015), may have played an important role creating less energetic conditions and thus providing sedimentation space, which could explain the sedimentation observed over the period 1998-2016. Benninghoff and Winter (2019) doubted this explanation, because an analysis of satellite-derived significant wave heights for the period 1998-2016 indicated a slight increase in winter mean wave heights. However, it's most likely that waves have only played a minor role in the development of tidal flats in this period. Wave energy of North Sea waves is dissipated by the barrier islands, the ebb tidal delta and tidal flats and only locally generated, low-energy waves will be present in the basin.

Storm surge-related set-up, on the other hand, might have decreased considerably up to 2012, thus lowering the shear stress exerted on the tidal flats and leading to less shoal erosion than in the preceding period. Unfortunately, no data of set-up could be analysed within the time available for this study.

That long-term changes may have played a role can be deduced from the annual variations in sedimentation rates per basin during the observation period 1998-2016. Normally an intertidal flat will react on a change in conditions in the course of several years (Pritchard et al., 2002; Friederichs, 2019). The observation that saturation for tidal flat height development is reached near the end of the observational period 1998-2016 in half of the tidal flat systems (and that 7 out of 24 continued to grow near linearly), suggests that the change in the German systems probably occurred just preceding and/or during the observation period. One explanation may be the reduction of storm surge-related set-up.

8.3 FUTURE MUD SEDIMENTATION

Climate change may complicate things further. The potential growth of tidal flats with sea-level rise depends on the availability of sediments as building material. In order to assess the future development of the Wadden Sea it is especially important to obtain realistic estimates for sediment availability and budgets. Two effects are of prime importance, as predictions for wave and storm climate suggest only slight changes with large uncertainties:

Mud availability

Already in the past century precipitation and evaporation patterns have been changing. Overall, run-off of rivers increased. However, during the summer period freshwater run-off is reduced strongly due to the increasing frequency of extremely hot and dry periods. By contrast, during autumn/winter precipitation increased leading to strong run-off into the Wadden Sea system. It remains unknown whether this leads to an increase in suspended matter influx. The increased outflow of fresh water will enhance the estuarine circulation in the estuaries and along the North Sea coast leading to a greater efficiency to trap mud. This might increase the concentrations of mud in these waters and the availability of mud for the system.

Mud demand

Global sea-levels have been rising with some 1.8 mm/yr during the first half of the past century. Since 1960 global sea-level rise is accelerating. Presently, it is some 4.8 mm/yr (Figure 8.5; Dangendorf et al., 2019). In the Wadden Sea sea-level rise is slower, most likely due to regional geological, glacio-isostatic and meteorological effects. It is expected that global sea-level rise will continue for centuries to come and it is foreseeable that also in the Wadden Sea, in the near future sea-level rise may proceed at a quicker pace.

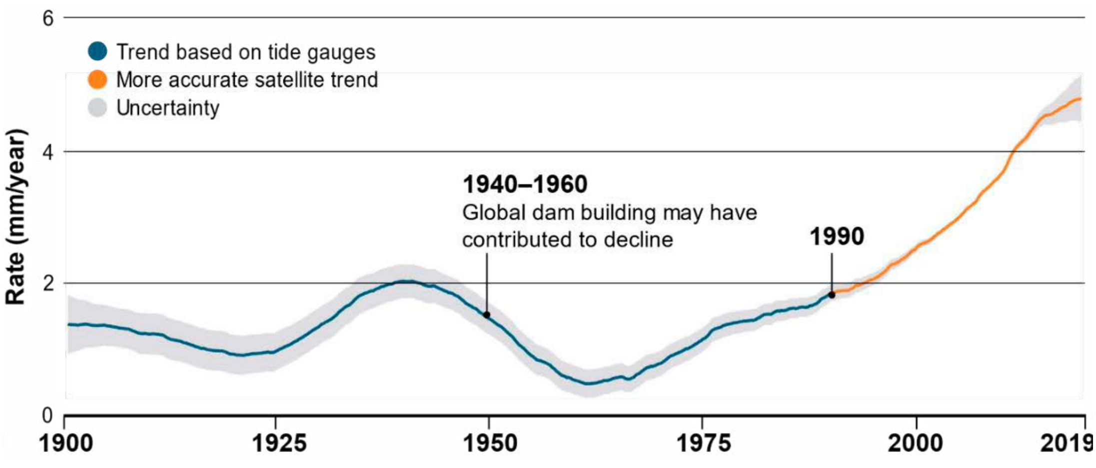

Figure 8.5 Measured rate of sea-level rise (in mm/yr) showing clear acceleration of the global rate since 1960 (after Dangendorf et al., 2019).

The present-day knowledge of the morphological response of tidal basins to sea-level rise is insufficient to confidently estimate the role of the sea-level rise on the mud budget. A number of scenarios may be formulated related to the response of sand and mud deposition rates under accelerated SLR:

Scenario 1: keeping pace with SLR

The present-day Wadden Sea basins keep pace with sea-level rise, including the horizontal distribution of sand and mud. The required annual mud mass is then the product of the areal extent of the Wadden Sea, the present-day mud content, and the rate of SLR. This is graphically displayed for the Dutch and German Wadden Sea in Figure 8.6, allowing assessment at which rate of SLR mud availability becomes limiting. The current mud supply is 10 – 14.4 million ton/yr, of which 2 million ton is annually extracted. The remaining 8 – 12.4 million ton completely contribute to vertical accretion to compensate sea-level rise for SLR rates between 4 and 6 mm/yr. This is in-between IPCC projections of 2.6 mm/yr (RCP 2.6) and 9.1 mm/yr (RCP 8.5) for the Wadden Sea (Vermeersen et al., 2018). The RCP2.6 scenario assumes that GHG emissions decline after 2020 whereas the RCP8.5 scenario represents a continued rise of GHG emissions throughout the 21st century. In reality, a sealevel rise in-between scenario RCP 2.6 and 8.5 is most likely. This then implies that the availability of mud is insufficient to keep pace with SLR, assuming that the the spatial mud distribution remains as it is today. For RCP8.5, already 7.5 million ton/yr of mud deposits is required in the Dutch Wadden Sea in order to keep pace with Sea-level Rise. If by that time extraction rates remain the same, only 0.5 – 4.9 million ton of sediment remains available to annually deposit (with SLR demanding 14 million ton to keep pace with SLR). Under these conditions, mud will become a limiting factor, especially in the eastern Wadden Sea. The system will either drown or become more sandy (depending on the availability of sand, which is not elaborated on here).

