Die Küste, 74 ICCE (2008), 1-417

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Die Küste

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## Contents

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This volume of "Die Küste" gives a comprehensive overview of the coastal zone along the German coastlines of the North Sea and Baltic Sea from a coastal engineering perspective. The volume provides background information on integrated management processes as well as on related matters concerning communication and public participation. Details of up-to-date facts and figures as well as references for further reading are also listed at the end of each article.

All authors, who are either actively involved in coastal research or hold responsible positions in public administrations or harbour management, have been invited to outline topics relevant to the German coastal zone by way of short articles. With the assistance of guest editors, these contributions have been grouped according to the following key themes:

- natural environment (RAINER LEHFELDT)
- coastal protection (BERND PROBST)
- coastal protection works (HOLGER SCHÜTTRUMPF)
- estuaries and fairways (HARRO HEYER)
- ports (BIRGITT BRINKMANN).

This collection has been published to mark the occasion of the 31st International Conference on Coastal Engineering from August 31 to September 5, 2008 in Hamburg, where more than 850 participants from Germany and abroad will discuss their latest scientific findings in the field of coastal engineering.

RAINER LEHFELDT
HOLGER SCHÜTTRUMPF

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# Geological Development of the North Sea and the Baltic Sea

By Klaus Schwarzer, Klaus Ricklefs, Alexander Bartholomä and Manfred zeiler

Contents



## 1. Introduction

Coastal evolution and coastal processes depend to a certain extent on the geological composition of the ocean basin. Tectonic structures in the subsurface as well as sinking or uplift rates of coastal regions may control the exposure and delineation of the coastline. The thickness of sedimentary layers, their texture and mineralogical composition have a strong influence on compaction and resistance against erosion. On the other hand, sediment availability is essential for the formation of all soft rock coastal elements such as e.g. barrier islands, spits and bars.

Sedimentary rocks can be sources for mineral resources such as oil and gas. Recently, they are considered as possible sinks for technical $CO_2$ – sequestration (Lackner, 2003). Moreover, the installation of offshore structures such as oil rigs or foundations for wind turbines, cable routes and the high demand for offshore aggregate resources to compensate coastal erosion and to be used for coastal protection and for construction purposes require a good knowledge of the geological evolution of the basin (Harff et al., 2004). The North Sea and the Baltic Sea are geographically close together, just separated by the geologically very young, only 60–80 km wide and 450 km long N–S extending Jutland peninsula, which consists mainly of quaternary deposits. Nevertheless, in parts they underwent a different geological evolution since the Palaeozoic period. For this reason, we describe the geological development of the North Sea and the Baltic Sea separately.

## 2. North Sea

The North Sea is a shallow continental shelf sea with an average water depth of 94 m. To the West, it is bordered by the British Islands, to the South by the Mid European mainland

and to the East by the western coasts of Scandinavia. It opens into the Atlantic Ocean to the North, via the English Channel to the Southwest, and it has a free connection to the Baltic Sea via the Skagerrak to the East. The sea-bottom of the relatively shallow southern North Sea off the Dutch and German coast shows no distinctive morphological variation. It is composed of young Pleistocene and Holocene soft-rock deposits (ZEILER et al., 2008).

### 2.1 Palaeozoic to Palaeogene Development

The basement of the North Sea basin consists of more than 543 million years old Precambrian crystalline rocks and faulted metamorphic rocks of Palaeozoic age (for stratigraphy see Table 1). This basement rises towards North and continues in the Norwegian Mountains and the Scottish Highlands. In the North Sea basin, the top of this basement is located in depths of 8–10 km. It is overlaid by terrestrial, lagoonal and liminic deposits into which coal seams are partly incorporated. At the beginning of the Perm Period (Tab. 1), the continental basement was strongly influenced by volcanic activity splitting it into several parts. During the Upper Rotliegend, mainly arid conditions prevailed. Thick series of terrestric sandstones were deposited, which later functioned as reservoir rocks for the economically used North Sea gas. During Zechstein (Perm period), the sedimentary basin was periodically flooded from North-west. As a consequence of repeated transgressions and high evaporation rates, series of siliclastic rocks, carbonates and salt strata, the latter of up to 1,200 m in thickness, were deposited. (RICHTER-BERNBURG, 1972). The maximum thickness of deposits can be found in the south-western-most part of the North Sea basin (Fig. 1).

Tectonic activity and changing shallow marine and terrestrial conditions persisted throughout the Mesozoic period (251–65.5 million years BP). In general, the sinking tendency of the North Sea basin as action at a distance of continental drift, continued, but 'Block-and-Graben' tectonics led to some relative movements with partiallly sinking but also uplifting tendencies. Already at the end of the Triassic period, the sediment load on top of the older salt strata started to deform the salt deposits by thermo-mobilisation, resulting in an early development of salt dome structures (Halocinesis). Later, as a consequence of ongoing salt tectonics and partly other factors leading to vertical dislocations, sills and deep anoxic basins were formed to later become the source areas for the development of hydrocarbons. The mobility of the salt continues until today. In the subsurface of the North Sea, the Northern German und Dutch lowlands, and below the most south-western part of the Baltic Sea, salt diapers in elongated form (Fig. 2), up to 100 km in length, exist. They expand vertically from a depth of up to 8,000 m to the present surface (ZIEGLER, 1990). An obvious example for salt tectonics is the island of Helgoland. Here the characteristic red sandstones were uplifted by more than 4,000 m (SCHMIDT-THOMÉ, 1987). Nowadays, not only the troughs along the salt structures are of economic interest as potential reservoirs for hydrocarbons (e.g. Mittelplate oil field) but huge artificial caverns in the saltdomes can be used for the storage of energy sources such as oil, gas or compressed air and $CO_2$ as well.

In the German part of the North Sea basin, the sedimentation history of the older Caenozoic period (Palaeogen, 65.5–23 million years BP) is characterised by shallow marine silica-clastic deposits. The subsidence, which already started during the Triassic period (Table 1), continued, giving the North Sea sedimentary basin its typical shape of a shallow bowl in which organic-rich sediments were subsided to depths, which allow the formation of oil and gas (TEICHMÜLLER et al., 1979).

Table 1: Geological Time Scales. *Ma = Abbreviation for mega-annum ($10^6$ years); a million years. Note on the Tertiary and the Quaternary: The Tertiary and Quaternary have been eliminated from the most recent International Stratigraphic Charts. The Quaternary was formerly considered to be made up of the Holocene and the Pleistocene. The Paleogene and older Neogene were defined as the Tertiary (INTERNATIONAL COMMISSION ON STRATIGRAPHY – ICS, 2003)

| | Eon | Era | Period | Sub-Period | Epoch | Ma* |
|---|---|---|---|---|---|---|
| | Phanerozoic | Cenozoic | Neogene | | Holocene | 0.01 |
| | | | | | Pleistocene | 1.8 |
| | | | | | Pliocene | 5.3 |
| | | | | | Miocene | 23.0 |
| | | | Paleogene | | Oligocene | 33.9 |
| | | | | | Eocene | 55.8 |
| | | | | | Paleocene | 65.5 |
| | | Mesozoic | Cretaceous | | | 145.5 |
| | | | Jurassic | | | 199.6 |
| | | | Triassic | | | 251.0 |
| | | Paleozoic | Permian | | | 299.0 |
| | | | Carboniferous | Pennsylvanian | | 318.1 |
| | | | | Mississippian | | 359.2 |
| | | | Devonian | | | 416.0 |
| | | | Silurian | | | 443.7 |
| | | | Ordovician | | | 488.3 |
| | | | Cambrian | | | 542.0 |
| Precambrian | Proterozoic | | | | | 2500 |
| | Archean | | | | | not defined |

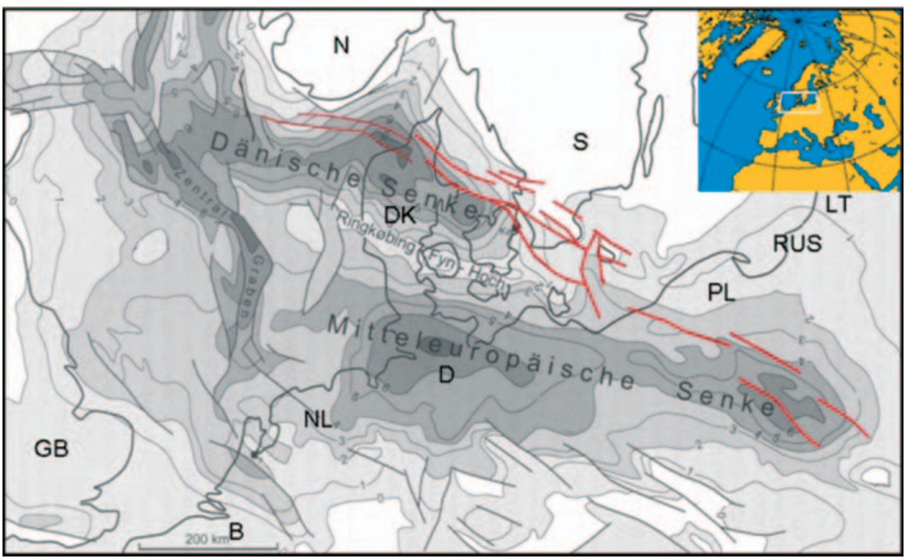


Fig. 1: Total thickness of sediments deposited in the Middle-European and Danish Depression since middle Perm. The red line marks the more than 2000 km long "Sorgenfrei-Tornquist-Teisseyre-Zone" (ZIEGLER, 1990, modified)

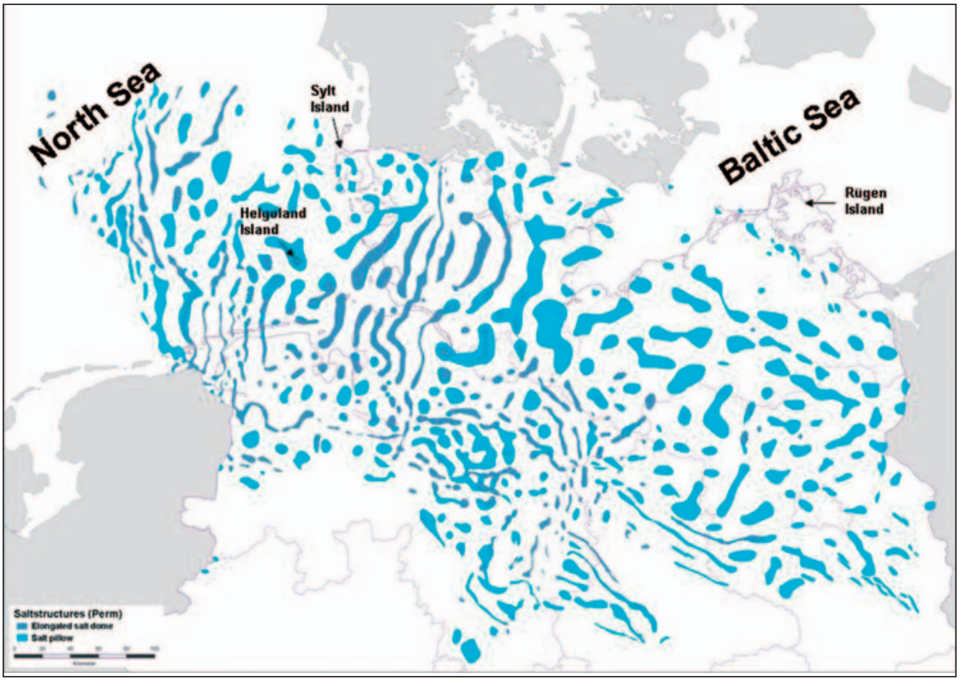


Fig. 2: Salt structures in Northern Germany (BUNDESANSTALT F. GEOWISSENSCHAFTEN U. ROHSTOFFE, 2008, modified)

### 2.2 Neogene

At the beginning of the Neogene (23 million years BP), the climate was still moderate. However, it changed to lower temperatures, starting approx. 5.3 million years BP, when the formation of ice caps on both poles began. Deposits of this phase are either of marine, terrestric/fluviatile or deltaic origin with partly incorporated brown coal seals. In the present coastal zone, sandstones of Miocene age are important aquifers while younger deposits, thick layers of Pliocene/early Pleistocene delta sands, are often used for coastal protection purposes such as beach nourishments.

#### 2.2.1 Pleistocene Development

The subsequent Pleistocene epoch of the Neogene period (Table 1) is characterised by several climatic changes, related fluctuations of the sea level and resulting depositional conditions. Especially the advances of inland ice masses from Scandinavia and the British/Scottish highlands during the Elsterian as well as the Saalian glacial stage (Fig. 3) left striking, still distinguishable traces such as terminal moraines in parts of the North Sea basin (STREIF, 2002; ZEILER et al., 2008). The depositional processes related to the Saalian glaciation also lead to the recent S-N orientated course of the river Weser (STREIF, 1999), and to morphological high point (shallows) in the North Sea such as *"Borkum Riffgrund"*, *"Sylter Außenriff"* or *"Horns Rev"* (Denmark). During the interglacial stages of Holsteinian and Eemian, which followed


Fig. 3: Maximum extent of the inland ice sheets during Saale- and Weichselian glaciations in middle-Europe. The lower courses of the rivers Ems, Weser and Elbe were forming a common spillway into the North Atlantic via the North Sea (BERNER and STREIF, 2000; modified)

the Elsterian and the Saalian glaciations, respectively, typical marine-brackish coastal sediments were deposited. With the exception of some deep embayments into the mainland, the spatial distribution of these sediments almost describes the recent Southern North Sea coastline (STREIF, 1990).

The ice cover of the subsequent youngest cold stage, the Weichselian glaciation (117,000–10,200 BP), did not reach the German Bight (BERNER and STREIF, 2000, Fig. 3). During the last glacial maximum (LGM), when the Weichselian ice cover had a thickness of approximately 3,000 m and its maximum extent, the global sea level was approximately 120 m lower than the present sea level (see Fig. 4). The entire North Sea area was exposed, the coastline was shifted approximately 600 km to the West (STREIF, 2002), and periglacial processes left their traces in the deposits. In the hinterland, huge amounts of meltwater eroded a wide valley along the southern glacial front (SCHWARZ, 1999) which today is the stream bed of the River Elbe. Together with the rivers Ems, Weser and Eider it formed a glacial spillway which emptied into the North Sea basin (Fig. 3) forming the wide Helgoland glacial valley (FIGGE, 1980; ZEILER et al., 2008). Its outline is still recognizable in the present bathymetry of the German Bight whereas most of the smaller channel structures are buried below younger deposits (SCHWARZ, 1996).

### 2.2.2 Holocene

After the LGM, melting of the inland ice caps led to a global sea level rise (Fig. 4). At the end of the Pleistocene and in the early Holocene, the magnitude of the sea level rise was approx. 2.1 m/100 years (STREIF, 2002). The southern North Sea basin was flooded around 9,000 to 8,000 BP, which is documented by tidal flat deposits from that time (EISMA et al., 1981). The depositional evolution along the German North Sea Coast began between 8,600 and 7,100 B.P, when the sea level rose from –45 to –15 m below the present German chart datum NN (see Fig. 4). At that time, the coastline was presumably located 5–10 km seaward of the present one (SINDOWSKI 1973; FLEMMING and DAVIS, 1994). During this period, tidal currents and waves penetrated further into the hinterland and eroded the exposed higher parts of the former submerged Pleistocene landscape. Large quantities of reworked sediment were shifted landward, building up a wedge-shaped body of Holocene coastal deposits. This sediment body, striking parallel to the coastline, has a width of 10 to 25 km. In the Weser- and Elbe estuary, its length goes up to 80 to 100 km. While the accumulation wedge tapers off towards the mainland, it can reach a thickness of more than 40 m (AHRENDT, 2006) at its relatively steep seaward slope. Here it mainly consists of fine- to medium-grained sand.

With a decelerating sea level rise from 7,000–3,000 BP (BEHRE, 2003) coupled with an increase of the tidal range from 1.3 m to 2.2 m (FRANKEN, 1987), the coastal zone was formed by salt marshes, tidal flat deposits and in parts by barrier islands with dunes of a height of up to 30 m. With the phase of a slower sea level rise of only 0.11 m /century (BEHRE, 2003) over the last 3,000 years BP, the Wadden Sea area was formed. This area is characterized by a complex pattern of marine and terrestrial deposits, reworked postglacial siliclastic drainage material of the underlying Pleistocene drainage deposits as well as several peat layers, which were deposited between tidal, brackish and lagoonal sediment layers. In the "drowning" landscapes, an also rising ground water table resulted in wide-ranging water logging and the formation of peat bogs. Although subsequent frequently eroded by the transgressing sea, these basal peat layers often mark the beginning of the Holocene depositional history of an area (STREIF, 2004).

Although regional differences exist, which are e.g. due to the palaeo-geomorphology, the characteristic series of Holocene deposits consists of strata of fine-grained sand, silt, clay and intercalated layers of peat (Fig. 5). Within this alternating sequence, marine and brackish deposits overlying peat mark phases of transgression. On the other hand, regressive overlaps with peat overlaying brackish and marine sediments indicate a seaward shoreline displacement (STREIF, 2004) due to phases of a dropping or – more likely – stagnating or slowly rising sea level.

The surface of the Holocene accumulation wedge is almost flat. Its elevation only varies between –1 m to +2 m in relation to the German reference datum NN. This also holds for the North Frisian islets (Halligen), which are relicts of a former very much wider marshland that was partly destroyed by storm surges in the 14$^{th}$ and 17$^{th}$ century. On the barrier islands along the German North Sea coast, the land elevation is often higher. This is either related to the presence of Holocene coastal dunes (East Frisian barrier islands) or to a combination of Holocene deposits combined with elevated cores of Pleistocene (Amrum and Föhr Island)

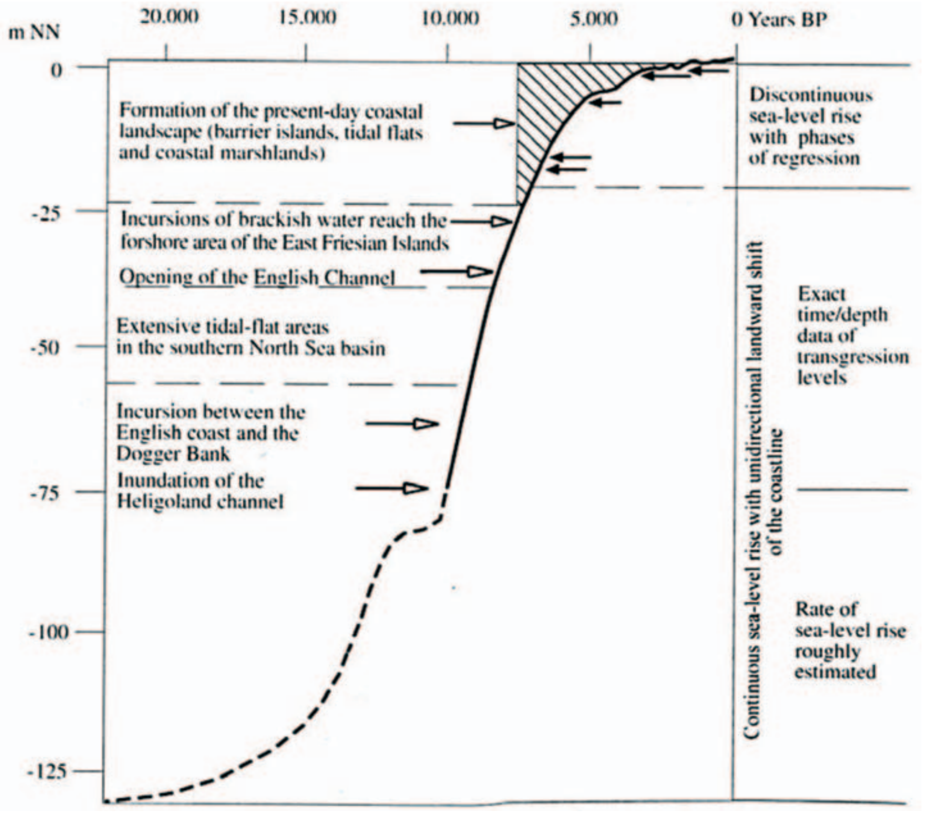


Fig. 4: Relative sea level rise since the last glacial maximum. The age is given in conventional $^{14}C$ dates. The marine transgression is divided into 3 phases. The last phase, which lasts since 7,100 years BP, led to the development of the present landscape (STREIF, 2004)

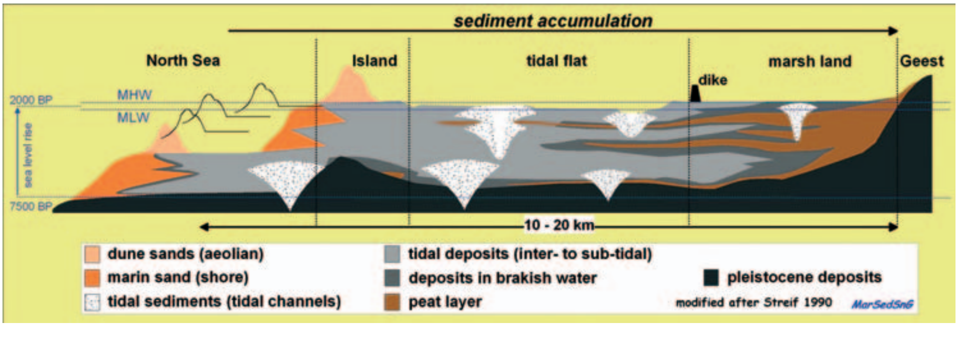


Fig. 5: Schematic cross-section through the Holocene coastal accumulation wedge; example from Lower Saxony (STREIF, 1990; modified)

and/or early Neogene age (Sylt Island), which can be found on the North Frisian barrier islands. The typical elongated shape of the East Frisian barrier islands with sandy foreshores and beach and dune sediments on the coast exposed to high wave energy, and with fine-grained organic-rich deposits on the sheltered lee indicate that their formation is very much related to the ongoing interaction of mobile sediments with currents and waves (DAVIS, 1994). However, the presence of erosional relicts of Pleistocene deposits in depths of only –5 to –10 m NN beneath almost all islands indicates that in a former stage of their geological evolution they also had a core of older deposits. As can be seen on the island of Sylt today, these cores are directly exposed to the forces of the rising water level and at least are partly erode during periods of lower water levels. These cores were finally inundated, and – in their temporarily last stage of island evolution –, they were buried under younger, now sea-born sediments. Under conditions of a presumably rising sea level, the development of these islands is characterised by an almost continuous landward shift of the shoreline.

Likewise elongated accumulation bodies located in Dithmarschen (north of the Elbe estuary) and on the Eiderstedt peninsula, on the other hand, underwent a completely different depositional evolution. Doubtlessly, in a former stage of the Holocene coastal evolution, these gravel and coarse sand accumulations were formed under strong wave and current action (HUMMEL and CORDES, 1996). A subsequent and in some areas still ongoing intensive import of sea-born sediments into this region leads to a pronounced seaward shift of the shoreline. Today these former wave exposed island-like structures are still visible as elongated low elevations in the flat marshlands some 10 kilometres inland.

## 3. Baltic Sea

The Baltic Sea is a non-tidal intra-continental shelf sea with a narrow connection to the North Sea through Kattegat and Skagerrak (Fig. 6). It is the second largest brackish water body in the world, covering an area of 412,560 km², with a volume of 21,631 km³, extending 1,300 km in S – N direction (54°–66°) and 1,000 km in E – W direction (10°–30°). The maximum width is approximately 300 km, the average depth is 52 m (HELCOM, 1990) and the deepest part, Landsortdeep, is 460 m in depth. The bathymetry is controlled by the presence of sills and deep basins, which developed mainly during the last glacial period. These basins increase in size and depth from West to East (Mecklenburg Bight, 25 m deep; Arkona Basin, 45 m deep; Bornholm Basin, 100 m deep; Gotland Basin, 250 m deep).

### 3.1 Palaeozoic to Palaeogene Development

The geological basement of the northern and central part of the Baltic Sea is dominated by Precambrian crystalline rocks belonging to the East-European-Craton. They have undergone a long term uplift until today forming the Scandinavian mountain ranges. Palaeozoic sediments (older than 251 million years) have been deposited on the southern rim of this craton, forming parts of the East European Platform (Fig. 1). Separated by the huge, more than 2,000 km long "Sorgenfrei – Tornquist – Teisseyre – Fracture Zone" (KATZUNG, 2001), the West- and Middle European Platform is dominated by sediments of Mesozoic age (251–65.5 million years old; EHLERS, 1990). Their basement is formed by deposits of Permian age (see Tab. 1), a period, when arid climate was dominating and the deposition of terrestrial sediments took place. At the end of the Perm period, marine conditions developed due to

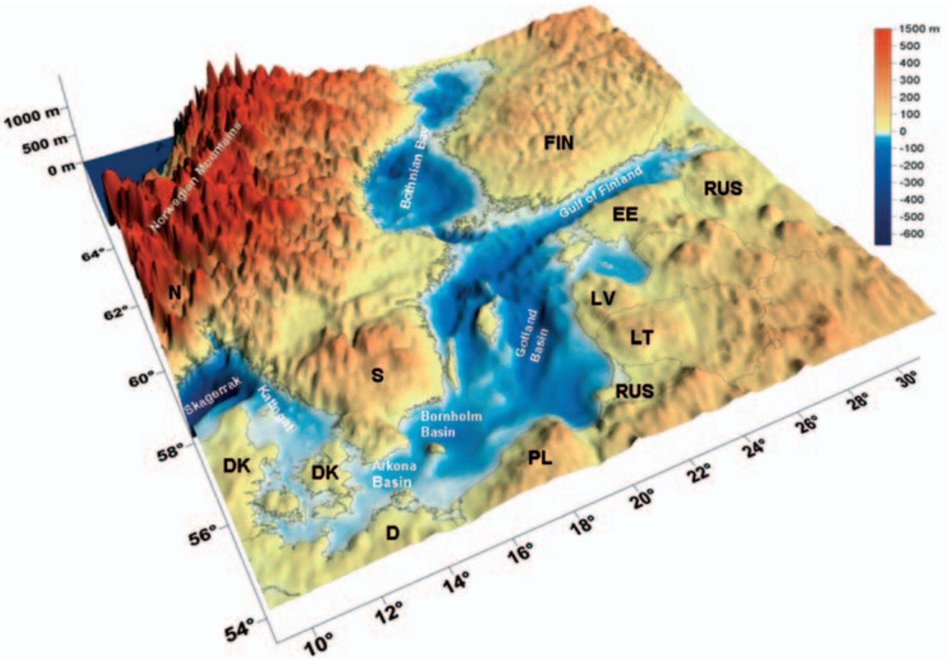


Fig. 6: The bathymetry of the Baltic Sea basin (based upon data abstracted from SEIFERT, TAUBER and KAYSER, 2001)

transgression from the North Sea. At that time, the continent was located approximately 25° north. The climate was subtropical – arid, and as the marine basin was shallow, layers of salt were deposited due to high evaporation. While in the North Sea basin the thickness of salt layers reaches up to 1,200 m, a maximum thickness of only 335 m was observed e.g. 50 km east of Ruegen Island, Baltic Sea (Petrobaltic Drilling K5-1/88; LINDERT et al., 1993). For this reason, the influence of salt tectonics is decreasing from West to East. In the most eastern German sector of the Baltic Sea, salt deposits are rare (see Fig. 2), and their thickness is less than 100 m (DUPHORN et al., 1995). Salt-tectonic was not active here.

During the Mesozoic Era, the general tendency of deposition continued. The thickness of the deposits decreased generally towards North, and close to the Rinkøbing-Fyn-Height (see Fig. 1) the layers are partly tapering off. Due to eustatic water level fluctuations and the exposure to hydrodynamic influence, deposits are ranging from fine- to coarse-grained sediments reflecting their depth of deposition. At the end of the Jurassic period (200–145.5 million years BP, see Table 1), limnic sediments were deposited. The Cretaceous period (145.5–65.5 million years BP) is dominated by a huge transgression reaching its peak during upper cretaceous time when subtropical oceanic conditions prevailed. Typical deposits are chalk layers which can be observed at the cliff-coast of Ruegen and Møn Island. The carbonate content of these layers is 90–98 %. The end of the cretaceous period is marked again by a huge regression. During the Palaeogen (62.5–23 million years BP), several transgressions and regressions took place, covering the entire southern Baltic Sea area during certain periods.

### 3.2 Neogene

Regression continued during the beginning of the Neogene, 23 million years ago (LOURENS et al., 2004). At the end of this period during the Pliocene Epoch, the climate became colder. The Baltic Sea area was marked by the development of a river system, the Baltic Main Stream, flowing in a NE–SW oriented depression, draining NE-Europe and transporting huge amounts of fluvial sediments which were mainly deposited as Kaolinitic sand in the North Sea basin. This is the material which is dredged offshore in the North Sea today to be used for beach- and dune nourishment.

#### 3.2.1 Pleistocene Development

The younger history of the Baltic Sea was dominated by decreasing temperatures over the past 2.4 million years and at least three glacial periods, when ice was advancing from Scandinavia towards NW-Europe. The depression already used by the Baltic Main Stream was carved out further by these ice advances, of which the latest formed the specific geomorphological shape of the basins, bays, fjords and coastal areas as we see it today (Fig. 6). Marginal contours of the ice cover are formed by end-moraines, indicating how far these advances and sub-advances, representing an oscillating ice front, were reaching. The distance between these different contours of the latest ice advance increase from West to East (Fig. 7). Between them melt-water sediments composed of silt, sand and gravel have been deposited. As such, the amount of sand and gravel below the veneer of the modern, post-littorina marine sediments increases from west to east, namely from Schleswig-Holstein via Mecklenburg-Vorpommern to Poland.

The whole south-eastern to south-western part of the Baltic Sea, the coastal areas of Latvia, Lithuania, Russia, Poland, Germany and Denmark, are built up of soft-rock Quaternary deposits (WINTERHALTER et al., 1981), mainly of Weichselian age. On the other hand, the northern part of the Baltic Sea is mainly composed of hard rock (LAMPE, 1995). There are only a few exceptions where hard rock is exposed along the south-western Baltic Sea, e.g. parts of Rügen Island (Germany) or Møns Klint (Denmark). Here, cretaceous deposits have been pushed up by glaciers during the latest ice advance.

Glacio-isostatic movement and climatically controlled eustatic sea level fluctuations have caused transgressions and regressions in the Baltic Sea and its precursors during the Holocene. From the early to middle Holocene, the Baltic Sea underwent 4 evolutionary stages (Fig. 8).These were the Baltic Ice Lake, the Yoldia Sea, the Ancylus Lake and the Littorina Sea (BJÖRK, 1995; ERONEN et al., 2001; LAMPE, 2005). As a result of the interaction of uplift rates and changes in relative sea level alternating fresh-, brackish- and marine water conditions occurred. The Holocene history of the precursor of the Baltic Sea started with the deglaciation and the opening of several drainage channels around 13,000 years BP. Due to these openings, the water-level dropped to at least – 25 m MSL (mean sea level) and caused extensive erosion in the lower river courses. During Alleröd, the waterlevel rose again from –40 to –20 m MSL (see Fig. 9). This phase (Bölling to Younger Dryas) is called Baltic Ice Lake. The opening of the gap at Mt. Billingen around 10,300 years BP due to the continuous retreat of the Scandinavian ice sheet from the southern Swedish mountains caused a drop of the water table to about –40m MSL (BJÖRCK, 1995). The early Holocene incision phase started with the Yoldia Sea (JANKE, 1978). It was the first connection with the Atlantic – North Sea system, which lasted only for some 700 years. By an accelerated isostatic uplift of Southern


Fig. 7: Ice margins of the Weichselian Glacial in the Southwestern Baltic Sea (modified after LANGE, 1984. F = Rosenthal Step, G = Velgaster Step, H = Nordrügen Step, E = margin of Sehberg Advance)

Scandinavia versus the postglacial sea level rise, the corridor to the North Sea was closed initiating a second freshwater phase – the Ancylus Lake period. This freshwater period began with a water level rise to a maximum highstand of –10 m to –8 m MSL (KATZUNG, 2004) followed by a water level drop during the second half of the Ancylus Lake period. For the first time now, the water gradually penetrated into the region of the present-day German coast (LEMKE, 1998). This was due to the slowly subsiding process of this area while Scandinavia is experiencing isostatic uplift (see Fig. 8).

Due to global eustatic processes, the Baltic Sea was again connected to the North Atlantic via the North Sea approximately 7,900–7,200 years BP. It is called the Littorina transgres-

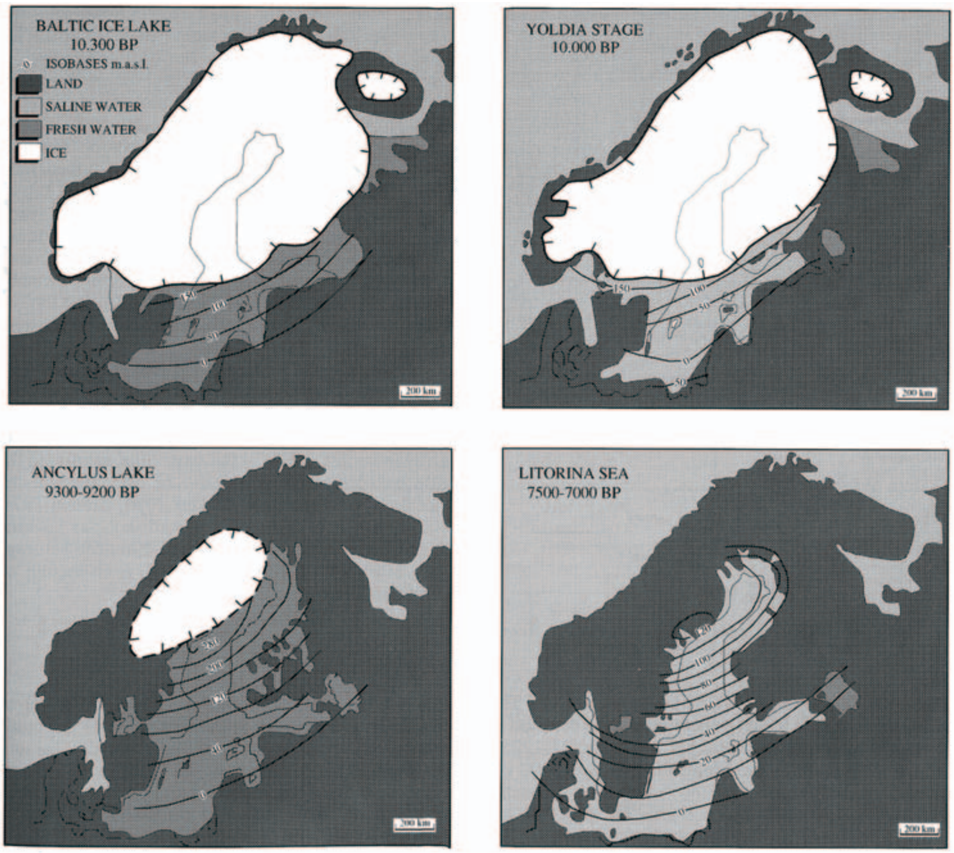


Fig. 8: The development of the Baltic Sea during the late glacial and postglacial (ERONEN et al., 2001)

sion. Since this time, the connection to the North Sea has been permanent. The first period of the Littorina Sea is marked by a very rapid water level rise with rates up to 2.5 cm/year (Fig. 7). This transgression into the south-western Baltic region led to a widespread inundation of the pre-existing glacial relief without any erosion. The landscape was just drowning. The typical landforms to be submerged were pronounced ridges and terminal moraines, widespread areas of undulating basal moraines and imbedded meltwater channels, all associated with ice- and glacier-tongue shaped troughs and fjords. During the period of rapid sea level rise, all terrain lying below –5 m of the present MSL was flooded.

Approximately 6,000 years BP, the water level almost reached its present position (JANKE and LAMPE, 2000). At this stage, wave impact as well as nearshore sediment dynamics began to effectively modify the coastal profile by intensive redeposition of sediments. Cliff coasts were eroded and cut back; longshore sediment transport led to the development of spits, sandy hooks and beach ridges (SCHWARZER et al., 2003). In the shallow water, small islands, built up of morainic material, were connected by these growing spits, initiating the development of the famous baymouth ("Bodden") coast (the term "Bodden" is the local name for the shallow, semi-enclosed coastal lagoons and backwaters behind the exposed Baltic Sea

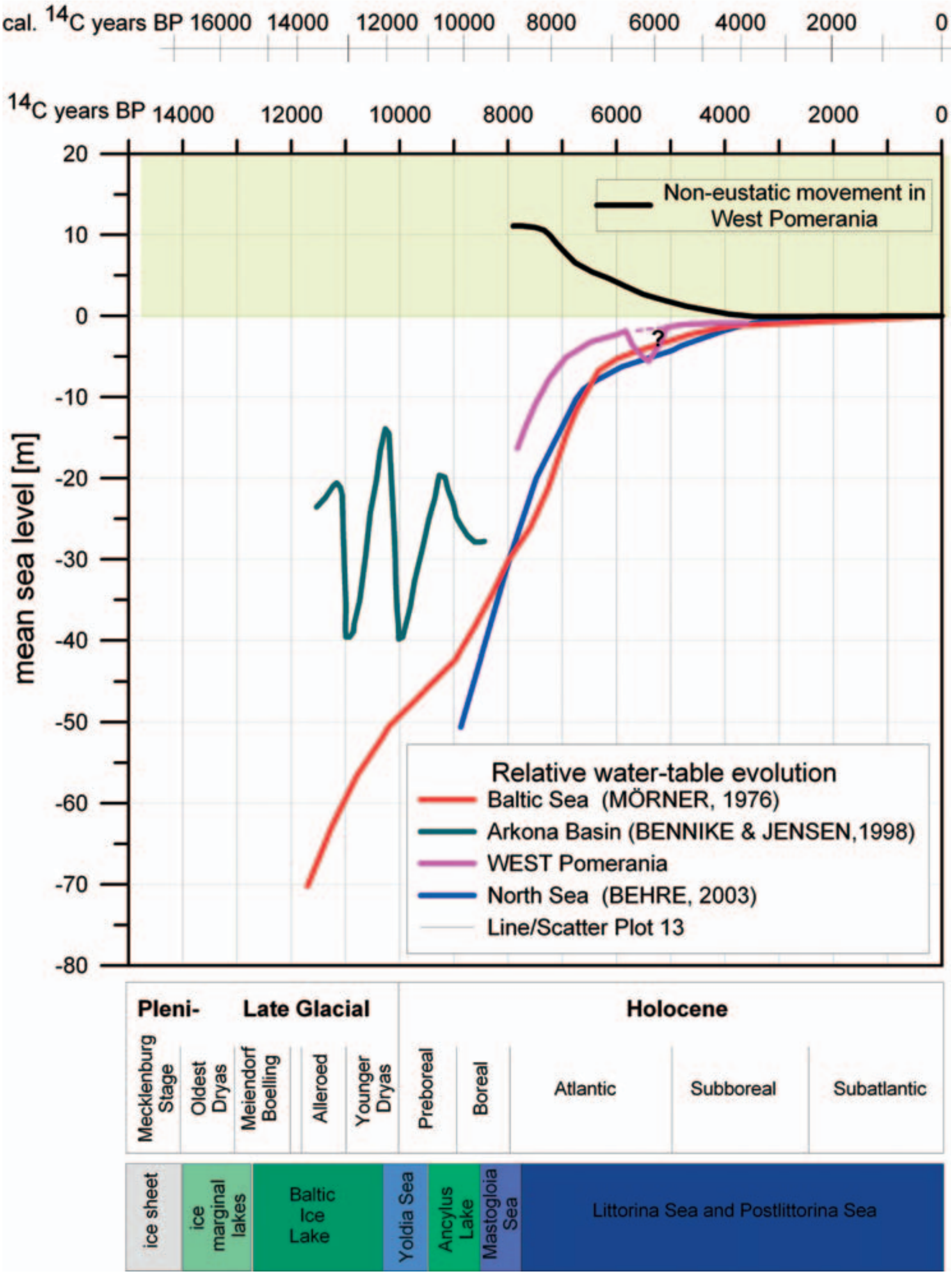


Fig. 9: The relative evolution of the water table in the West Pomeranian coastal area compared with the eustatic curves derived from MÖRNER (1976) and BEHRE (2003) and the relative evolution of the water table in the Arkona Basin according to BENNIKE and JENSEN (1998) and JENSEN (1995). In the upper part of the diagram, the estimated non-eustatic movement component is shown, calculated as the difference between the eustatic and the relative water table (LAMPE, 2005, modified)

coast). Rügen Island as well as the Fischland-Darss peninsula are excellent examples where several small islands, consisting of a core built up of Pleistocene deposits, were connected by beach ridges. These ridges are built up of material which is eroded from cliff sections and offshore abrasion platforms: Then it is transported by longshore currents (BELLEC et al., 2008). Rügen, the largest German island, was formed by these cliff falls and abrasions.

In response to glacio-isostatic rebound, the northern part of the Baltic Sea is still dominated by an uplift relative to the present sea level, with rates up to 9 mm/year in the Bothnian Bay (MÖRNER, 1977; HARFF et al., 2005, see Fig. 9). In the southern part, subsidence rates of up to 2 mm/year occur (MEYER 2002; MEYER and HARFF, 2005). Such subsidence generally causes erosion and coastal retreat along the entire southern Baltic Sea coastline, because these areas consist of an alternation of cliffs and lowlands, built up of soft glacial and postglacial deposits.

Based upon the modelling of large scale palaeo-coastline changes since the onset of the Littorina transgression 7,900 $^{14}$C years BP, the sea level in the northern part has dropped significantly, in some areas by more than 200 m (CATO, 2004). This process has resulted in a regression, by far out-weighing the southern transgression. According to MEYER and HARFF (2005) the spatial extent of the Baltic Sea has diminished by approximately 30 % since then, whilst the volume has decreased from 47,000 km$^3$ to 22,000 km$^3$, or by 47 %.

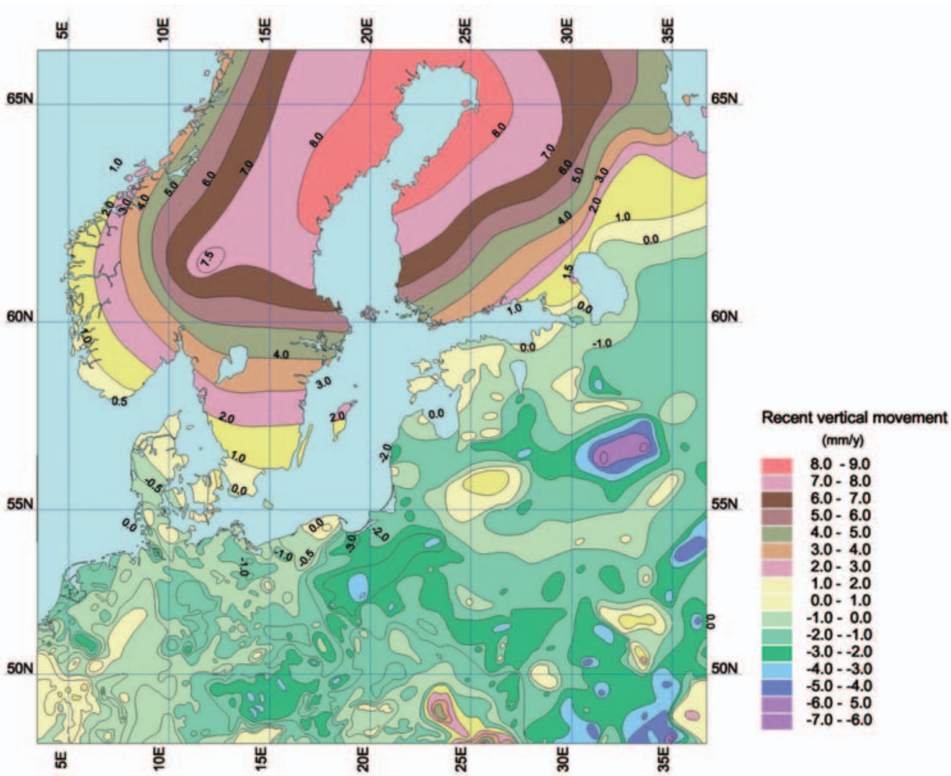


Fig. 10: Present isostatic movements around the Baltic Sea Basin (HARFF et al., 2001)

## 4. Conclusion

The data presented show well-based facts about the development of the North Sea and the Baltic Sea. However, they also point to numerous remaining uncertainties. From the results presented above, it is obvious, that the correlation of postglacial sea level fluctuations between the North Sea and the Baltic Sea is complicated because of both a lot of local phenomena (compaction, influence of salt tectonics) and far-field factors (gradient in isostatic uplift, neotectonics), which are superimposed. These geologically caused movements have to be correlated with the eustatic water level fluctuations. Up to the present, Holocene sea level curves from the Baltic Sea and the North Sea do not match due to a lack of comprehensive data sets, especially from offshore regions.

The younger geological development of the North and Baltic Sea documents, that the natural coastal depositional system has a relatively high capacity to adapt to a fluctuating – but especially to a rising sea level. This, however, is often associated with a dislocation or even breakup and/or a new formation of morphological elements. Since this does not in any case fit with human interests, coastal engineering efforts have been necessary in the past and will be necessary in the future to manage the coastal anthroposphere.

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Die Küste, 74 ICCE (2008), 1-417

# The Historical Geography of the German North-Sea Coast: a Changing Landscape

By DIRK MEIER

Contents



## 1. The Natural Landscape and the First Settlements in the Clay Districts from Prehistoric Time until 1000 AD

One of the earliest geographic descriptions of the German North Sea coast is from the Roman Pliny the Elder (23/24-79 AD). In his *Historiae Naturae* (XI, 2pp., 405 pp) he wrote: *There, twice in each period of a day and a night the ocean with its vast tide sweeps in a flood over measureless expanse, covering up natures age-long controversy and the region is disputed as to whether it belongs to the land or the sea. There, a miserable race occupies elevated patches of ground or platforms built up by hand above the level of the highest tide experienced, living in huts erected on the sites chosen, and resembling sailors in ships when the water covers the surrounding land, but shipwrecked people when the tide has withdrawn, and round their huts they catch the fish fleeing with the receding tide. It does not fall to them to keep herds and live on milk like the neighbouring tribes, nor even to fight with wild animals, as all woodland growth is banished far away. They twine ropers of sedge and rushes from the marshes for the purpose of setting nets to catch the fish and they scoop mud in their hands and dry it by the wind more than by sunshine, and with earth as fuel warm their food and so their bodies, frozen by the North-Wind. Their only drink is supplied by strong rainwater in tanks in the forecourts of their homes. And these are the races that if they are nowadays vanquished by the Roman nation say that they are subjected to slavery. That is indeed the case: fortune often spares men as a punishment*.

Probably Pliny has visited the North Sea region after a storm flood during a campaign of the Roman fleet against the Germanic tribe of the Chauci (Fig. 1), which had been documented by other Roman historians (MEIER, 2006) During this time a natural landscape of salt marshes and large peat bog areas dominated the environment.

### 1.1 Late Bronze Age, Pre Roman and Roman Period

Around 7500 years BP during the rise of the Holocene sea level after the last Ice Age the North-Sea extended to the edge of the Saale-Glacial moraine landscape of Lower Saxony and Schleswig-Holstein (Northwest-Germany) (STREIF, 2004; EHLERS, 1988). Around this time the evolution of the present-day coastal landscape started when the sea level reached a position of about 23–25 m below its present elevation. From about 7500 BP onwards, temporary


Fig. 1: Salt marshes, peats and coastline along the North Sea coast coast with Roman fleet expeditions and Germanic settlements. Fig. Dirk Meier

reversals are indicated by regressive overlap of peat layers on clastic tidal flat and brackish sediments. Ideal conditions for the formation of widespread peat layers along the coast between the Ems and Elbe estuary apparently prevailed between 4800 and 4200 BP and between 3300 and 2300 BP. At some locations peat layers date between 2000 and 1600 BP. Within a phase of a generally rising sea level the peat layers indicated a temporary decrease of water levels (Streif, 2004).

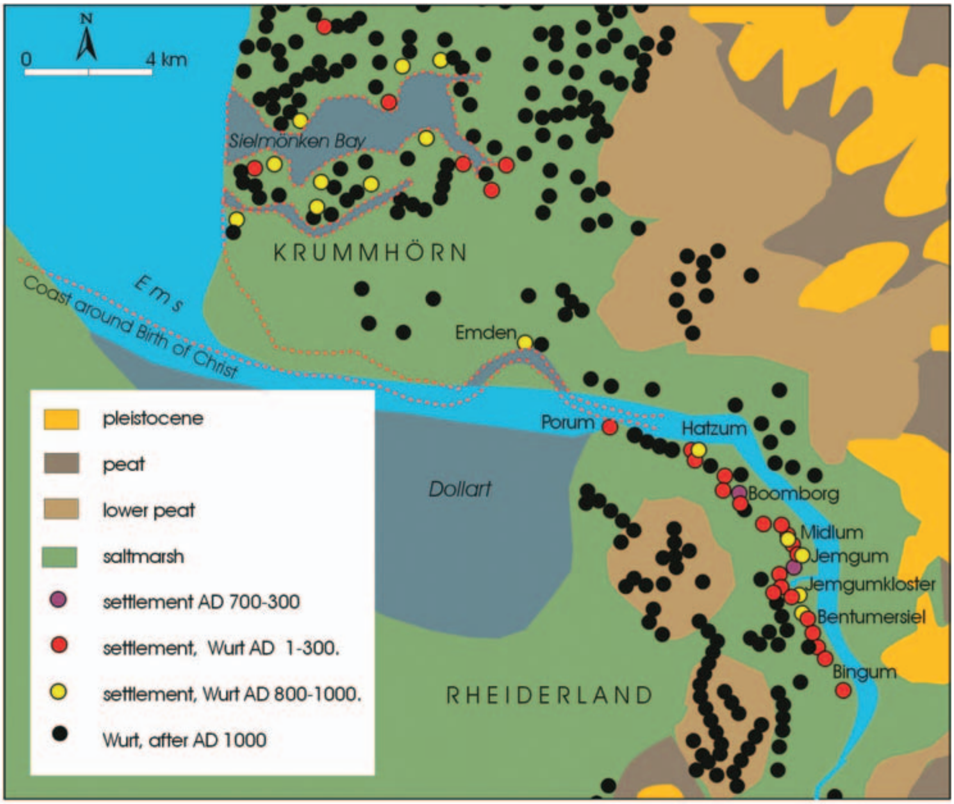


Fig. 2: Estuary of the Ems with settlements and Wurten. Fig. Dirk Meier

First marshe developed along the rivers, since Pre-Roman time along the North-Sea coast. The oldest settlements are known from the Weser and Ems river marshes, established during a period of water level regression (BEHRE, 2004). On the river bank of the Lower Weser a long-aisled stable house was erected in the 10/9th century BC. Botanical investigations have shown that arable farming was practised and that the settlement was situated in the upper part of a *Weichholzaue*, dominated by *Alnus*. In the beginning of the Pre-Roman Iron Age between 700 and 660 BC, early settlers cleared also the uppermost part of the riverbank forests along the river Ems. Early ground level-single storey settlements (*Flachsiedlungen*) of this time are known from Boomborg-Hatzum (Fig. 2) and other places (HAARNAGEL, 1969). The main base of the economy of these settlements was stock-farming. Around 300 BC, settlement locations along the Ems were abandoned during a period of higher water levels and subsequently covered with sediments (MEIER, 2006).

The most active phase of this new transgression with the sedimentation of clastic deposits lasted in northern Germany for only two and half centuries, i.e. 400–150 BC (Fig. 3). Since 100 BC, salt marshes have developed on the surface of these deposits in the northern Netherlands as well as in Lower Saxony and the southern part of the North-Sea coast of Schleswig-Holstein between the estuaries of the rivers Elbe and Eider (BEHRE, 2004). These layers of soil deposited during a time of receding sea levels around the Birth of Christ.

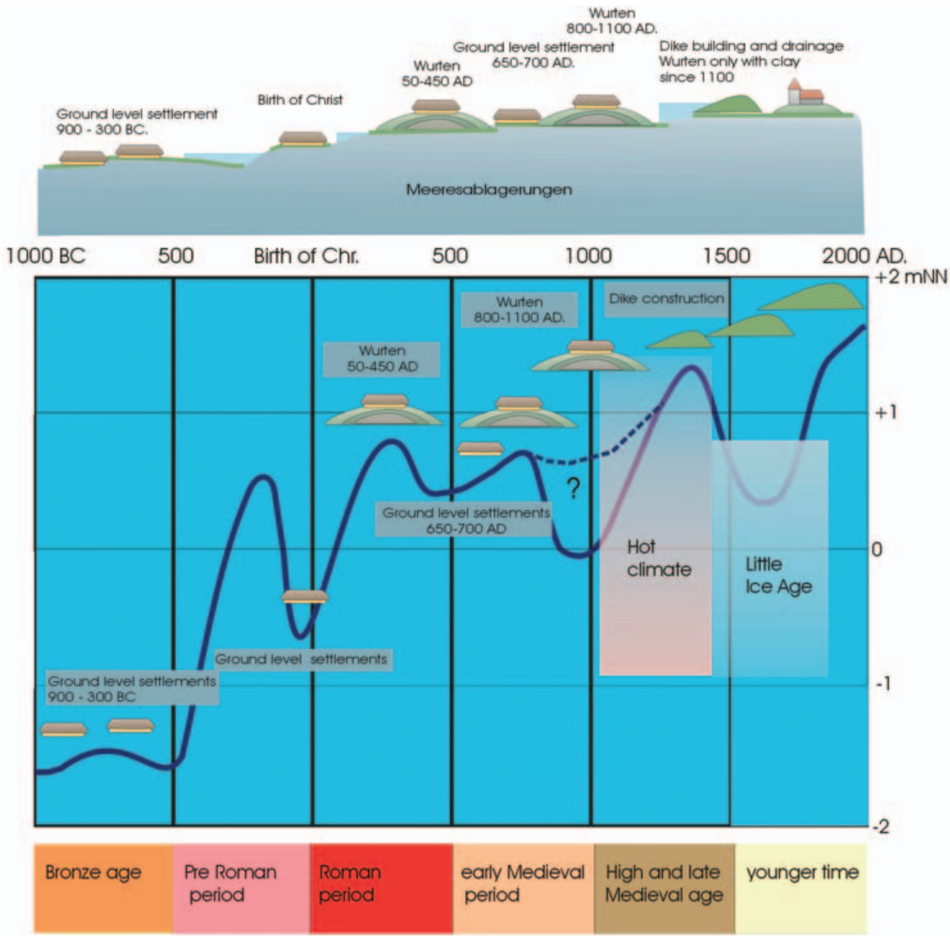


Fig. 3: Connection between Sea level, ground level settlements and Wurten as a model.
Fig. Dirk Meier

Another important consequence of this regression is the start of the formation of the East-Frisian barrier islands.

During this time, the salt marshes of Lower Saxony and those in the southern part of Schleswig-Holstein were inhabited. To the west, in the northern Netherlands, the settlement history is rather different because the clay districts of the provinces of Friesland and Groningen date back to approximately 600 BC. During the time of receding water levels around the Birth of Christ, ground level settlements were founded on high banks along the estuaries of the Ems, the Weser and Elbe in North-West Germany as well as in the clay district along the North-Sea coast. Examples are the Krummhörn around the Bay of Sielmönken north of the Ems estuary, Wangerland North of Wilhelmshaven, Butjadingen between the Jadebusen and Weser as well as the Land Wursten in Lower Saxony (Meier, 2006). Most of these settlements were founded on high silted banks near the coast or river banks because large parts of the inland, e.g. the so-called Sietland, was covered with peat.

The inhabitants of these settlements protected themselves by constructing their houses on artificial earth mounds, called *Terpen, Wierden, Wurten or Warften*. These mounds had to be raised continuously due to rising sea levels or storm surges. The larger mounds (*Wurten*) with their numerous cultural layers, erected to protect people against storm surges, can in turn sometimes be used as fossil tide-gauges today. Some of these were 'village mounds', extended to protect entire communities e.g. Feddersen-Wiede in the Land Wursten/Lower Saxony (Haarnagel, 1979), Süderbusenwurth in Dithmarschen/Schleswig-Holstein (Meier, 2004, 2005) or Tofting in Eiderstedt/Schleswig-Holstein (Bantelmann, 1955).

The large excavation of the Federsen Wierde in Land Wursten north of the Weser estuary has helped to form our perception of a marsh settlement in the Roman period (Fig. 1). The development started with a little group of stable houses which were erected on a high beach ridge. Earth mounds were erected and raised starting in the 1st century AD. From the 2nd to the 4th century AD, a larger village mound existed before the settlement was finally abandoned during the 5th century AD (Haarnagel, 1969).

The salt marshes of Dithmarschen (Schleswig-Holstein), which have grown westward from the moraines and beach ridges of the older coastline since 500 BC, have been settled since the early 1st century AD. The earliest settlements were placed on lines with a southern-north orientation. Between 1998 and 2002, extensive excavations in Süderbusenwurth south-west of Meldorf have pointed out the existence of 'Wurten' with stable houses on a higher bank of a tidal channel around 50 AD. Consequently, they were raised after 150 AD (Fig. 1). The elevated settlement was abondoned at the end of the 3rd century AD. In the northern salt marshes of Dithmarschen small settlements are arranged on two lines west of the Pleistocene hinterland (Meier, 2004, 2005).

Larger mounds (Wurten) existed also along the Eider estuary (Fig. 1). The best known example is Tofting near Tönning in Eiderstedt, which was founded in the 1st century AD on a high silted-up river bank northward of the Eider. The settlement consisting of a group of stable houses was raised with dung and clay in the following centuries, before it was abandoned during the 6th century AD (Bantelmann, 1955).

North of Eiderstedt the present North-Frisian Wadden-Sea was a peat bog landscape east of a barrier coast of beach ridges and old moraines of the present islands of Amrum, Föhr and Sylt. Therefore, settlements of the Roman period are only known from the moraines (Bantelmann, 1967; Meier, 2006; Müller-Wille et al., 1988).

The economy of these mound-settlements was based on stock-farming with cattle grazing in the salt marshes around the settlements. Small-scale agriculture based on plants such as horse beans *(Vicia faba)*, barley *(Hordeum vulgare)*, oats *(Avena sativa)*, Emmer *(Triticum dicoccon)* and flax *(Linum usitatissimum)* were only possible on higher banks during the summer months.

The first phase of the colonization of the clay district ended in most areas late in the 5/6th century AD. This may not have been the result of more frequent storm surges but also the consequence of the Migration period. There is no doubt that groups of Angles and Saxons migrated to England, but the question is how large these groups were. Too little is known about the settlement pattern in the time between 400 and 600 AD in North-Western Germany. In other clay districts such as Westergo in Frisia the colonization continued into and during the Migration period. This may also apply to East-Frisia, as recent excavations indicate (Bärenfänger, 2005). In Westeraccum, colonization started with a ground level settlement around the Birth of Christ. In the following centuries, the 'Wurt' was raised and continued to be a settlement during the 6 and 7th century AD (Fig. 4).

## 1.2 Early Medieval Time

Favourable natural conditions permitted the renewed colonization of the salt marshes in the North-West German clay district starting in the 6/7th century AD. During this time, new salt marshes had developed (Fig. 4). At some areas, the coastline shifted westward, in other areas large bays were generated by floods inside the old marshland, such as the Lay Bay,


Fig. 4: Salt marshes, peats and coastline of early Medieval time. Fig. Dirk Meier

the Harle Bay and the Crildum Bay in Lower Saxony. Along the shorelines of these bays 'Wurt' settlements were founded on higher banks. The renewed colonization by Frisian settlers in Lower Saxony, starting in the 7th century AD, began with ground level settlements during a time of a decreasing sea levels. The start of this phase was dated dendrochronogically at Upleward in the Krummhörn to be around AD 670 (Bärenfänger, 2005). Similarly, in Oldorf on a peninsula of the Crildum Bay in the Wangerland north of Wilhelmshaven, the start could be timed at AD 630 (Behre, 2004; Schmid, 1994). In the course of the 8th century other salt marshes – such as the Krummhörn between the Ems estuary and the Lay Bay, Butjadingen and Land Wursten were settled again. Also the river banks along the Elbe were densely populated (Meier, 2006).

The resettlement of the old salt marshes of Dithmarschen between the Elbe and the Eider by rural people started at the end of the 7th century AD. At this time, this area belonged to three North Elbian Saxonian tribes, which are described by Adam von Bremen in the history of the church of Hamburg (II, 17) with the words: *Transalbianorum Saxonum populi sunt tres. Primi ad occenaneum sunt Tedmarsgoi, et eorum ecclesia mater in Melindorp* [Meldorf]. Charlemagne conquered these Saxonian tribes in AD 798. During this time, the salt marshes of Dithmarschen were one of the regions of clay districts in Schleswig-Holstein with the highest population. In southern Dithmarschen the settlements of this period occur in the same area as the settlements of Roman times (Meier, 2004; Meier, 2006). In the northern part between the present Bay of Meldorf and the Eider estuary the early Medieval 'Wurten' were established west of the region of the old Roman settlements, because bogs had spread over the inner part of the salt marshes after AD 400. The best example of a 'Wurt' of the early Medieval time with many habitation layers is Wellinghusen near Wöhrden (Meier, 2001a). Here, a ground settlement was established at the end of the 7th century AD. Since the beginning of the 9th century the new stable houses were erected on single 'Wurten' (Fig. 4 and 5). Later, a large village mound evolved and was raised several times to an elevation of +6,2 m NN until the 14th century AD. The 10th century saw the beginning of an increase in

Fig. 5: Excavtion of the village Wurt Wellinghusen, Dithmarschen. Fig. Dirk Meier

colonization and resulted in the establishment of new 'Wurten' such as Hassenbüttel or Wesselburen (Meier, 2001a, 2006).

The colonization of the salt marshes north of the river Eider, which occurred during the 8th century AD, is connected with a Frisian immigration (Fig. 4). On the higher river banks large mounds were built in Elisenhof near Tönning (Bantelmann, 1975) and Welt (Meier, 1997). Botanical investigations show that extremely halophytic conditions existed around these settlements. In Elisenhof a group of stable houses, surrounded by fences, were built as ground level settlements and later on raised with dung and clay. As during the Roman period, livestock was the economic basis of these settlements. Also the beach ridges of Eiderstedt were populated at that time.

Unfavourable environmental conditions due to the extensive peat bogs and swampy areas along the many parts of the North-Frisian coast prevented colonization before AD 1000 (Hoffmann, 1988). Only the Pleistocene areas and flooded salt marshes in the western part of the tidal flats around the present island of Pellworm and Hallig Hooge were inhabited. These findings indicate that in early Medieval times salt marshes, located inland of the sand ridges, existed in the western part of the present North-Frisian Tidal flats. Excavations during the "Norderhever-Project" have discovered a ground level settlement of the 9/10th century AD, which was flooded in the late Middle Ages (Müller-Wille et al., 1988). By then, the sea level had risen so much that people could no longer live in houses built on top of the marsh land in North Frisia. Beach ridges in the West had been eroded and destroyed by waves and currents and, consequently, salt marshes were flooded too often during storm surges. Thus, mounds (Wurten) had to be built to protect against the rising waters. A number of settlements and burial mounds are also recorded on the Pleistocene deposits of the islands of Amrum, Föhr and Sylt.

## 2. The Cultural Landscape: Dike Building and Drainage from 1100 to 1634

Since the high Medieval Age, the entire area of the sea and river marshes were intensively cultivated and more densely populated than ever before. In the 11th and 12th century the building of dikes and drainage of land began. Initially, the dikes were not high enough to protect low-lying land against higher storm surges. More salt marshes – such as those in the northern part of Eiderstedt in Schleswig-Holstein – were colonized, and the landward swampy areas were drained. The local people generally took the initiative for the construction of dikes. Economic associations of high social standing and organised as cooperatives were established on larger 'Wurten' in the clay districts from East- to North-Frisia. Moreover, big chiefs ("Häuptlinge") in East-Frisia and "Regenten" in Dithmarschen constituted and maintained complete independence from outside nobles and landlords until the late Middle Age, in Dithmarschen until 1559. The wealth of the leading families was based on the systematic drainage and colonization of the inland marshes and bogs. This started the transition from a natural landscape to the present cultivated landscape (Meier, 2006).

The earliest dikes were built around the arable fields and meadows to keep out the occasional spring and summer floods. Examples of these local ring dikes, which are not very well preserved, are known from the northern part of Butjadingen near Sillens between the Jadebusen and the Weser estuary and Land Wursten in Lower Saxony (Behre, 2004). In the 13th century, these ring dikes were connected and raised. During this time the first sea dikes were erected along the coast in Land Wursten.


Fig. 6: East Frisia with Dollart and Jadebusen. Map of Blaeu in the *Theatrum Orbis Terrarum* (1645). Wikimedia

A consequence of diking was the water level increase during storm surges due to the reduction of the flood plains. Especially storms from the North-West forced water into the German Bight and the estuaries, and breaches of the dikes were common. Therefore, the dikes were built higher after the 13/14th century. Since the late Medieval time, heavy storm surges eroded and destroyed the higher banks near the coast. Salt water penetrated the low lying swampy areas and covered the peat with sediments. Due to extensive draining and subsequent compaction of the soil the surface had sunk. Several catastrophic storm floods eroded vast areas and created new large bays such as the Dollart in the Ems estuary and the Jadebusen between Wilhelmshaven and Butjadingen caused terrible losses of land, people and cattle (MEIER, 2006). In 1509 the Dollart reached its maximum extension which was close to six times its present size (Fig. 6). The reclamation of the lost land started after the middle of the 16th century. In the western part of East-Frisia the smaller bays of Sielmönken were embanked during the late Medieval times. The waters of the bay where cut off when, to the North, the Lay Bay developed in the 12/13th century and extended far to the South (BEHRE, 2004).

The largest of these catastrophes took place in the Jade area. The first Marcellus flood in 1219, the Lucia flood in 1287 and the second Marcellus flood in 1362 destroyed the dikes on the higher banks and salt water eroded the peat of the hinterland. The Jadebusen was formed and partly embanked in the following centuries (BEHRE, 2004; MEIER, 2006).

The sea dikes along the Dithmarschen between the Elbe and the Eider were built by cooperatives which had been organised in parishes. These cooperatives – in Dithmarschen called "Geschlechter" – decided about the location, design, construction and maintenance of dikes, drainage systems and sluices. In the newly drained areas the farms of the cooperative settlements were built on little single 'Wurten' against flooding from inland waters. These Wurten were arranged in the landscape like beads on a string. Their narrow strips of fields penetrated farther and farther into the peat marsh. Moreover, in the salt marshes of Dithmarschen new village 'Wurten' such as Büsum, Schülp or Lütjenbüttel were established. These mounds were mostly constructed with clay (MEIER, 2001a; MEIER, 2003).

On the low marshes of northern Eiderstedt numerous tidal channels separated island-like patches with mounds of clay. Even today these mounds still determine the appearance of the landscape in Westerhever, around Osterhever and Poppenbüll (MEIER, 2001b). Because salt water often inundated the low marshes, many of the mounds were suddenly raised in one construction effort. Excavations in Hundorf have documented an artificial mound of the 12$^{th}$ century with a height of +3 m NN, which was raised to +4 m NN in the 14$^{th}$ century (MEIER, 2001a).

The cooperatives, which settled on these 'Warften'. also built dikes around their cultivated land and within single house 'Warften' were constructed (Fig. 7). The historical sources give no clear information about the social structure of the society, the dike building and marsh colonization during the high medieval time. Therefore, this process can only assessed by an analysis of field forms, settlement patterns and the names of churches mentioned in historical documents. Inside the ring dikes irregular field strips were common. The best remaining example of this medieval landscape is the polder of St. Johannis. The surrounding

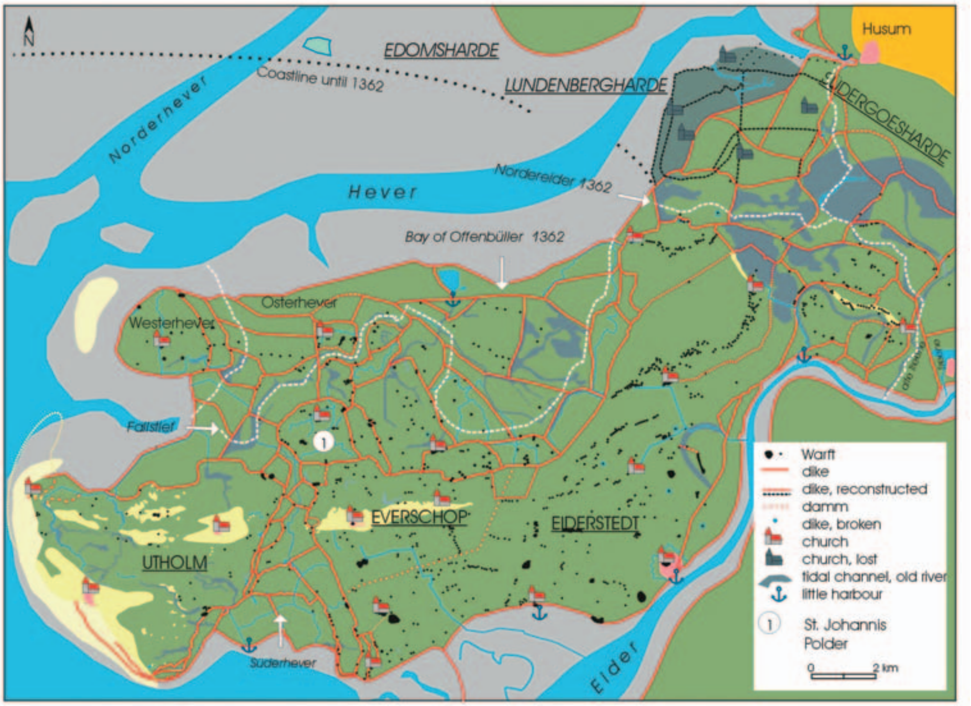


Fig. 7: Eiderstedt with Warften and dikes. Fig. Dirk Meier


Fig. 8: Coastline of the North Sea coast of Schleswig-Holstein before 1634 with older coastline before 1362. Fig. Dirk Meier

low summer dike, constructed with an inside and outside trench, reached a height of +1.5 m NN in the 12th century and was raised further in the late Middle Ages (Meier, 2001). Inside the polder we find the church and some single 'Warften'. To the West and Northwest, this ring dike of the St. Johannis polder borders on the wide Fallstief, which was not dammed off until the mid-15th century (Meier, 2001b). With the construction of higher dikes starting in the late Medieval time, the floodplain was reduced. The more recent dikes built by order of (feudal) authorities are characterized by greater height and straight lines and no longer follow natural landscape structures.

According to numerous archaeological investigations, the outer salt marshes of North-Friesland were not colonized until the early Middle Ages. Several archaeological sites around Hallig Hooge, as well as the island of Pellworm delimit an area of earliest Frisian habitation in the 8th and 9th century. Similarly, in the north-part of Eiderstedt the oldest 'Warften' date back to the 12th century. After building dikes, the low-lying marshes were also colonized between the 12th and 14th century (Müller-Wille et al., 1988).

Since the late Middle Ages North-Friesland (Uthlande) suffered great losses of land (Fig. 8). During the catastrophic storm surges of 1362 and 1634, a large part of the Uthlande between Eiderstedt in the South and the island of Sylt in the North was completely lost. The so-called Edomsharde with the famous port of Rungholt was totally destroyed. The salt marsh areas below Mean High Water (MHW), which had been occupied and cultivated by man since the 9th and 12th century, became a permanent part of the tidal flats. Cultural remains dating back to the 12th to 14th century AD have been unearthed around the younger Hallig Südfall. The reasons for the catastrophes are the geological development as well as the activity of the inhabitants draining and mining salt. Thus, in particular, the exploitation of the coastal area by its inhabitants has to be blamed for the disaster (Hoffmann, 1988; Meier, 2006).

However, the coastal population could not know that the geological subsidence of the land, which depended on the relief of the glacial surface and the type and thickness of the overlying marine deposits, had not yet come to an end. Large tidal channels and gullies such as the Norderhever cut into the salt marsh area. These tidal creeks followed old glacial smelt water valleys of the pre-Holocene landscape.

But also the settlers themselves contributed to the subsidence of the coastal marshland by the construction of dikes, systematic drainage of the area and, in particular, by peat cutting for the production of salt. Remnants of peat cutting activities can be observed in the vicinity of the Hallig Langeness and at other locations of the inner part of the North-Frisian tidal flats (Meier, 2006). In Medieval times the settlers in this area sustained themselves on the basis of agriculture and salt production. The raw material for salt production was the peat of the upper organic deposits. It was cut systematically over large areas. The earliest report of salt production is from Saxo Grammaticus (1180). Around the time of AD 1230, taxes had to be paid for salt production.

The second disastrous storm surge of 1634 also turned extended areas of coastal marshland into tidal flats. The large island of Strand was divided into the islands of Pellworm and Nordstrand as well as a group of smaller islands *(Halligen)*. Subsequent attempts of reclamation of these aeras were unsuccessful. They are still part of the cultural heritage and signs of the changing geography, landscape and settlement history.

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# Seabed Morphology and Sediment Dynamics

By Manfred Zeiler, Klaus Schwarzer, Alexander Bartholomä and Klaus Ricklefs

Contents



## 1. Introduction

The German coasts extend along two different seas, the tide-dominated North Sea and the intra-continental non-tidal Baltic Sea. While the North Sea has an open transition to the Atlantic Ocean, the Baltic Sea has its only connection to the world's oceans through the North Sea and the shallow and narrow Danish straits and sounds (Fig. 1). Both shelf seas are not only different in their hydrographic characteristics, but also in their geological development (Schwarzer et al., 2008, this volume), their sediment conditions and their geo-morphological features.

Although the seafloor in the German sectors of North and Baltic Sea is built up mainly of loose Quarternary deposits, the driving forces leading to environmental changes are quite different. While in the North Sea the sedimentological and geomorphological development (morphodynamics) is ruled by tides and waves, waves and wind driven currents are relevant for the seafloor conditions and sediment dynamics in the Baltic Sea. In both seas, however, phases of storm-induced high water levels often lead to severe changes of the coastal geomorphological environment. For the German North Sea coast this holds especially for storms from (north-)westerly directions, which can induce water levels of up to five meters above mean sea level usually for the duration of one or two tidal cyles. For the western Baltic Sea coast, storms from north-easterly directions have the strongest influence on coastal changes. Here, high water levels and therefore hydrodynamic extremes can last for days (Schwarzer, 2003).

## 2. North Sea

The German Bight is a meso-tidal to low macro-tidal environment with a tidal range between two and four meters. According to geo-morphological features and sedimentological environments, the German sector of the North Sea can be divided into the three zones: the offshore waters, the tidal flats of the Wadden Sea and the funnel-shaped estuarine river mouths (Fig. 2). In the meso-tidal environment, the barrier island chain of the East Frisian as

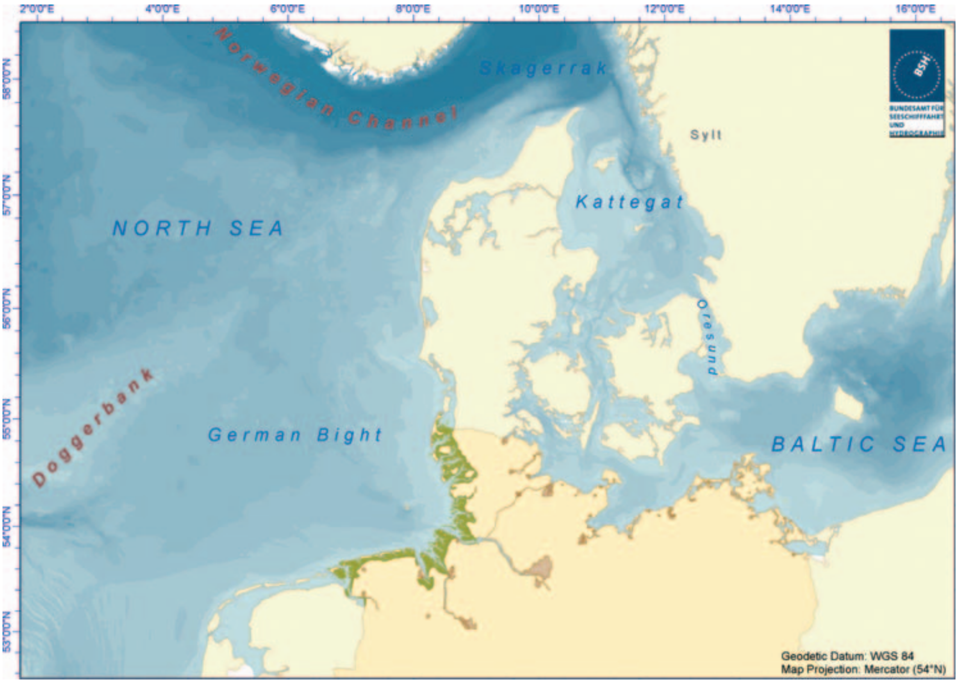


Fig. 1: Seabed Morphology of the North Sea and South-western Baltic Sea.
(Data source for water depths: dhi Water Environment Health)

well as the North Frisian Islands separate the tidal flats from the deeper offshore waters, while in front of the low macro-tidal estuaries of the Elbe and Weser Rivers barrier islands are not developed.

## 2.1 Offshore Waters

The seabed morphology of the eastern German Bight is characterized by a relatively smooth slope and an uneven sea floor. The most prominent morphological features are the shoal Amrum Bank and the island of Helgoland together with the adjacent Steingründe, a submarine lag deposit area. Relict deposits of the Saalian terminal moraines are present towards the NNW oriented slope of the former Elbe glacial spillway, which forms the western boundary of the eastern German Bight. Strips of coarse sand, submarine dunes, sand ribbons and biogenic patches are described as typical bed-form features for this area (KÖSTER, 1974; TABAT, 1979; WERNER, 2004). Other recent morphological elements are the longitudinal sand bars in the nearshore zone of Sylt Island, which are in equilibrium with the present hydrodynamic regime (FIGGE, 1976).

Along the southern coastline of the German Bight, the seabed has a relatively steep slope. In the shallow parts, seawards of the East Frisian barrier islands, long-shore sand bars occur down to water depth of approx. 6 m below MSL (Mean Sea Level). Further offshore, shoreface connected sand ridges are present (REINECK and SINGH, 1973; SWIFT et al., 1978). These

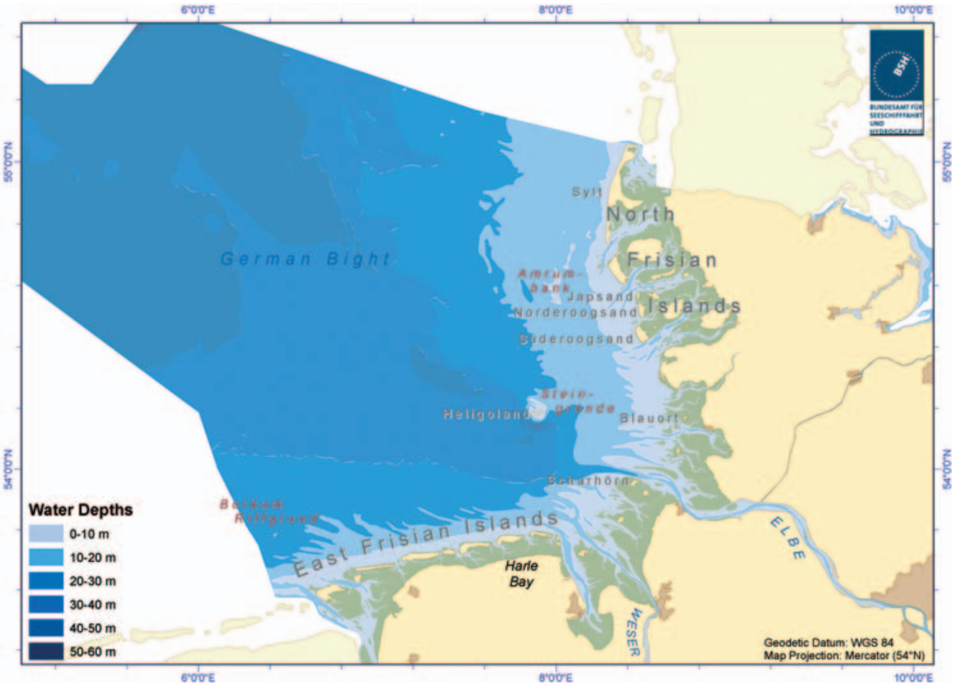


Fig. 2: Seabed Morphology of the German Bight (North Sea) including localities mentioned in the text. (Source: CONTIS [BSH])

sand ridges are 2–5 m in height and occur in water depth between 12–18 m MSL. The core of such ridges is at least of early Atlantic age, i. e. approx. 7,500 years Before Present (LABAN and SCHÜTTENHELM, 1981). These morphological features exhibit a pronounced dynamic behaviour having cross-shore migration rates of between 100 and 200 m $a^{-1}$ at their maximum (ANTIA, 1996).