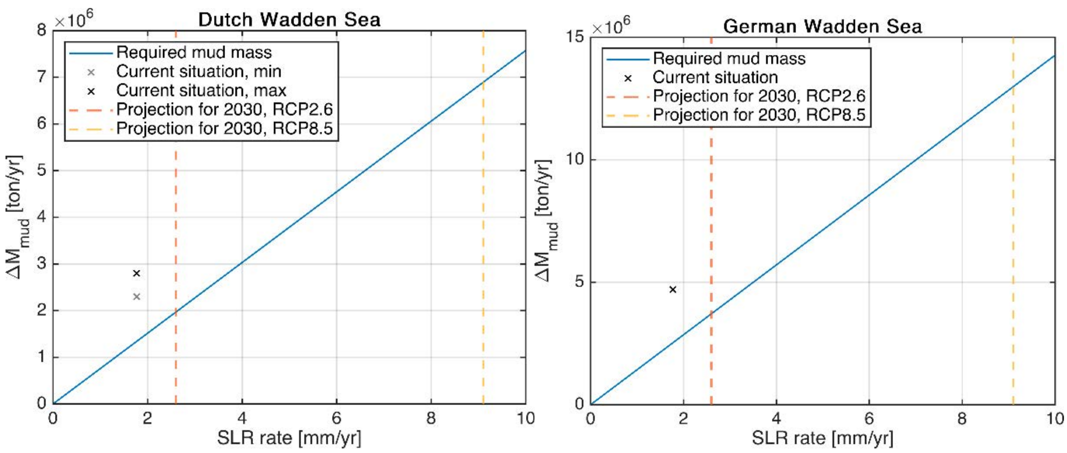

Figure 8.6 Required amount of mud for the Dutch and German Wadden Sea to grow with SLR, assuming unchanged distribution in the sand-mud ratio. See Figure 6.1, Figure 6.2, and Figure 6.3 for area definition (evaluated area excludes salt marshes); density is computed using Mulder (1995). The uncertainty range for mud deposition (min / max) in the Dutch Wadden Sea originates from the range in the net deposition at the Ems-Dollard estuary (see Chapter 6.1.2).

Note that in the long-term, the supply of mud could possibly change, e.g. because of sea-level rise, changes in wind- or wave climate, changes in freshwater discharge, human interventions such as coastline changes and sand mining, temperature increase resulting in different mud composition and settling velocity etc. Still it remains unknown how these processes and conditions would change mud supply. This is the more important, since we see that supply might become limiting in the future.

Scenario 2: partial growing with SLR

Above a critical limit, it is expected that the sandy flats can no longer keep up with sea-level rise and start to drown gradually. The critical threshold value is estimated to be somewhere between 0.5 – 1m/100 yr (Burghard pers. com.; Becherer et al., 2017; Hofstede et al., 2018). This may have two contrasting impacts on mud deposition. On the one hand, when mud supply is sufficient, part of the present-day sandy morphology could become muddy. This scenario is suggested for the Ems Estuary (van Maren et al., 2019). Mud may develop on previously sandy morphology in response to sea-level rise either as (1) a more unstable substrate (where mud is eroded during more energetic conditions as these sandy areas are typically more energetic, but re-deposits under more quiet conditions) or (2) result from higher sediment concentrations, resulting from modified residual transport of fine sediment). This would require even more mud than the previous scenario (which was already limiting). On the other hand, the disappearance of sandy shoals / flats leads to a gradual reduction in wave energy dissipation. The resulting increase in energy leads to lower mud deposition rates in the intertidal and supratidal areas, which would set in motion a scenario leading to complete drowning (scenario 3).

Scenario 3: drowning

As explained above, the disappearance of sand flats may lead to an increase in hydrodynamic energy over the mudflats, probably lowering deposition rates or even a switch to erosion. Both the sandy and muddy parts drown. Drowning of mud-dominated parts may also result from a shortage in mud availability (more likely for the eastern parts of the Wadden Sea).

In the short term, the response will probably be a combination of scenario 1 and 2 (keeping pace with SLR or partial drowning). For both scenarios, this implies an increasing mud demand. Especially the mud demand for scenario 2 is difficult to predict, as this involves a transition of sand-dominated areas to mud-dominated areas. With the current state of our system knowledge, such transitions are difficult to predict. Under current conditions, the mud availability (supplied largely by the NSCF) exceeds mud demand. At a critical rate of SLR, the mud demand will exceed the mud availability. This will introduce a shortage in mud, primarily in the Eastern Wadden Sea. Given the source of mud supply located in the southern North Sea it is unlikely that a shortage in sediment (mud) will develop in the western Wadden Sea.

9 MODELLING PRACTICES: FOCUSING ON MUD

Analytical and numerical models play an important role in understanding, hindcasting and predicting mud behaviour in the Wadden Sea. Models serve as tools to better understand observations through detailed process analysis, or extrapolate these observations in time and space. Modelling tools may also be applied to investigate the impact of past or future interventions, including the morphologic response to SLR. It is also helpful for improving our system understanding and is thus an important research tool. In this chapter we discuss the reliability and accuracy of the models that are developed to simulate mud dynamics, as well as required improvements in terms of process knowledge and implementation, model calibration and validation.

Models for simulating the morphological development of tidal inlet systems such as those in the Wadden Sea can be classified into three types (Wang et al., 2012, 2018): process-based, aggregated and linearized. Here we use the same classification but focusing more on mud transport. We advocate the use of these different model classes as complementary approaches, rather than as competitive. Also, when interpreting the result of any model, it should always be realised that the model is setup for a specific purpose with associated confidence limit (for instance, a model developed for simulating the short-term dispersion of a dredged plume may not be adequate to model the long-term residual sediment flux through the Wadden Sea).

9.1 PROCESS-BASED MODELS

Mud transport models are applied for two types of applications addressing (1) morphological changes or (2) the sediment concentration (for turbidity / visibility in e.g. water quality modelling relating SSC values to primary production of algae). It is noted that the two types of models, even when they are applied for the same system, may have different parameter settings (combinations of settling velocity, critical bed shear stresses for deposition and erosion, erosion coefficient). This is because mud models are developed and calibrated for a specific purpose, and settings that generate realistic morphological changes may not predict the correct residual transport or turbidity. Mud transport models that are accurate for a wide range of purposes (simultaneously accounting for morphology and sediment concentration) are rare or non-existent.

9.1.1 Morphological models

Process-based models aim at the most realistic description of the physical processes and conditions for the scientific question addressed within the existing practical constraints (imposed by time and spatial scales as well as process knowledge). An example is the Delft3D system (Lesser et al., 2004), in which the mathematical equations representing the physical processes of water movement and sediment transport are approximated numerically to determine the morphological changes based on a mass-balance for sediment. Such models, also indicated as “complex” and “quasi–realistic” in the literature, can be used for detailed simulation of morphological changes. More importantly, they can be used to understand the underlying physical processes and mechanisms for, e.g., the observed morphological and sedimentological developments. It is important to realize that even process-based models are not reality, but aim to represent reality as closely as possible, depending on the model purpose. This representation of reality is as good as the underlying equations and model deployment. Some of these equations are well-studied and well-known (e.g., hydrodynamics), some contain a considerable margin of error and unknowns (e.g., sediment transport).