Borkum Riffgrund extends towards the Dutch offshore waters and represents a relict of a former Pleistocene terminal moraine. Below approx. 20 m MSL, the seafloor of the western German Bight is comparatively flat and smooth except some patchy areas showing current ripples. Dogger Bank (Tail's End) dominates the seabed morphology at the north-western end of the German North Sea sector.

Because the North Sea was not covered by ice during the last glacial period, the seafloor underwent one regressional and two transgressional phases which shaped and levelled the sediment surface (FIGGE, 1981). Accordingly, the sediment distribution pattern in the German Bight (Fig. 3) to a high degree reflects reworking processes acting since the retreat of the Saalian ice shield. On one hand, relict sediments ranging from fractions of coarse sand to boulders usually cover glacial till and protect the sea floor against further abrasion. On the other hand, fractions of fine to medium sand are almost permanently reworked by wave-induced and tidal currents.

The thickness of the mobile sediment cover along the German North Sea coast down to a depth of 20 m below MSL shows three distinct zones which are running more or less parallel to the coastline (Fig. 4). Seaward of the Wadden Sea in shallow water depths between

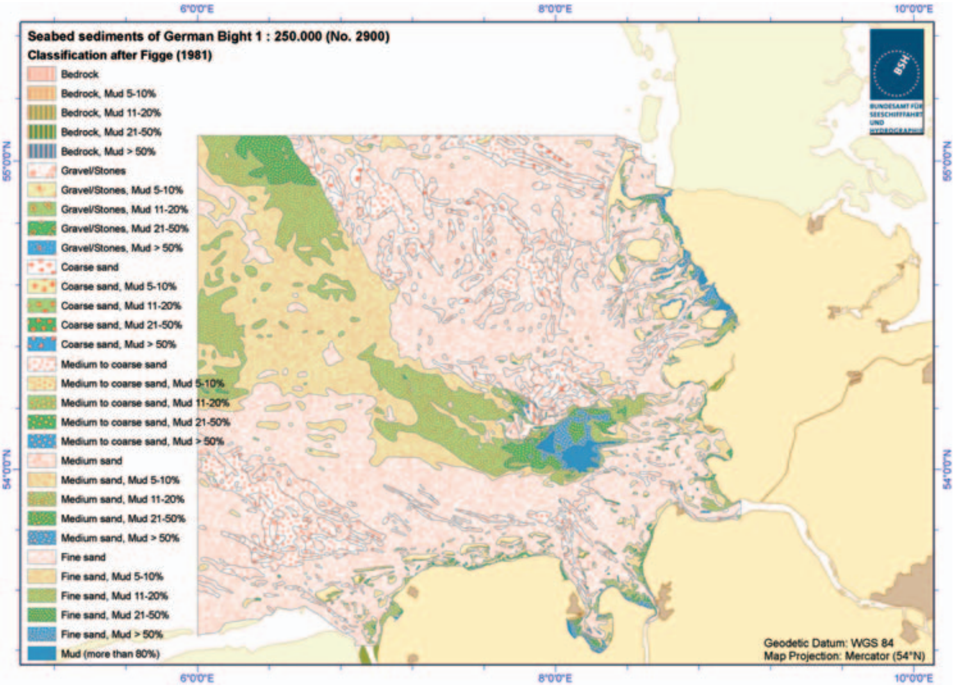


Fig. 3: Distribution of the surficial sediments (0–20 cm) of the German Bight (FIGGE, 1981). (Source: Shelf Geology Explorer, BSH)

0–10 m, the thickness of the mobile sediment cover is up to 10 m; a relatively thin layer of mobile sandy material is located between 10–15 m of water depth, and a slight increase in thickness of 2–3 m with local maxima of about 5–6 m can be observed in water depths between 15–20 m. A conceptual model of the net sediment transport regime is inferred from this pattern. It comprises a relatively narrow zone of sediment in the littoral drift, resulting in a substantial sediment supply in the innermost German Bight and a shore-normal bed-load transport shifting sand to and fro in the coastal profile, with a net offshore component (ZEILER et al., 2000).

During storm surges, sediment from tidal flats and sand bars can be transported offshore for more than 50 km down to water depths of 40 m below MSL. The average volume of sediment transported by a single storm has been estimated to be about $4.2 \times 10^6$ $m^3$ (GADOW and REINECK, 1969). WUNDERLICH (1983) demonstrated that large-scale sedimentary structures are shifted during storm wave action and remain stable during calm weather periods. They undergo only slight reworking processes.

Similar processes are postulated by DIESING et al. (2006) for so-called "sorted bedforms" in offshore waters of the eastern part of the German Bight. They assume that extreme storm events play a major role in the generation of these structures, whereas average tidal currents form and maintain their final shape. It is noteworthy that the widespread sorted bedforms have shown stable patterns over a period of more than 26 years.

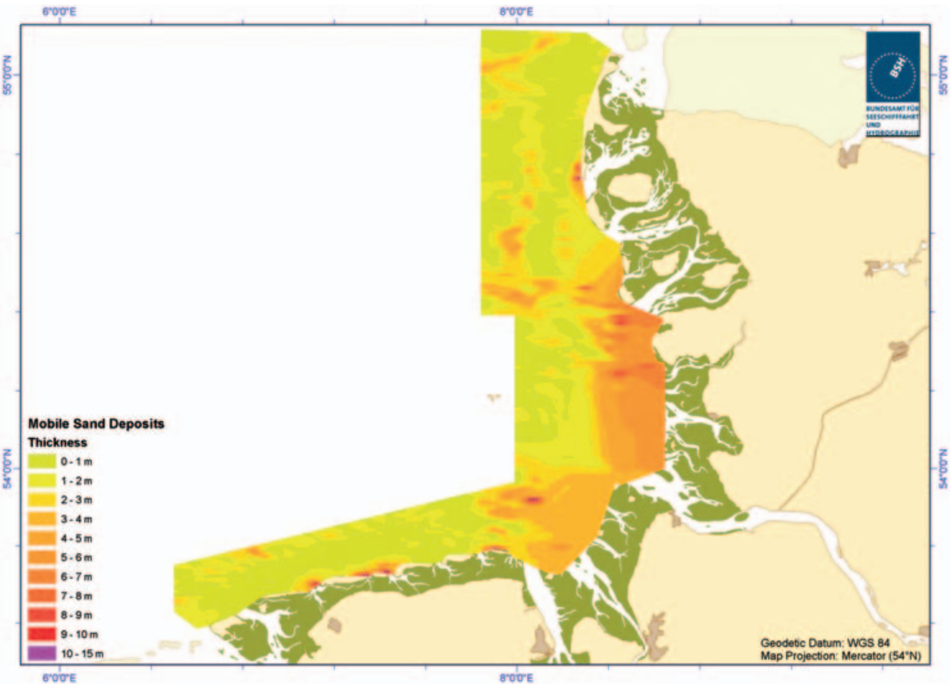


Fig. 4: Thickness of the mobile sand cover along the German North Sea coast (Zeiler et al., 2000).
Source: Shelf Geology Explorer (BSH)

## 2.2 Tidal Flats

The tidal flats of the Wadden Sea form the interface between the open North Sea and the mainland. They extend from Denmark to the Netherlands over a distance of about 450 km and can reach a width of up to 25 km along the German coast. This marginal belt between the barrier islands, whose genesis differs from the North to the South (Kohlus, 1998), and the mainland is comprised of salt marshes, extensive intertidal flats, numerous tidal gullies and streams. The sediments mainly consist of fine sand with various proportions of slightly coarser material or mud (silt and clay) (Ahrendt, 2006). Depending on the geological development, locally peat or clay-rich layers can be found in the subsurface (Streif, 1990).

The overall thickness of the sediment body can reach nearly 40 m (Ahrendt, 2006). The surficial sediments show a typical zoning from predominantly sandy sediments in more exposed areas to muddy deposits in sheltered or more elevated parts. Overall, a dominance of sandy flats with a mud content of less than 10 % is observed (Berner et al., 1986; Bayerl et al., 1998; Köster, 1998; Ricklefs and Asp Neto, 2005). The present distribution of muddy intertidal sediments (more than 50 % silt and clay), however, is mainly limited to small areas. This is due to a lack of adequate depositional environments mainly as a consequence of intensive land reclamation activities along the marshland coasts since the early Middle Age (Flemming and Ziegler, 1995; Brockamp and Zuther, 2000). Land reclamation and the substantial reduction of catchment areas resulted in an enlargement of the East Frisian barrier islands and a decrease of mudflats and salt-marsh areas as well. Along with a rising MSL and the increase in wave energy, fine-grained particles have been eliminated from the sheltered backbarrier areas behind the islands (e.g. VAN STRAATEN and KUENEN, 1957; FLEMMING and BARTHOLOMÄ, 1997).

The deposits in the channels cover a wide range of different sediment types. It can reach from very coarse lag sediments of Pleistocene till (AHRENDT, 1992) over strongly cohesive Holocene layers (BERNER et al., 1986; RICKLEFS and ASP, 2006) to outcrops of peat. Most common, however, are recent sandy to partly muddy deposits (e. g. POERBANDONO and MAYERLE, 2005). On pure sandy channel beds, mega-ripples and submarine dunes are very common (ULRICH, 1979; MAYERLE et al., 2005). Especially in the main tidal channels of North Frisia, where coarser sandy sediments prevail, the seabed is partly characterized by sand waves of up to several meters height (ULRICH and PASENAU, 1973; HENNINGS et al., 2004).

The system of the tidal flats has always undergone an intensive internal rearrangement of deposited sediments. According to ZEILER et al. (2004), bed-load transport rates of 400 $m^3$ $m^{-1}$ $a^{-1}$ in the North Frisian Wadden Sea are around five times higher than in the adjacent open water zone of the German Bight. Especially under the influence of an increasing sea level and/or an augmented mean tidal range, a deepening of inlets and tidal channels is expected (HOFSTEDE, 2002) and can be partly observed (e.g. HIGELKE, 1998). Another evidence of the adaptation of the depositional environment to a changing hydrodynamic forcing is the landward migration of characteristic morphological elements. This holds for the sandy barriers with a migration rate between 15 and 27 m $a^{-1}$ (HOFSTEDE, 1997) along the meso-tidal coasts of East and North Frisia as well as for the small supra-tidal sands (EHLERS, 1988; RUNTE, 1994) and exposed sand banks of the open tidal flats in the low macro-tidal innermost German Bight (RICKLEFS et al., 2005).

Input from the English Channel, erosion of the East Anglian coast as well as discharge from the rivers can be considered as the main sources of fine-grained material (silt and clay) in the North Sea. Based on clay mineral analyses, PACHE et al. (2008) could demonstrate that the Helgoland mud area is a main deposition centre for suspended particulate matter discharged by the River Elbe. The distribution of fine-grained material (especially clay) is coupled to hydrodynamic transport patterns in the German Bight. According to EISMA and IRION (1988) most of the fine-grained sediment deposition takes place in the tidal flats (Wadden Sea). While 3–7 $\times$ $10^6$ tons of suspended particulate matter (SPM) is accumulated in the German Bight, 12–19 $\times$ $10^6$ tons per year are transported into the Norwegian Channel (DYER and MOFFAT, 1998).

### 2.3 Estuaries

In the Elbe and Weser Estuary, the seabed is dominated by distinct morphological features such as channels and sand spits, sand waves in channels or longitudinal sand bars (REINECK and SINGH, 1973) dependent on the strong tidal influence, grain size distribution and sediment availability.

Pronounced migrating bed-forms occur on the sandy river bed of the Elbe and Weser estuary. WEVER and STENDAL (2000) measured a migration speed of a minimum of 45 cm $d^{-1}$ in the Elbe River. For the Weser/Jade estuary, minimum migration speed is higher by a factor of 2 (SCHROTTKE et al., 2006). The migration of these bed-forms shows a cyclic pattern which correlates with the tidal cycle.

## 3. Baltic Sea

The Baltic Sea is the second largest brackish water body in the world. For its ecosystem, the Drodgen Sill in the Øresund and the Darss Sill between Gedser Rev and Fischland-Darss, with depth of only 7 m and 18 m, respectively, below Mean Water Level (MWL) are the most important features (Fig. 5). These sills control the water exchange with the North Sea, which is not continuous, but depends strongly upon westerly storms. This results in oxygen-rich North Sea water inflow into the Baltic Sea basin, 73 % of which pass via the Darss Sill (JACOBSEN, 1980), whilst the remainder goes over the Drodgen Sill.

The Baltic Sea is a very 'young' brackish water environment, which is extremely diverse compared to other seas regarding geological prerequisites, physical forcing of sediment mobility and environmental conditions. Due to its young geological history and the on-going uplift and subsidence processes (SCHWARZER et al., 2008, this volume), the surface sediment distribution and the upper part of the subsurface are very patchy; they are mainly of Quaternary origin. Particularly, compared to the tide-dominated North Sea, the surficial sediment distribution in the non-tidal Baltic Sea is much more heterogeneous; it is patchy on both, small and large spatial scales. This observation is confirmed by different maps (Fig. 6 and 7), for example TAUBER and LEMKE (1995), TAUBER et al. (1999), HERMANSEN and JENSEN (2000). The deep basins function as sinks for fine-grained sediments (silt and clay), whilst sandy material is deposited in the more shallow areas. Relict sediment remains, where till or other glacial deposits pinch out at the seafloor and are directly affected by waves.

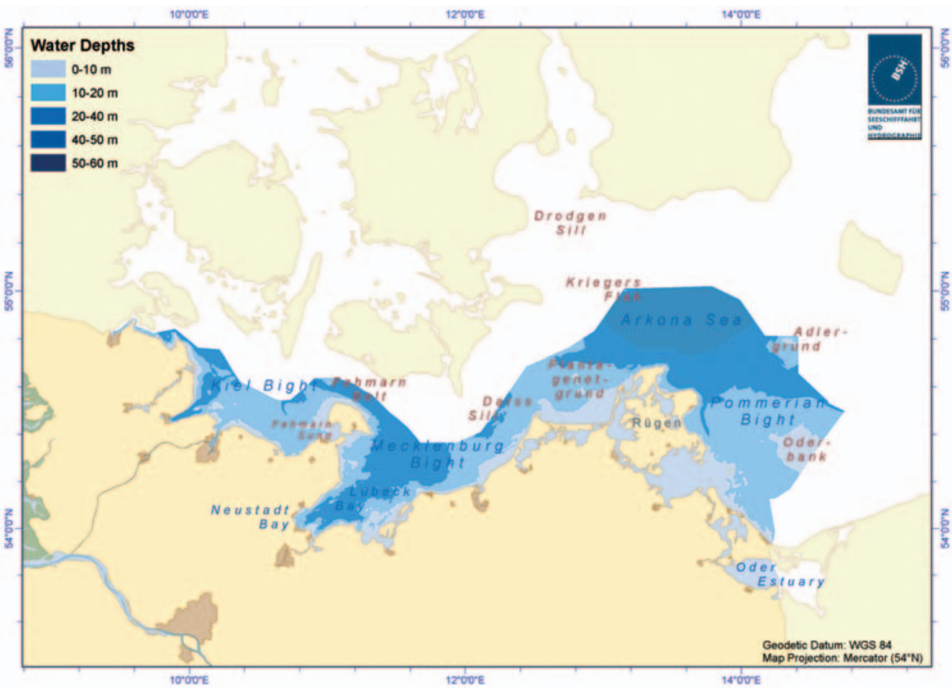


Fig. 5: Seabed Morphology of the South-western Baltic Sea including localities mentioned in the text. (Source: CONTIS [BSH])

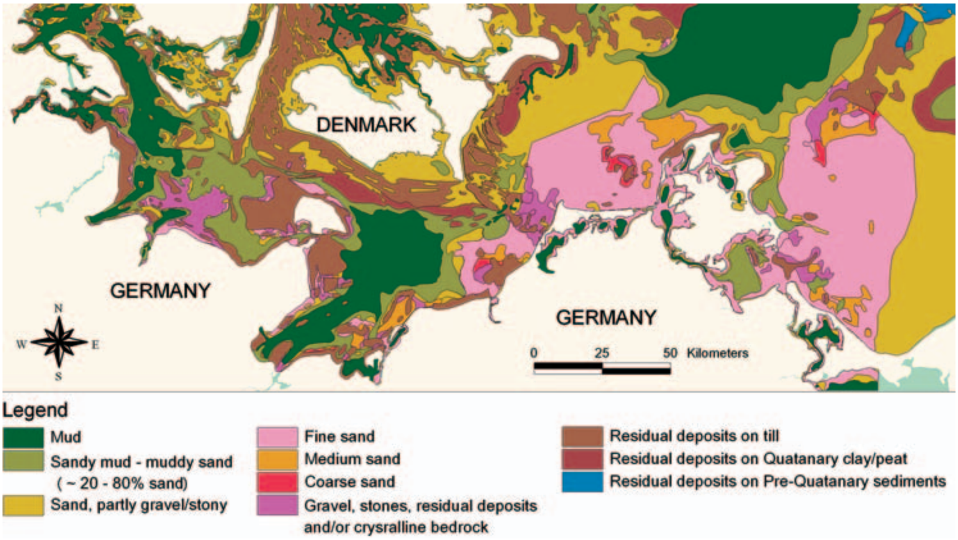


Fig. 6: Distribution of the surficial sediments of the South-western Baltic Sea. Source: REIMERS, H.-CH. (2008): Sea Bottom Sediment Map of the Westen Baltic, State Agency for Nature and Environment Schleswig-Holstein; based on HERMANSEN and JENSEN (2000): Digital Sea Bottom Sediment Map around Denmark and data of the Federal Maritime and Hydrographic Agency, Germany (BSH) and the Christian-Albrechts-University of Kiel; compiled by A. SEKINKER (2002)

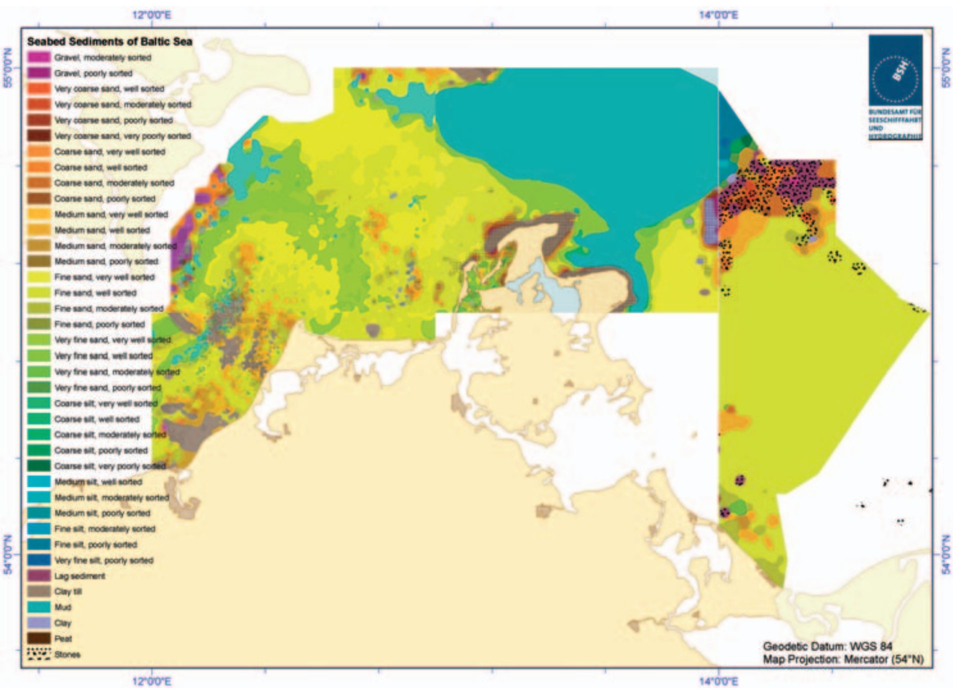


Fig. 7. Distribution of the surficial sediments of the German Baltic Sea (TAUBER and LEMKE, 1995; TAUBER et al., 1999; TAUBER, unpubl.). (Source: Shelf Geology Explorer, BSH)

## 3.1 Offshore Waters

The bathymetry of the Baltic Sea is controlled by the presence of sills and deep basins, which developed during the last glacial period. These basins increase in size and depth from west to east.

The morphological structure of the south-western Baltic Sea is formed by Kiel Bight in the western part. It is mainly characterized by the presence of deep (c. 35 m) melt-water channels. Fehmarn Belt and Sund separate Kiel Bight from Mecklenburg Bight. This bight has a maximum water depth of 25 m and splits up into several smaller bays, namely Lübeck Bay and Neustadt Bay. In the eastern part of the German sector, Arkona Basin is the deepest basin of the south-western Baltic Sea with a maximum water depth of 45 m. It is flanked by the shoals of Kriegers Flak and Adlergrund at the eastern edge. Both shoals are of glacigenic origin. The Pommeranian Bight is situated between Adlergrund and the Oder estuary. It features a relatively shallow sandy bottom with the prominent shoal of Oder Bank.

In offshore waters, morphological features are mainly coupled to the strong-current-environments of the straits. In Fehmarn Belt (Fig. 8) and Darss Sill, the strong inflow of saline bottom waters from the North Sea form sand wave fields with crest heights of up to 5 m (WERNER and NEWTON, 1970; WERNER et al., 1974; LEMKE et al., 1994; SCHWARZER and DIESING, 2003; FELDENS, 2008). Mega-ripples were also observed on the shoals in shallow waters such as Plantagenetgrund (GROMOLL, 1992).

Although the sediment distribution is strongly affected by the subsurface geology, a depth-dependent overall zoning of surface deposits can be found (SEIBOLD et al., 1971). Along the coasts and on the submarine sills and shoals of the south-western Baltic Sea, coarse-grained lag deposits form a thin layer of a few decimetres on top of till deposits in water

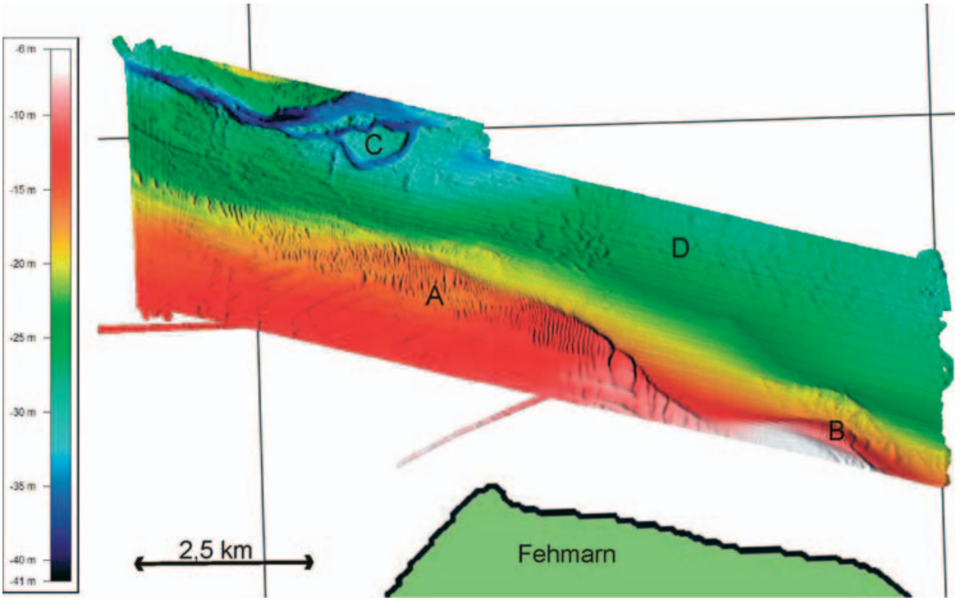


Fig. 8: Morphological features in the highly dynamic Fehmarn Belt (FELDENS, 2008). (Source: Institute of Geosciences, University of Kiel)

depths of 5–15 m. These sediments result directly from the abrasion of the underlying till deposits. Material with grain sizes within the range of sand is removed by wave and current action, leaving the coarser components behind (SWIFT et al., 1971; TAUBER et al., 1999). Lag deposit areas are often found to be surrounded by well-sorted fine to medium sands. Except for areas in the immediate proximity of the coast and abrasion platforms, these sand layers are relatively thin, for example only 0.5 to 2 m in Kiel Bight (SEIBOLD et al., 1971) and the inner Mecklenburg Bight. Significant amounts of marine sediments are found in the deeper basins and channels of the Baltic Sea, where fine-grained, organic-rich sediments (mud) accumulate (WERNER et al., 1987; LEMKE, 1998; HARDERS et al., 2005). Depending on the water depth, the grain-size decreases from coarse to fine silt while the content of organic matter increases to 10–15 % (WINTERHALTER at al., 1981).

Comparison of two sonar images (mosaics) in the Pommeranian Bight confirm the relatively stable pattern of seabed sediments of several years on the lower shore-face (TAUBER and EMEIS, 2005). Even bottom currents with maximum velocities of 30 cm $s^{-1}$ could not mobilize the sand. However, a significant portion of fine-grained material (mud, fluff) has evidently been advected in the bottom boundary layer under moderate hydrodynamic conditions.

ZIERVOGEL and BOHLING (2003) observed that the erosion behaviour of mud in the Mecklenburg Bight was dominated by the fluffy surface material, whereas the underlying silt fraction showed a higher erosion threshold due to its cohesive behaviour. Their comparison of near-bottom hydrodynamic forcing and experimentally derived critical shear velocities indicates a storm-controlled particle (mud and fine sand) transport in the bight. Based on statistical analysis of sedimentological parameters and hydrodynamic modelling, BOBERTZ and HARFF (2004) found evidence that the preferred transport pathways for clastic material in the south-western Baltic Sea are based on the direction of the average current vectors. An exception represents the Pommeranian Bight, where sediments have not been accumulated under present-day conditions. According to WEHNER (1990, in BOBERTZ and HARFF, 2004), they are of glacio-fluviatile genesis during the late Pleistocene.

### 3.2 Nearshore Zone

Typical features in shallow waters are nearshore bars which are highly dynamic morphological structures depending on wave climate and sediment availability (SHORT, 1999; SCHWARZER, 2003). They occur mainly in front of lowlands where several nearshore bars exist down to 6 m below sea level. Seawards of active cliffs these nearshore bars are often missing or exhibit only one long-shore bar. Their thickness seldom exceeds 2.5 m in the south-western Baltic Sea. However, these morphological features have a significant influence on coastal stability as waves are breaking and energy is dissipated around these bars.

Wave conditions and sediment transport in shallow coastal waters depend upon exposure to the main wind and wave direction. Within this context, the coastline of the southern Baltic Sea is exposed to both north-easterly and westerly winds. For comparison, within the south-western Baltic Sea (Germany and Denmark) where fjords and bays are common, the most effective wind direction inducing coastal currents and sediment mobilisation varies considerably; it includes all directions, even south for some stretches of islands.

SCHWARZER et al. (2003) could demonstrate that waves are the main controlling factor of seasonal variations of the upper shore-face. Morphological changes induced by storm events remain on a decadal scale, whereas the lower shore-face shows a more stable sedimentological and morphological behaviour; changes are only measureable on centennial and millennium scale, because long-term process such as sea-level fluctuations or neo-tectonics are the main driving forces there. Schwarzer and Diesing (2001) investigated the sediment dynamics and geo-morphological changes on seasonal and annual scales in two different sandy nearshore areas of the south-western Baltic Sea. By using a new method called "tracer stick method", they found a geographical variation of seasonal maximum mobility which moves offshore during the stormy winter conditions. However, the intense sediment mobility did not invoke substantial morphological changes in every case, especially with respect to seasonality.

### 3.3 Coast

There are several types of coastlines along the south-western Baltic Sea. In general, Pleistocene cliffs are alternating with Holocene barrier systems, mainly consisting of spits and lagoons. Large sections of these coastlines are retreating at an average rate of 0.2–0.3 m per year and maximum rates of up to 1.5 m per year (Schwarzer et al., 2003; Ziegler and Hayen, 2005). East of Rügen Island, the coastline turns towards a formation which looks as if equilibrium conditions between erosion and accumulation predominate; however, even here the coast is eroding. Approximately 70 % of the coastline of the State of Mecklenburg-Vorpommern, extending from Mecklenburg Bight to Oder Estuary, is under permanent retreat (Harff et al., 2004).

Natural sediment sources within the region are active cliffs and the seafloor, from which sediment is abraded (Schrottke, 2001). The erosion of the active cliffs is controlled by storm events combined with high water levels. The rate of retreat of the active cliffs of Schleswig-Holstein is 24 cm $a^{-1}$ on average (Ziegler and Hayen, 2005) and up to 30 cm $a^{-1}$ for the cliffs of Mecklenburg-Vorpommern. Schwarzer (2003) emphasizes that the nearshore processes have to be taken into consideration for a comprehensive understanding of coastal dynamics. The rates do not increase linearly with depth, but are highly dependent of the type of substrate and wave dissipation. Material from cliff retreat and nearshore abrasion is transported by long-shore currents and is substantially involved in the formation of the Holocene barrier systems. Schrottke (2001) measured seafloor-abrasion rates of 2–5 cm $a^{-1}$ in water depths down to 6.5 m and at a distance from the shore of up to 300 m. In many cases, the amount of sediment supplied by seafloor abrasion is underestimated, sometimes completely neglected. Depending upon the composition of the Quaternary deposits and the exposure to the main wind and wave direction, such sediment supply can be of the same order of magnitude as the supply from the exposed parts of the retreating cliff (Schrottke and Schwarzer, 2006).

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# The Climate in the North and Baltic Sea Region

By Christiana Lefebvre and Gudrun Rosenhagen

Contents



## 1. Natural Region

The German coastal areas of the North and Baltic Seas are part of the North German Lowland. The North Sea shore merges seaward into wide tidal flats, the so-called "Watten" with flat dune islands. Only the island of Helgoland has a rocky coast landscape. The Baltic Sea coast is characterised by the varied relief of flat coasts lined by dunes, steep cliffs, spits and coastal lagoons known as "Bodden" or "Haffs". Here, the by far largest islands of Germany are situated: Rügen, Usedom and Fehmarn.


Fig. 1: Station map

## 2. Overview of the Climatic Conditions

The coastal areas of the North and Baltic Seas lie in the mid-latitude Westerly wind belt. The climate is predominated by low and high pressure areas that bring air masses of varying thermal and hygric properties, thus causing a continuous change in the weather conditions. In the Baltic Sea part of the region, the continental influence on the climate increases slowly towards the East. A characteristic climate feature of the North and Baltic Sea region is the constantly blowing wind. The following description of the climate of the German coastal areas is based on weather observations and the corresponding analyses for the period from 1971 to 2000. Fig. 1 gives an overview of the stations referred to and their location.

### 2.1 Air Temperature

The annual mean air temperatures in the North and Baltic Sea region (Fig. 2) range between 8 °C and 9 °C, with decreasing values towards the East and the North. The highest values, i.e. 9.4 °C, occur on the East Frisian Islands and on the island of Helgoland. Fig. 3 vividly illustrates a higher frequency of too warm years since the end of the 1980s.

Due to a higher heat capacity, the North and Baltic Seas have an attenuating effect on the daily and annual temperature variation. As an effect of the increasing influence of the continental climate, the annual curve (Fig. 4) shows more pronounced variations in the Baltic Sea part of the region and gives for the coldest months January and February mean temperatures of 2 °C in the North Sea and 1 °C in the Baltic Sea area. The warmest month is August, with a mean temperature of about 17 °C. The mean daily maximum temperatures

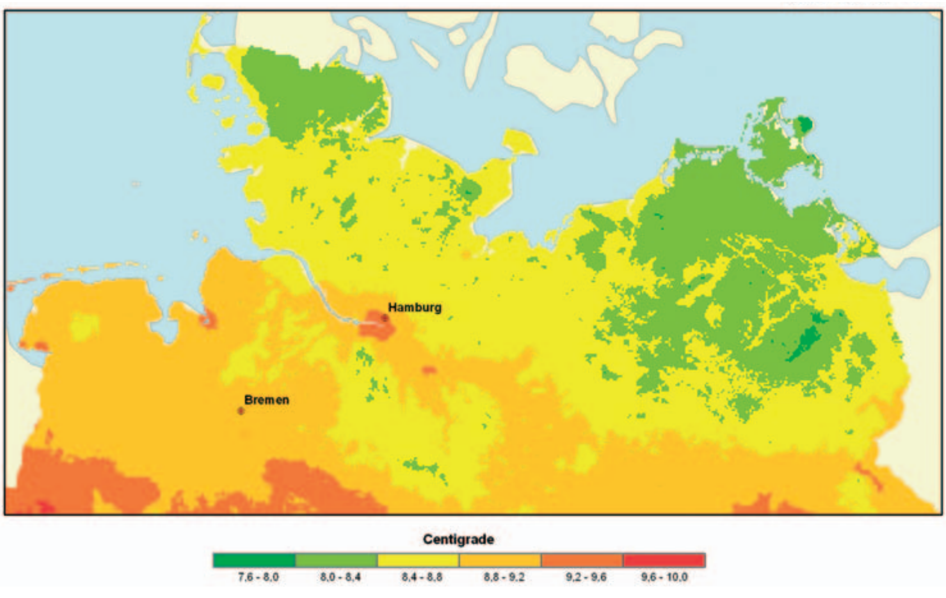


Fig. 2: Annual mean temperature, reference period 1971–2000

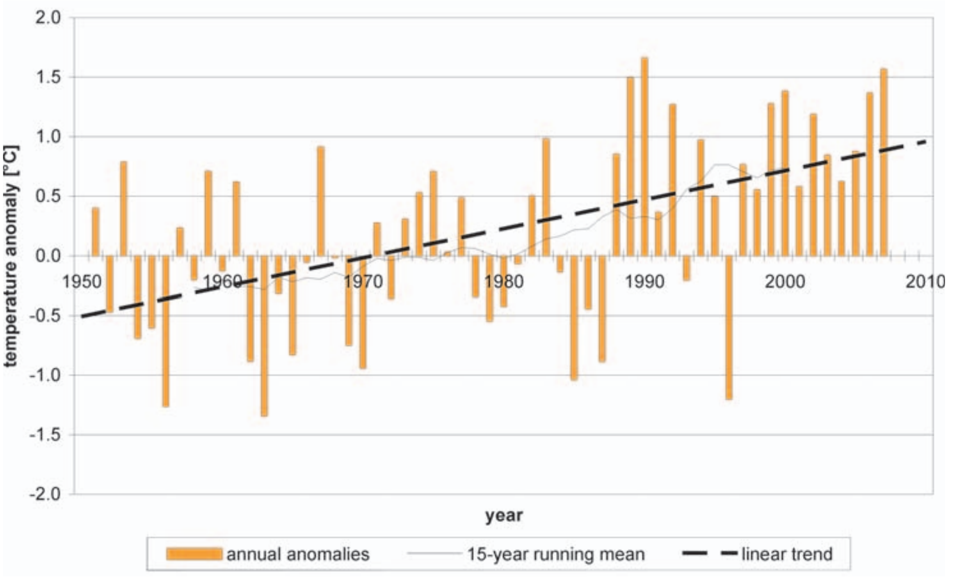


Fig. 3: Anomalies of annual mean temperatures in Boltenhagen from 1951–2007 (reference period 1961–1990)

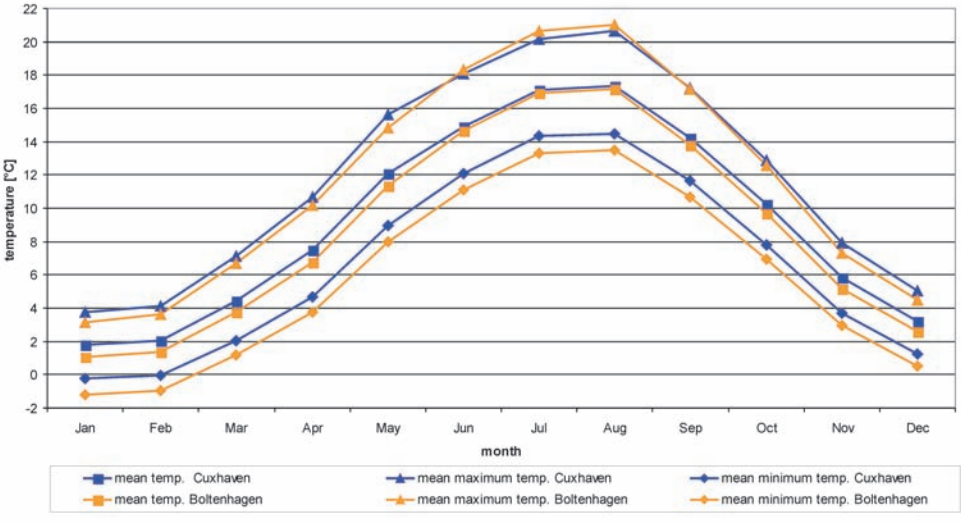


Fig. 4: Monthly variations of mean, mean maximum and mean minimum temperatures at Cuxhaven and Boltenhagen (reference period 1971–2000)

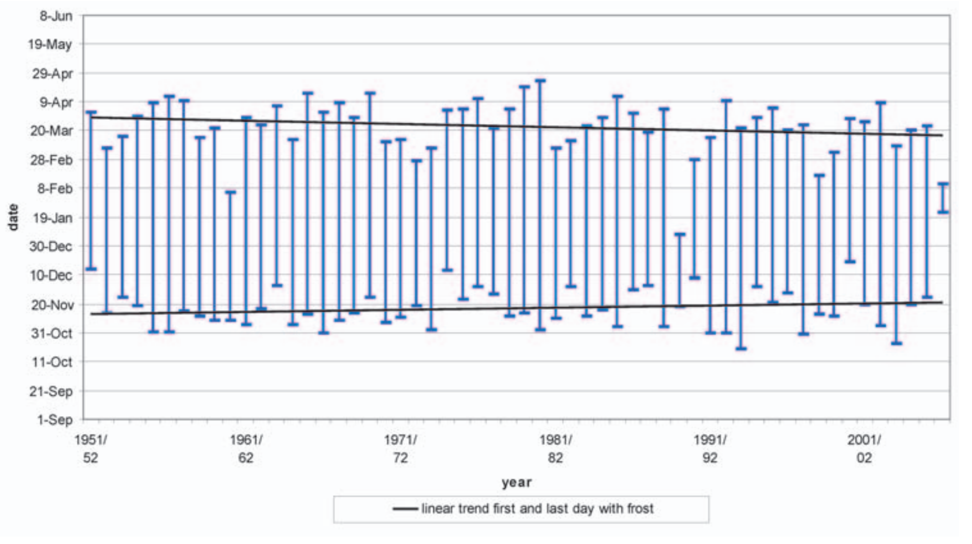


Fig. 5: Annual period between first and last frost (temperatures minimum below 0 °C) in Cuxhaven from 1951/52 to 2006/07

range between 3 °C and 4 °C in January and February and 20 °C to 22 °C in August. Between May and September, the daily temperatures can reach a maximum of about 30 °C. The highest temperatures were recorded in August on the Lower Saxony and Mecklenburg parts of the mainland coast, with a maximum of 36 °C. The mean daily minimum temperatures in January and February range between 0 °C and +1 °C in the North Sea and –1 °C in the Baltic Sea area. Lowest air temperatures occur if under a high pressure area, dry cold air prevails in clear, calm nights with snow cover. Under such conditions, temperatures may well go down to –15 °C. Very often, however, there is no frost due to the inflowing maritime air masses or the blowing winds. The probability of frost increases from the North towards the Baltic Sea and with increasing distance from the sea. For this reason, the annual mean number of days with air frost is 28 on Helgoland, 40 on the East Frisian Islands and about 50 on the coasts of the North Sea, whereas in the Baltic Sea area, there are about 60 frost days. The highest number, i.e. 75 to 80 frost days, is recorded east of the island of Rügen where the continental influence is strongest. In years with extremely cold winter months, such as in 1996, the number may even double (e.g. Boltenhagen had 112 frost days in 1996 and 60 on average in the period from 1971 to 2000), whereas in years with a very mild winter, such as 1974, 1990 or 2000, only about 10 to 20 frost days in the North Sea, 20 to 30 frost days in the Baltic Sea area and 30 to 40 frost days east of Rügen occurred. Since the end of the 1980s, an increasing frequency of occurrence of mild winters can be observed, which results in a significant decrease in the number of frost and ice days and in the shortening of the period between the first and the last frost. As shown in Fig. 5, Cuxhaven station provides an excellent example for this. What is noticeable here, is the extraordinarily mild winter of 2006/2007.