A key part of the sediment transport model formulation is the bed boundary condition for the advection-diffusion equation for sediment concentration. This part of the model formulation is also essentially different for mud than for sand. For sand the equilibrium concentration or equilibrium concentration gradient in the vertical direction, calculated from a sediment transport formula is prescribed. For mud the erosion and deposition fluxes are calculated using the Krone-Partheniades type formulation. In the classical way of using this formulation, viz. with critical bed shear stress for deposition smaller than that for erosion, there is an essential difference with the formulation for sand. For sand an equilibrium concentration can be calculated as a continuous function of the flow condition characterized by e.g. the bed shear stress, and for mud it is not the case. However, Winterwerp and Van Kesteren (2004) recommend setting the critical bed shear stress for deposition infinitely large, i.e. let deposition always take place, removing this difference between the formulations for sand and for mud.

Furthermore, mud transport is more complicated than sand transport as sediment parameters such as settling velocity and critical shear stress for erosion are not directly linked to particle size, but may change in time due to processes of flocculation of suspended sediment (influencing settling velocity) and consolidation of bed sediment (influencing erosion properties). Also, sand transport is steered mainly by actual and local hydrodynamic conditions determining transport capacity and gradients herein, whereas mud transport is more steered by hydrodynamic conditions in a much wider area and with important memory effects. Typically, mud transport is driven by supply (sinks and sources) rather than by transport capacity as for sand. Sand-mud interaction makes the sediment transport modelling even more difficult in areas like the Wadden Sea.

Morphological models such as Delft3D have reached a stage that they can be used to investigate hydro- and morphodynamics and greatly improve our fundamental understanding of the processes driving sediment transport (see Elias and van der Spek, 2006; Lesser, 2009; Van der Wegen, 2009; Elias and Hansen, 2012). Van der Wegen (2009) illustrated that long-term (centuries) morphodynamic simulations are capable of reproducing concepts and equilibrium relationships based on measurements and laboratory experiments (similar findings were presented in the studies of Hibma et al., 2003a, 2003b, 2004; Marciano et al., 2005; Dastgheib et al., 2008; Dissanayake et al., 2009a, 2009b). Lesser (2009) demonstrated, through agreement between modelled and measured morphodynamic behaviour of Willapa Bay (WA, USA), that a process-based numerical model could reproduce the most important physical processes in the coastal zone over medium-term (5 year) timescales. Also, recent modelling of morphological changes of the Zandmotor mega-nourishment along the Holland coast illustrates that the Delft3D model can capture morphodynamic developments on a decadal scale (Luijendijk et al., 2017; Huisman et al., 2018). Studies that aimed to predict the morphodynamics of the Wadden Sea inlets (e.g. Ameland Inlet) were less successful (De Fockert, 2008; Teske, 2013; Elias et al., 2015; Wang, et al., 2016). One of the important lessons learned from the above models is that these are very well capable to predict the morphodynamic evolution after large-scale distortion of the system (e.g. construction of the Zandmotor) but cannot easily predict the smaller-scale (natural) evolution of inlets, unless abundant field data (and model development) are available (Lesser, 2009). Applications of process-based models for simulating impact of SLR to the Wadden Sea (Stanev et al., 2006, Dissanayake et al., 2012; Hofstede et al., 2018; Becherer et al., 2018) have only demonstrated limited success.

9.1.2 Turbidity models

Turbidity models have other requirements for hydrodynamic model calibration than morphological models. Next to the proper reproduction of peaks in flood and ebb velocities and their asymmetry and peaks in current- and wave-induced bed shear stress, also residual currents and the residence time of water masses are important. These are influenced by tidal asymmetry, but also by wind speed and direction and density gradients (induced by salinity, temperature or the sediment concentration itself if sufficiently high). To reproduce density gradients, a 3D approach is adopted by default for suspended sediment modelling, whereas for morphological models often still a 2D approach is applicable. From 3D hydrodynamic models using the k-ε turbulence model also the vertical mixing intensity is known, from which in combination with the particle settling velocity the vertical suspended sediment concentration profiles can be computed and hence near-bed and near-surface residual SPM (Suspended Particulate Matter) transport.

Ridderinkhof (1990) was one of the first to study residual currents in the western Wadden Sea using a numerical model. Ever since, models have been developed with increasing resolution and complexity in forcing and processes. Whereas focus was initially most on tidal transport, more and more also the effect of density gradients on transport and mixing was studied. Also, the analysis extended from average forcing conditions to variable conditions with regard to water level set-up and set-down, wind speed and direction, wave height, freshwater discharge (including rain and evaporation) and heat balance. Notably in shallow areas such as tidal divides, residual transport is steered more by wind- and wave-induced transport than by tidal transport.

The PACE-project provides an excellent tri-lateral overview of recent advances in hydrodynamic and suspended sediment modelling in the Wadden Sea (Burchard et al., 2015). For the western Wadden Sea, Duran-Matute et al. (2014) discuss the residual circulation and freshwater transport based on the PACE numerical model study, highlighting the importance of wind-driven circulation. This model is available both in GETM and Delft3D. Based on this hydrodynamic model, a suspended sediment transport model was developed as reported by Sassi et al. (2015). They evaluate the sensitivity of SPM fluxes on tidal and meteorological forcing. An important outcome of their work is that the residual transport is not only sensitive to meteorology and geometry, but also to subtle variations in sediment parameters used as model input (settling velocity, erodibility). This dependence on (often limitedly known) input parameters introduces an uncertainty associated with the predictability of net fluxes. Later, this model was extended in Delft3D with a second bed layer of consolidated mud. This model introduces more realistic time lags and delayed response of the system (van Kessel, 2015 and Van Duren et al., 2015) but does not reduces the dependency of residual fluxes on model input parameters. Recently, this model was converted to DFLOW-FM and its resolution was further increased (Vroom et al, 2020). For the Ems-Dollard area, a model is available based on the same philosophy (Van Maren et al., 2015a and 2016). An unstructured suspended sediment transport model for the German Bight, with high resolution in the three main estuaries, was recently developed by Stanev et al. (2019) using the SCHISM model.