### 2.2 Water Temperature

As compared to the air temperature, the water temperature shows a delayed annual variation. In spring, the water does not warm up as rapidly as the air. In autumn, it cools down more slowly. The highest water surface temperatures are recorded in August, with a monthly average of 18 to 19 °C. Along the straight and flat coastline, where tourists enjoy themselves, the daily mean values even rise to 20 to 23 °C. From September to February, the sea is warmer than the air, reaching its maximum with an air-sea temperature difference of –2 Kelvin in November and December. The waters are coldest in February when the mean temperatures range from 2 to 3 °C or below (east of Rügen) or 4 °C in the German Bight. In winter, sea ice may form. Sea ice begins to grow preferably in the protected and shallow inner parts of fjords and bays or on the tidal flats of the North Sea. For the years 1961–2000, the sea ice season starts here in the last decade of December or within the first days of January on average. In the more open sea areas and visible from the coast, icing begins around January 10th. The ice season at the North Sea ends by the second half of February, at the Baltic Sea in the first half of March. The frequency of occurrence and duration of ice covers in the Baltic Sea exceed those of the North Sea. Due to predominant mild winter seasons, the ice cover has been poor since 1998.

### 2.3 Precipitation

Precipitation in northern Germany is mainly caused by Atlantic low pressure systems and their frontal systems. In the coastal areas, they are influenced by the destabilising and stabilising effects, which the water surfaces of the North and Baltic Seas exert on the air masses moving across. In Western Schleswig-Holstein, where westerlies prevail, coastal convergence and increasing friction effects behind the coastline intensify precipitation, whereas precipitation decreases due to divergence, cloud dissolution, and increasing continentality along the Baltic Sea coast. Annual mean precipitation heights (Fig. 6) decrease eastwards from about 900 mm in Western Schleswig-Holstein to 500 to 550 mm in the Szczecin Lagoon (Stettiner Haff). Precipitation in the North Sea area features a maritime maximum in late autumn, whereas at the coasts of the Baltic Sea, the influence of the continental climate expresses itself in summer precipitation maxima (Fig. 7). The lowest amounts of precipitation throughout the year are recorded in February and April, with 30 to 40 mm in the North Sea and 20 to 30 mm in the Baltic Sea area. In spring, the intensity of convective precipitation lessens due to the stabilising effects of the thermal stratification of the air masses moving over still cold sea surfaces. The month of May, when high pressure areas frequently produce long periods of dry weather, marks the transition into the summer months with precipitation amounts of about 60 to 70 mm per month in the North Sea and 50 to 60 mm in the Baltic Sea area. While precipitation amounts in the Baltic Sea area start decreasing again in autumn, the destabilisation of air masses over the warmer North Sea provokes another increase of the monthly totals to 80 to 90 mm. Even up to 100 mm/month on the west coast of Schleswig-Holstein have been recorded. By December, the weather in the North Sea area has also become dryer again. Depending on the large-scale synoptic situation or the occurrence of heavy precipitation events, the monthly totals may vary significantly between sometimes twice or three times the average rainfall or dry periods with only a few millimetres.

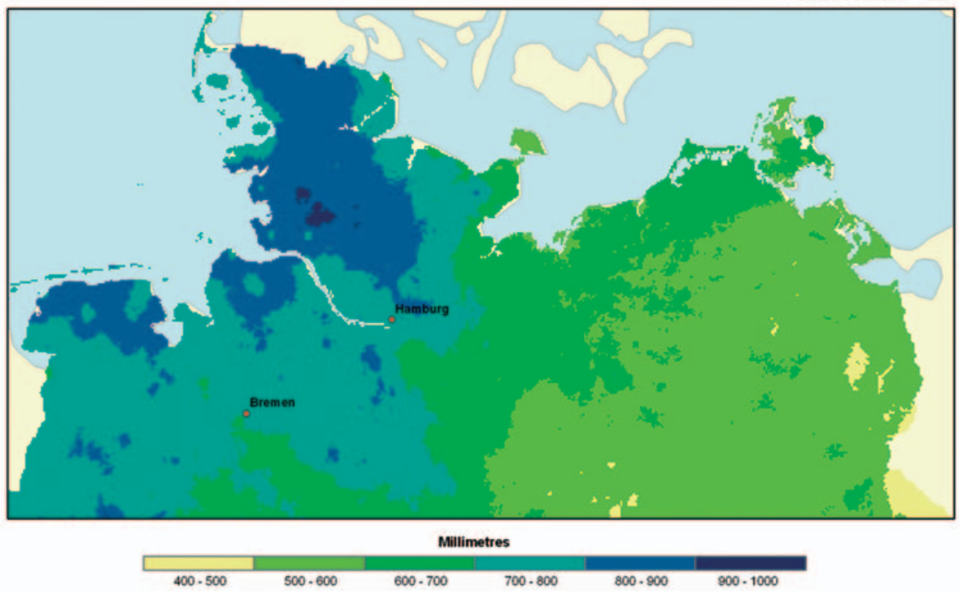


Fig. 6: Annual mean precipitation totals, reference period 1971–2000

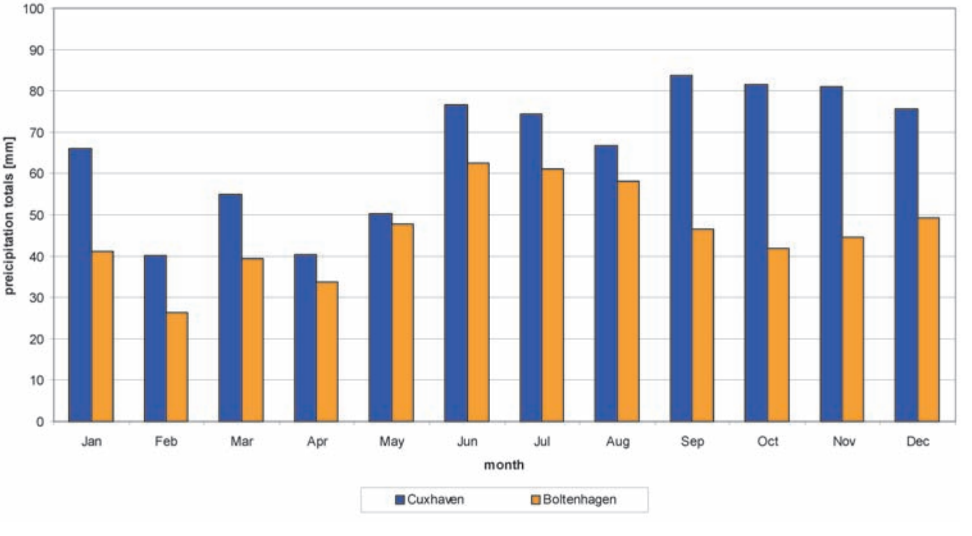


Fig. 7: Monthly variations of precipitation totals in Cuxhaven and Boltenhagen (reference period 1971–2000)

Between November and April, precipitation can occur as snow. The annual mean number of snow cover days is around 20 along the North Sea coast and between 20 to 30 days along the Baltic Sea shore. In years with heavy snow, the number of snow cover days may even rise to 70 to 80. A particular event to remember is the snow disaster at the turn of the year 1978/1979 with massive snow falls and storm. The weather stations along the North Sea coast reported snow depths of about 70 cm. Regionally, snowdrifts were far higher. The more frequent occurrence of mild winters since the end of the 1980s is paralleled by a decrease in snow depths and the number of days with freshly fallen snow.

The number of thunderstorms in the coastal areas is relatively low. The sea winds during the summer months reduce the thermal lift needed for such an event. In the warm season, thunderstorms occur on 3 to 4 days per month on average. The annual average is about 20 days. In autumn, when the water is still relatively warm and there is an inflow of cold air, however, thunderstorms are more frequent on the islands than on the mainland. The least risk of thunderstorms occurs in the period between January and April in the North Sea and November and March in the Baltic Sea area.

### 2.4 Sunshine Duration

The map of annual sunshine (Fig. 8) distinctly shows the increasing number of sunshine hours from land to coast and from West to East. In the North Sea area, the annual sunshine duration ranges largely between 1,550 and 1,650 hours on the mainland coast and between 1,700 and 1,740 hours of sunshine on the islands. On the Baltic Sea side, the sunshine duration increases from the North towards the South. While north of the Kiel Bight (Kieler Bucht) the annual mean sunshine duration ranges between 1,550 and 1,600 hours, it amounts to between 1,650 and 1,750 hours per year in the area between the Lübeck Bight (Lübecker Bucht) and the Szczecin Lagoon (Stettiner Haff) as well as on the island of Fehmarn. Records on the islands of Rügen and Usedom show a particularly large amount of sunshine: with approx. 1900 sunshine hours they are the sunniest areas in Germany. Due to long days, frequent high pressure influence and the stabilising effect of the low sea temperatures, May has the highest average sunshine duration (Fig. 9), with between 230 and 270 hours.

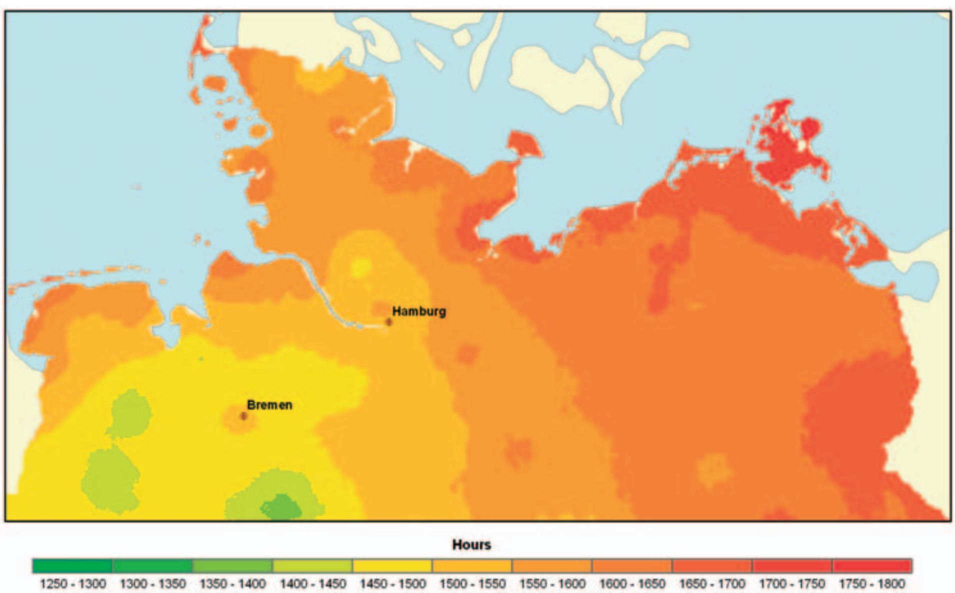


Fig. 8: Annual mean sunshine duration, reference period 1971–2000

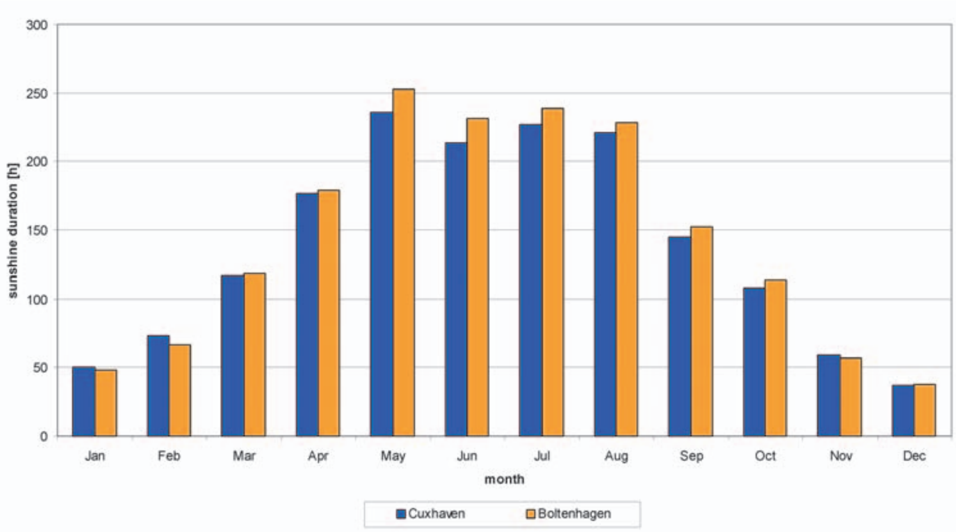


Fig. 9: Monthly variations of sunshine duration in Cuxhaven and Boltenhagen (reference period 1971–2000)

## 2.5 Cloudiness

A way of measuring cloudiness is to determine the cloud cover as the fraction of the sky covered by clouds in octa (e.g. a cloudless sky has a cloud cover of zero octa, an overcast sky of eight octa).

During the course of the year, the mean cloud cover shows only little variation, ranging between 6 octa in the winter months and 4 to 5 octa between April and September (or October at the coast of Mecklenburg-Western Pomerania).

The "lee effect of Scandinavia", is a particular phenomenon which occurs during weather situations with high reaching northerly airflows in the rear of large low pressure systems. Descending air on the leeward side of the Scandinavian mountains and the related decrease in air humidity result in dry weather with little cloud cover (Fig. 10) across Schleswig-Holstein and the western parts of the Baltic Sea.

## 2.6 Wind

The most distinctive climate element in the German coastal areas is the wind. Generally speaking, the mean wind speed is lower in the Baltic Sea than in the North Sea area (Fig. 11). The prevailing westerly and south-westerly winds blow towards or parallel to the North Sea coast. Therefore, they are mostly stronger than in the Baltic Sea area, where off-shore winds predominate along most parts of the coast. Along the islands and coastlines of East and North Frisia as well as of Hiddensee and Rügen in the Baltic Sea, that are exposed to the west, the mean wind speeds sometimes rise above 7 m/s. Along the other North Sea coastal regions they range between 6 and 6.8 m/s on both sides of the Elbe mouth, around 6 m/s in the northern parts of the Baltic Sea coast of Schleswig-Holstein and on the Darß and 4 to 5 m/s

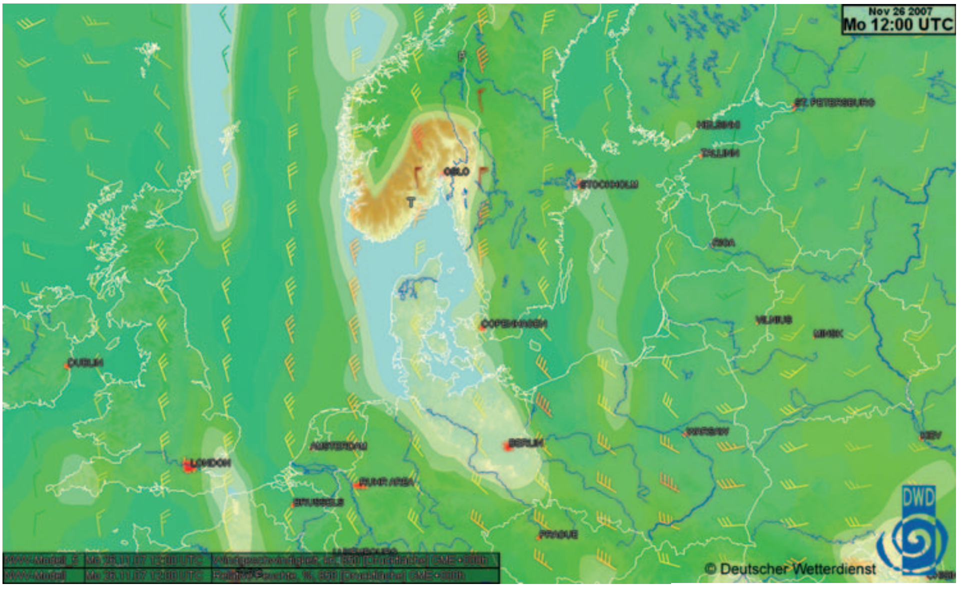


Fig. 10: Lee effect of Scandinavia

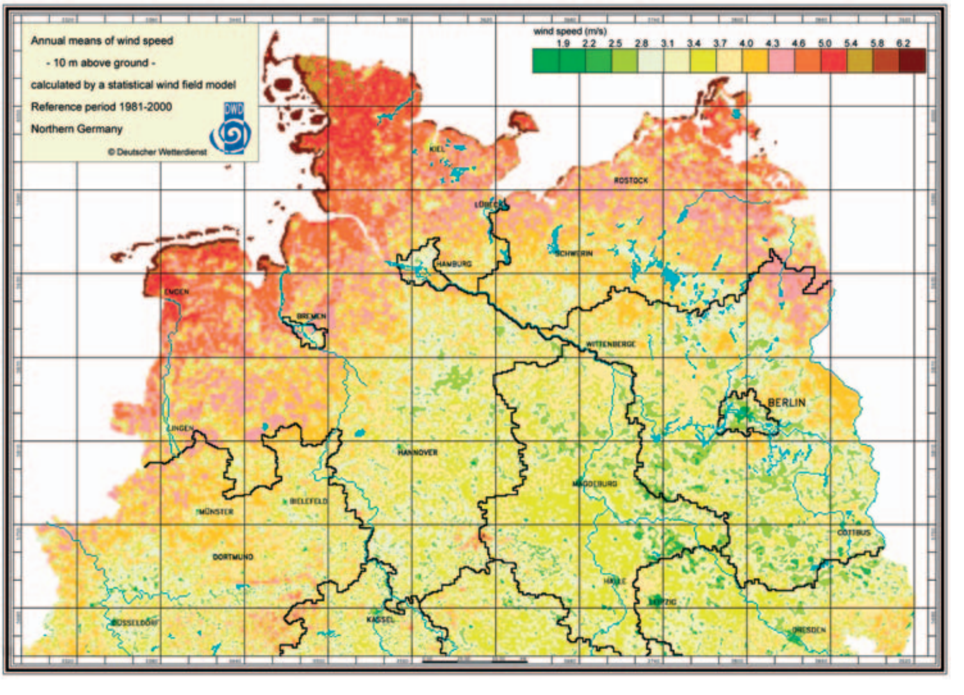


Fig. 11: Annual means of wind speed (reference period 1981–2000)

along the coasts of Mecklenburg-Western Pomerania and in the Lübecker Bucht (Lübeck Bight). With an annual mean wind speed close to 8 m/s, the windiest area is the island of Helgoland.

From the beginning of November until the end of March, the winds are stronger due to the larger temperature differences between the polar and the subtropical regions. Average wind speeds are approx. 1 to 2 m/s and higher in winter than in summer. They are weakest in May, June or August.

The richness of wind along the coasts manifests itself in the large number of days with strong wind or storm, i.e. days on which the maximum 10-minute mean wind speed is 11 m/s or higher. This corresponds to a Beaufort force 6 and above. Table 1 shows, that there is a wide spread of days with strong breezes ranging from between 30 to 40 days in the protected inner parts of fjords as well as in shallow bays to approx. 200 days at the exposed island sites, such as the most northern part of Rügen, Cap Arkona, and Helgoland in the North Sea. At open coastlines of North and Baltic Seas strong breezes are recorded on approx. 90 days. The more exposed the location, the higher is the frequency of occurrence of storms. Wind is defined as a storm if the 10-minute mean wind speed exceeds 34 m/s, corresponding to a force 8 on the Beaufort scale. In most parts of the region, the annual mean storm frequency varies from 5 to 10 days. In wind-rich island locations of the North Sea, it amounts to about 20 days. In protected bays, the average number of storm days per year is only one or two. Storm-force winds occur almost exclusively from the beginning of November until the end of March on 1 to 3 days per month. The highest average number of storm days per month, i.e. 6 to 8 days, is recorded at Cap Arkona. With the wind-rich years between 1991 and 1995, automatically a higher frequency of occurrence of storms is connected. In particular months, for example, the number of days with storm-force winds was up to 10 in wide parts of the region; at Cap Arkona it was even close to 20 days (January 1983).

Table 1: Mean monthly and annual numbers of days with wind forces of 6 Bft and more (reference period 1971–2000)

| Station name | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Helgoland | 21 | 16 | 17 | 12 | 9 | 9 | 9 | 11 | 16 | 20 | 22 | 23 | 185 |
| Norderney | 13 | 10 | 12 | 10 | 9 | 9 | 9 | 8 | 10 | 11 | 13 | 14 | 127 |
| Cuxhaven | 10 | 9 | 10 | 7 | 7 | 5 | 5 | 5 | 6 | 9 | 9 | 10 | 92 |
| List/Sylt | 17 | 14 | 16 | 12 | 12 | 12 | 12 | 11 | 14 | 16 | 18 | 19 | 171 |
| Westermarkelsdorf* | 11 | 8 | 8 | 8 | 6 | 6 | 7 | 6 | 8 | 10 | 11 | 12 | 100 |
| Boltenhagen | 13 | 12 | 13 | 10 | 9 | 7 | 7 | 7 | 8 | 10 | 13 | 14 | 121 |
| Rostock-Warnemünde | 9 | 7 | 8 | 7 | 5 | 8 | 8 | 6 | 7 | 7 | 9 | 9 | 90 |
| Arkona | 22 | 19 | 20 | 17 | 16 | 13 | 14 | 14 | 17 | 19 | 21 | 23 | 214 |
| Ueckermünde** | 5 | 5 | 6 | 5 | 2 | 1 | 2 | 1 | 2 | 3 | 4 | 5 | 42 |

* Ref. period 21 years
** Ref. period 15 years

Table 2: Mean monthly and annual numbers of days with fog (reference period 1971–2000)

| Station name | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Helgoland | 6 | 7 | 8 | 6 | 5 | 3 | 1 | 1 | 1 | 2 | 2 | 4 | 46 |
| Norderney | 8 | 7 | 6 | 5 | 3 | 2 | 1 | 1 | 2 | 4 | 5 | 7 | 52 |
| Cuxhaven | 8 | 7 | 6 | 4 | 2 | 1 | 1 | 1 | 2 | 4 | 5 | 6 | 49 |
| List | 10 | 9 | 9 | 7 | 3 | 2 | 1 | 1 | 2 | 5 | 5 | 8 | 63 |
| Westermarkels-dorf* | 5 | 6 | 6 | 4 | 2 | 1 | 1 | 2 | 2 | 2 | 3 | 5 | 41 |
| Boltenhagen | 6 | 5 | 5 | 4 | 3 | 1 | 1 | 2 | 3 | 5 | 4 | 4 | 45 |
| Warnemünde | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 1 | 2 | 5 | 4 | 4 | 45 |
| Arkona | 8 | 7 | 8 | 7 | 5 | 3 | 2 | 2 | 3 | 5 | 5 | 7 | 59 |

Despite the relatively high number of days with strong wind, gentle to moderate winds (between Beaufort force 1 to 3 resp. wind speeds of 0.3 to 5.4 m/s and Beaufort forces 4 to 5 or wind speeds of 5.5 to 10.7 m/s) predominate with a share of 75 to 90 %. The percentage of gentle winds is higher at the Baltic Sea coast. Due to the frequent on-shore winds at the North Sea coast, the annual average share of gentle winds is 30 to 40 %, the annual average share of moderate winds 40 to 50 %. In the open coastal regions of the Baltic Sea, gentle and moderate winds are almost equally frequent, with a percentage of approx. 40 to 45 %.

In the German coastal areas, the wind mainly blows from the Southwest to West, making an annual average of 35 to 40 % (Fig. 12). Apart from that, winds vary around the eastern

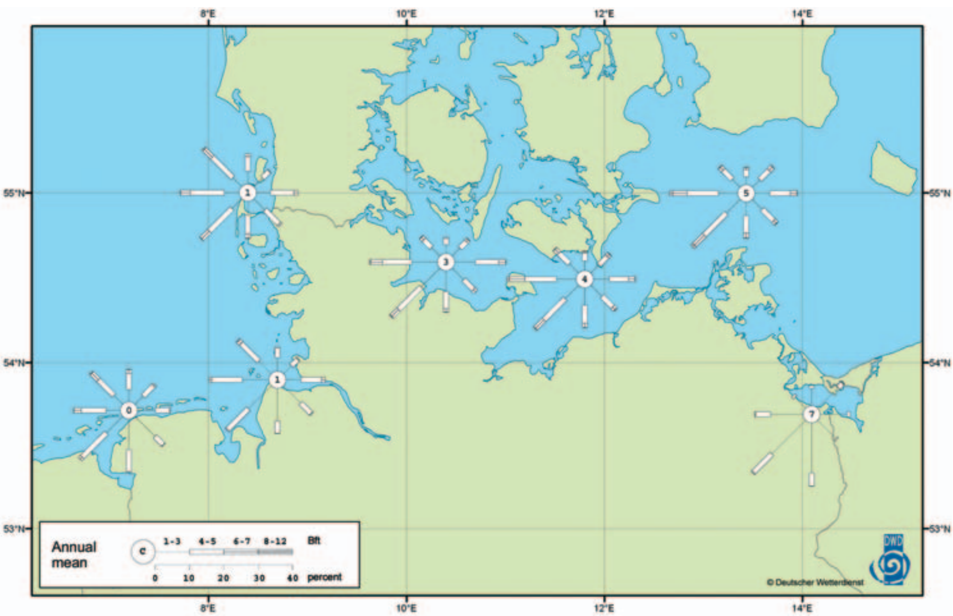


Fig. 12: Mean annual distribution of wind speed and direction

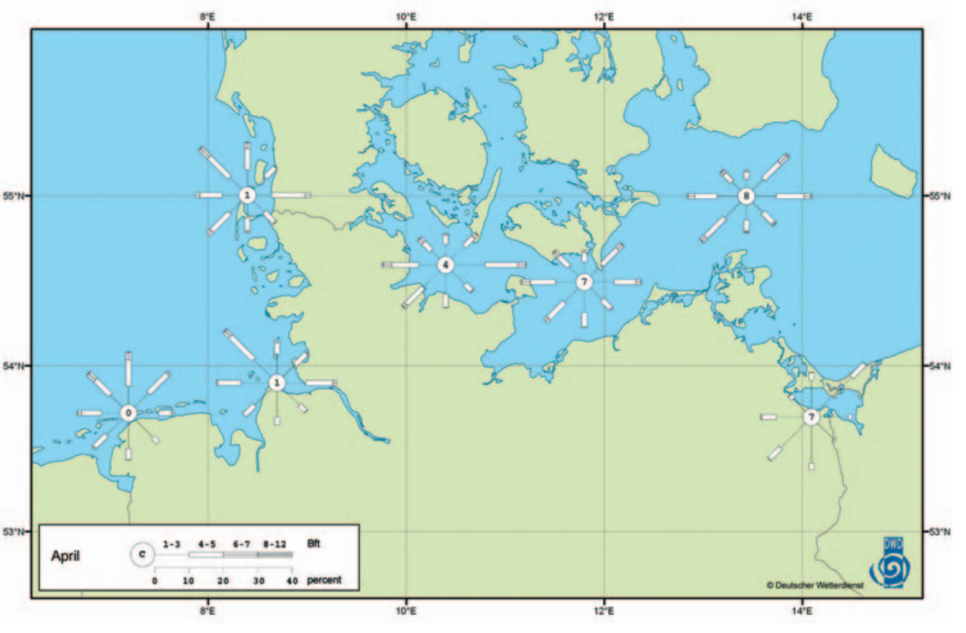


Fig. 13: Mean distribution of wind speed and direction in April

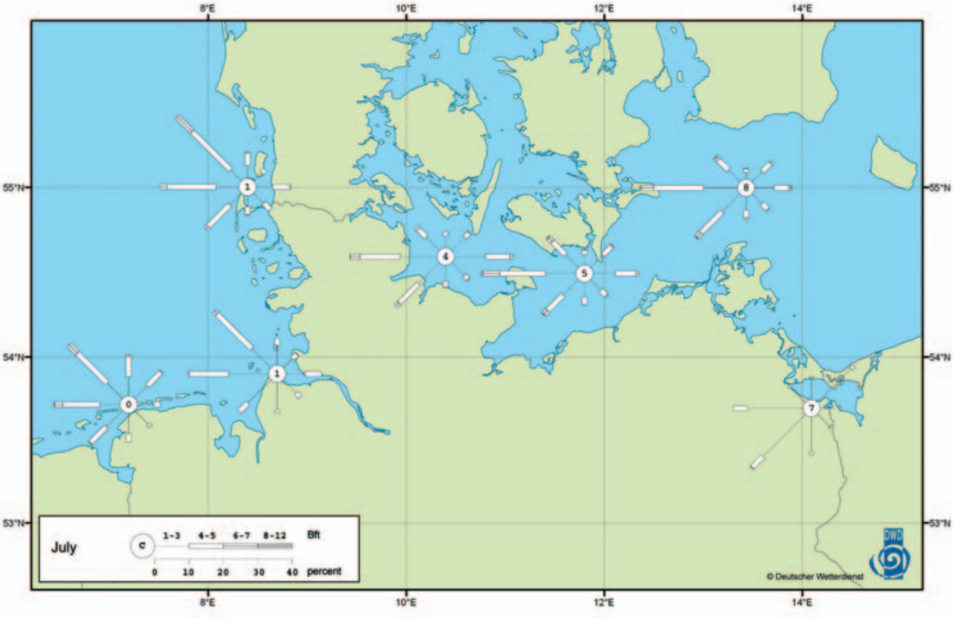


Fig. 14: Mean distribution of wind speed and direction in July

sector, i.e. from the Northeast to Southeast at about 30 % of the time or directly from the South at about 10 to 15 % of the time. The varying shape and changing orientation of the coastlines are the reason that general wind conditions are modified on a regional level. In the Szczecin Lagoon (Stettiner Haff), for example, the south-westerly winds give mainly way to southerly winds and, though less frequently, to westerly winds. The main wind direction varies throughout the year. In April, the wind very often blows from the northern to eastern direction (Fig. 13). Moderate winds from the western wind sector are more frequent in the summer in July (Fig. 14). North-westerly wind directions predominate at the North Sea coast, while the coasts along the Baltic Sea mainly receive westerly and south-westerly winds, which often blow gently. October is dominated by winds from southern directions (Fig. 15), with the winter being characterised by southerly/westerly winds at elevated wind speeds (Fig. 16).

Due to the different temperatures of land and water surfaces, land/sea circulation evolves during the warm season at high pressure situations with weak wind. This type of circulation is of a small scale and brings fresh air from the sea to the coastal areas during the day. In Northern Germany, it often extends only over a few kilometres into both directions along the coast, but may, however, also reach as far as 100 kilometres into the mainland. Above all, the land/sea circulation is responsible for the summer wind conditions in the Baltic Sea area where the on-shore wind reaches its maximum speed between 2 p.m. and 5 p.m. CEST. In the North Sea area, the phenomenon is less distinct. As an effect of the windward orientation of the coast, the wind freshens up due to the component from offshore and changes the direction of the large-scale wind towards a more onshore direction. At night, the nocturnal offshore wind often cannot prevail over the large-scale onshore winds.

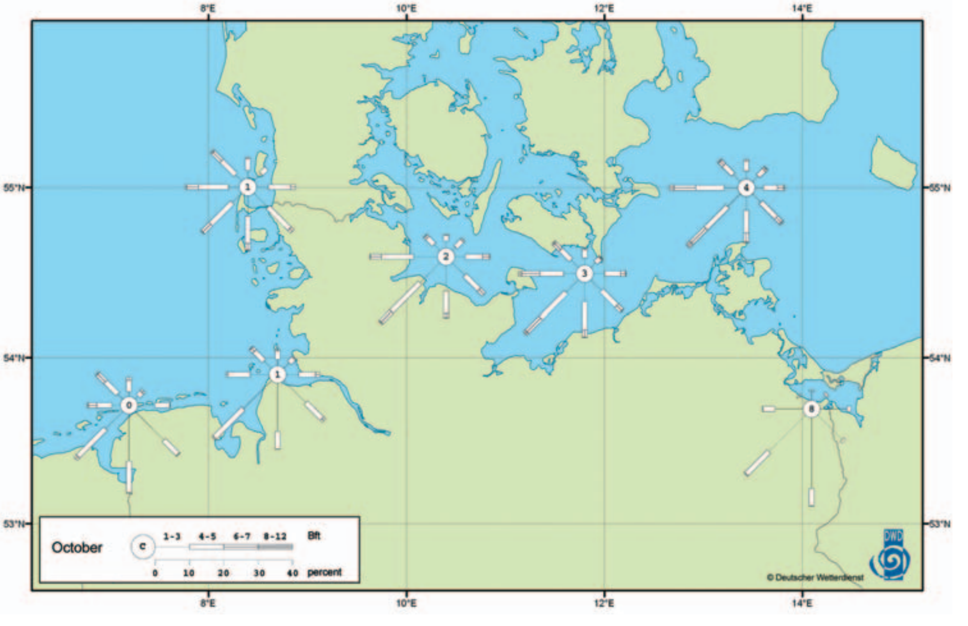


Fig. 15: Mean distribution of wind speed and direction in October

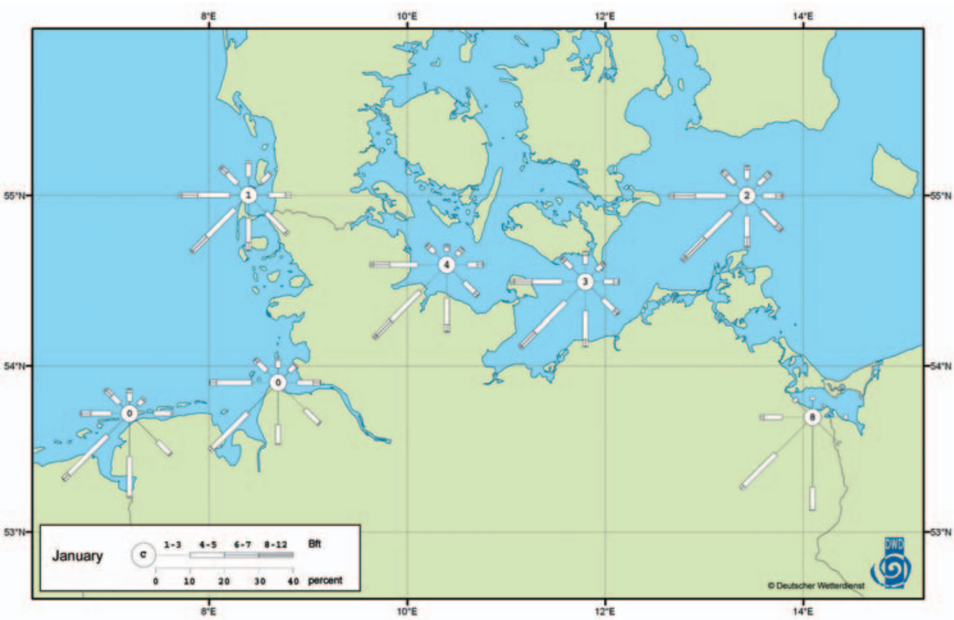


Fig. 16: Mean distribution of wind speed and direction in January

## 2.7 Visibility and Fog

Fog forms above the sea mainly in spring, when warm and humid air moves across cold water and cools down to temperatures below the dew point, or in autumn and winter, when cooler air drifts across the still relatively warm sea water. Above land, so-called radiation fog forms preferably in autumn and winter under clear high pressure weather conditions with little wind due to the nocturnal cooling resulting from radiation losses at the Earth's surface.

A particularity is the coastal and sea fog which mainly occurs in late spring. It forms when the water surface is much colder than the land surface. If the warm air masses then move horizontally from the land towards the sea, they cool down rapidly over the water and a thin fog layer develops over the water surface.

Such sudden occurrence of coastal fog causes considerable and sudden changes in the visibility and temperature conditions. The sudden occurrence of sea fog is extremely dangerous for people on mudflat excursions. These events are mostly limited to the specific part of the coast and in many cases are not recorded to their full extent by the weather and observing stations.

The frequency of occurrence of fog shows a distinct annual variation, with a maximum in winter when fog occurs mostly on 6 to 8 days per month, and a minimum in summer (Tab. 2). On average, there is only one day with fog in the months of July and August. The annual mean number of fog days is 40 to 50, in some regions even 60 days (Sylt and Rügen).

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# Oceanographic Processes in the German Bight

By Holger Klein and Alexander Frohse

Contents



## 1. Introduction

The North Sea is a shallow shelf sea connected to the Northeast Atlantic at its wide open northern boundary, which significantly affects the oceanographic state of the North Sea – defined by salinity (S) and temperature (T). Less important is the interaction via the shallow English Channel in the south-western part of the North Sea.

The Baltic Sea is connected to the North Sea via Skagerrak, Kattegat, Belt Sea and the shallow Sound. The less saline Baltic outflow influences the north-eastern part of the North Sea significantly. However, for the southern North Sea and especially the German Bight continental river run-off is a more important factor affecting S distribution and haline stratification. Temperature and thermal stratification vary with the season, whereas circulation pattern and intensity exhibit seasonal as well as a strong inter-annual variations. This paper summarises the major physical processes in the German Bight based on long-term observation and modelling results.

## 2. Currents

North Sea currents result from the superposition of semi-diurnal tidal currents, wind driven, and density driven currents. If the tidal currents are eliminated by averaging over one or more tidal periods (12.5 hours), we get the so-called residual current which is a measure for the net transport of an individual water particle at a particular point within the observation period.

Generally, the North Sea is a dominated by a cyclonic (anti-clockwise) circulation pattern. During winter and spring its intensity is influenced by the winter (DJFM) North Atlantic Oscillation index (NAO): High values of the NAO index (>2) are associated with a strong zonal wind component causing an intensification of the North Sea circulation which also affects the German Bight (Löwe et al., 2003). The NAO has a typical periodicity of about 7.7 years and is also strongly correlated with the pattern of rainfall and freshwater run-off. If the NAO is low and negative the intensive circulation is restricted to the northern part of the

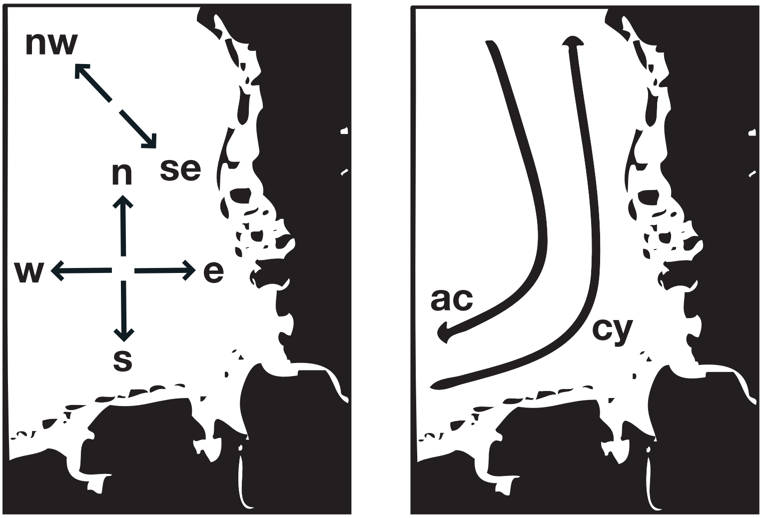


Fig. 1: Typical circulation types in the German Bight. Left: directional circulation pattern, right: cyclonic and anti-cyclonic pattern. The variable pattern is not shown

North Sea. The inflow over the western slope of the Norwegian Trench is reaching the Skagerrak and is then re-circulated within the Baltic Outflow and the Norwegian Coastal Current.

Depending on the NAO index and the local wind field, the German Bight exhibits 9 typical circulation patterns which are determined daily from the residual currents produced by the operational circulation model 'BSHcmod' of the Bundesamt für Seeschifffahrt und Hydrographie (BSH). The dominating pattern is the cyclonic circulation (ca. 43 %) with a broad inflow at the south-western boundary of the German Bight and a pronounced outflow at the northern or north-western boundary. It is followed by the inversely directed anti-cyclonic pattern (13 %) and a variable pattern (25 %). The latter is sometimes characterised by eddy structures which can be observed for several days during periods of calm weather conditions. The 6 directional types (see Fig. 1 left), which are mostly related to strong wind events, are of minor importance.

Apart from their frequency, the circulation types are also characterised by their persistence. Generally, there is a very high variability; the patterns frequently change from day to day. For the cyclonic type a long phase of stable circulation lasts about 8–10 days, but isolated events with a duration of 16 and 28 days have been observed also. Anti-cyclonic and variable phases last up to 6–8 days, whereas directional phases have a maximum duration of 3–4 days only; mostly they last only 1 day.

KLEIN (2002) analysed all current data recorded by BSH between 1957 and 2001 in different areas of the German Bight (see Fig. 3 and Table 1). Mean velocities and residual currents were determined in the near-surface (3–12 m) and near-bottom (0–5 m above bottom) layer. Included were time series with a minimum duration of 10 days and at a minimum water depth of 10 m. Positions strongly influenced by topography were rejected because the data are to represent the conditions in the open sea. Velocities in the small channels between the East and North Frisian islands and close to strong topographic gradients can be much higher. Port of reference for the tidal stream analysis is Helgoland (KLEIN and MITTELSTAEDT, 2001).

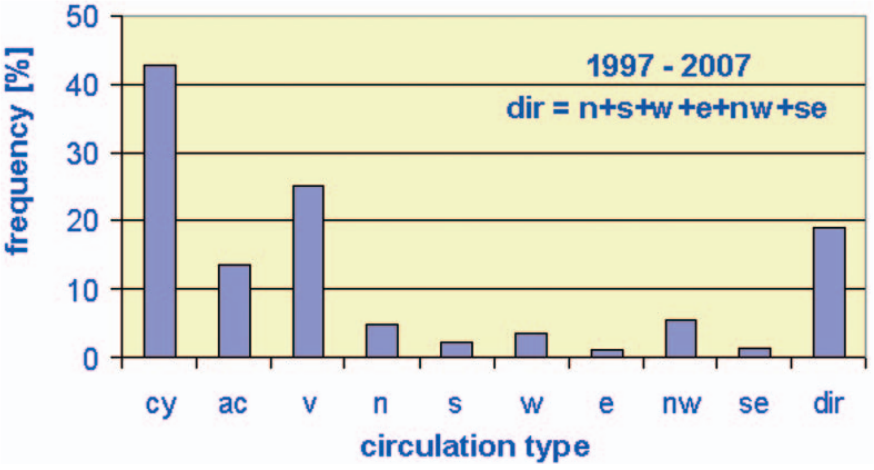


Fig. 2: Frequency percentage distribution of circulation types in the German Bight, 1997–2007

Table 1: Mean velocities, residual and tidal streams in the German Bight

| **area:** | **GB1** | **GB2** | **GB3** | **GB4** | **C1** | **C2** | **C3** | **C4** | **C5** |
|---|---|---|---|---|---|---|---|---|---|
| **near-surface:** | | | | | | | | | |
| mean velocity [cm/s] | 35.3 | 31.8 | 40.9 | 37.9 | 55.9 | 46.9 | 38.8 | 41.4 | 25.5 |
| std-deviation [cm/s] | 6.2 | 7.7 | 6.1 | 4.3 | 15.6 | 17.7 | 5.4 | 15.9 | 6.0 |
| max. velocity [cm/s) | 116 | 123 | 113 | 105 | 182 | 108 | 151 | 160 | 77 |
| vector mean [cm/s] | 6.2 | 2.4 | 4.5 | 2.1 | 1.5 | 5.8 | 1.5 | 0.9 | 3.5 |
| mean direction [°] | 20 | 27 | 43 | 10 | 18 | 27 | 65 | 204 | 45 |
| tidal max [cm/s] | 52.8 | 45.2 | 65.0 | 66.7 | 158.8 | 68.4 | 75.9 | 86.0 | 35.3 |
| data days [-] | 412 | 1522 | 664 | 1473 | 463 | 420 | 1166 | 369 | 354 |
| **near-bottom:** | | | | | | | | | |
| mean velocity [cm/s] | 15.8 | 20.8 | 31.9 | 27.3 | 42.2 | 28.0 | 33.5 | 33.8 | 23.5 |
| std-deviation [cm/s] | 3.7 | 5.4 | 6.2 | 5.7 | 5.9 | 6.5 | 5.5 | 8.8 | 6.2 |
| vector mean [cm/s] | 2.1 | 1.1 | 2.5 | 0.7 | 0.3 | 1.3 | 2.1 | 1.3 | 3.0 |
| mean direction [°] | 13 | 18 | 53 | 172 | 300 | 198 | 35 | 33 | 35 |
| tidal max [cm/s] | - | 45.1 | 46.9 | 53.5 | 57.1 | 60.7 | 72.7 | 47.5 | 26.8 |
| data days [-] | 142 | 793 | 510 | 1383 | 204 | 579 | 856 | 290 | 311 |

tidal max: maximum tidal current

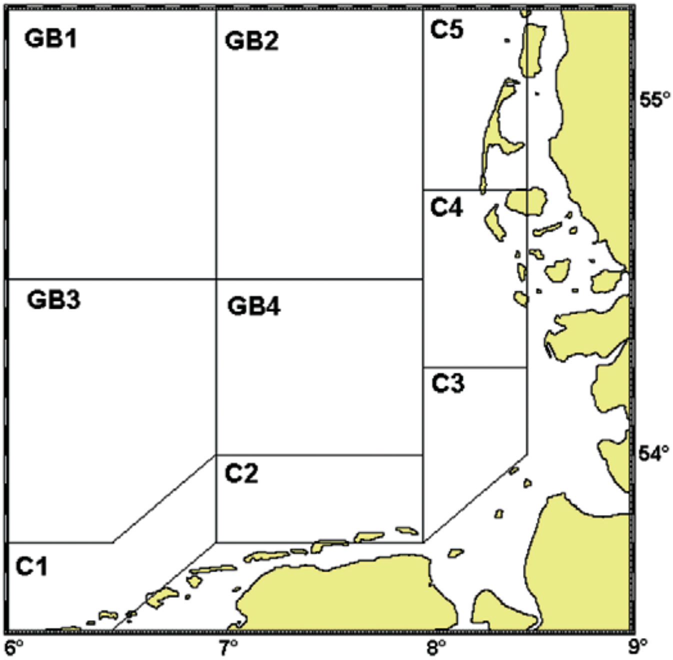


Fig 3: Off-shore (GB) and coastal areas (C) used in Table 1

The large-scale seasonal circulation pattern of the North Sea is shown in Fig. 4. It is a four-year average (2004 – 2007) based on daily averaged residual currents of BSH's circulation model 'BSHcmod'. The persistence of the currents is given in percent, 100 % corresponds to a constant current direction, 0 % means that all direction occur with the same frequency. During all seasons a cyclonic circulation is prevailing. The topographic guidance in the German Bight generates a high stability of the flow in the coastal areas. A part of the Atlantic inflow is re-circulated in the northern part of the North Sea as the so-called Dooley Current (KLEIN et al., 1994). During summer, the Baltic outflow is hardly discernible. However, the seasonal circulation patterns exhibit a high year-to-year variability.

## 3. Waves

The observed sea state is a superposition of wind waves generated by the local wind field and swell, which has a greater wave length and a longer period as the local wind sea. Swell was generated elsewhere and has left its area of origin. In the southern North Sea and the German Bight swell is mostly generated by storms in the North Atlantic or northern North Sea.

The height of wind sea depends on wind speed and the length of time the wind has been blowing with this speed. The third factor is the fetch, the unobstructed distance of sea over which the wind blows. In the German Bight the fetch for south or south-easterly winds is much shorter compared to winds blowing from north or north-west. The waves are characterised by their significant wave height which is the average height of highest one-third of all waves observed in a particular time interval.

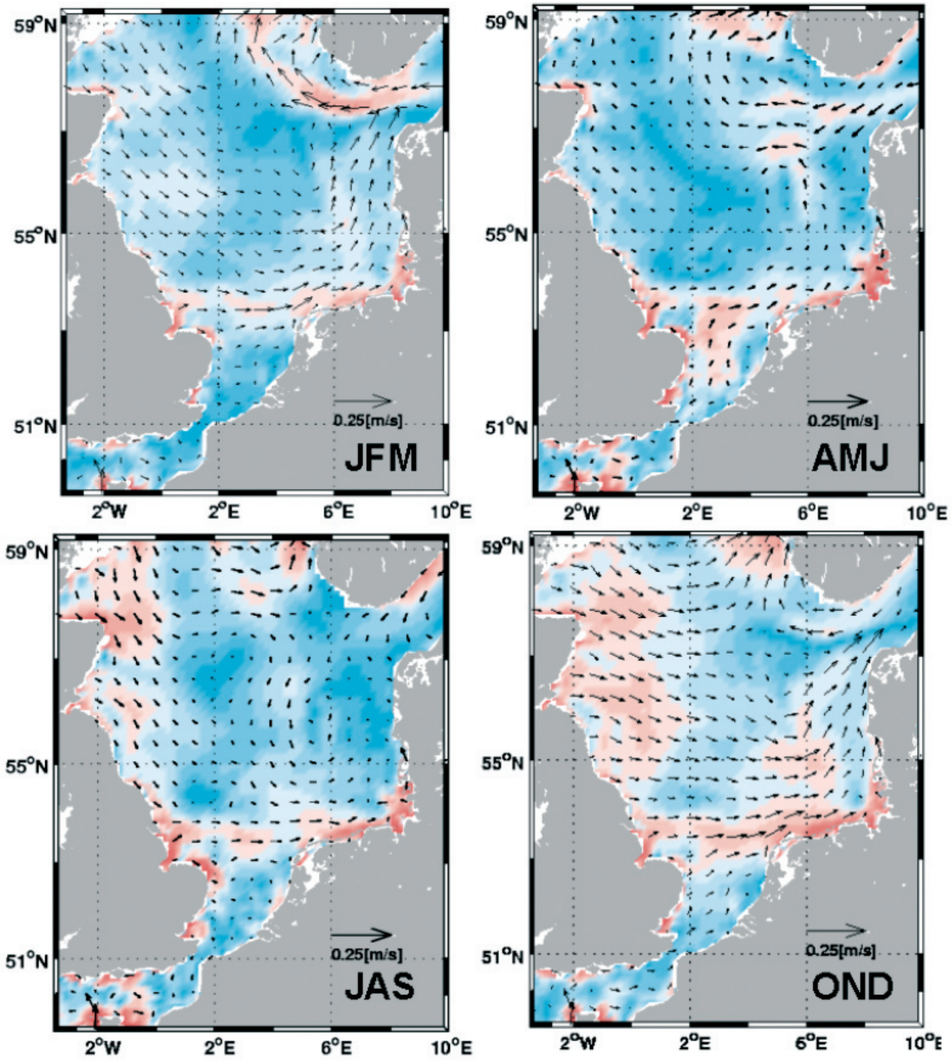


Fig. 4: Seasonal North Sea circulation pattern, BSHcmod model data, 4-year average based on daily residual currents. The colour gives the persistence in percent

In the long-term mean (1950–1986) the highest wind speeds in the German Bight occur in November (9 m/s) and decrease until February to 7 m/s. During March there is a local maximum of 8 m/s, then the values decrease rapidly to a value of about 6 m/s between May and August. Then the values increase again until they reach their maximum at the end of autumn (BSH, 1994). This seasonal cycle based on monthly means is conferrable to the sea state. At the light vessel 'German Bight' the percentage frequency distribution of both wave and wind direction shows a maximum for winds and waves from the West-south-west and a second maximum for East-south-east (LÖWE et al., 2003).

Table 2: 5-year-average of wind speed and sea state at the North Sea Buoy II location. Data are from the operational wave model of the German Weather Service (DWD)

| | NSB II 55° 00‘ N, 006° 20‘ E | | | | |
|---|---|---|---|---|---|
| | mode | mean | std | minimum | maximum |
| **wind:** | | | | | |
| speed [m/s] | 11.0 | 8.0 | 4.0 | 0.7 | 27.4 |
| direction [°] | 240 | 243 | | | |
| **significant wave height [m]** | 1.0 | 1.6 | 1.2 | 0.0 | 10.0 |
| **Wind Sea:** | | | | | |
| wave height [m] | 0.5 | 1.1 | 1.2 | 0.0 | 9.7 |
| period [s] | 3.0 | 4.0 | 2.3 | 0.0 | 13.8 |
| direction [°] | 240 | 257 | | | |
| **swell:** | | | | | |
| wave height [m] | 1.0 | 0.9 | 0.6 | 0.1 | 5.3 |
| period [s] | 8.0 | 7.0 | 1.7 | 3.5 | 18.0 |
| direction [°] | 330 | 302 | | | |

Table 2 gives a 5-year statistics of wind speed and sea state at the North Sea Buoy II (NSB II) based on data from the German Weather Service's operational wave model. The model results are validated by BSH wave rider buoys, however, compared to observational data the model data show no gaps. In addition to a mean value, also the mode is given, which represents the physical conditions much better: At NSB II for example, the most common wind speed is about 11 m/s: But due to periods of calms the average amounts to just 8 m/s. The data are representative for a wide area of the open German Bight. At the position of the light vessel 'German Bight' (54° 10‘ N, 007° 27‘ E), the statistics for the same period of time reveal nearly the same values.

## 4. Sea Surface Temperature and Thermal Stratification

The North Sea temperature is influenced by the advection of warm Atlantic water, local solar heating, and heat exchange with the atmosphere. In the German Bight atmospheric forcing is the dominant influence on temperature, as shown by a strong correlation between the NAO Index and temperatures at Helgoland Roads (Klein et al., 2007).

Weekly and monthly maps of area-averaged sea surface temperatures (SST) for the entire North Sea have been produced by BSH since 1968. The 1972–2004 monthly SST anomalies reveal a bistable SST regime with a warm period starting before 1972 followed by a cold period from December 1976 until August 1987. The system switched back rapidly to the warm status in September 1987 (Löwe et al., 2005). Fig. 5 shows clearly, that the linear trend of 0.3 ± 0.1 K/decade is not an adequate description of the real SST history. In fact, this history is characterised by spontaneous jumps between warm and cold regimes. The mean temperatures of the phases differ by 0.6 – 0.9 °C. These sudden changes between warm and cold phases can also be observed in the Helgoland Roads data for at least 130 years (Franke et al., 2004; Wiltshire and Manly, 2004). The last warm period peaked in 2002 which was the warmest year since the beginning of the area-averaged SST records in 1968. Since June 2001 the SST anomalies have been consistently higher than normal, with the exception of June and August 2005 and of March, April, and June 2006. The highest anomaly was observed in October 2006 (+2.4 °C). The summer periods became longer and warmer and winters became less cold. The amplitude decrease of the annual cycle of sea surface salinity, beginning in the mid-nineties, could still be observed in 2007.

Based on data from JANSSEN et al. (1999), Fig. 6 a/b provide the monthly averaged SST distribution in the German Bight; both figures have an identical colour scale. The lowest SST appear in February. Seasonal warming starts in May, and the SST maximum is reached in August. Cooling starts in September. The most extreme SSTs appear in the shallow coastal areas.

The thermal stratification in the German Bight is shown in Fig. 7 based on the investigations of FREY and BECKER (1987). They analysed two data sets: The first set contains observational data from 1919 – 1985 which are irregularly distributed in space and time. The second data set contains time series of weekly T and S profiles recorded at the former light vessel 'Elbe 1' between 1961 and 1984. The area of investigation was sub-divided into 10' × 10' bins, and it was assumed that the data have been recorded in the centre of these bins. Shown are the borderlines between vertically mixed and thermal stratified water for different months of the year. With increasing solar radiation, thermal stratification builds up in May. In June the extension of stratified water reaches its maximum with a borderline running close to the 20–30 m contour. In shallower areas, tidal mixing is effective and prevents thermal stratification. In the transit area between mixed and stratified water there is a permanent development and decay of tidal mixing fronts (see below). In the long-term mean, the German Bight is vertically mixed again completely at the end of September.

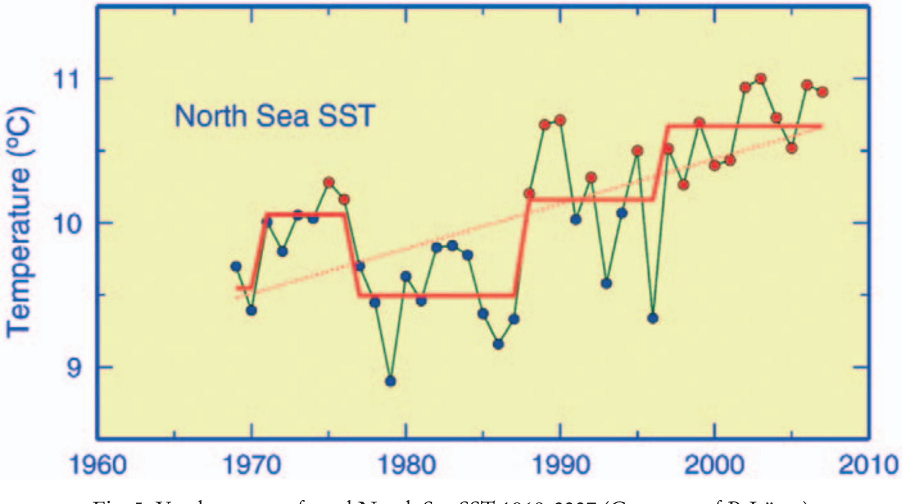


Fig. 5: Yearly means of total North Sea SST 1968-2007 (Courtesy of P. Löwe)

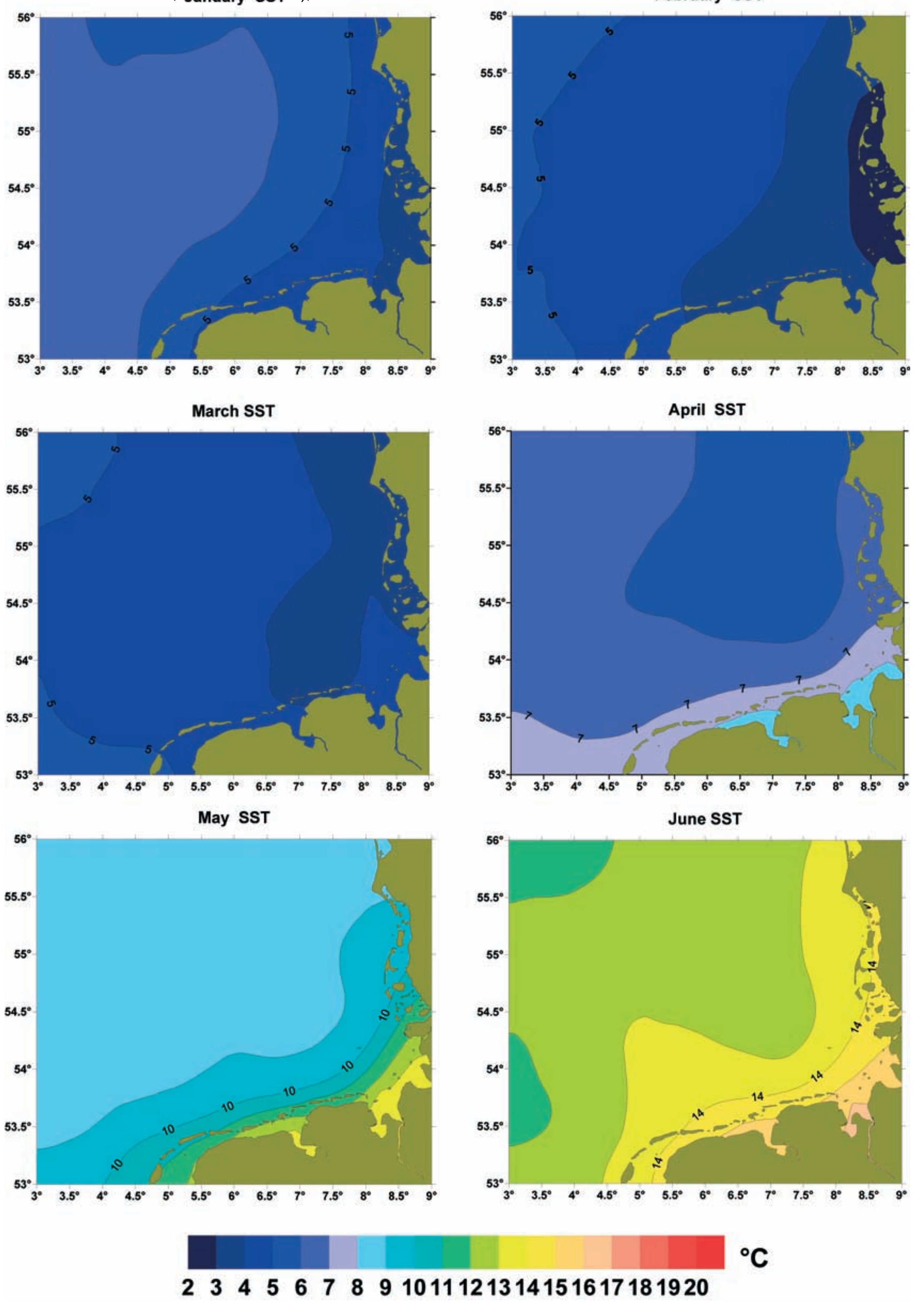


Fig. 6a: Climatological monthly means of sea surface temperature (1900–1996) for January until June (after JANSSEN et al., 1999)

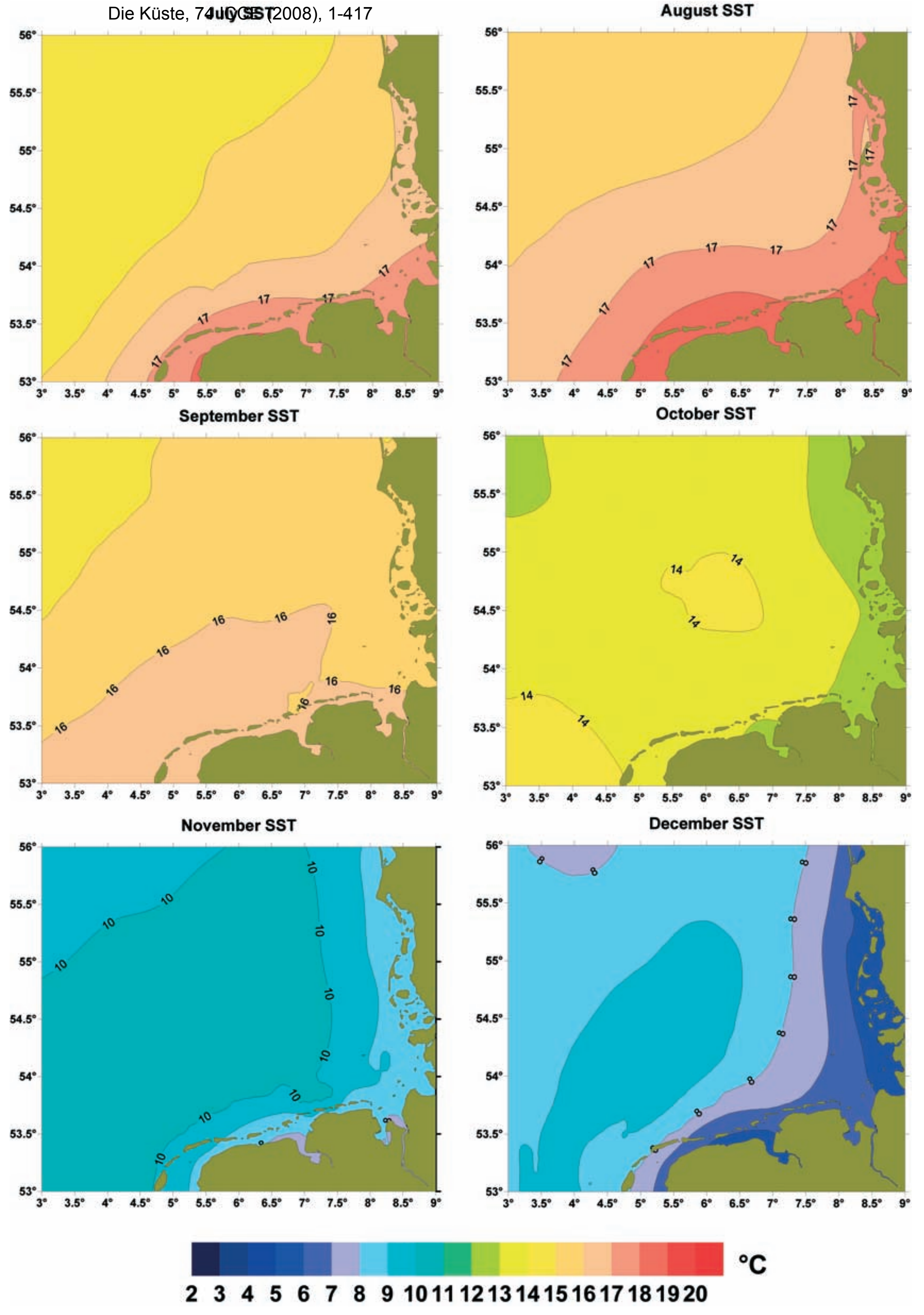


Fig. 6b: Climatological monthly means of sea surface temperature (1900–1996) for July until December (after JANSSEN et al., 1999)

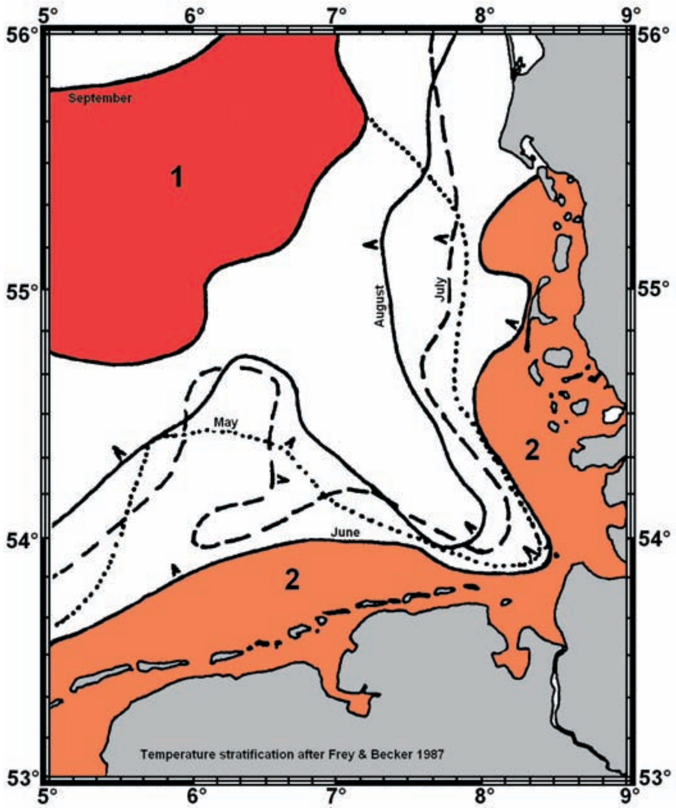


Fig. 7: Thermal stratification of the German Bight according to FREY and BECKER (1987). 1: Stratified from Mai until September, 2: all-the-year vertically mixed

## 5. Salinity Distribution and Stratification

The mean seasonal cycle of sea surface salinity (SSS) distribution is shown in Fig. 8, again based on the data of JANSSEN (1999). Because the seasonal SSS cycle is less pronounced compared to SST, only every second month is presented. Noticeable are the low salinity values in the estuaries of Elbe and Weser with minimum values of about 12 PSU (Practical Salinity Units) in January, April, and December due to strong river run-offs. Due to a less intensive circulation, the 34-isohaline moves seaward between April and August. Because the rivers permanently supply freshwater, there is an enhanced amount of brackish water in the German Bight during this time. The long-term run-off of the Elbe river, for example, amounts to about 22 km³ per year, that is about 700 m³/s.

The seasonal evolution of salinity stratification according to FREY and BECKER (1987) is given in Figure 9. The Dogger Bank area and the North-Frisian wadden sea are vertically mixed all-the-year due to bottom friction and/or tidal mixing. The area of the Elbe outflow is permanently stratified. From spring until summer, the stratified area expands towards North-north-west, while the remaining area is temporarily stratified, depending on the meteorological conditions and the intensity of river run-offs.

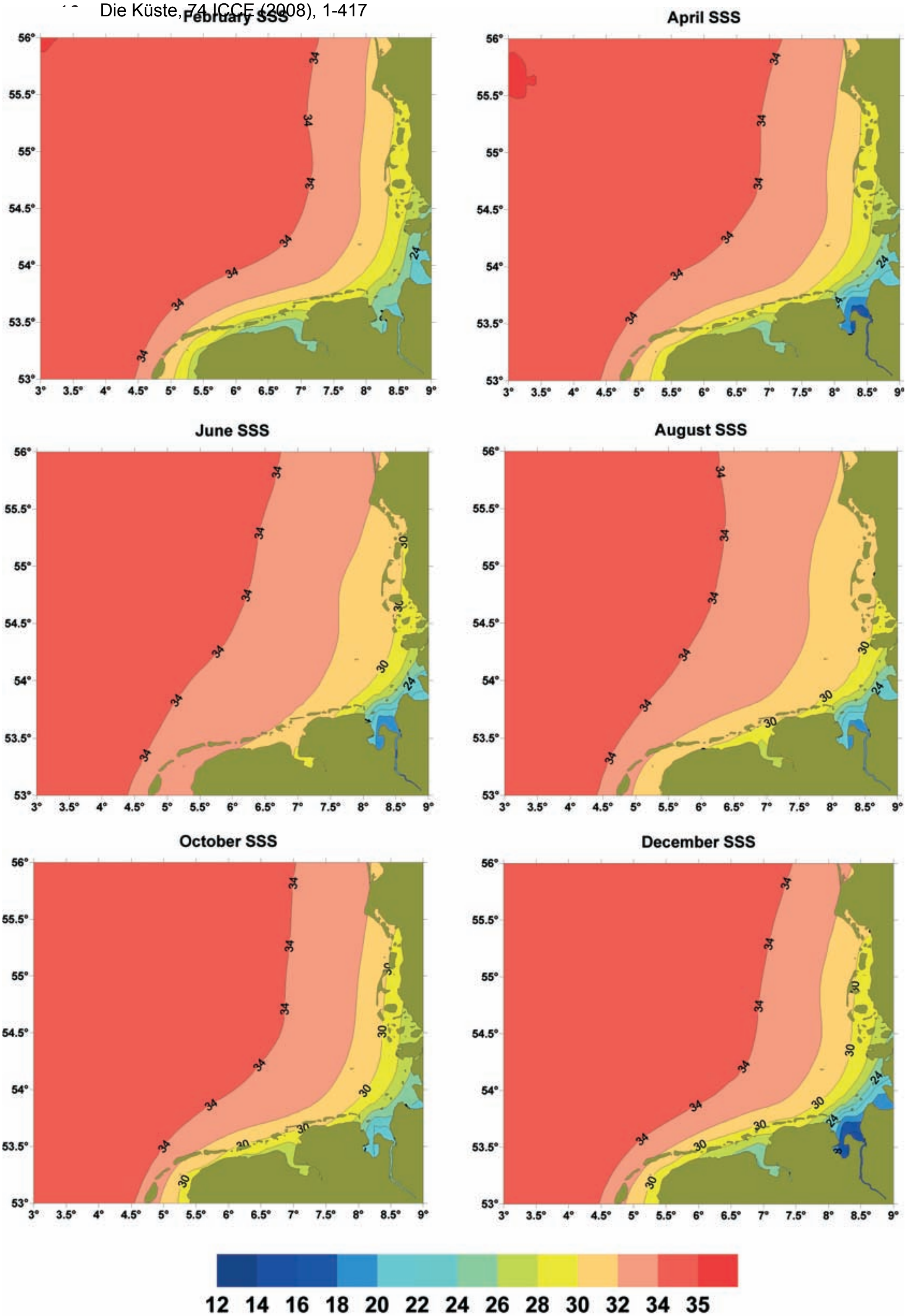


Fig. 8: Climatological monthly means of sea surface salinity for every second month of the year (1990–1996) (after JANSSEN et al., 1999)

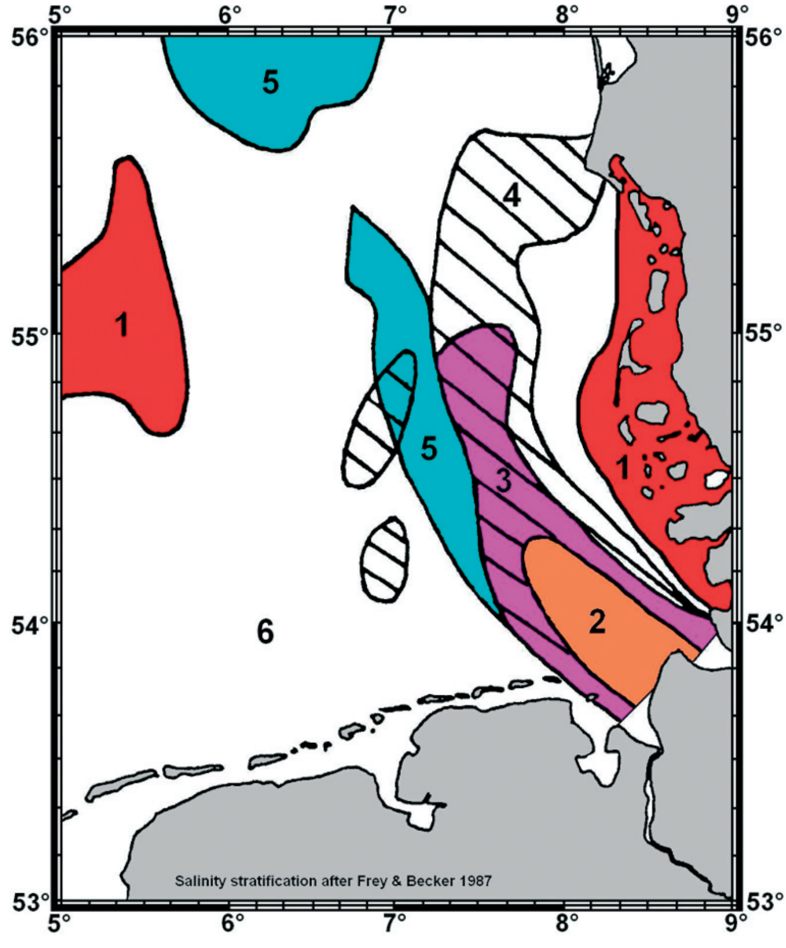


Fig. 9: Haline stratification according to FREY AND BECKER (1987): 1: all-the year vertically mixed (homohaline), 2: all-the-year stratified, 3: stratified between March and August, 4: stratified between March and May, 5: stratified between June and August, 6: temporarily stratified, covers all areas without area 1

## 6. Fronts

A front is a transition area between water masses with different properties. The sharpness of a front is defined by its horizontal gradient. Fronts in the German Bight are known for nearly 60 years. DIETRICH (1950) and GOEDECKE (1968) described them as "Konvergenz der Deutschen Bucht" (Convergency of the German Bight), a transition area between the brackish coastal waters diluted by river run-off and denser haline North Sea water. With the invention of self-recording instruments, knowledge grew significantly (BECKER and PRAHM-RODEWALD, 1980). Infra-red satellite data revealed that fronts are no static features but a system of smaller fronts and eddies with a spatial scale of 5–20 km. They permanently develop (frontogenesis) and decay (frontolysis) with a typical time scale of between 1 and 10 days. Rate and intensity of frontogenesis and frontolysis are influenced by meteorological conditions, river run-off, and circulation. Only during calm weather conditions, discrete frontal structures can be observed over several days.

In the German Bight two types of front can be observed, thermal and river plume fronts. The position of thermal fronts can be determined by a stratification parameter (SIMPSON and HUNTER, 1974) that depends on the strength of tidal currents and water depth. Its critical value determines the transition from stratified to vertically mixed water. Due to their dependency on topography these fronts are relatively stationary (OTTO et al., 1990). The stratification parameter divides the German Bight into two areas: The seaward area exhibits the above mentioned seasonal stratification whereas the inner coastal area is vertically mixed. Both areas are separated by the above mentioned tidal mixing fronts.

Fig. 10 shows a seasonal composite picture of thermal gradients between 0.2 and 0.6 °C/km. All available thermal satellite pictures have been analysed in order to identify spatial or seasonal patterns. The summer of 1995 was very cloudy. Therefore, the summer picture (day

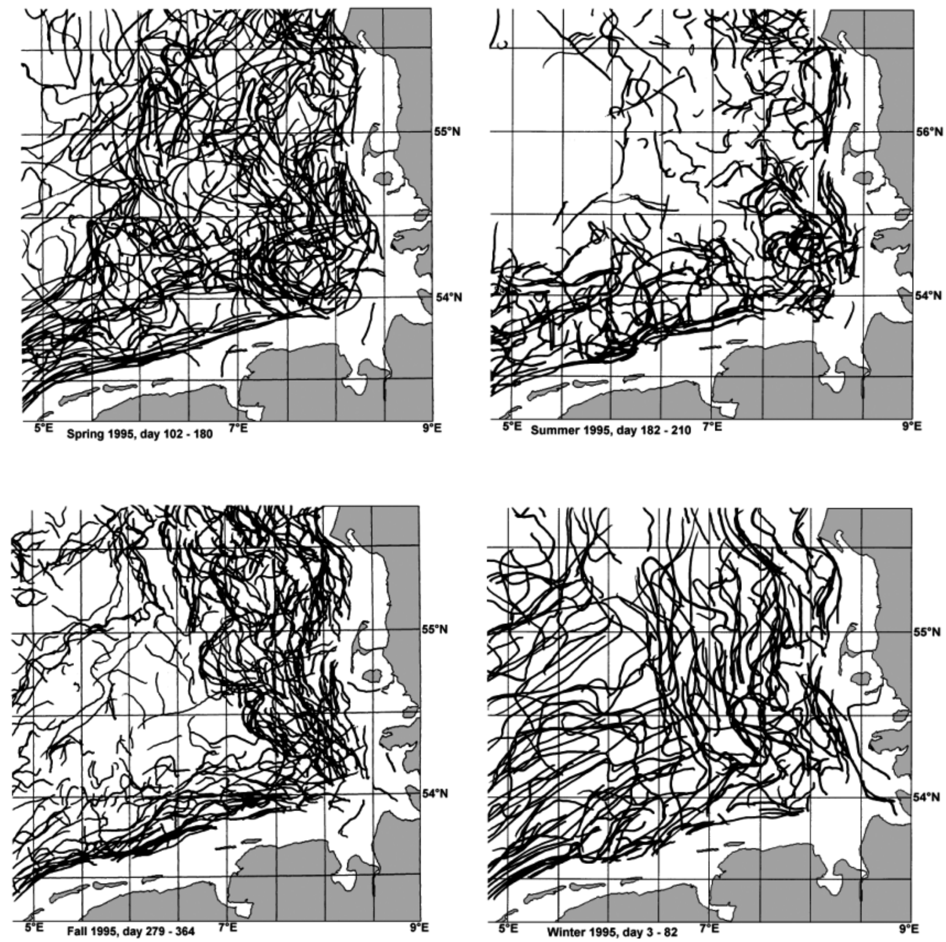


Fig. 10: Thermal fronts in the German Bight during each season of 1995. SST satellite data with horizontal gradients between 0.2 and 0.6°C/km

182–210) is based on 29 single images only. Especially along the East-Frisian coast, a clear concentration along the 30 m depth contour can be seen, but thermal fronts can be observed everywhere in the German Bight and in every season.