The Wadden Sea wide models are able to reproduce the main features of observed suspended sediment dynamics, such as average concentration levels, spatial gradients, tidal and seasonal variations and storm peaks. However, the goodness of fit for a direct comparison with long timeseries of high-frequency observations (e.g. with OBS) is often open for further improvement (e.g. van Maren et al., 2015b). This indicates that some processes are still lacking or not well described in these models. But also observations on suspended sediment concentrations have inherent uncertainties (Fettweis et al., 2019). Apart from the three Wadden Sea wide models developed in GETM/GOTM, Delft3D, and SCHISM, a large number of small-scale models have been developed in the past years for a specific part of the Wadden Sea which often attain a better data-model comparison than the large-scale models. These models are often project- and question-specific, and they are only operational for a limited amount of time.

Notwithstanding their limitations, these models have the big advantage over field observations that it is easy to derive a mud balance from them as they are synoptic. Also, it is easy to switch some processes on or off and investigate the sensitivity to variations in hydro-meteo forcing, i.e. to identify the main drivers for mud import and export. The results by Sassi et al. (2015), Van Kessel (2015) and Vroom et al. (2020) suggest that the interannual variability in mud dynamics and transport in the Dutch Wadden Sea is large. Therefore averaging over a multi-year period is required to obtain a mean mud balance. A major shortcoming of complex numerical models is that net sediment transport in systems with small residual sediment fluxes relative to the gross (tidal) sediment fluxes is sensitive to model input (meteorology, geometry, and sediment settings). This limits the predictability of the residual transport, requiring calibration against aggregated parameters such as net transport. Such observations are, however, rarely available and only limitedly accurate.

9.2 AGGREGATED MODELS

Aggregated models, or (semi-)empirical models, are also known as behaviour-oriented models. These models make explicit use of empirical relationships to define a morphological equilibrium. An important assumption is that the morphological system after a disturbance (through natural evolution or human interference) always tends to develop to a state satisfying the empirical equilibrium relationships. The ASMITA model (Stive et al., 1998; Stive and Wang, 2003; Townend et al., 2016a, 2016b), which is used as an important tool for determining the effects of interventions in the Wadden Sea, is a typical example of this type of model. The model uses a schematisation in which a tidal-inlet system is divided into the main morphological elements ebb-tidal delta, channels in the basin and intertidal shoals and flats. These elements exchange sediment with each other and with the adjacent coast, to develop a morphological equilibrium as defined by the empirical relationships. The model is easy to handle and simulates long-term developments. This makes it suitable to study the effects of SLR (Van Goor et al., 2003) and large-scale human interventions (Kragtwijk et al., 2004) on the morphology of the Wadden Sea. Since these models are depending on the basic assumption concerning morphological equilibrium, sufficient historical data for the calibration and validation is essential.

Recently, Townend et al. (2016a, 2016b) demonstrated that the difference between ASMITA and a process-based model such as Delft3D is in the level of (spatial and temporal) aggregation rather than in the extent of empiricism. The ASMITA model is based on the same principles as a process-based model in the case that the suspended sediment transport is dominant. Both models try to represent the same physical processes, but at different levels of aggregation. The difference between the two models is in the formulations for the exchange between the bottom sediment and the water column. In Delft3D this is arranged via the bottom boundary condition in 3D mode or a formulation derived from an asymptotic solution of the (3D) advection-diffusion equation (Galappatti and Vreugdenhil, 1985; Wang, 1992) in 2DH mode. In both cases, the local equilibrium concentration for sediment needs to be calculated. This requires a sediment transport formula that relates the transport capacity to the strength of the flow and the properties of sediment. A sediment transport formula is often derived by considering the relevant physical processes, but it always contains parameter(s) to be calibrated with observations from the field and/or laboratory. In that sense, a sediment transport formula is thus empirical. One must also consider the uncertainties associated with the application of such a formula. This is shown by the fact that there are not one but many sediment transport formulas available. An indication of the uncertainty is given by Van Rijn (1984a, b) who suggested that sediment transport estimates and measurements can differ easily by a factor of 2. In ASMITA, a single formulation is used for the exchange between the bottom and the water column for each large morphological element, e.g., the whole ebb-tidal delta. This is based on morphological equilibrium relationships of the elements and aggregated hydrodynamic parameters, reflecting the aggregation in time and space. These relationships are, like the sediment transport formula, based on physical considerations (to determine relevant hydrodynamic parameters and morphological relationships) and observations from the field (to calibrate the parameters in the relationship). The local equilibrium concentration is related to the ratio between the equilibrium volume and the actual volume. The empirical relationships for the morphological equilibrium also contain uncertainties, just like the empirical aspects of a sediment transport formula in Delft3D.

The existing ASMITA models only consider a single fraction sediment. However, recent research (Wang and van der Spek, 2015; Wang et al., 2008) made clear that sand as well as mud are important for the Wadden Sea in its response to sea-level rise, and that the models produce good results only because the parameter settings in the models mimic sand-mud transport with a single fraction formulation. Extension of the models with a multi-fraction sand-mud transport module is needed in order to have the parameters in the model clearly related with the parameters in the process-based models. A complicating factor is that for sand, transport may be assumed to be close to equilibrium (i.e. the transport capacity of the flow), but for mud transport is typically limited by supply. So, a bed module keeping track of the bed composition (and hence the availability of mud) is essential for mud models, whereas for single fraction sand models a transport formula to compute the equilibrium concentration suffices

9.3 IDEALISED MODELS

An idealised model is a process-based model that makes use of simplified physical and mathematical descriptions to analyse the behaviour of a morphodynamic system. The difference with the 'complex' models is that they do not pursue full description of geometry, forcing and physical processes, but try to reduce these to essential principles. Idealised models themselves have great variability in complexity as well (see also the review in De Swart and Zimmerman, 2009). An example of a simple idealised model is the conceptual model of Postma (1961) on landward sediment transport in the Wadden Sea. More recent and more complex idealised models developed for the Wadden Sea include the schematised 1D model of Van Prooijen and Wang (2013) and those developed by Roos et al. (2013) and Reef et al. (2020).

Idealised models can be used to study specific phenomena, such as regime shift in estuaries. A recent example of an idealised model is IFlow developed by Dijkstra (2018), building on the models developed by Chernetsky et al. (2009) and Schuttelaars et al. (2013). Such idealized models have been used to understand the transition to high turbidity in the Ems Estuary (Winterwerp and Wang, 2013; Winterwerp et al., 2013; Dijkstra, 2018). A model developed for investigating the response of mudflats to sealevel rise is Mudflats (Elmilady, et al., 2019, 2020).

10 DISCUSSION AND CONCLUSIONS

10.1 DISCUSSION OF THE RESEARCH QUESTIONS

In this section the research questions formulated in Chapter 1 will be addressed, based on the results formulated in Chapters 2 to 9.