The thermal frontal system is superimposed by the so-called river plume fronts with strong salinity gradients generated by the permanent river run-offs of Elbe, Weser and Rhine (FRANZ and KLEIN, 1986; KLEIN, 1986). Due to convergence and down-welling, these fronts accumulate organic and inorganic material and cause an increase of metabolites ('fish follows fronts'). During periods of calm weather fronts can be detected easily by eye due to a meandering strip of foam and flotsam, the so-called 'siome'.

## 7. Sea Ice

In the eastern North Sea the general weather situation prevents a regular ice formation during winter. During fall and winter westerly winds are dominating, bringing mild air to central Europe which avoids or delays seasonal cooling. Another factor is the advection of warm saline Atlantic water. However, easterly winds can cause a rapid cooling of sea temperatures. Extent and duration of ice cover depends on the strength and duration of the cold spells and on their time of occurrence. A strong ice formation, caused by an early start of winter and long-lasting frost periods, normally does not start before end of January or mid-February.

Normally, in early spring the heat reservoir of the haline North Sea water in the open German Bight is still big enough, so that ice formation occures only infrequently. The open-sea areas between North- and East-Frisian islands are ice-free during two thirds of the winter. In the long-term mean the ice in coastal areas is melts in the third decade of February; only during strong ice winters the last ice melts not before end of March. A detailed description of the ice conditions is given by BSH (1994).

## 8. Suspended Matter and Turbidity

Suspended matter denotes all suspended particles in sea water with a diameter >0.4 µm. The suspended matter content, called 'suspended particulate matter' (SPM) is the material gained after filtering and drying a water sample of a defined volume with a 0.4 µm pore size filter.

Suspended matter contains organic and/or inorganic material. The organic fraction exhibits a seasonal cycle with high concentrations during the plankton blooms in early summer. During stormy weather with high waves SPM concentration is enhanced within the whole water column due to re-mobilisation of bottom sediments with swell being the most effective mechanism (KLEIN et al., 1999). Intensive low-pressure systems can easily enhance the SPM load by a factor of 10. The dominant signal in SPM time series is the semi-diurnal tidal stream. The ebb-currents carry turbid water from the wadden sea into the open North Sea, whereas the flood currents carry less turbid water into coastal areas. Further sources of suspended matter are the river run-offs from the big European rivers.

Fig. 11 shows the mean SPM distribution on the German continental shelf based on all data available in the German marine environmental data bank (MUDAB, Oct. 2005) between the surface and 10 m depth. It must be kept in mind that these data are ship-born data and that SPM sampling is not possible during stormy weather when SPM concentrations are significantly enhanced. In the wadden areas and estuaries the mean values are of the order of

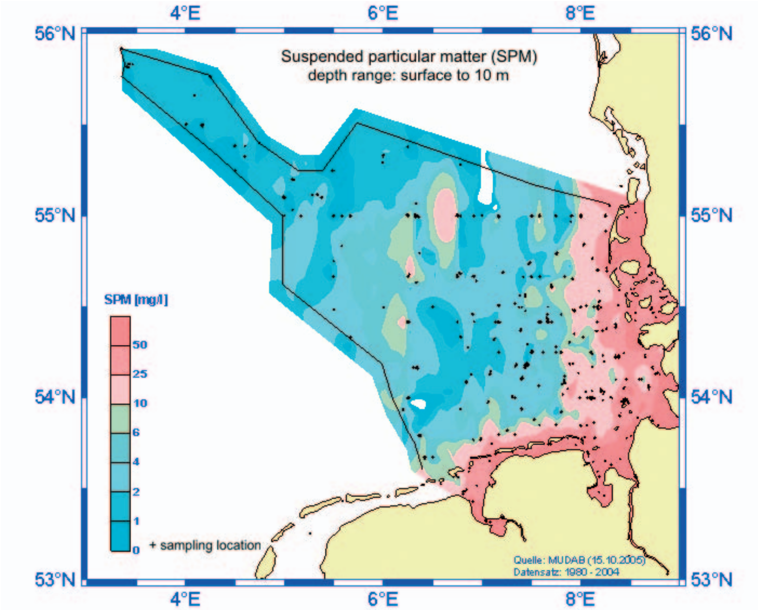


Fig. 11: Mean suspended particulate matter (SPM) concentration on the German continental shelf

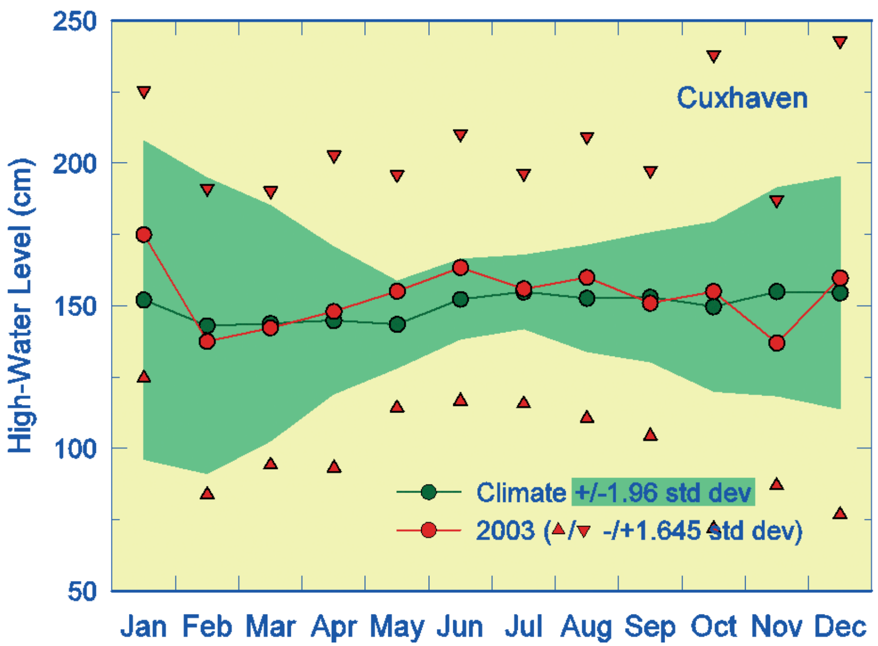


Fig. 12: High water levels at the tide gauge Cuxhaven-Steubenhöft. Green line: monthly means 1971 – 2000 with 95 % confidence interval of inter-annual variation. Red line: monthly means 2003 with intra-monthly variation (90 % quantile, red triangles)

50 mg/l with extreme values > 150 mg/l. Seaward, the concentrations decrease rapidly ranging between 1 and 5 mg/l.

## 9. Water Levels

Based on water level records at different locations in the North Sea covering up to 100 years, water levels in the North Sea can be analysed and predicted on different time scales. The tide gauge at Cuxhaven-Steubenhöft, which is not influenced by topographical changes, is used as port of reference by BSH for water level predictions and statistical classification of high waters.

The monthly high water climatology at Cuxhaven for the period 1971 – 2000 is shown in Fig. 12 (green line) together with the 95 % confidence interval. The climatology exhibits a weak seasonal signal oscillating around the mean high water at 150 cm. The variability during fall and winter exceeds that during spring and summer significantly. The broad bandwidth of high water levels during winter and fall clearly documents the effects of meteorological disturbances, with wind being the most effective factor. Generally, air pressure differences are much weaker during summer producing predominantly fair weather conditions. Therefore, water level variations are basically predominated by tides.

As an example, the red line in Fig. 12 gives the values for 2003 which show no significant variations compared to climatology. The intra-monthly variability is marked by red triangles. The enhanced values in May and June (11 cm above the long-term mean) are caused by extreme high waters due to strong north-westerly winds. Owing to its geographical location in the Elbe estuary with its broad opening towards the north-west, the highest water level and strongest storm surges connected with north-westerly winds occur in this area. Accordingly, the lowest water levels occur during south-easterly winds.

Concerning the long-term sea level rise, Jensen and Mudersbach (2004) estimated an increase of 19 cm/100 years for the period 1965–2001 and of 15 cm/100 years for the period 1826–2001, based on the analysis of 12 tide gauge stations along the German North Sea coast.

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# Oceanographic Processes in the Baltic Sea

By WOLFGANG FENNEL and TORSTEN SEIFERT

Contents



## 1. General Description

The Baltic is a tideless semi-enclosed sea consisting of several basins, which are connected by sills or channels. A map of the bathymetry of the Baltic is shown in Fig. 1. The Baltic has only narrow connections to the North Sea through the Danish straits which reduce the water exchange distinctly. Water transport is also hindered by the shallow Darss Sill (maximum depth 18 m). This sill is the western boundary of the Arkona Basin (maximum depth 45 m), which is connected by the Bornholm Channel to the Bornholm Basin (depth maximum 95 m). At the eastern flank of the Bornholm Basin, the Stolpe Channel follows, which is connected to the central Baltic Sea, the Gotland Basin with a maximum depth of 250 m. The northern part of the basin extends to the East into the Gulf of Finland and towards the North, through the Aland Sea with its numerous islands, into the Gulf of Bothnia.

Being located in the latitudinal range from 54 to 66°N, the Baltic Sea is exposed to subarctic climatic conditions in the North and temperate conditions in the central and southern parts, and subject to highly variable winds and many storm events. The northern parts of the Baltic are regularly ice covered during winter. General overviews of the oceanographic features of the Baltic Sea are given, for example, in OMSTEDT (2004), STIGEBRANDT (2001), KULLENBERG (1981) and FEISTEL et al. (2008).

Owing to the substantial fresh water input from several rivers, the Baltic Sea has a positive water balance. The annual total contribution of all rivers is about 450 km$^3$ while the excess of precipitation over evaporation amounts to 60 km$^3$ per year. This would raise the sea-level by a little more than 1 m per year if the Baltic Sea were not connected to the North Sea. As a result of the freshwater surplus and the restricted water exchange, the Baltic is one of the largest brackish water seas in the world with a water volume of about 21,000 km$^3$.

In the eastern and northern parts of the Baltic Sea the salinity is low (about 4 g/kg), but increases towards the Danish Straits. Owing to the freshwater supply and the near bottom inflow of saline water, the Baltic is characterized by a strong vertical stratification,

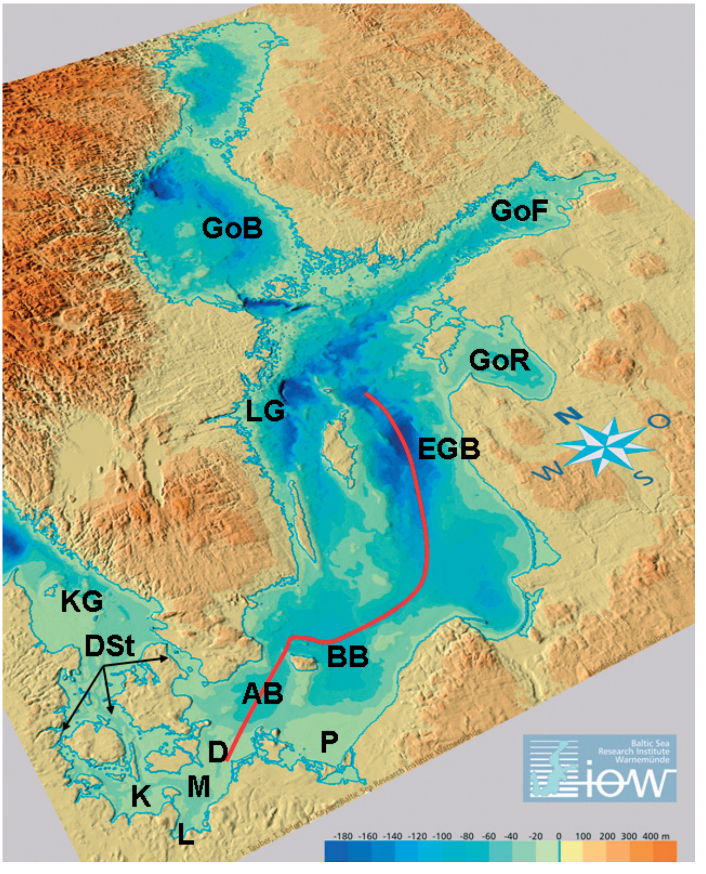


Fig. 1: Topographic map of the Baltic Sea (SEIFERT et al., 2001): Kattegat (KG), Danish Straits (DSt), Kiel Bight (K), Lübeck Bight (L), Mecklenburg Bight (M), Darss Sill (D), Pomeranian Bight (P), Arkona Basin (AB), Bornholm Basin (BB), Eastern Gotland Basin (EGB), Landsort gauge (LG), Gulf of Riga (GoR), Gulf of Finland (GoF), and Gulf of Bothia (GoB). The bold red line indicates the ship track for the records shown in Figs. 2 and 3

where a strong halocline separates the brackish surface water from the more saline bottom water.

The halocline is associated with a high vertical stability, implying a weak vertical exchange through the halocline. As a consequence, hypoxia or even anoxia occurs frequently in the deep waters below the halocline. The general structure of the salinity and oxygen distribution is shown in Fig. 2 by means of a section along the path of the maximum depths. The poor ventilation of the deep water below the halocline favours variations in oxygen and occasional switching to hydrogen sulphide. This affects the biogeochemistry in the bottom water and the upper sediments.

The annual cycle of solar radiation drives a yearly cycle of surface temperatures and the formation of a seasonally varying thermocline. Hence the vertical temperature distribution shows a strong seasonal cycle with the formation of a warm upper layer of 10 to 20 m thickness and a strong thermocline below. Examples of the temperature distributions along the

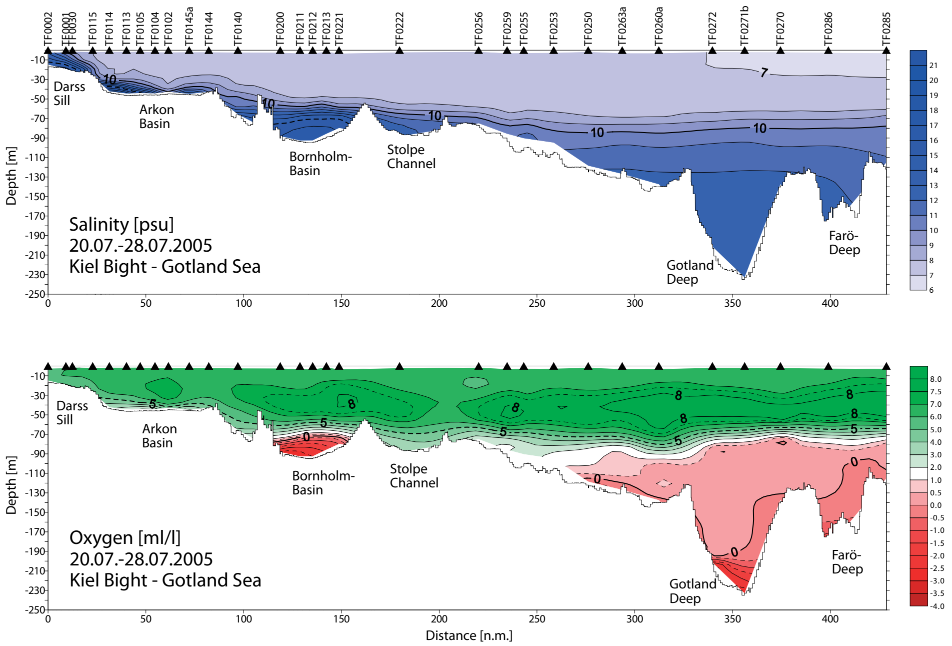


Fig. 2: Horizontal-vertical sections of salinity (top) and oxygen (bottom) as recorded during a Baltic monitoring cruise in 2005 (see Fig. 1). Negative oxygen is used to indicate hydrogen sulphide

path of the maximum depths in winter and summer are shown in Fig. 3. Vertical profiles of temperature and salinity show usually stronger gradients than suggested by the vertically and horizontally interpolated distributions plotted in Figs. 2 and 3.

The permanent halocline and the seasonal thermocline are important for the ecosystem of the Baltic Sea. The horizontal and vertical salinity gradients associated with the permanent halocline set the long term conditions for the marine ecosystem. Salinity gradients affect osmotic regulations of living cells and, therefore, the number of species in the Baltic is relatively small. The annual cycle of temperatures, i.e., the formation of the thermocline in spring and its disappearance in fall, defines a seasonal time scale. Irregular weather patterns and storms with time scales of a few days are typical for the latitudes between 50 to 60°N and generate a variety of mesoscale currents in the Baltic Sea, such as eddies, coastal jets and associated up- and downwelling patterns with time scales of a few days to weeks. Mesoscale features can influence the distribution patterns of plankton, eggs and larvae etc., because particulate biomass can either be dispersed or concentrated by the combined effect of swimming or sinking in conjunction with advection and turbulent diffusion.

## 2. Processes and Time Scales

The most energetic part of the currents is due to wind forcing. Frequent synoptic-scale cyclonic activity is typical in the Baltic area and implies a high variability of the prevailing westerly winds. Maximum speeds are reached during November to March. In May and June

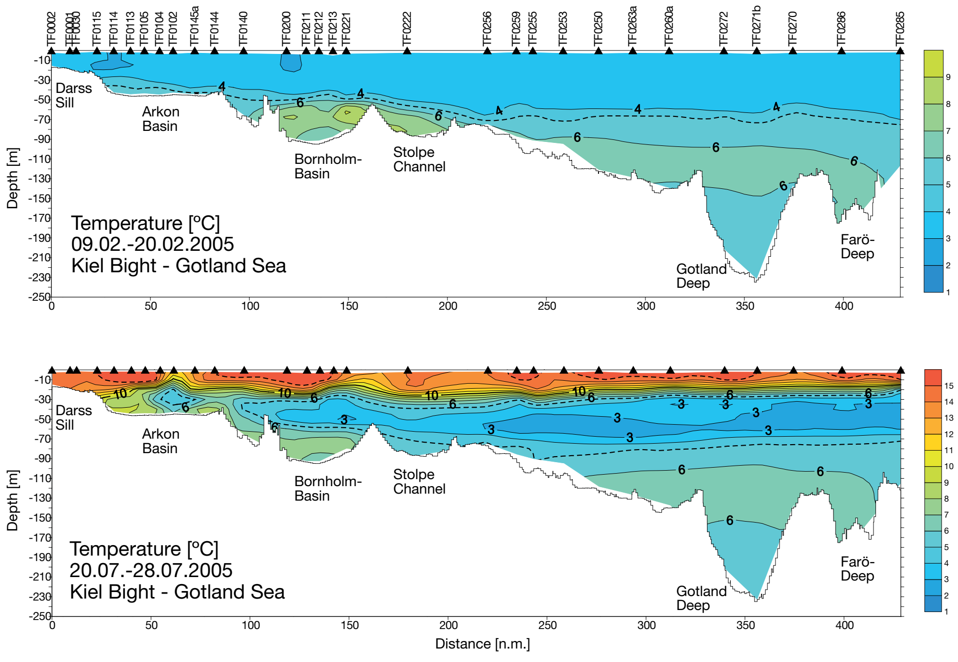


Fig. 3: Horizontal-vertical sections of temperature as in Fig. 2 as recorded during Baltic monitoring cruises (see Fig. 1) in winter (top) and in summer (bottom)

the average wind is minimum. In the high frequency range the wind generates waves which produce turbulence in the upper mixed layer and can mix the whole water column in the shallower regions.

## 2.1 Waves and Seiches

Compared to sea level elevations by tides and winds in the open ocean, the sea surface variations of the Baltic Sea are rather weak. Owing to its small spatial extent the tidal range is limited to some centimeters only (MÜLLER-NAVARRA, 2003), and the tidal signal propagating from the North Sea into Skagerrak and Kattegat is filtered out by the narrow and shallow Danish straits.

Therefore, the sea level of the Baltic Sea oscillates like in closed basins (so-called seiches). According to WÜBBER and KRAUSS (1979) the first mode comprising the entire Baltic has a period of 31 hours and forms a cyclonically rotating wave with the amphidromic point in the northern Baltic proper. Hence, the sea level observed at the tide gauge at Landsort is a reliable measure for the filling level of the Baltic Sea. The second mode shows two separate seiches of the Bothnian Sea and of the central Baltic including the Gulf of Finland and the Gulf of Riga with periods around 26 hours. The relative change of sea level by seiches is 5–10 cm in the open basins and up to 30–40 cm in the western Baltic, the Bothnian Bay, and especially in the eastern Gulf of Finland.

Stronger surface elevations are generated by wind set-up (Windstau). For example, long-lasting easterly or westerly winds can change the filling level of the Baltic Sea by ±50 cm on average. The wind induced piling-up of water at the coasts may rise to 1 m and more. Extreme high water levels can be generated when such a set-up flows back in resonance with the seiches, while a storm from the opposite direction forces a wind set-up at the other side of the basin. This was the case in November 1872, when a floodwater of 2–3 m height damaged the German and the Danish coasts (ROSENHAGEN and BORK, 2008).

The height of the surface waves, which are produced by the exchange of momentum between the atmosphere and the sea, increases essentially with the wind speed and with the fetch, which is the directional length over which a nearly constant wind acts upon the sea surface. The fetch is limited in the relatively narrow Baltic Sea to some 200–700 km along the main axes of the open basins. Wave models show that, despite of the fetch limitation, a saturated sea state develops for stronger winds within 12–24 hours with significant wave heights of 9 m in the central Baltic and up to 7 m in the south-western Baltic. In correspondence to the seasonal variation of the wind, the monthly mean wave heights vary between 1–3 m in winter (October–February), whereas the average is less then 1 m in summer (see for instance JOENSSON et al., 2002).

In Fig. 4 the mean significant wave height (in colours) is shown as taken from a simulation for the decade 1990–1999. The computation was done with an adaptation of the parametric wave model of SCHWAB et al. (1984), using a resolution of 3 nautical miles (approximately 5.5 km). The maximum of the simulated waves are indicated by contours (full lines for 1–4 m, and broken lines for half meter steps). To validate the model results, data from a wave rider buoy were used. The wave rider was operated by GKSS (Institut für Küstenfor-

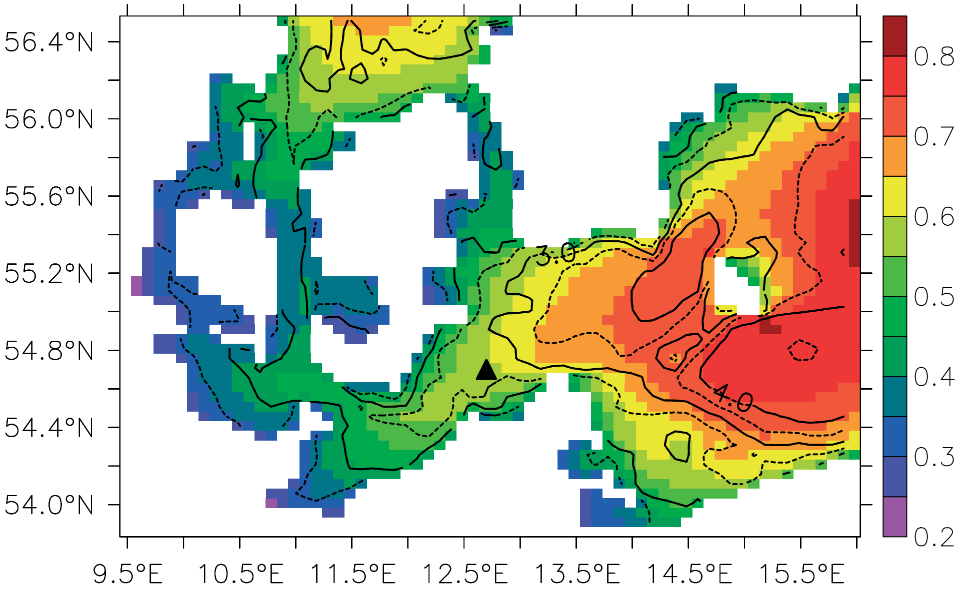


Fig. 4: Mean significant wave height (colours, in meters) and maximum waves (contours) in the period 1990–1999 simulated with an adaptation of a parametric wave model (SCHWAB et al., 1984) with ERA-40 wind forcing (UPPALA et al., 2005). The triangle shows the position of the GKSS wave rider buoy used to validate the model results

schung, Geesthacht) in the frame of the MORWIN project (http://morwin.baw.de) and was deployed near the permanent monitoring station on Darss Sill, the location of which is indicated by a triangle symbol in Fig. 4. The data comparison showed that the significant wave height is reproduced by the wave model with a scatter of ±0.25 m explaining 70–80 % of the data variance. On average the simulated wave heights under-estimate the real sea state by 20 % (slope of 0.8 of the regression line between model and data). That is partly caused by the wind forcing taken from the reanalysed weather model data set ERA-40 (UPPALA et al., 2005), since transient local wind maxima are smoothed out by six-hourly forecasts within a spatial resolution of 60–120 km.

Despite of these restrictions, the wave simulation shows realistic mean wave heights below 0.9 m in the south-western Baltic. In the sheltered bights of Kiel and Lübeck a low sea state is found. Maximum significant wave heights of 2–3 m are obtained in the Mecklenburg Bight, and up to 4 m in the Arkona Sea. However, the assessment of wave action in the coastal zone requires the application of more elaborate models, including swell and wave breaking, with a significant higher resolution of the model grid and the forcing data. For a recent comprehensive overview of waves, tides and seiches in the Baltic Sea see SCHMAGER et al. (2008).

### 2.2 Currents

Although the winds can be strong during gales, the variance of the wind is high while mean values are small. Consequently, the currents are dominated by the transient phases of the oceanic responses to episodic forcing. Virtually there are no significant permanent currents which deserve their own name. Weak general circulation patterns can be detected by the large scale distribution of surface salinity, which points to a small basin-wide cyclonic water motion. In the central Gotland Basin, a relatively persistent low frequency dense bottom flow has recently been detected by HAGEN and FEISTEL (2004).

Strong current signals are often observed in the western Baltic and in the Danish straights, where the flow is driven by local and remote forcing. In particular, large scale sea level gradients between the Kattegat and the Baltic Proper can generate strong gradient currents in the narrow channels of the transition area between the Baltic and the Kattegat even at low wind episodes.

The responses of the sea to wind forcing are in particular seen as coastal jets, usually associated with up- and downwelling patterns (see e.g. FENNEL and STURM, 1991; FENNEL and SEIFERT, 1995 and LEHMANN et al., 2002). The upwelling is well documented by satellite images of the sea-surface temperature (SST), where the cold intermediate winter waters wells up near the coast and leave a very clear signature (see the example shown in Fig. 5).

The spirals and eddy-like patterns have typical scales of 5 to 20 km and demonstrate a rich mesoscale circulation. Since the spatial scales of the meteorological forcing and irradiation are much larger, say several hundreds of kilometres, it is clear that the mesoscale structures reflect the response of the sea. The upwelling signal off the Polish coast refers to the typical response of the coastal waters to eastern winds. The cold water area in the south-western Baltic shows upwelled water that spreads over the entire channel due to the off-shore Ekman transport.

An illustration of the high variability of the current signals in the channel of Fehmarn Belt is shown in Figs. 6 and 7. In Fig. 6, the three snapshots of the currents through the Fehmarn Belt, observed in November 1994, show inflowing waters. However, the current is not homogeneous but varies over the cross section over a range of up to 100 cm/s.

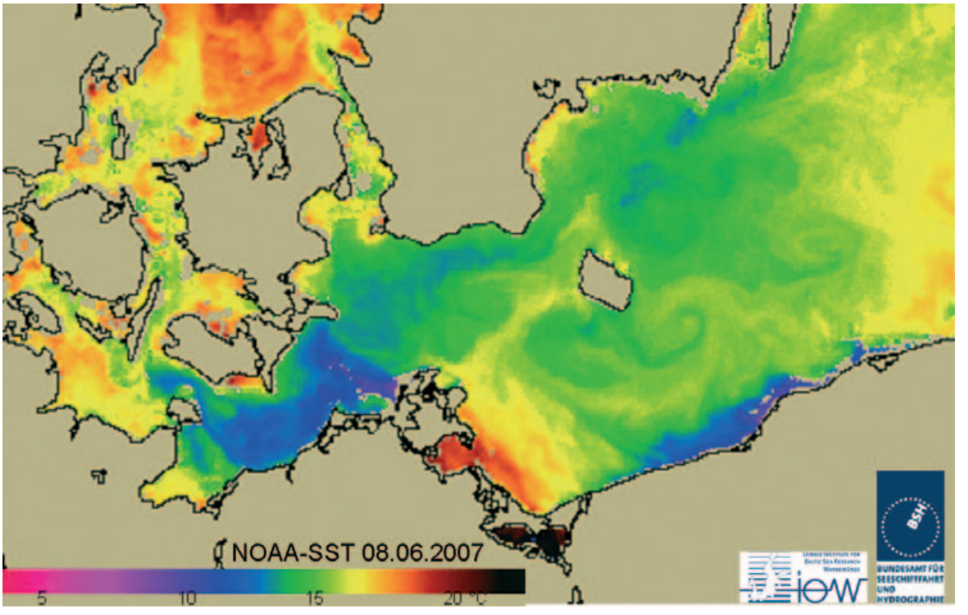


Fig. 5: Satellite image of the south-western Baltic in June 2007.
The blue areas indicate cold upwelled water

The second example, shown in Fig. 7, was observed in summer 1995. The saline stratification is stronger than in autumn, and the isohalines indicate a geostrophic balance of the currents and the cross-channel pressure field. The current has a remarkable spatial cross-channel structure and varies in the vertical and horizontal direction. The speed ranges from –80 to +80 cm/s.

### 2.3 Adjustment Processes

It is illuminating to look at the response of the sea to a sudden onset of wind. The scenario starts with inertial oscillations and inertial waves along with Ekman transports. Coastal boundaries and wind stress curls generate convergences or divergences of the Ekman transport, which produce vertical water motions and generate pressure gradients and geostrophically adjusted flows, such as coastal jets. Eventually, the adjustment of the flow results basically in currents along isobaths.

The response scenario can be characterized by several time scales: the geostrophic adjustment is related to the time needed by inertial waves to travel along the channel-like Baltic Sea (crossing time = $c_1$ L, where $c_1$ is the first mode phase speed of inertial and Kelvin waves and L is a cross-sectional length (scale) of the Baltic channel. The phase speeds vary both spatially among the basins and seasonally due to the cycle of the thermocline (FENNEL et al., 1991). The adjustment time scales range from about one day in the Arkona and Bornholm basin to about two days in the central Baltic. The coastal flows are also shaped by Kelvin waves, or more general, topographically trapped waves, which propagate around the basins and set up alongshore pressure gradients.

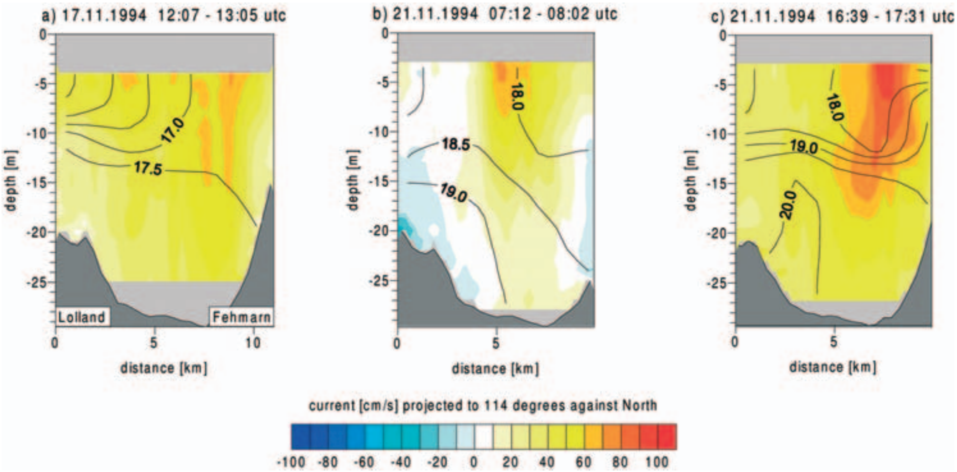


Fig. 6: Three snapshots of salinity stratification (contours) and flow (colours) through the Fehmarn Belt during autumn conditions. The flows show basically an inflow, but the flow pattern is structured and varies over a range of almost 1 m/s

The corresponding time scales are given by the travel time around the basins and are about 12 days in the Arkona Sea, 9 days in the Bornholm Sea, and 27 days in the central Baltic. These time scales often exceed the synoptic scales of weather patterns, which range from a few days to a few weeks.

Semi-enclosed systems can globally be characterized by residence times, which can be derived from the ratio of the water volume to inputs or outputs in terms of fluxes through the system boundaries. For the Baltic Sea, the residence time varies in the range between 15 to 35 years, depending on the choice of in- or output. However, this type of timescale does not represent the residence time of constituents, say dissolved nutrients, in a water parcel. The fate of a water parcel is affected by a variety of different processes acting on different temporal and spatial scales. Apart from the physical transport processes, i.e., advection and diffusion, the characteristic time scale of nutrients depends also on the way how matter is cycling through the food web. Hence attempts to characterize semi-enclosed systems by just a few numbers should also reflect the physical biological interaction.

## 2.4 Salt Balance and Major Inflows

The salt balance is maintained by a dynamical equilibrium between near-bottom inflow of saline water, outflow of brackish surface water and vertical salt diffusion through the halocline. From the conservation of mass (Knudsen theorem) it can be derived that the annual outflow of brackish water is approximately 1,400 $km^3$, while the near bottom inflow of saline water is about 830 $km^3$ per year.

The deeper water can only be ventilated through horizontal propagation of dense saline bottom water, which is formed in the transition areas between the North and the Baltic Sea and cascades over the sills until it arrives in the central basin. In particular, irregularly occurring major salt water inflows renew the deep water in the central Baltic (e.g. MATTHÄUS and FRANCK, 1992). The inflow of dense saline deep water near the bottom occurs in particular during major inflows when a substantial water volume passes the Darss Sill and advances through the Arkona Basin into the Bornholm Basin. In the Bornholm Basin the dense water must first fill the basin till the depth level of the Stolpe Channel (60 m) before it can propagate further into the central Baltic, where it can renew the bottom water.

If the density of the inflowing water is less than that of the bottom water, it will replace the water sheet of equivalent density within the halocline. This 'interleaving' pushes old water upwards while ventilating the halocline. Since major inflows are initiated by strong winds, which imply strong vertical mixing, a substantial part of the saline water will be mixed with brackish surface water in the Arkona Sea and leave the Baltic (MATTHÄUS and LASS,

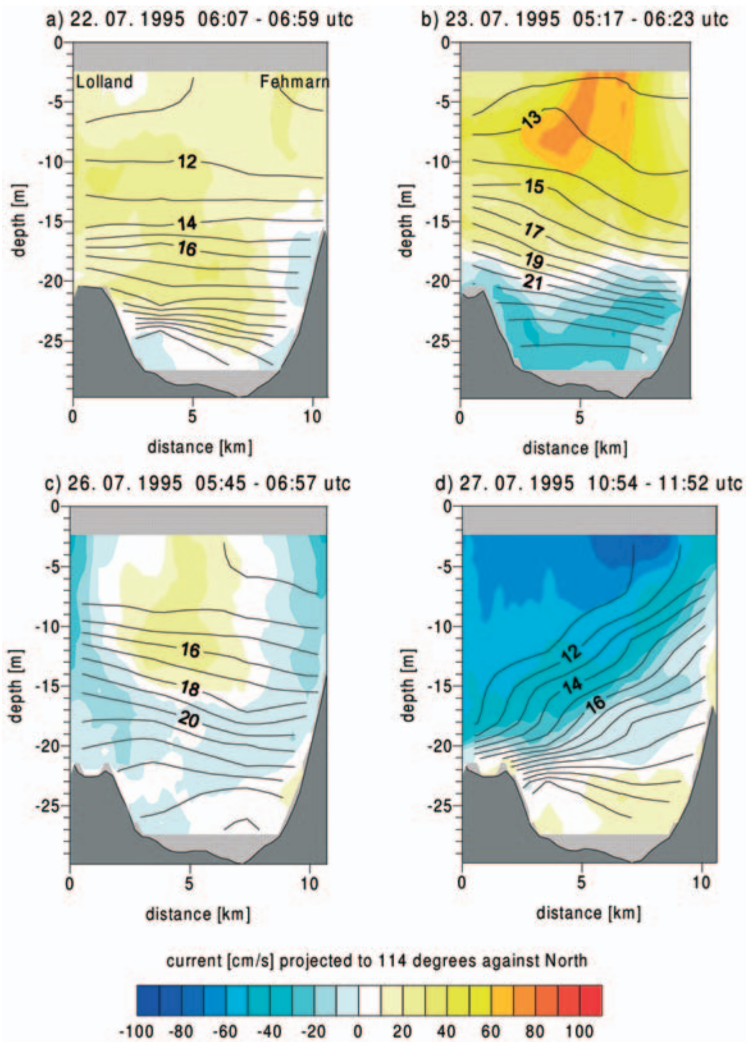


Fig. 7: Four snapshots of salinity stratification (contours) and flow (colours) through the Fehmarn Belt during summer stratification. The shape of the isohalines indicates the geostrophically adjusted status of the currents. The speed ranges from +80 to –80 cm/s, for inflow and outflow, respectively

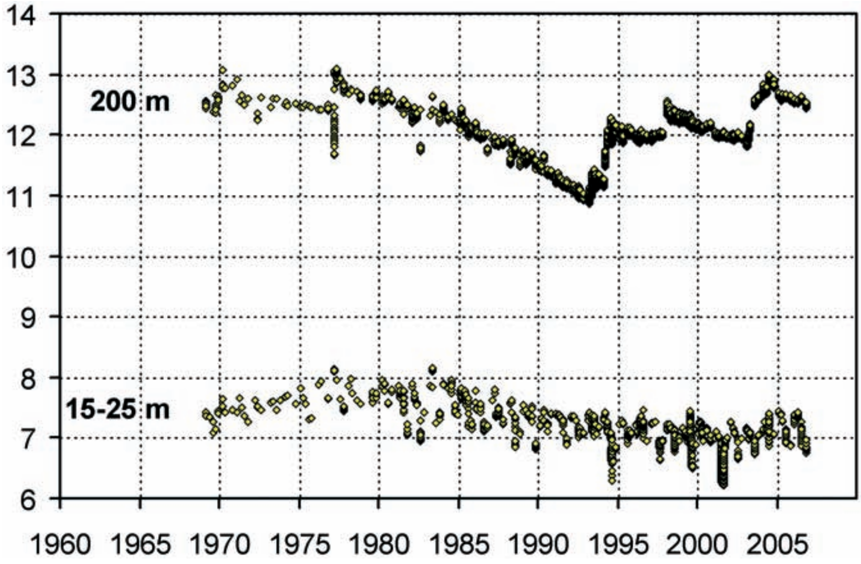


Fig. 8: Time series of salinity in the deep water and near the surface at a station in the central Baltic. The data are taken from the data base of the IOW

1995). The time scale of the propagation of inflowing dense bottom water toward the Gotland Basin ranges from a couple of weeks to several months.