1. *What are at present the main sources for the input of mud in the Trilateral Wadden Sea, and how much mud is annually gross, and net imported and subsequently deposited?*

The main source for inorganic mud influx in the trilateral Wadden Sea is sediment from the Dover Straits, which is transported along the French, Belgian and Holland coasts by the North Sea Continental Flow (NSCF). The estimates show that via the NSCF some 10-14.3×10^6 ton/yr of mud is transported towards and along the Wadden Sea area up to the Weser-Elbe-Helgoland triangle. Other sources are local rivers which supply an additional 1.6×10^6 ton/yr of mud to the Wadden Sea area and its estuaries. Primary production and eolian dust deliver an additional 0.5×10^6 ton/yr. The resulting total mud supply is estimated at 12.1 to 16.5×10^6 ton/yr. The average decadal deposition and extraction of mud (i.e. excluding sand) ranges between 10.8 and 11.3×10^6 ton/yr, which means that presently the supply is 1.1-1.5 times larger than demand (extraction and deposition). Note that gross import rates are 1-2 orders of magnitude larger than the net import (i.e. the demand), but it is the net import that contributes to the mud budget. If it is assumed that suspended sediment transport via the NSCF stops in the Weser-Elbe-Helgoland triangle (perhaps leading to the formation of the Helgoland mud field), then net deposition is 2×10^6 ton/yr (the amount of mud settling in the North Frisian Wadden Sea), implying supply is 1.3-1.8 times larger than demand.

In case of a temporal mud shortage, local mud stocks in the North Sea and in the Wadden Sea could make up the difference between the supply and the demand, temporarily closing the imbalance. However, this would not hold for the long-term balance, since these mud stocks are limited.

More suspended matter might be delivered via the East Anglia Plume (EAP), but the fate of sediment from this sediment source is poorly known. There are indications that at least some 2×10^6 ton/yr of the EAP may reach the NSCF, especially in the North Frisian area (e.g. Rick et al., 1998). The EAP is thought to be responsible for strong sedimentation in deeper water, leading to muddy offshore areas. Part of the mud deposited offshore may be intermittently released during storms and transported to the NSCF region.

It is important to note that this is the first time that the mud balance has been estimated for the Trilateral Wadden Sea, and that the results should therefore be interpreted as such.

2. *What are the main hydrodynamic processes and sediment transport mechanisms relevant for the import, transport and deposition of mud in the Wadden Sea and How important is the exchange of mud between individual tidal basins?*

Both in the Wadden Sea and along the North Sea coast the variations over a tidal cycle, a neap-spring cycle, the annual wind influence and interannual variations in storminess all lead to marked changes in the availability of suspended matter. In general, sediment is transported from the North Sea into the Wadden Sea. Tidal currents transport mud to the intertidal areas, driven by horizontal and temporal tidal asymmetries and lag effects. Some of this material may be exported during storm events. Redistribution within the Wadden Sea, and transport between tidal basins, is strongly governed by wind-driven flows during storm conditions. Both waves and wind-driven currents remobilize fine sediments (Figure 3.1) deposited during low energy conditions, and transport sediment in the eastward direction. In addition, density gradients and vertical mixing can strongly influence mud transport, which is especially the case in the estuaries.

3. *What is the natural range of mud concentrations as a function of local environmental conditions and how have these concentrations changed in response to human interventions?*

In general, the natural range of suspended mud concentration may vary due to the above described variations over 1 to 2 orders of magnitude. On average there is a narrow zone of higher mud concentrations along the coasts from Holland up to Minskerooge: the easternmost barrier island of the Wadden Sea of Lower Saxony. From the Weser up to Sylt this transport pattern is not present. From Sylt onwards it is restored. Nevertheless, on average SPM concentrations are very low of the order of 4 (summer period) -18.5 mg/l (winter period). Into the Wadden Sea area the concentrations of suspended matter increase in the channels with increasing distance from the inlet (Postma, 1961; Van Prooijen and Wang, 2013). Above the tidal flats we see a similar pattern.

Within the Weser and Elbe estuaries there is clearly defined turbidity maximum zone present, where a combination of estuarine circulation and tidal pumping generates high turbidity up to several 100 mg/l. Concentrations may be as high as 10’s of g/l in the hyperturbid lower Ems River

For the second part of the question we refer to Question 4.

4. *How have these concentrations been influenced due to large-scale interventions which have been structural over time (poldering, closure works, substantial landfill with dredged materials)? Are there alternatives to deal with mud-related problems?*

The two interventions that have most strongly impacted the sediment concentration are land reclamation and channel deepening.

Reclamation of naturally accreting land (the extensive pristine intertidal and supratidal areas south of the Wadden Sea) introduced a major loss in sediment sinks. Sediment transported from west to east is no longer able to settle, resulting in an increase in the suspended sediment concentrations (van Maren et al., 2016). Thus, with the closure of large basins such as the Zuiderzee and the Lauwerszee and the gradual diking of the tidal marshes, it may be expected that less sedimentation space was available (see also van der Spek and van der Valk, 1994; Flemming and Nyandwi, 1994 and Mai and Bartholomä, 2000). This would result in a higher concentration of fines in the water column. Reclamations also influence the tidal dynamics, especially in the estuaries. Narrowing of the estuaries increases the amplification and flood dominance of the tides, contributing to landward transport of sand and mud.

Deepening of tidal channels for navigation purposes also increases the range and flood dominance of the tides, contributing to landward sediment transport. In an area with horizontal salinity gradients (primarily the estuaries), deepening will also strengthen a salinity-driven residual circulation cell promoting near-bed landward sediment transport. For all three major estuaries in the trilateral Wadden Sea, the combined effect of deepening has led to a substantial increase in suspended sediment concentrations, with the Ems river as the most extreme example (resulting in a 100-fold increase in sediment concentrations).

Large-scale managed realignment may reduce the mud-related problems in the Wadden Sea. See also the answer to Question 7.

5. *What is the spatial distribution of mud in surface deposits on shoals, tidal flats and salt marshes?*

The available SIBES measurements as well as the observations in other parts of the world have shown that there is a strong bi-modal distribution of the mud content of bed sediments (Herman et al., 2018; Colina Alonso et al., in prep) with a mode at a low percentage of mud and a mode at a relatively high percentage. This suggests that sand-rich and mud-rich sediment mixtures behave very differently, and therefore also respond differently to external changes (e.g. human interventions, sea-level rise). The locations where mud settles are characterised by low-energy hydrodynamic conditions, and are in general persistent. Additionally, the presence of mud itself also promotes mud sedimentation (Colina Alonso et al., in prep) for different reasons. These reasons may be physical (related to bed roughness and erodibility of the mixtures) and/or biological (stickiness of benthic diatoms growing over mud beds). Mud sedimentation is important in abandoned channels, at mudflats on distance of 10 km from the inlets, in tidal marshes and in quiet embayments, and in the estuaries around the turbidity maximum and in fairways and harbours with overdepth.

6. *What kind of management strategies, interventions and tools have been used so far to deal with mud-related problems in the Wadden Sea? How were their effects measured in terms of physical and ecological changes? How cost-efficient were the measures?*

The most widely applied sediment management technique is dredging. Dredged sediment is disposed in within the system, disposed offshore, or brought on land. Offshore disposal or bringing sediment on land can be considered extraction of suspended sediments.

Disposal of sediments primarily leads to a redistribution of sediment, rather than an increase in suspended sediment concentrations (van Maren et al., 2015a), because the estuarine sediment concentrations effectively decrease when sediment settles in the ports or fairways. Subsequent disposal restores the sediment concentration to a level comparable with a situation without settling in ports and fairways, at least on large time and spatial scales. Close to disposal sites, the sediment concentrations increase. On top of this, dredging can be considered a permanent stirring mechanism, leading to higher suspended sediment concentrations compared to a situation without dredging (i.e. comparable to an estuary with or without permanent wave-induced resuspension). If dredged material is released close to the dredging location, important return flows may occur, enhancing local sediment concentrations substantially.

Landfill or deposition far outside the Wadden area of dredged sediments will result in an artificial extraction of sediment from the estuaries and a decrease of the SPM concentrations in the estuaries. If the dredged sediments are heavily contaminated, as is the case near Hamburg (Elbe) and in the Weser, then there is no other option than to store such sediments on land as they are detrimental to the ecology of the Wadden area. However, if clean mud is deposited on land to heighten the land or fill former sand pits, this should be regarded as a loss to the system. The question arises if the benefits (lower SPM concentration in the estuaries) outdo the effects (less mud available for ecosystem services in downdrift basins). At the same time, a reduction in mud availability may also be considered positive, as it may lead to a reduction in maintenance dredging and higher primary production rates. At the present rates of SLR, the reduction in mud availability may not lead to a substantial negative ecological impact. However, the large-scale and long-term impact of sediment management strategies needs to be accounted for when designing such strategies.

Landfills are beneficiary for the estuary, but also for conditions on land. Estuarine mud is composed of nutrients, and historical landfills (especially in the areas around Emden and the lower Ems River) show that the quality of the agricultural land significantly improves. In the near-future, the Netherlands will also experiment with landfills or semi-natural flooding to improve the soil quality of agricultural lands. A second positive effect of landfills / artificial flooding is that the land grows vertically, reducing flood risks. A less disrupting method to enrich agricultural lands is through mechanic spreading of marine mud as an alternative for manure. The subsoil of the low-lying coastal areas in the north-east of the Netherlands consist of compacted peatland which is poor in nutrients. Experiments with mechanic spreading of limited volumes of mud (sufficiently low to allow agricultural functions to be continued) lead reveal that the soil quality improves. However, the volume of extracted mud is too low to significantly influence the mud balance.

An alternative to storage on land is managed realignment. In the past, realignments were often accidental when dikes were breached and had to be given up (e.g. Paesummer lannen).

Nowadays, with the increased quality of the dikes, realignment is a choice. Managed realignment (or de-embankment) can be done via the reintroduction of tidal (storm surge) influence to polders by breaching or removing dikes. In total more than 30 realignment projects have been realized in the trilateral Wadden Sea and some 1800 ha has been converted into Wadden area (Esselink et al., 2017). Sedimentation rates in these areas are slightly higher or comparable to averages found in the near tidal marshes (Spadenländer Spitze: 8.8 mm/yr; Holwerder summer polder: 10 mm/yr; APA, 2013). However, sometimes sedimentation rates are very high, especially in estuaries. An example is the Kleinsieler Plate in the Weser with a sedimentation rate of 500 mm/yr (APA, 2013). Occasionally, sedimentation rates may be very low (e.g. Bildtpollen: 1.2 mm/yr; Bakker et al., 2014), resulting in a lag relative to mean high water level rise, but that is rare. The reasons for differences in sedimentation rates are the hydrodynamic conditions (full tide or dampening), SPM concentrations, wave effects, elevation and inundation of the site, the slope of the terrain and the number of breaches.

Up to present, most of the realignment schemes have been rather small in areal extent. Even at sedimentation rates of 10 mm/yr, this does not allow for large-scale permanent storage of mud. To that end larger-scale realignment projects are needed. The silting up of a basin of 10 km^2 with 1 cm/yr, would require 0.1×10^6 m^3/yr of mainly mud. Presently, several possibilities are being considered: from a totally open landscape without dikes to strongly regulated tidal basins.

7. *Are there other options (not yet explored) to deal with mud-related problems and, if so, what would be the efficiency of these measures (in reducing the problem and with respect to the costs)?*

The most comprehensive and futuristic plan is “Rijzend Land” of Bureau Lamaland (Figure 7.6). It envisages to open polders surrounded by inland dikes which function as sedimentation basins. When the area has become high enough it can be reclaimed, or if sea-level rise is too fast: left to nature. At the same time, other realignment projects are still silting up. Variants of the plan have been brought forward by the bureau and other stakeholders.

To store considerable amounts of dredged mud, and thus reduce the SPM concentrations, several of these large-scale realignment initiatives would be needed along the estuaries. Such managed realignment will mainly be implemented on agricultural land, which will turn into nature reserves. But depending on financial compensation, farmers are likely willing to sell their land. Alternatively, the land may be exploited economically while being regularly flooded. This includes recreation (nature reserves, as above), (shell)fish farming or salty agriculture. Recently Roggema (2020) showed that higher-value future crops take up much less land and deliver the same amount of income. But even these lands retain some economic value, additional investments will be needed.

8. *What has been the impact of long-term sea-level rise on the supply and deposition of mud and how will climate change and (accelerated) sea-level rise alter these processes?*

As argued in Chapter 7, this is difficult to predict. It is anticipated that as long as sandy flats can keep up with SLR, they will provide shelter for the more inland mudflats. However, with increasing rates of SLR, the sandy flats increasingly lag behind and become somewhat deeper with reference to MSL and wave action and tides will become stronger. It is not known what will happen with mud sedimentation. A second point is that more mud will be needed to keep up with accelerated SLR. As already at present mud supply is limited, it may be expected that for the more eastward basins this may become problematic in the longer run. It is not known to what extent sea-level rise will enhance coastal erosion at Dover Strait and thus mud influx. Stronger fluctuations in run-off due to changing precipitation patterns may lead to increased mud supply via the rivers. However, this may be hindered if river water levels increase due to sea-level rise, which might lead to mud entrapment in the riverbeds.