Examples of the effect of salt water inflows into the deep waters of the central Baltic Sea are shown in Fig. 8 in terms of a long time series of salinity observed in 200 m depth. A strong major saltwater inflow occurred in 1976, as is indicated by the sudden increase in salinity. This event was followed by an unusual long stagnation period until in 1993 a new major inflow was observed. After this event, the sudden slight increases in salinity of the bottom near waters give a clear indication of a series of smaller inflows during 1997 to 2005.

A comparison of the long time series of salinity near the surface and the deep water, as shown in Fig. 8, implies an upward transport of salt. The decrease of salinity of the deep water after the inflow of 1976 till the next inflow in 1993 is also reflected in the surface salinity, but starts with a delay of about 10 years. This is a clear indication of a slow effective upward salt transport (see FEISTEL et al., 2006). The near-surface salinity shows also strong seasonal variations that reflect freshwater pulses due to seasonally varying river discharges and melting of ice.

The effective vertical diffusion is to some extent caused by vertical turbulent diffusion through breaking internal waves, which may be generated by the interaction of inertial oscillations and topography (e.g. FENNEL and SCHMIDT, 1992). Further mechanisms that drive upward salt transports are displacement of water layers in the halocline through interleaving of inflowing waters and upwelling of the halocline at steep slopes due to Ekman recirculation.

The freshwater reaches the Baltic mainly through river runoff. The river plumes propagate like Kelvin waves alongshore with the coast to the right. Without mixing and water transformation the buoyant plumes would stay near the coast, but due to wave induced mixing, wind driven alongshore flows and cross shore Ekman transports the river water is mixed and entrained into the brackish surface waters (see e.g. FENNEL and MUTZKE, 1997).

### 2.5 Sea Surface Temperature and Sea Ice

Synoptic basin-wide measurements of the sea surface temperature (SST) of the Baltic Sea have become available with the deployment of thermal radiation sensors on polar orbiting satellites since the 1980ies. SIEGEL et al. (2006; 2008) have compiled and analysed a continuous series of monthly mean SST fields of the Baltic Sea for the period 1990–2005 and found a distinct seasonal cycle with minimum temperatures of 0–2 °C in ice free areas during February and March. The warmest months are July and August when the temperature reaches 16–18 °C on average with an inter-annual variation between 15–20 °C. During the 16-year period of investigation, the annual mean SST reveals a positive trend of approximately 1 °C, which is above the average warming of the northern hemisphere. The increase of the SST varies regionally and seasonally. The strongest warming in the central Baltic and the Gulf of Bothnia occurs during summer and autumn implying a later onset of the ice formation. Similar SST trends have also been derived by MACKENZIE and SCHIEDEK (2007) from long-term observations. However, the Baltic SST shows significant correlation with climate indicators like the North Atlantic Oscillation index (NAO) only during the winter, especially March, when a slight decrease of the monthly mean surface temperature is observed.

Sea ice is formed if the SST drops below the freezing point. Owing to the low surface salinity freezing starts in the Baltic just below zero Celsius, and sea ice covers a considerable part of the sea during each winter. However, the ice thickness and the ice extent show strong regional and inter-annual variations because of the relatively large latitudinal extent of the Baltic Sea. Heavy ice conditions occur every year with a probability of 70–100 % in the Bothnian Sea, in the Gulf of Finland, and in the Gulf of Riga, whereas in the deep basins of the central Baltic Sea ice covers are observed only during very severe winters (see e.g. SEINÄ and PALOSUO, 1996). In the shallow south-western Baltic ice formation occurs if high pressure over Scandinavia or Russia leads to prolonged cold northerly and easterly winds, which force an outflow of low saline Baltic surface water. But the more frequent weather pattern are troughs associated with strong westerly winds that bring warm air from the Atlantic and push saline Kattegat water into the Baltic. Consequently, the open Arkona Basin and the Mecklenburg Bight remain usually ice free in wintertime. Only in the inner waters along the German coast fast ice of a thickness of 10–50 cm occurs regularly (SCHMELZER, 1996 and the overview in SCHMELZER et al., 2008).

The ice cover of the Baltic Sea can well be reproduced by models ( HAAPALA and LEPPÄRANTA, 1996; MEIER et al., 2002a, b; LEHMANN and HINRICHSEN, 2000 and SCHRUM et al., 2003). As an example, the maximum yearly ice extent during the period from 1961–2004, calculated by the IOW Baltic Sea model, is shown in Fig. 9. The model is based on the Modular Ocean Model (MOM–3.1, PACANOWSKI and GRIFFIES, 2000) and the thermodynamic three-layer ice model of WINTON (2000). In comparison to the data compiled by SEINÄ and PALOSUO (1996) the simulation follows the essential inter-annual variations, see Fig. 9 (left panel). The yearly difference in ice extent is also realistically simulated for the south-western Baltic. During the two severe winters of 1962/63 and 1995/96 70–85 % of the area were covered by sea ice, whereas in a mean season like 2002/03 only 10–15 % are covered, as shown in Fig. 9 (right panel). Moreover, both the duration of the ice season (from mid-December till March) and the occurrence of relative maxima in ice extent (varying inter-annually

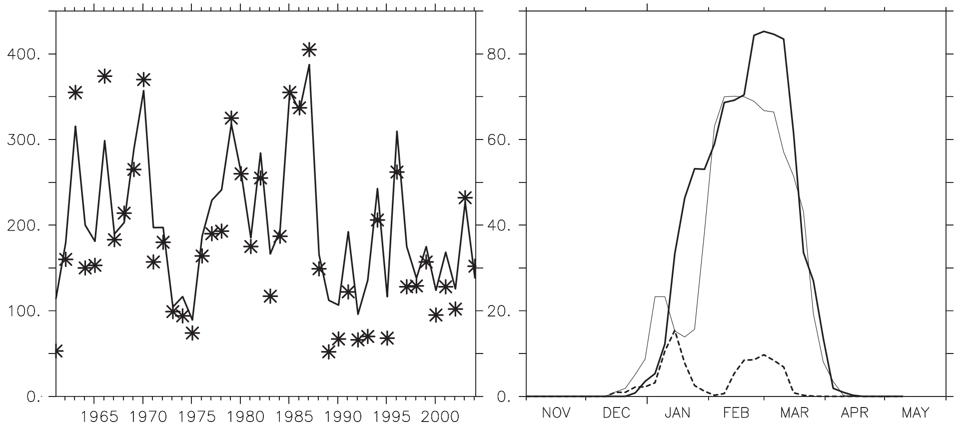


Fig. 9: Yearly maximum ice extent ($10^3$ km$^2$) of the Baltic Sea (left panel); the bold line indicates the simulated ice cover and star symbols show the estimates by SEINÄ and PALOSUO (1996). Relative model ice extent (%) in the south-western Baltic (right panel); bold, thin, and dotted lines correspond to the winters 1962/63, 1995/96, and 2002/03

from early January to end of February), are in agreement with the observations (see for example SCHMELZER et al., 2008).

### 2.6 Transport of Suspended Material

For the transport of matter from the river plumes towards the central basins, the main physical mechanisms are currents across the isobaths, in particular the non-geostrophic Ekman-transport.

For the transport of suspended sedimentary material from river mouths to the accumulation areas in the deep basins, fluffy layers are important. Fluffy material is assumed to consist of flocks which accumulate at the sea bottom and are easily eroded if the bottom shear stress exceeds 0.02 N/m$^2$ (CHRISTIANSEN et al., 2002). Strong wind events generate wave mixing in shallower areas from the surface to the bottom and re-suspend the fluffy layer material, which is then transported into the basins in a few days or weeks time. Calm situations and strong summer stratification imply a slow exchange between the coastal zone and the open sea, as was shown in KUHRTS et al. (2004) and SEIFERT et al. (2008) by means of experiments with a numerical model.

The relative frequency of fluff erosion events in the south-western Baltic is shown in Fig. 10, as derived from a model simulation with a high spatial resolution of approximately 2 km. The reference period December 1992 till October 1993 was chosen for a series of strong wind events, especially during the winter season. The bottom shear stress is evaluated from an adaptation of the wave boundary layer after GRANT and MADSEN (1979) and the skin friction layer after SMITH and MCLEAN (1977). A detailed analysis of the model fields shows that the oscillatory motion induced by surface waves is the predominant contribution to the bottom shear stress. Therefore, the probability of erosion events decays exponentially with water depth. Fig. 10 shows that no erosion of fluff is calculated for depths below 40 m, whereas in the shallow areas above 20 m erosion events are rather frequent. As a rule-of-thumb, one

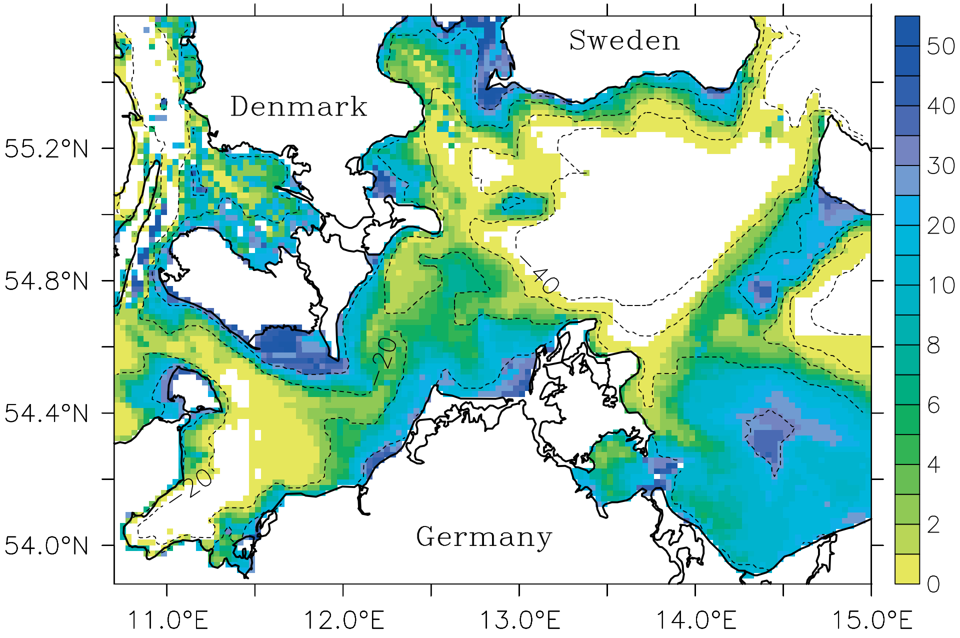


Fig. 10: Modelled frequency of occurrence (%) of fluff erosion in the period Dec. 1992 till Oct. 1993. Broken lines indicate the water depth in 10 m steps

may assume that fluffy material will be washed off from regions above 20–40 m if the wind speed exceeds 10 m/s for at least 2 days. Because of its sheltered location, the inner Lübeck Bight is an accumulation area already below 20 m water depth. In contrast to that, the coastal zone off Fischland, Darss and Hiddensee appears to be a rather active area of sediment transports. Strong winds above 15 m/s are necessary to move fine particulate matter and grainy sediments such as sand. Since the threshold for incipient motion is above 0.2 N/m$^2$ the resuspension and bed-load transport of such material occurs only in regions above 20 m depth with a probability of less than 5 % of the simulation period.

## 3. Acknowledgement

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# Storm Surges on the German Coast

By Jürgen Jensen and Sylvin H. Müller-Navarra

## Contents



## 1. Introduction

Storm surges are natural events that have always threatened life at the coast, and which may cause heavy damage due to an increasing use of the coastal regions nowadays. Both coastal protection and natural disaster defence measures are based on analyses of extreme flood levels. One of the oldest accounts of storm surges at the North Sea coast dates from the year 340 or 120 B.C. when, according to historical records, storm surges forced the Cimber people to leave the area of Holstein and Jutland. A reliable early record of a Baltic Sea storm surge dates back to the year 1044 (cf. Jensen and Töppe, 1990).

Frequency and occurrence of historical extreme storm-surge events have to be considered in the context of the climate or weather conditions prevailing at the time. After early settlers had begun colonising Greenland around the year 1,000, when the climate was warming (Greenland ice-free, long and warm summers, route to America ice-free), a colder period set in around 1300 (the ice returned). Around the year 1400 the last Viking settlement on Greenland had to be abandoned. During this period, many disastrous storm surges occurred along the North Sea coast (cf. Tab. 2). It should be considered though, that chroniclers describing such catastrophic events focused primarily on the effects and damage caused by the surges. In bad times (poverty, epidemics, wars), even smaller storm surges may have had catastrophic consequences (e.g. due to poor condition of dikes). Over the past decades, the economic damage caused by natural disasters has multiplied, which is attributable to increasing urbanisation, industrialisation and population growth in exposed coastal regions (Kron, 2005).


Fig. 1: Development of the island of Sylt; top left: Sylt before the severe storm surge of 1362; top right: Sylt before a strong storm surge in 1634 (from DANCKWERTH, 1652); bottom left: Sylt in 1793 (from BUGGE and WILSTER, 1805); bottom right: Sylt today (sylt.citysam.de/landkarte-foehr-amrum.htm)

In the following, the history of coastal development and surge events will be briefly outlined, followed by a discussion of present storm surge forecast methods and future trends to be expected against the background of climate change. Rising sea levels caused by climate change would lead to dramatic morphological changes at shallow coastlines and in tidal estuaries.

## 2. Development of the German North and Baltic Sea Coasts

Extreme storm surge events causing major losses of land have shaped the North Sea coastline and islands over the centuries. An example is shown in Fig. 1, which depicts the development of the largest German North Sea island of Sylt since the 14$^{th}$ century. The Figure illustrates the enormous losses of land suffered during several surge events. First studies on the frequency of surge events were conducted by BRAHMS (1754) and WOEBECKEN (1924) (cf. e.g. SCHELLING, 1952). Although storm surges have hit the North Sea coasts again and again during the past centuries, surges in the recent past, beginning with the disastrous flooding of the Netherlands in 1953, have given rise to the question whether there has been a change in the pattern of storm surge occurrences in the North Sea region (cf. e.g. FÜHRBÖTER, 1976 and 1979; SIEFERT, 1978; FÜHRBÖTER, JENSEN and TÖPPE, 1988).

The development of North Sea water levels since the end of the last glacial period has been characterised by alternating transgression (rising water level) and regression (falling water level) phases. Sea level development directly affects the morphology of the coastal foreshore and coastal erosion processes.

Tab. 1 provides a hydrographical and hydrological comparison between the North Sea and the Baltic Sea, which refers not only to the German waters but to the complete body of water in each case.

Table 1: Hydrographical and hydrological comparison of the North Sea and Baltic Sea

| | **North Sea** | **Baltic Sea** |
|---|---|---|
| Area | 580,000 km² | 415,000 km² |
| Mean depth (largest depth) | 93 m (Norwegian Deep 725 m) | 52 m (north of Gotland 459 m) |
| Mean salinity | ≈ 35 ‰ | 3–5 ‰ |
| Tides | Mean tidal range = 3.5 m | Almost free of tides (< 10 cm) |
| Hydrographical classification | Shallow marginal sea of the Atlantic Ocean | Enclosed sea, connection with North Sea (Kattegat) |
| Chart datum | NN = „Normal Null“ (approx. MSL Amsterdam) | HN = „Höhen Null“ (MW Kronstadt)<br>HN = NN + 14 cm |
| Coastal properties | Tidal flats, long coastline including tidal estuaries, sandy and dune coasts and barrier islands | Graded shoreline, coastal lagoons and cliffs |
| Coastal defence structures | Dikes, some sea walls, revetments and groynes on the islands, storm surge barriers | Groynes, breakwaters dikes and dams at parts of the coastline |
| Extreme event | Storm surge | Storm high water |
| Historical extreme events | Storm surges in 1953, 1962, 1976 | 1872 |
| Storm surge levels | NN + 5.1 m (Cuxhaven 1976) | HN + 3.3 m (Travemünde 1872) |
| Development of storm surges | “Wind surge”<br>– meteorological influences: gale-force winds from N–NW; repetitive weather patterns (wind force, direction and duration)<br>– impact on tides (spring tide)<br>– external surges from the Atlantic | “Seiches”<br>– meteorological influences: gale-force winds from E–NE; large water volume of the Baltic Sea; very rare weather patterns (wind force, direction, change in direction from W to E and duration of wind) |

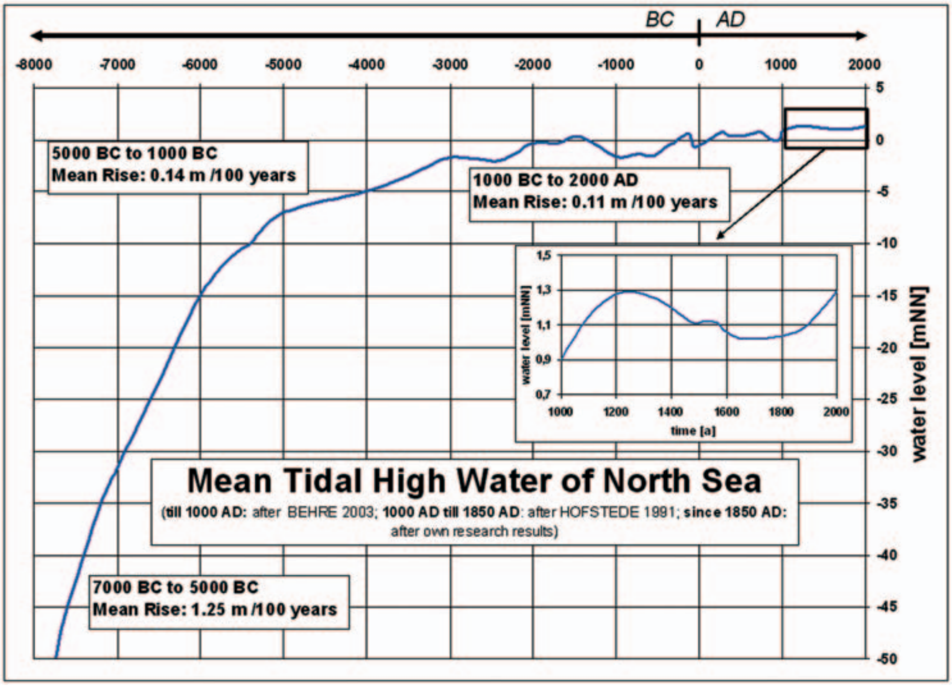



Fig. 2: Post-glacial sea level changes on the German North Sea coast (after BEHRE, 2003; HOFSTEDE, 1991 and own research results)

Fig. 2 shows probable post-glacial sea level changes on the German North Sea coast. On the whole, the transgression process has not been continuous but interrupted by short regression phases.

To be able to classify historical storm surges, i.e. storm surges up to the early 19th century, it is necessary to know the temporal development of mean (tidal) levels because the sea level data are referred to mean water level (MW) in the Baltic Sea, and mean high water (MHW) or mean sea level (MSL) in the North Sea. Since not only the impacts of glaciation but also of coastal movements (tectonics) have to be taken into account, an exact assessment of the temporal development of the mean sea level is hardly possible. Detailed data on water level developments at the North and Baltic Sea coasts are available from about 1850. Since the end of the last glacial period, both the Baltic Sea and North Sea coasts have been shaped by melting ice masses; the maximum of the Weichselian glaciation has been dated at 25,000 to 18,000 years B.P. After a rapid initial sea level rise, the rate of increase slowed down about 5,000 years B.C. and has been as low as a few decimetres during the last thousand years. Apart from eustatic processes, which affect the world-wide water regime, also movements of the Earth's crust and load reductions due to melting inland ice masses have an impact on relative movements between land and sea levels in the Baltic region. It may be assumed that 4,000 years ago the water level of the south-western Baltic Sea was about 1 m below the current mean level. Around the time of Christ's Birth, it was about 50 cm higher than in the Middle Ages, likewise in the North Sea coastal area (JENSEN and TÖPPE, 1990).

## 3. Storm Surge Generation

PETERSEN and ROHDE (1977) defined a storm surge as a "period of time during which water levels on the coasts and in estuaries are high, due primarily to strong winds". Accordingly, high water levels at the coast and in the estuaries which have not been caused by storm should not be termed storm surges. In studying the generation of storm surges, a clear distinction has to be made between the North Sea and the Baltic Sea, which have different hydrological regimes. The factors leading to storm surges in the two bodies of water are summed up in the following.

### 3.1 Generation of North Sea Storm Surges

Storm surges at the German North Sea coast result mainly from a build-up of water masses along the coasts (e.g. wind set-up), i.e. they are caused by stochastic (stochastic: science of random processes, i.e. of time variable processes) impacts of meteorological origin which are superimposed on the astronomical tides. Wind set-up at the North Sea coast may reach more than 5.00 m. For example, at the Husum gauge station, a wind set-up of 5.70 m was observed on February 10, 1949, though at the time of tidal low water. As a rule, extreme storm surges at the German North Sea coast occur when heavy storms from north-westerly directions reach wind speeds in excess of 25 m/s. Basically, two types of North Sea storm surges can be distinguished. The wind set-up type is characterised by winds blowing for a long time from a north-westerly direction, driving water masses into the south-eastern North Sea. Storm surges of the wind set-up type can be reliably forecasted, and warnings can be issued up to 18 hours and more in advance. In contrast, the circulation type is clearly more difficult to forecast, because here a small intense low-pressure system tracks across the British Isles at high speed, gaining strength over the North Sea. Consequently, there may be situations in which no exact forecasts can be made until a few hours before peak level. (MÜLLER-NAVARRA, 2005). The ratio of stochastic influences in relation to deterministic influences (e.g. astronomical tide) in water levels at the German North Sea coast is very high. This has to be taken into account when computing storm surge levels based on probability calculations.

### 3.2 Generation of Baltic Sea storm surges

Whilst by definition the North Sea is a semi-enclosed sea, the Baltic Sea constitutes a (nearly) closed system. The differences between the systems (cf. Table 1) account for the different mechanisms of storm surge generation. Unlike the North Sea, the Baltic Sea is hardly subject to tidal influence, which explains why the term "storm surge", which is normally used to describe high water levels, is usually replaced by the term "storm high water" in context with the Baltic Sea. The Baltic Sea is connected to the North Sea through narrow Belts and the Sound which, far from simplifying the system, lead to an even more complex system behaviour.

In the Baltic Sea, different weather patterns may be involved in the generation of a storm high water; the Baltic Sea, unlike the German Bight, does not have a certain predominant weather pattern creating particularly high water levels. The principal difference among storm surge events in the Baltic Sea is their classification either as a wind set-up event, where wind is the only cause, or a storm surge where seiches involving the whole water body of the Baltic Sea can influence the water level in the western Baltic by a few decimetres. Moreover, the actual water volume in the Baltic Sea also affects the development and peaks of extreme water levels in this region.

Thus, leaving aside flood events caused exclusively by wind set-up, there are several wind directions that may cause high water levels and will lead to a storm surge if they occur in a certain sequence. The maximum water level reached in a particular storm surge event thus depends not only on local winds but is decisively influenced by the temporal sequence of particular wind directions and on wind forces acting in the different regions of the Baltic Sea – including regions that are quite distant from the western Baltic. These specific scenarios are linked closely to the tracks of storm surge relevant cyclones and to the speed at which they travel. Studies have shown that the weather situations leading to the different types of storm surge are fundamentally different (MEINKE 1998 and 1999; HUPFER et al. 2003). The water level records of storm surges since April 1952 have been evaluated and classified according to their generation mechanism (MEINKE 1998).

### 3.3 History of North and Baltic Sea Storm Surges

Available studies of storm surge events and extreme water levels on the North and Baltic Sea coasts either deal with individual extreme events, e.g. the catastrophic Baltic Sea storm surge of November 1872 (BAENSCH, 1875), or are based on extreme values, e.g. annual maxima (e.g. BRAHMS, 1754; WOEBCKEN, 1924; SCHELLING, 1952; HUNDT, 1955; LIESE, 1963; LÜDERS, 1971; FÜHRBÖTER, 1976 u. 1979; SIEFERT, 1978; JENSEN, 1985; BAERENS et al., 1995); there also exist current studies of the contribution of wind set-up to storm surges (GÖNNERT, 1999) on the North and Baltic Sea coasts. From a statistical point of view, storm surges are subdivided into three categories: small, severe, and very severe:

– small storm surge (wind surge): mean frequency of occurrence (n) of maximum water level: n = 10 to 0.5 annually (North Sea), 2 to 0.2 annually (Baltic Sea)
– severe storm surge (storm surge): n = 0.5 to 0.05 annually (North Sea), 0.2 to 0.05 annually (Baltic Sea)
– very severe storm surge (hurricane surge): n = <0.05 annually (North and Baltic Seas); the frequency of such surges on the North and Baltic Sea coasts is less than once in twenty years

In practice, for operational warnings, distinct deviations from mean high water (North Sea: MHW) and mean water level (Baltic Sea: MW) are given (Tab. 3).

Tab. 2 is a compilation of historical storm surges events on the German North and Baltic Sea coast (southwestern Baltic Sea coast). The total number of storm surges with extreme water levels is substantially higher on the North Sea coast than on the Baltic Sea coast. The main cause is the meteorological situations triggering such events: weather situations causing extreme water levels on the Baltic coasts are relatively rare.

Table 2: History of storm surges/high-water events on the German North and Baltic Sea coasts after Kramer, 1989; Jensen und Töppe, 1990; Petersen und Rohde, 1991

| North Sea | | Baltic Sea | |
|---|---|---|---|
| Date | Comments / heights | Date | Comments / heights |
| 340 B. C. | So-called "Cimbrian Flood" (possibly 120 B. C.) | 1044 | ? (details unkown) |
| 17.2.1164 | First St. Juliana's Flood, entire North Sea coast | | |
| 16.1.1219 | First St. Marcellus Flood (Netherlands) | | |
| 14.12.1287 | Lucia's Flood, entire North Sea coast | 1304 (1307, 1309) | New deep created between Rügen and Ruden |
| | | 30.11.1320 | Lübeck: MW + 3.10 to 3.20 m |
| 23.11.1334 | St. Clemens Flood, Flanders to East Friesland | | |
| 16.1.1362 | Second St. Marcellus Flood, East Friesland to North Friesland | | |
| 9.10.1374 | First St. Dionysius Flood, East Friesland | 1374 | ? |
| 9.10.1377 | Second St. Dionysius Flood, Flanders, Zeeland, Holland, East Friesland | 1396 | |
| 1400 | Frisian Flood | 1412 | ? |
| 18.11.1421 | St. Elizabeth's Flood, East England and Netherlands | | |
| 1434–1501 | Six "Gallic Floods" | | |
| 11.1.1436 | All Saints' Flood, German North Sea coast | 1449, 1467 | ? |
| 6.1.1470 | Three Kings' Flood, German North Sea coast | 30.11.1497 | ? |
| 26.9.1509 | Kosmas and Damian Floods, Netherlands, East Friesland | | |
| 16.1.1511 | St. Antonius Flood, German North Sea coast | 1519 | ? |
| 31.10.1532 | Third All Saints' Flood, North Sea coast: Canal to Eiderstedt | 1552, 1558 | |
| 1.11.1570 | Fourth All Saints' Flood, Flanders to Eiderstedt | Summer of 1570 | Lebamünde destroyed? |
| 1572 | Grain Flood | 1573/96, 1609 | ? |
| 26.2.1625 | Carnival Flood, South Holland to Jutland | 10.2.1625 | Lübeck: up to MW + 2.84 m |
| 11.10.1634 | Second "Mandränke" (Great Drowning), Schleswig-Holstein | 1645 | ? |
| 22.2.1651 | St. Petri Flood, Friesland | 1663, 1690 | ? |
| 12.11.1686 | St. Martin's Flood, Groningen to Land Wursten | 10./11.1. 1694 | Lübeck: MW + 2.86 m<br>Travemünde: MW + 2.65 m |

continued on the next page

continuation of Table 2

| | | | |
|---|---|---|---|
| 24.12.1717 | Christmas Flood, North Sea coast | 1709 | |
| 31.12.1720 1.1.1721 | New Year's Flood, Zeeland to North Friesland | 1736, 1741, 1784 | |
| 3./4.2.1825 | February Flood, East to North Friesland (highest tidal high water) | 19.12.1835 | Flensburg: MW + 2.54 m |
| | | 26.12.1836 | Lübeck: up to MW + 2.20 m<br>Schleswig: up to MW + 2.75 m |
| 1./2./ 4.1.1855 | January Flood, East Friesland | 30.12.1867 | Lübeck: MW + 2.04 m |
| | | 12./13.11. 1872 | Highest storm surge so far in Lübeck / Travemünde: up to MW + 3.40 m |
| | | 25.11.1890 | Travemünde: MW + 2.10 m |
| | | 30./31.12. 1904 | Travemünde: bis MW + 2.22 m<br>Flensburg: MW + 2.33 m |
| 13.3.1906 | March Flood, East Friesland (highest tidal high water) | 29./31.12. 1913 | Travemünde: MW + 2,00 m |
| 31.1./ 1.2.1953 | Holland Flood, Netherlands and England | 4.1.1954 | Travemünde: MW + 2.07 m |
| 16./17.2. 1962 | Catastrophic storm surge, East Friesland to North Friesland (highest tidal high water) | 14.1.1960 | ? |
| 23.2.1967 | Adolph Bermpohl hurricane with the highest wind speeds measured so far | | |
| 19./20.11 1973 | November Flood, Lower Saxony and Schleswig-Holstein | | |
| 3./4.1. 1976 | January Flood, Lower Saxony and Schleswig-Holstein (highest tidal high water north of the Elbe) | 31.12.1978<br>15.2.1979 | |
| 24.11.1981 | November Flood, Schleswig-Holstein (highest tidal high water in North Friesland) | 13.1.1987<br>27./28.8. 1989 | Summer flood causing considerable damage |
| Jan./Feb. 1990 | 5 hurricanes in 3 days, Schleswig-Holstein | | |
| 21./22.1. 1993 | Several storm surges, sand losses on Sylt, Schleswig-Holstein | | |
| 28.1.1994 | Hamburg, Schleswig-Holstein | 6.11.1995 | Baltic Sea to Mediterranean Sea |
| 6.2.1999 | Entire North Sea coast | | |
| 3./4.12. 1999 | Elbe (Hamburg), Schleswig-Holstein to Denmark | | |
| 29./30.1. 2000 | Denmark, substantial sand losses on Sylt (cliff) | | |
| 9.11.2007 | Storm surge caused by low-pressure system "Tilo" affects almost the entire North Sea coast | | |

### 3.4 Recent Storm Surges

Whilst Tab. 2 lists all recorded historical storm surges in the North and Baltic Seas, including available information on their severity and areas affected, recent storm surges which have occurred since the beginning of continuous gauge data recording (about 1820) will be discussed in more detail in the following, as part of the systematic study of storm surges.

#### 3.4.1 Storm Surge Levels at the North Sea Coast

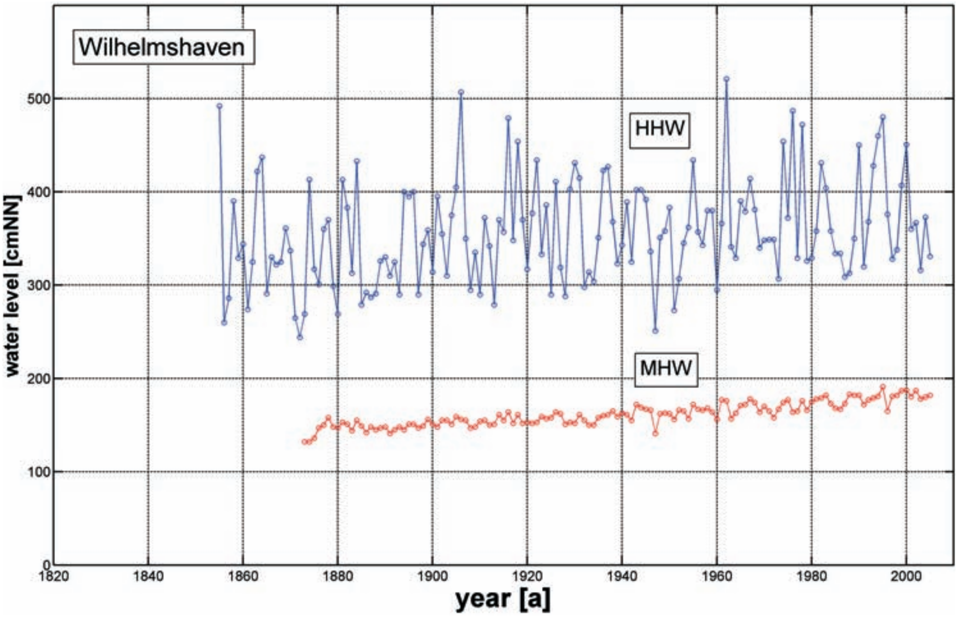
A comparison of maximum wind set-up data for the coast of Lower Saxony shows that storm surges vary considerably in their characteristics depending on local wind conditions and the shape of the coastline. The highest water levels in East Friesland were produced by the storm surge of 1906, in the Jade-Weser area by the storm surge of 1962, and in the Elbe area by that of 1976.

The extreme storm surges of the past 30 years produced maximum water levels especially in the inner German Bight and in North Friesland; this is evident from the fact that the highest tidal high water level at the Borkum and Emden gauge stations was recorded during the 1906 storm surge, whereas in the area between the Weser and Elbe estuaries the highest storm surge level ever recorded occurred on 16 February 1962. In Cuxhaven and on the west coast of Schleswig-Holstein, the historically highest storm surge level was measured on 3 January 1976; this in turn was exceeded by the levels recorded at the Dagebüll and List/Sylt stations which are located farthest north.

In January and February 1990, 5 hurricanes caused storm surges on the coasts of Schleswig-Holstein; several storm surges on 21/22 January 1993 reached particularly high levels on the North Sea coast of Schleswig-Holstein and caused substantial losses of sand on the island of Sylt. Also the storm surge of 28 January 1994 led to the highest water levels ever observed on the northern coasts of Schleswig-Holstein. The storm surge event of 6 February 1999 affected the entire German North Sea coast. The storm surges of 3/4 December 1999 and 29/30 January 2000 which again caused very high water levels on the North Sea coasts of Schleswig-Holstein and Denmark also constitute extreme events because of the tracks of the depressions and of the wind speeds involved. The most recent storm surge in this series, caused by the low-pressure system "Tilo", is that of 9 November 2007 which led to relatively minor damage because flood protection measures were taken at an early stage.

Fig. 3 shows the time series of mean tidal high water (MHW) and high tidal high (HHW) water for the gauge stations at Wilhelmshaven and Bremerhaven, and Fig. 4 those of Büsum and Cuxhaven. The individual time series will not be analysed in detail here (e.g. with respect to trends). The gauge stations (island and mainland stations) have been selected on the basis of their time-series length and location, which should be distributed along the whole North Sea coastline.

On the whole, it has been found that during the past three decades the north-to-south coastline of Schleswig-Holstein and the Elbe estuary were affected more often by extreme water levels than the west-to-east coast of Lower Saxony.



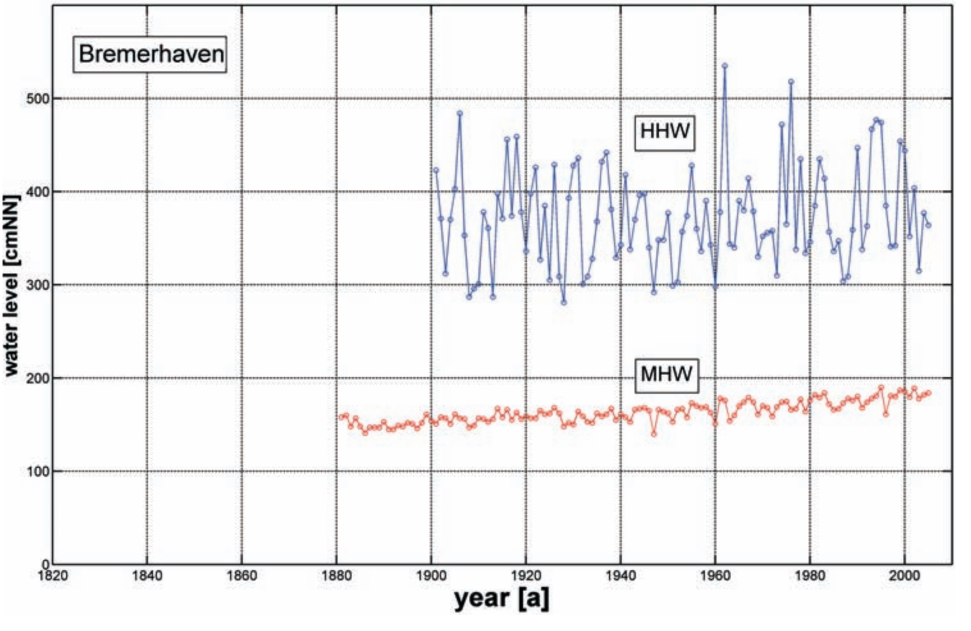
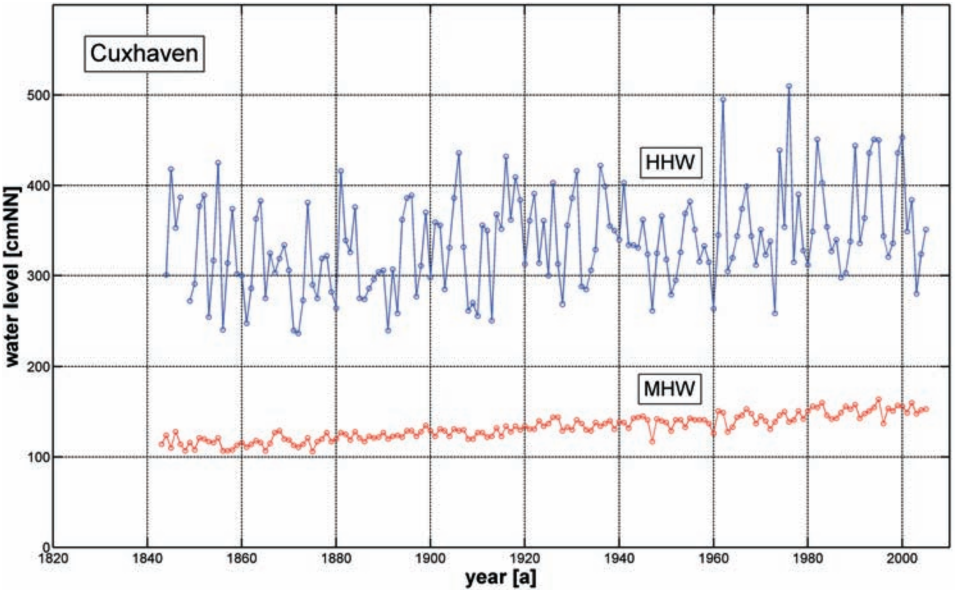




Fig. 3: Time series of mean tidal high water and high tidal high water at the Wilhelmshaven and Bremerhaven gauge stations



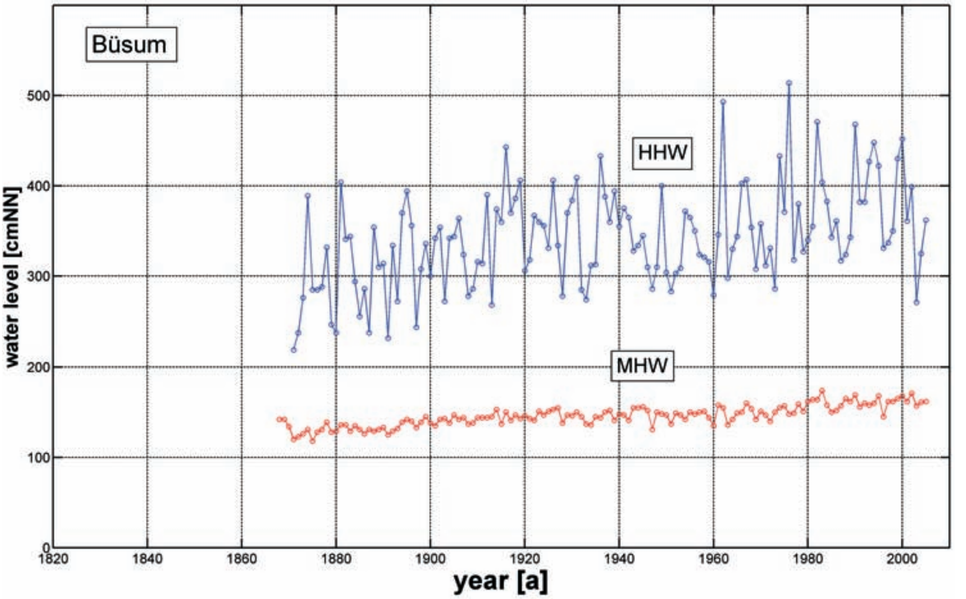




Fig. 4: Time series of mean tidal high water and high tidal high water at the Cuxhaven and Büsum gauge stations

### 3.4.2 Storm Surge Levels at the German Baltic Sea Coast

The first records of storm surge events at the Baltic Sea coasts, including the maximum water levels measured, date back to the 14th century. The first precise measurement showed an elevation of 3.2 m above the Baltic Sea mean water level, measured at Lübeck during the storm surge of 1320 (JENSEN and TÖPPE, 1990). In November 1872, a storm surge of unprecedented severity hit the Baltic coasts, with a maximum of up to 3.5 m above mean water level. Many authors have described this catastrophic storm surge event at the Baltic Sea coasts (e.g. BAENSCH, 1875).