Above a certain critical limit sandy tidal flats are expected to be no longer able to keep up with SLR and they will start to drown. Then wave energy on the mudflats will increase. This may lead to erosion or reduced vertical accretion.

9. *Who is presently working on which mud-related research question in the trilateral Wadden Sea and what is the type of projected outcome of this research (e.g. dose-effect field studies, model scenarios)?*

See Chapter 12

10. *Analytical and numerical models play an important role in understanding, hindcasting and predicting mud behaviour in the Wadden Sea. How reliable and accurate are these models? What kind of improvements are necessary in terms of process knowledge and implementation, model calibration and validation?*

A large number of models developed for different purposes and different spatial and temporal scales, summarized in Chapter 9.

10.2 TESTING THE HYPOTHESIS

Hypothesis I: Sand and mud deposits are spatially segregated, which influences not only their distribution but also their response to human interventions and sea-level rise

Conclusion: Confirmed for at least the Dutch Wadden Sea, but probably for the whole Wadden Sea area.

From Chapter 4 and 5 it appears that overall strong sand-mud segregation in the sediment bed of the Dutch Wadden Sea has been observed by many researchers (Postma, 1954; van Straaten and Kuenen, 1957; de Glopper, 1967; van Ledden, 2003; Zwarts, 2004). Detailed data indicate that the segregation is not only explained by the bathymetry (with sandy channels and muddy shoals), but is also observed on intertidal flats, where sediments tend to be either mud-rich (average ca 30% mud) or mud poor (average ca 4%) (Herman, et al., 2018). This bimodal distribution of the mud content was shown to be relatively stable over decennia (Colina Alonso, 2020). The probability of finding bed sediments in between these two modes is much lower. The intermediate samples show large fluctuations in grain size distributions and may be the result of sampling mixed beds of flaser and linzen structures (clay rich and clay poor layers of sediment which alternate). Thus, as a first approximation, one might think of the back-barrier area as consisting of two separate "worlds": one of mud-rich sediments that are generally cohesive and one of sand-rich sediments that are non-cohesive. Of course, the idea of two separate worlds is an over-simplification and it should be noted that in both worlds (cohesive and non-cohesive) the bed sediments exist of both sand and mud. Moreover, these two worlds interact in their morphodynamic development. These interactions take place at various scales. At small (grain-grain) scales sand and mud particles mutually influence their erosion rates (with mud particles reducing sand erosion rates, while an addition of sand strengthens a pure mud bed – see Winterwerp and van Kesteren, 2004. At larger scales, sandy shoals shelter fine-grained tidal flats from wave-induced erosion whereas simultaneously deposition of mud on intertidal areas reduce the tidal prism, and therefore flow velocities in the dominantly sandy tidal channels.

The existence of bimodality is probably brought about by both hydrodynamic conditions and the strongly differing sedimentary behaviour of sand and mud in terms of entrainment, transport and settling (Postma, 1961; Van Prooijen and Wang, 2013). Furthermore, it appears that mud settles preferentially in mud fields over periods of a century or more (Colina Alonso et al., in prep). A possible explanation is the organic matter on mud which stimulates benthic diatom development and hence sediment binding, thus increasing entrainment velocity.

The existence of bimodality in the German Wadden Sea could not yet be studied in this project because the available data (AUFMOD) consists of interpolated data and the original datasets were not available. However, since the bimodality is also observed on other areas with sand- and mudflats around the world it is assumed that it is also true for the German and Danish Wadden Sea.

The implications of this observation are far reaching. Upon accelerated sea-level rise it does not suffice to only consider the availability and transport of sand. For more landward areas the availability of mud should also be considered (see further sea-level rise).

Hypothesis II: The contribution of mud to total sedimentation rates in the whole trilateral Wadden Sea is substantial

Conclusion: true

The bed sediment in the Wadden Sea consists of approximately 10% mud (by mass) see e.g. Oost et al. (1995). However, large interventions may lead to a larger contribution (than this 10%) of mud to total deposition. This was shown for the western part of the Dutch Wadden Sea after closure of the Zuiderzee, where about 27% by volume of the deposited sediment consisted of mud (see Figure 6.1 and Table 6.1). The contribution of mud to deposition in the Eastern part of the Dutch Wadden Sea was largest after closure of the Lauwerszee (22% by volume) since 1971 (Figure 6.2 and Table 6.1). In reality, mud contributes even more to the net deposition rates because the 22% and 27% do not account for salt marsh sedimentation rate, where mud constitutes >95% of the deposit. In the Ems Estuary, mud contributes 31-62% (by mass) to infilling since 1985 (see Table 6.2). In the sandier parts of the Lower Saxony coast and the North Frisian German Wadden Sea, mud contributes much less (~5% by mass, see Table 6.3 and Table 6.5). Much more mud deposits in some of the sheltered embayments (Leybucht, Jade Bay, Melthof Bight) and the salt marshes. The estuaries of the Elbe and Weser are primarily muddy, but quantitative values for the mud contribution to total sedimentation are not available.

Overall, we conclude that mud substantially influences morphodynamic behaviour and the sediment budgets in the Wadden Sea.

Hypothesis III: The sources and the sinks of mud are closely balanced.

Conclusion: true, for the current situation (past decades)

This hypothesis is confirmed for the current sedimentation rates. The potential influx of mud originating from the aforementioned sources is estimated at 12.1-16.5×10^6 ton/yr of mud. Based on a literature review and an additional data analysis we have shown that recent mud deposition, consisting of net sedimentation and extraction by human, is estimated at 10.8-11.3×10^6 ton/yr. this shows that, at the moment, the sources are only approximately 1.1-1.5 times the net total sedimentation. However, two things should be noted:

1. Mud sedimentation in the German Bight has been calculated based on data of the period 2000-2010 only, which means that we cannot conclude what the long-term mud budget of the Wadden Sea looks like. Therefore, we recommend extending this analysis to a longer period of time.
2. The mud sources are still difficult to quantify, which creates uncertainty in the calculations. Therefore, we strongly recommend further research on their magnitude and pathways. However, it is also clear that although supply may be highly variable, it

will not be an order of magnitude larger than current estimates. It implies that in general supply and deposition of mud are quite comparable in size.

Hypothesis IV: Sea-level rise may lead to a shortage of mud

Conclusion: partly true, depending on SLR rates

The deposition rate of mud is expected to increase with sea-level rise. With the present-day rate of SLR (or a slight increase) and current mud extraction rates, there is no shortage of mud. However, the mud balance is nearly closed (see hypothesis III), which implies that a critical rate of SLR exist where mud deposition rates are so large that a shortage in mud may develop – especially in the east of the Wadden Sea. This critical rate of SLR is now estimated at 4-6 mm/yr, but this number needs to be quantified in more detail with additional studies. On the short term, this response is further complicated by the sediment buffers in the Wadden Sea. The stock of mud in and around the Wadden Sea is so large that sedimentation may continue for a limited period of time at rates of SLR exceeding 4-6 mm/yr. However, as the available mud stocks will become depleted in time, this buffer capacity only provides a delayed response to SLR.

A major uncertainty is to what extent hydrodynamic conditions change (for instance due to the drowning of more seaward sandy shoals or parts of barriers). Such a change will become likely for more extreme rates of SLR, and lead to a reduction in mud deposition rates.

Hypothesis V: Anthropogenic sediment extraction may lead to a shortage of mud.

Conclusion: partly true

Human mud retrieval is estimated at 2×10^6 ton/yr, which is about 10-15% of the net mud supply by the North Sea Continental flow, the rivers, primary production and aeolian dust combined. This 2 million ton/year can be considered large compared to the 8.7-9.2 $\times 10^6$ ton/yr of mud which naturally deposits in the Wadden Sea basins and the saltmarshes. Under current conditions, the amount of mud available in the entire trilateral Wadden Sea is sufficient. However, on a large scale and over a longer period of time there is a limit on the amount of mud that can be extracted, especially considering the expected acceleration of SLR (see hypothesis 5), on the scale of the entire Wadden Sea. Locally, enough sediment may be available (especially in the Western Wadden Sea) but in time sediment shortages may develop in the eastern Wadden Sea. Sustainable sediment management strategies including sediment extraction schemes should account not only for the local impact, but also the large scale, long term implications.

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12 WADDEN SEA RESEARCHERS AND PRACTITIONERS

Overview of researchers and practitioners that are currently working on topics related to mud in the Wadden Sea. Note that this list is most likely incomplete and will be rapidly outdated.

Name	Research institute	Research
Emil V. Stanev	Helmholtz-Zentrum Geesthacht, Geesthacht, Germany	Model
J. Staneva	Institute for Coastal Research, GKSS Research Center, Max-Planck-Strasse 1, D-21502 Geesthacht, Germany	Model
J-O Wolff	Institute for Chemistry and Biology of the Sea (ICBM), University of Oldenburg	
Aart Kroon	University of Copenhagen, Physical Geography	Model/Field
J. Bartholdy	University of Copenhagen, Physical Geography	Field
H. Nielsen	Danish Environmental Protection Agency	Management
H.P.G. Jørgensen	Danish Environmental Protection Agency	Management
K. Bolding	Danish Wadden Sea Secretariat	Management
F.Kösters	Hydraulic Engineering in Coastal Areas, Federal Waterways, Hamburg, Germany	Model
T. Elscher	Min. ELUND SH abteilung 5 Naturschutz und Forstwirtschaft	Management
C. Reimers	Min ELUND	Management
P. Müller	Universität Hamburg	Model
K. Ricklefs	Institute of Geosciences, Christian-Albrechts-Universität zu Kiel	
C. Winter	Institute of Geosciences, Christian-Albrechts-Universität zu Kiel	Model/Field
M. Benninghoff	Universität Bremen, MARUM – Center for Marine Environmental Sciences, Bremen, 28359, Germany	Model/Field
A, Plüß	Bundesanstalt für Wasserbau	Management
P. Herman	Deltares	Field
J. Vroom	Deltares	Model
A. van der Spek	Deltares	Field
J Cleveringa	University Utrecht	Field
M. Kleinhans	University Utrecht	Field/Model
P. Hoekstra	University Utrecht	Field
B van Prooijen	Technical University Delft	Model
Z.B. Wang	Technical University Delft	Model
P. Vos	TNO	Reconstructions
K. Philippart	NIOZ	Ecology field
T. Gerkema	NIOZ	Model/Field
H. Ridderinkhof	NIOZ	Model/Field
E. Folmer	NIOZ	Field
Duran Matute	Technical University Eindhoven	Model
B. Borsje	University Twente	Model/Field
P. Roos	University Twente	Model/Field

Name	Research institute	Research
M. Baptist	Wageningen University	Field
K. Elschot	Wageningen Marine Research	Field
M. van Puijenbroek	Wageningen Marine Research	Field
P.J.T Dankers	Royal Haskoning DHV	Field
M. Zeiler	Bundesamt für Seeschiffahrt und Hydrographie, Sachgebiets Geologie	Management
J. Valerius	Bundesamt für Seeschiffahrt und Hydrographie, Sachgebiets Geologie	Management/Field
H.-Ulrich Rösner	Leiter Wattenmeerbüro WWF	Management
U. von Bargen	Bremen Ports, Env. and Sust. Issues	Management
I. Krämer	Referatsleiter Hafenwirtschaft und Schifffahrt	Management
S. Klötz	Hamburg Landesbetrieb Strassen, Brücken und Gewässer (LSBG) - Geschäftsführer	Management
O. Müller	Hamburg Landesbetrieb Strassen, Brücken und Gewässer (LSBG) - Gewässer und Hochwasserschutz	Management
J. Hofstede	Min ELUND	Management/Field
K. Jensen	University of Hamburg	Field
P. Mueller	University of Hamburg	Model/Field
F. Thorenz	NLWKN-Betriebsstelle Norden-Norderney	Management/Field
A. Wurpts	NLWKN	Management/Field/Model
M. Sobottka	NP Niedersachsischen Wattenmeer	Management/Ecology
P. Martinez Arbizu	Deutsches Zentrum für Marine Biodiversitätsforschung	Field/Ecology
B. Flemming	Deutsches Zentrum für Marine Biodiversitätsforschung	Field/Model
A. Bartholoma	Deutsches Zentrum für Marine Biodiversitätsforschung	Field/Model
M. Firet	Programma Rijke Waddenzee	Management
W.Schoorlemmer	Programma Rijke Waddenzee	Management
P. Esselink	Puccimar	Field
J. van Loon	Wageningen University	Field/Ecology
H. Marencic	Common Wadden Sea Secretariat	Management
J. Busch	Common Wadden Sea Secretariat	Management
B. Baerends	Common Wadden Sea Secretariat	Management
M. de Vries	HVHL	Field/Ecolgy
C. Schmidt	RWS-WVL	Management
H. Mulder	RWS-WVL	Management
A.K. Svendsen	The Danish Wadden Sea Secretariat	Management
P. Friis-Hauge	Varde Municipality	Management
D.J. Pedersen	CEO Port of Esbjerg	Management
R. Zijlstra	RWS Noord	Management
T. Bouma	NIOZ	Field/Ecology/Model
C. Maushake	Bundesanstalt für Wasserbau (BAW)	Mangagement
M. Krebs	Wasser- und Schifffahrtsamt Emden	Management
H. Burchard	Leibniz Institute for Baltic Sea Research	Model

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