Fig. 5 shows the available time series of mean water level (MW) and high water level (HW) at the Travemünde and Warnemünde gauge stations, representative of the Baltic Sea coast; an analysis of the time series (e.g. with respect to trends) is not provided here (JENSEN and BLASI, 1998). The gauge station at Travemünde has the longest uninterrupted time series of measurements in this area.

In the 20th century, peak values of more than 2 m above mean water level were measured during the storm surge events of 30/31 December 1904, 30/31 December 1913, 4 January 1954, and 6 November 1995. Flood events on the Baltic Sea coasts, like those on the North Sea coasts, normally occur in the winter months from October to March. The flood event of 27/28 August 1989 came unexpected because it occurred during summer, and caused heavy damage. The extreme flood of November 12/13, 1872, has to be considered a singular event with regard to its maximum water level, and thus will continue to serve as design flood in the future.

## 4. Future Developments

As has been pointed out above, life at the coast has always been strongly influenced by recurring storm surges. In order to be able to assess future risks and take early action to strengthen coastal defences, some detailed studies still have to be made. In particular, questions concerning the probability of occurrence of extreme storm surges and the impact of climate change on storm surge events at the German coasts still have not been answered satisfactorily.

### 4.1 Probabilities of Occurrence of Extreme Storm Surges

Storm surges at the coast are natural phenomena which occur at irregular intervals and differ in severity. To be able to carry out long-term coastal risk management, it is essential to determine the probability of occurrence of certain storm surge levels. Within the framework of the German Coastal Engineering Research Council GCERC (Kuratorium für Forschung im Küsteningenieurwesen KFKI) funded research project 'MUSE – Model-based studies of storm surges with very low probabilities of occurrence' (Modellgestützte Untersuchungen zu Sturmfluten mit sehr geringen Eintrittswahrscheinlichkeiten), observed and simulated extreme water levels were analysed statistically. The model simulations had been carried out using modelling chains of the German Meteorological Service (Deutscher Wetterdienst DWD) and the Federal Maritime and Hydrographic Agency of Germany (Bundesamt für Seeschifffahrt und Hydrographie BSH). DWD computed physically possible wind and weather situations capable of causing exceptionally high storm

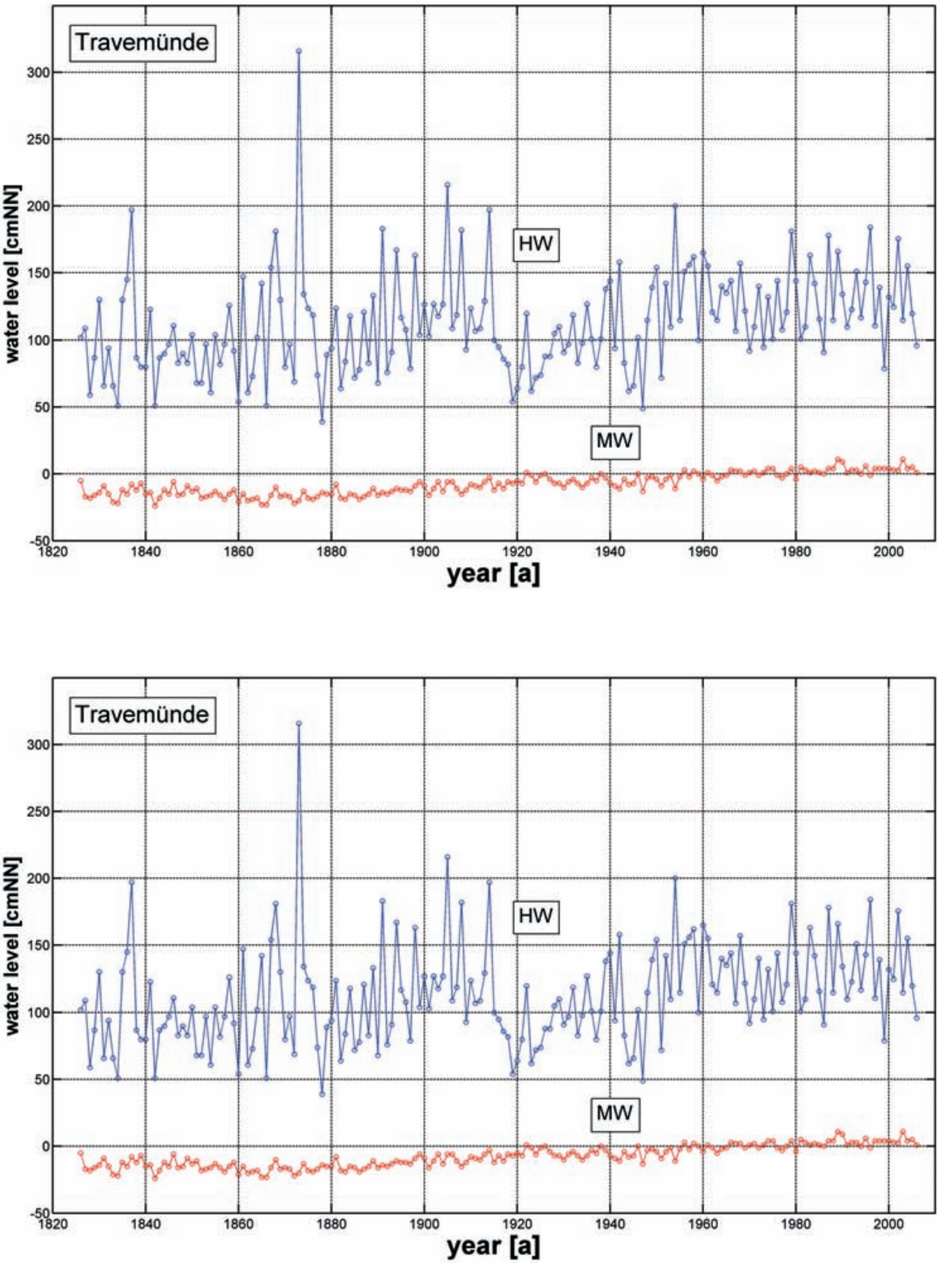



Fig. 5: Time series of mean water and high water levels at the Travemünde and Warnemünde gauge stations

surges in the German Bight, using numerical forecast models in a hindcast mode. Its results were transferred to the BSH, which computed the resultant water levels and wind set-up data for several coastal locations, using physically consistent numerical 2D and 3D water level forecast models which are in routine operational use at the BSH to forecast storm surges. The statistical evaluation of modelled and measured water levels was made at Siegen University's Research. It used a statistical method based on the Gumbel type III distribution (GUMBEL, 1958) which allowed the modelled extreme values to be correlated with the observed data with a view to improving the statistical evaluation of very rare storm surges.

The results show that, in the German North Sea region, storm surge producing weather conditions are possible that may lead to water levels exceeding historical maximum levels by up to 1.4 m. On the basis of the modelled water levels, it will be possible to better assess the probability of occurrence of extreme storm surge peak water levels.

Detailed information on the MUSE research project and its results was published by JENSEN et al. in 2006.

### 4.2 Storm Surges and Climate Change

An important research issue in the field of coastal engineering is the question how climate change will influence storm surge occurrences. As storms are a characteristic element of the regional climate in Northern Germany, any change in the storm regime will have significant effects on the coastal areas. Research carried out by the coastal research institute of GKSS (Geesthacht research centre) and the Coastal Research Station Norderney (Forschungsstelle Küste) has shown that despite the temperature increase that has taken place in the winter months (about 1 degree Celsius during the past 150 years) no major changes in the storm surge regime (VON STORCH and NIEMEYER, 2008) can be detected. However, future scenarios show an increase in wind speeds (especially westerly gale-force winds) by up to 10 % in the North Sea by the end of this century, which will of course have an impact on the storm surge regime and, consequently, on coastal protection measures. In addition to sea level rise and the resultant higher static load, there would also be a higher set-up during storm surges. Moreover, due to increased water depths, more extreme sea states and strong dynamic loads on the coastal flood defences structures can be expected. Studies of WOTH, VON STORCH and WEISSE (2005) have shown a possible increase in storm surge levels by 20–30 cm along the 10 m bathymetric contour. Adding this increase to the 40 cm sea level rise which IPCC considers possible by the end of the 21st century, assuming certain emission scenarios, there is a risk that climate change alone might lead to 60–70 cm higher water levels in the German Bight. Taking into account the results of the MUSE research project as well, the conclusion is that by the end of this century there is a possibility for the occurrence of water levels during extreme storm surge events which may exceed historical maximum levels by 2.0 to 2.1 m. There are uncertainties in these computations regarding the emission scenarios used such as the behaviour of ice covers and glaciers and possible combinations of the above effects (increasing storm surge levels, rising sea level, more severe wave regimes). These may have to be taken into account. Further research should be aimed at defining and minimising these uncertainties.

## 5. Storm Surge Forecasting

### 5.1 Organisation

Storm surge forecasts for the German coasts are issued by Bundesamt für Seeschifffahrt und Hydrographie (BSH, Federal Maritime and Hydrographic Agency of Germany) in Hamburg (MÜLLER-NAVARRA, 2006), in conformity with the "Seeaufgabengesetz" (Federal Maritime Responsibilities Act) (ANON., 2006). The forecasting service, which provides information to the public, was started by the BSH's predecessor "Deutsche Seewarte" in 1924 and is the longest standing public warning service in any of the North Sea states (TOMCZAK, 1955).

According to available records, storm surge warnings for the Baltic Sea coast of Schleswig-Holstein have been issued sporadically by Deutsche Seewarte since 1940 (archives of the BSH's water level forecasting service). Warnings for the Baltic coast of Mecklenburg-Vorpommern have been issued since 1952. Until 1990, different institutions of the German Democratic Republic (GDR), located in Warnemünde, were in charge of the water level forecasting service. The first of these institutions was the "Ostseeobservatorium des Seehydrographischen Dienstes" (Baltic Sea observatory of the hydrographic service). The last one prior to the reunion of Germany was the hydrographical department of the coastal waterways directorate (O. MIEHLKE, pers. comm.). After the reunion, this service was integrated into the BSH at its Rostock headquarters.

The BSH's tidal service has an even longer tradition. The first tide table for the German North Sea coast and other European coasts was issued for the year 1879 (ANON., 1878). This time series has been continued uninterrupted to the present day. Tidal predictions are in fact the prerequisite to any storm surge forecast for tidal waters.

Because of the considerable effort and expense involved in maintaining a storm surge warning service (Fig. 6), centralised operation is the preferable approach, as will become apparent from the following description. Nevertheless, local warning services for the German North Sea coast exist in the German federal states (NLWKN in Lower Saxony, LKN-SH in Schleswig-Holstein, and HPA in Hamburg) which use the BSH's forecasts and supplement them in adaptation to local conditions or additionally use own empirical methods (WADI Hamburg, SIEFERT, 1968; SIEFERT et al., 1983).

The terms used at BSH to characterise the severity of storm surges and deviations of ($\Delta h$) from mean high water (MHW) and mean water level (MW) are listed in Tab. 3. While the classification for the German Bight has been generally accepted, different categories exist in the western Baltic Sea (HUPFER et al., 2003, from p. 116). For example, it might be reasonable to introduce an additional category "very severe storm surge" for water levels exceeding 2.0 m.

Table 3: Classification of storm surges according to the BSH

| German Bight | | Western Baltic Sea | |
|---|---|---|---|
| **Term used** | **Deviation from MHW** | **Term used** | **Deviation from MW** |
| Storm surge | 1.5 m $\leq \Delta h <$ 2.5 m | Small storm surge | 1.0 m $\leq \Delta h <$ 1.25 m |
| Severe storm surge | 2.5 m $\leq \Delta h <$ 3.5 m | Moderate storm surge | 1.25 m $\leq \Delta h <$ 1.5 m |
| Very severe storm surge | $\Delta h \geq$ 3.5 m | Severe storm surge | $\Delta h \geq$ 1.5 m |

## 5.2 Problems Involved

In mathematical terms, the problem of water level forecasting is closely related to that of weather forecasting. Both are initial-boundary-value problems. The atmosphere and ocean are dynamically coupled at the water surface. Wind forces currents and causes wave action, and the wind profile depends on the roughness of the wave-dominated water surface and on the air/water temperature difference. Current operational forecasts are still made in two steps: the weather forecast is made first; the water level forecast follows as a second step, as a partial problem of ocean forecasting.

For about 25 years, a chain of numerical forecast models has been used at BSH to deal with these problems (DICK et al., 2001; MÜLLER-NAVARRA, 2003). So far, numerical forecast methods have not yet been able to fully replace empirical methods using latest measurement data, especially in forecasting extreme events. In the field of weather forecasting, synoptic methods have a long tradition (SCHERHAG, 1948; KURZ, 1990); the term used correspondingly in water level forecasting is empirical statistical methods (SAGER et al., 1956; SCHMAGER, 1984; MÜLLER-NAVARRA et. al., 1999).

Under hydrological aspects, storm surges at the German North Sea coast and in the western Baltic Sea have identical causes. However, their development takes place in different types of ocean basin, which are connected in different ways with the open ocean (see Tab. 1). The latter fact leads to a fundamental difference in operational storm surge forecasting. In large areas of the North Sea, the tides are the essential factor which determines the time of the storm surge maximum. In contrast, the weak tides in the Baltic Sea are virtually unnoticeable during a storm surge, and the surge maximum is determined primarily by hydrological and meteorological factors. To arrive at a deeper understanding of storm surges in the Baltic Sea, especially in its western part, the existence of a combined North and Baltic Sea system has to be assumed. During the passage of low pressure systems and storms across the transition area between the North Sea and Baltic Sea, enormous water masses of alternating directions are passing through the Belts and Sound and have a strong impact on local water levels (WEIDEMANN, 1950; MÜLLER-NAVARRA, 1983). This has often been described by the poorly defined term of "pre-filling", which is not suitable for operational forecasting. Particular storm tracks with hurricane-force winds may first cause a storm surge in the German Bight and one day later a surge in the western Baltic Sea (e.g. "All Saints Flood", November 1/2, 2006, MÜLLER-NAVARRA, 2006).

## 5.3 Weather Forecasting

Without the occurrence of intense low-pressure systems, there would be no storm surges in the North Sea or Baltic Sea. In the German Bight, only wind directions from the sector WSW to NNW can produce storm surges. In the western Baltic Sea, by contrast, surges are caused by winds from the sector N to E. The tracks of low-pressure systems causing such storms may vary considerably (KOHLMETZ, 1967). In most cases, the low-pressure systems are generated in the North Atlantic Ocean and travel eastward across Great Britain. However, storm surges in the Baltic Sea may also be caused by low-pressure systems tracking both from the Mediterranean area across Central Europe or southward from the Polar Seas (MIEHLKE, 1962).

All these weather situations have in common that they involve special problems of maritime meteorology. Three questions are at the centre of the forecasting problem:

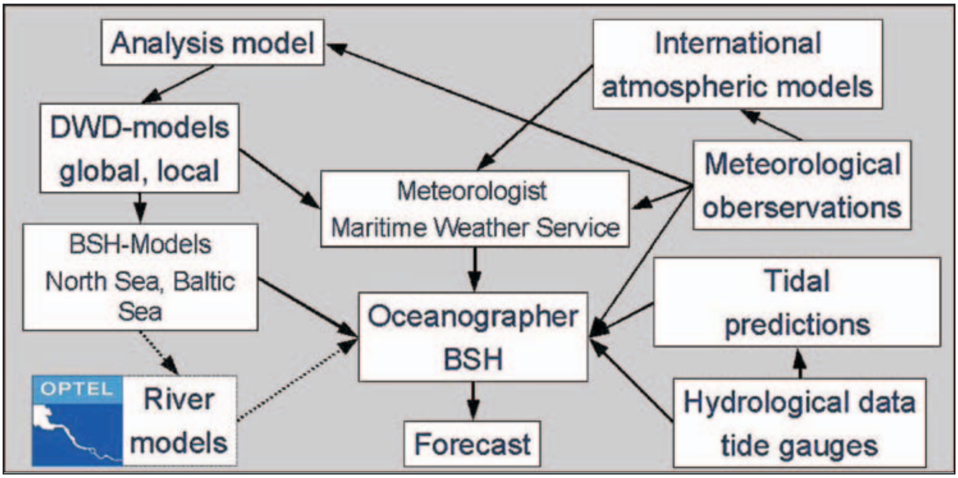



Fig. 6: Information sources used by the oceanographer in storm surge forecasting

1. How fast does the low pressure system move, and on what track?
2. Will the cyclone increase in intensity?
3. How will the near-bottom wind profile, depending on stratification, develop?

The first question concerning track and speed is of special relevance with regard to small, high-intensity cyclones, because the time of wind maximum must be related in a particular way to the computed time of astronomical high water on the German North Sea coast. It is not helpful to state that maximum wind will occur sometime in the next 18 to 24 hours, because the only effect might be an extremely high low water. This happened, for example, in the early morning of February 10, 1949 (TOMCZAK, 1950). The tidal phase problem does not exist in storm surges in the western Baltic Sea. But the track of such small cyclones is equally important to the North and Baltic Sea coast because wind direction and the area of maximum wind fetch depend on it (storm "Anatol" on December 3, 1999, MÜLLER-NAVARRA, 2002). Without this data, no reliable regional storm surge forecasts can be made.

The relevance of the second point "increase in intensity" to short-term forecasts is often underestimated. Particularly over the sea, there is no sufficient number of observation stations which would allow an estimate of whether the hurricane has already lost its force or is still increasing in intensity. This also gives rise to the problem that insufficient data availability makes it impossible to compute satisfactory analyses, and that the initial distributions of model runs are missing important features (frontal zones, cold air troughs). This problem resulting from poor data availability over the oceans is not new but was already encountered when Deutscher Wetterdienst (DWD, German Weather Service) ran the very first baroclinic models (BUSCHNER et al., 1973). Thus, in the individual case, it is still the experienced synoptic meteorologist at the maritime weather service who has to compile and evaluate the model results and incoming station data in order to make a reliable forecast.

The third point "stratification and wind profile" is a problem often overlooked. Although it has been a research topic in meteorology for many years (HASSE, 1968), gaps of knowledge concerning the atmosphere/ocean impulse transfer at very high wind speeds still exist. Because of this, parameterisation of the impulse transfer in numerical modelling chains still involves major uncertainties (JENSEN et al., 2006). Two examples may illustrate this point. In a situation of unstable stratification, wind gustiness can increase wind stress and water set-up on the coasts; such conditions probably prevailed during the storm surge caused by the Hamburg hurricane (RODEWALD, 1962; KOOPMANN, 1962). An inflow of cold air on November 12/13, 1872, probably contributed to the extreme peak levels reached during the storm surge of November 13, 1872 (ROSENHAGEN et al., 2008).

### 5.4 Storm Surge Forecasts for the North Sea

The water level forecasting process is closely linked to the availability of operational data and information. Today, first preparatory work can be done and information provided much earlier than, e.g., 20 years ago. Moreover, the tides establish a certain time frame, and extreme storm surge levels can only occur within a narrow time window of ± 2 hours around the time of astronomical high water. This requires different warning strategies depending on the individual case. Neither should warnings be issued too early, nor should the public be confused by contradictory information or by too much detail. Warnings, once issued, are never cancelled because two successive storm surges are not so uncommon events. Looking at past experience, storm surge warning routines for the German North Sea coast can be broken down into five phases:

#### Phase 1: 72–24 hours before high water

First information about the existence of intense low-pressure systems in the Northeast Atlantic with a storm surge potential, whose track is governed by high altitude flow, is provided by global models of the national weather services several days before their approach (MAJEWSKI et al., 2002b). This poses the first problems, because, in the past few years, radio and TV stations have increasingly focused on natural disasters. Each station wants to be the first to issue a concrete forecast. As has been pointed out above, model forecasts of track and speed over the sea are still very uncertain. Therefore, the following cannot be overemphasised:

**Public warnings of storm surges should not be issued too early, because this would confuse the coastal population and cause them to lose trust in the longer term due to frequent forecasting errors.**

Nevertheless, BSH's storm warning service does not stay inactive during this phase. Over a three-day period, the modelling chain of DWD and BSH provides updated high-water forecasts every six hours. The modelling chain comprises five models. Data are provided by DWD's two atmospheric models, a global model termed GME (MAJEWSKI et al., 2002b) and a local model, COSMO-EU (formerly called LM, STEPPELER et al., 2003), and by BSH's three interactively coupled ocean models which are based on the BSHcmod method: the Northeast Atlantic model, the North and Baltic Seas model and the coastal model (DICK et al., 2001). A wind set-up model with limited model physics is run parallel to these models.

First discussions, mainly regarding the quality of these early model forecasts, are held with the meteorologists of the maritime weather service during this phase (Fig. 6). Experience in storm surge forecasting has shown that currently used atmospheric models generally overestimate the severity of storms which are a longer time ahead. Another important issue in these discussions is whether the weather situation under review is comparable to past storm surge situations. Here, the expertise and experience of the meteorologist on duty is of crucial importance.

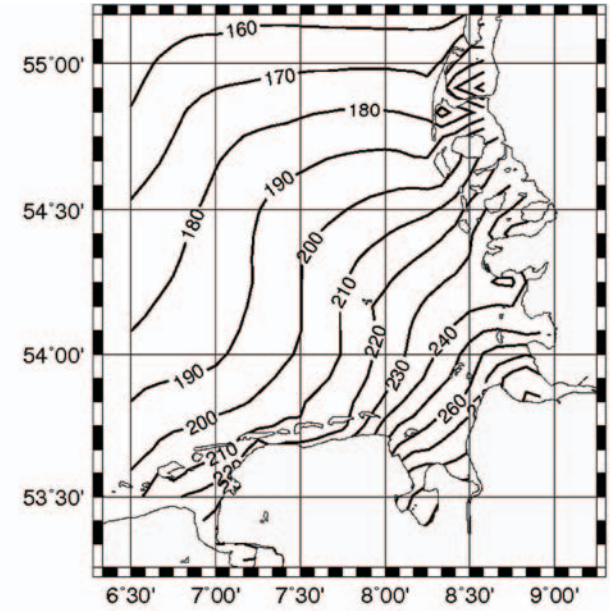



Fig. 7: Forecast of wind set-up of BSH's operational model system for the storm surge of November 9, 2007

The maximum water levels computed by means of this system (Fig. 7) form the basis for consultations held with the emergency control committees of the German coastal states. For example, when a storm surge has been predicted for the weekend, emergency personnel have to be alerted as early as Friday.

**Phase 2 "Consolidation": 24–18 hours before high water**

Almost 24 hours before the predicted high water, the runs of the various global and local models begin to resemble each other more and more, and variations in the temporal development are becoming less from one forecast run to the next. There are normally four model runs per day, starting with the analyses at 0, 6, 12, and 18 hours UTC. In this phase preceding the storm surge, a consolidation of results is taking place. The modelling data now reach a period of time that is accessible to synoptic treatment of such weather situations (SCHERHAG, 1948). This means that the model runs are supported by meteorological observations and synoptic forecasts made on that basis. When both of these components form a harmonic, convincing picture, the oceanographers and meteorologists on duty know that there will be a storm surge.

When a homogeneous, quasi-stationary wind field is expected over the North Sea, satisfactory results can be obtained for the German North Sea coast using historic methods which take into account the atmospheric pressure gradient over the entire North Sea (LEVERKINCK, 1915; RAUSCHELBACH, 1925). Better results can be obtained using empirical/statistical methods if data from wind monitoring stations in the German Bight are available (MÜLLER-NAVARRA et al., 1999). In that case, so-called wind set-up diagrams for individual locations are particularly easy to use (Fig. 8). In the consolidation phase, they provide a first rough idea of the maximum water levels to be expected. The required input is wind data – areal mean values in the southern German Bight, 3 hours before the time of high water at Cuxhaven. The thick, nearly vertical line in the diagram indicates the wind direction most likely to produce a set-up at Cuxhaven at certain wind speeds; at 50 knots the attached direction is 295° (WNW).

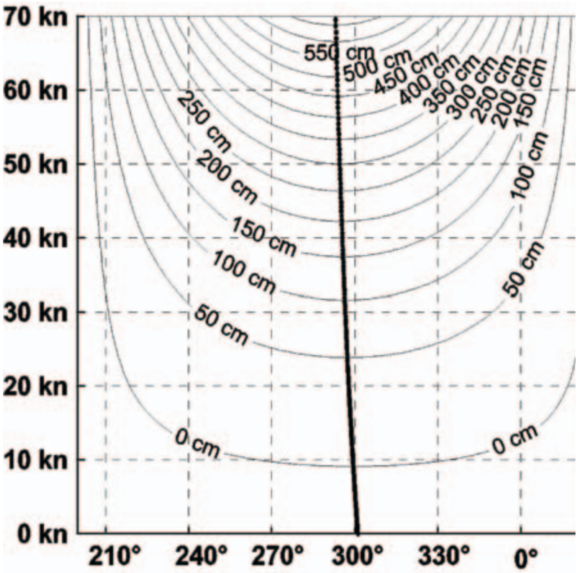



Fig. 8: Wind set-up diagram for Cuxhaven (MÜLLER-NAVARRA et al., 1997)

Cuxhaven, the central location on the German North Sea coast, serves as a reference point for the other coastal locations. Depending on wind direction and speed, deviations are added or substracted to the set-up value computed for Cuxhaven to obtain the values for the individual coastal locations (TOMCZAK, 1952a, 1952b). In this way, empirically calculated storm surge maximum levels are obtained for the different coastal regions. This method, which may seem outdated at first sight, provides fairly good results in the presence of homogeneous, stationary wind fields in the German Bight. However, the empirical method has weaknesses in non-stationary weather situations. It presupposes that a dynamic equilibrium develops between wind and water level gradient, and between surface currents and near-bottom compensating flow (Fig. 9), which is not always the case.

In non-stationary weather situations, the above-mentioned modelling chain of DWD and BSH is indispensable. Wind set-up is determined by parallel computation using two different model variants, one variant with all boundary conditions and another one without meteorological forcing. The computed difference is the wind set-up, although only wind set-up at the time of the low and high water maximums (skew surge) is computed. Another advantage of the model is an spatial representation of the set-up (Fig. 7). The occurrence of storm surge levels is sometimes limited to certain coasts. During SSW winds, for example, storm surge levels occur only along the North Frisian coast.

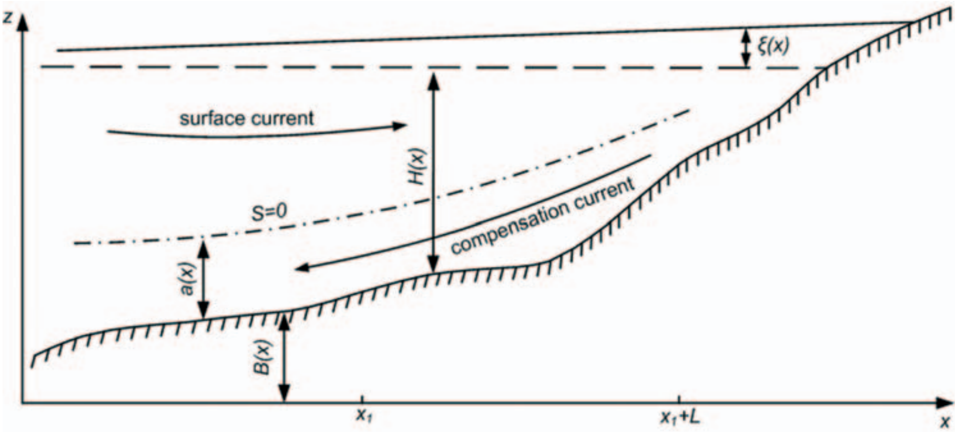



Fig. 9: Vertical current profile and wind set-up on shallow coasts (ERTEL, 1972)

### Phase 3 "Warnings": 18–9 h before high water

Once the set-up has been computed using the method described above, the set-up value is added to the values of the computed astronomical high water, and the total value is referred to the local mean high water (MHW) value. If it is more than 1.5 m above MHW at any location, this is by definition a storm surge; above 2.5 m it is a severe storm surge, and more than 3.5 m above MHW is defined as a very severe storm surge (Tab. 3).

The BSH updates its water level forecasts four times a day, at 8 h, 14 h, 20 h, and 24 h, in case of storm surges even more often. Then, the water level forecast becomes a storm surge warning. The warning has to be worded unambiguously in such a way that it cannot be misunderstood, particularly when broadcast on the radio. On November 8, 2007, at 20:30 h, the following warning was issued for noon on the next day, i.e. about 16 hours earlier:

"There is a risk of a severe storm surge at the German North Sea coast. On Friday, high water levels at noon and in the afternoon are expected to be 3–3.5 m above MHW at the East Frisian coast and in the Weser and Elbe estuaries, and about 2.5 m above MHW at the North Frisian coast."

Detailed forecasts for places at the German North Sea coast are published on the Internet, and special warnings are sent to about 320 recipients by telegram (FACT24 Alarm Service, F24 Communication Services) (Fig. 10). The recipients are mostly organisations or agencies forwarding the warnings (e.g. emergency services, fire brigades, operators of barrages and container terminals, dike administrations, city utilities, nuclear power stations, pilot stations, navy, police and port authorities, local warnings services). Besides, there are numerous other communication channels with a major problem being the promulgation of identical information on all channels.

### Phase 4 "Concretisation and updates": 9–4 hours before high water

In phase 4, the oceanographer of BSH is busy updating the forecasts of maximum water levels for the entire German North Sea coast. Concretisation and updates are supported, on the one hand, by new model runs as required and, on the other hand, by meteorological

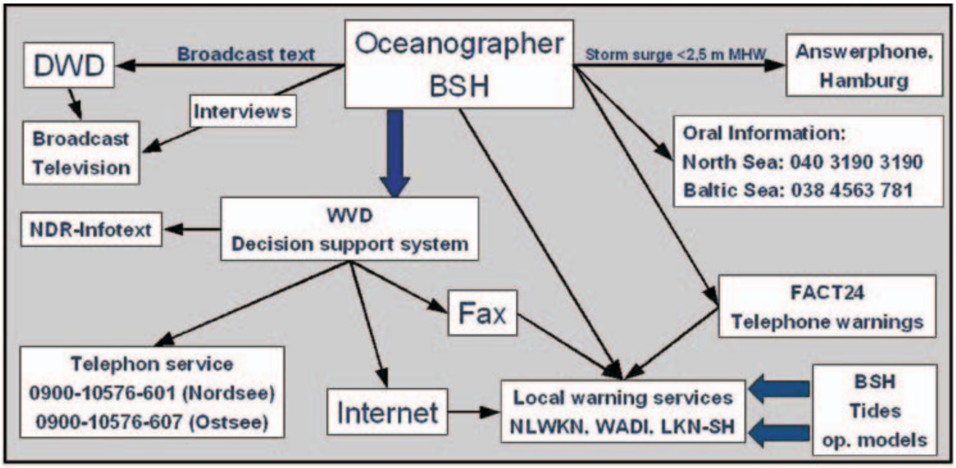



Fig. 10: Promulgation of warnings and information following the issue of a storm surge forecast by BSH's oceanographer

advice provided continuously by the synoptic meteorologist at the maritime weather service. Depending on the situation, BSH's oceanographer may contact the meteorologist every hour to obtain the latest data on storm development in the North Sea region. Another purpose of the continual updates is to provide forecasts for smaller areas. Radio broadcast messages and FACT24 warnings, as described above, only refer to the general situation and provide water level data for larger coastal areas.

If the situation becomes more threatening, different warning levels are used. Now, recipients of warnings have to prepare for higher peak levels. If, however, the present situation is considered less serious than expected, warning levels will not be lowered since the risk of the storm regaining strength is too high.

The continually updated peak levels are also communicated to people living in risk areas. During storm surges, lots of people will call pre-defined telephone numbers in order to obtain personal advice (Fig. 10).

Nine hours before the computed astronomical high water in Hamburg is also the earliest point of time that expected peak levels for Hamburg can be determined using the empirical method of WADI, the Hamburg warning service, at Hamburg Port Authority (HPA) (SIEFERT et al., 1983). This is the theoretical point of low water at Borkum. Moreover, the wind set-up computed for Borkum is available to be used – among other input parameters – for the WADI forecast. However, in case of pronounced non-stationary weather situations, this method is lacking accuracy, and the results have to be checked and revised by the responsible official at HPA. The forecasts for Hamburg are co-ordinated orally between HPA and BSH in order to be able to promulgate consistent forecasts.

### Phase 5 "Tidal rivers": 4–0 hours before high water

It takes about 3.5 hours for a storm tide to travel from the mouth of the river Elbe to Hamburg. This time span and available data on storm surge peak levels in the Elbe estuary allow a precise forecast of peak levels to be expected in Hamburg. A similar method is used for the city of Bremen at the Weser estuary.

It is worth noting that the first warning systems in Hamburg, which date back to the 19th century, were based on water level data that had been transmitted by telegraph from the Cuxhaven gauge station (Official order, ANON., 1855).

In the last four hours before peak level is reached, some difficult work remains to be done. The exact large-area water level situation in the Elbe estuary and local wind conditions cannot be recorded precisely by the small number of operational measuring stations. But it is exactly in this area that the shape of the surge wave undergoes characteristic deformations which determine its progress and shape. The time series of water levels at Cuxhaven, supplemented perhaps by one recorded in the inner German Bight at "Beacon A", does not provide sufficient data for an estimate of the upstream evolution of the surge wave. Other factors to be considered in forecasts of peak water levels in Hamburg are wind conditions along the estuary (RUDOLPH, 1997) and the freshwater discharge, even though periods of high freshwater discharge (spring and autumn) do not usually coincide with the storm surge season.

Unfortunately, the "Elbe lightship" monitoring station, which used to provide important data for empirical computations of wind set-up in the inner German Bight, does not exist any more. As storm "Anatol" tracked across the area on December 3, 1999, the vessel capsized in heavy seas and suffered heavy damage. Unlike the aftermath of the "Elbe 1 hurricane" on 27 Oct 1936 (SCHERHAG, 1938), the unmanned lightship "Elbe" was considered unnecessary as an aid to navigation and was taken out of service. This meant the loss of an important oceanographic and meteorological monitoring station with a long tradition, whose data have been sorely missed in several storm surge forecasts since then.

Today, we try to compensate for the loss of this monitoring station by closely observing developments upstream, at the next important gauge station at Brunsbüttel (Fig. 11). There is no problem extrapolating the increase in wind set-up at Brunsbüttel, in comparison with the Cuxhaven station, to Hamburg. It has been found that, as good rule-of-thumb, wind

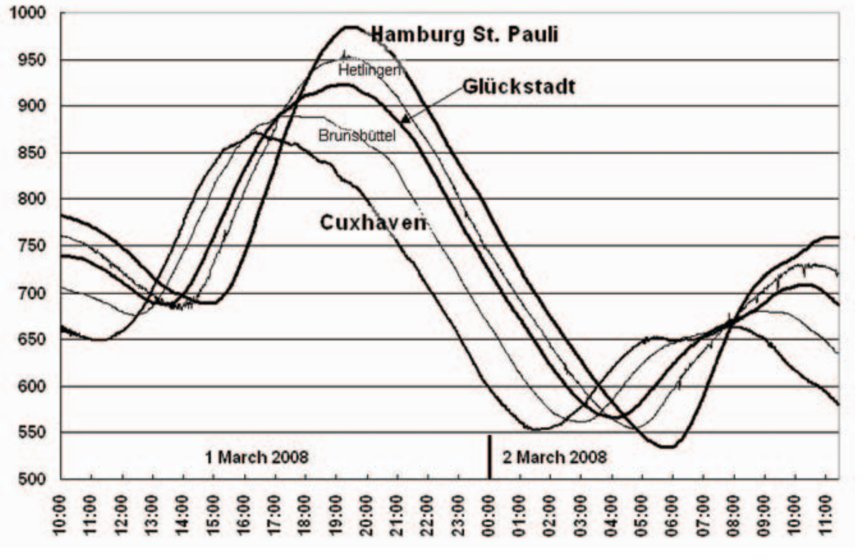



Fig. 11: Time series of water levels on March 1, 2008

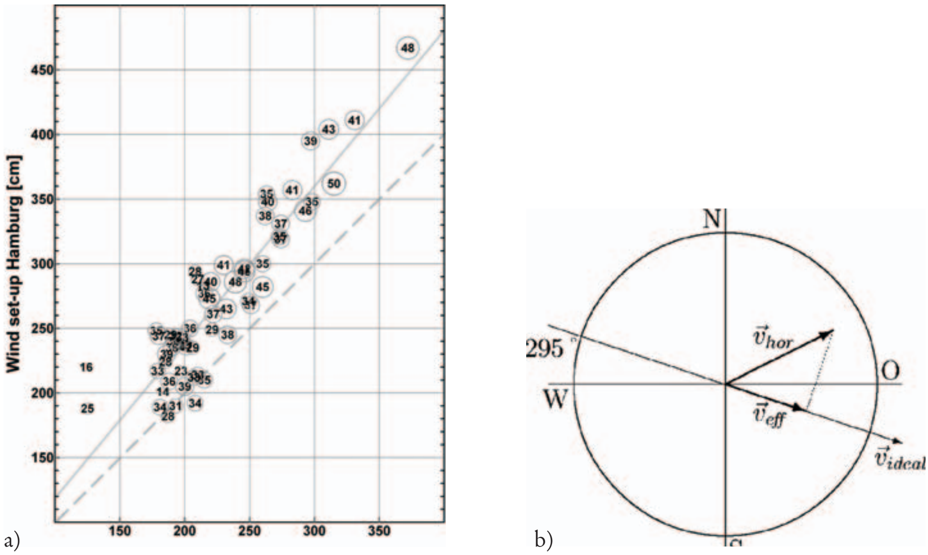



Fig. 12a): Wind set-up at Hamburg plotted against wind set-up at Cuxhaven (February 1965 to March 2008, cases with peak levels of 2 m above MHW in Hamburg). The figures in circles indicate the effective wind speed (knots) in the German Bight. b) Definition of effective wind speed: projection of wind vector onto the abscissa of a co-ordinate system which has been rotated 25°

set-up increases by 20 % on its way from Cuxhaven to Hamburg (Fig. 12a). There is a considerable scatter of data, though.

In historical storm surges of the late 19th and early 20th century, wind set-up in Hamburg was lower than in Cuxhaven. Additional harbour basins built in Hamburg during these years dampened the storm tide (HENSEN, 1955). The coastal defence measures taken after the severe storm surge of February 1962 (MÜLLER-NAVARRA et al., 2006) had a decisive impact on the situation. The frequency of storm surges in Hamburg as compared to Cuxhaven has increased markedly since early 1970, after the completion of barrages and straightening of dikes (DÜKER et al., 2006). In the period from 1950 to 1972, the same number of storm surges was recorded in Hamburg and Cuxhaven, on average; between 1972 and 2007, however, Hamburg experienced about 3–4 storm surges more per year (Fig. 13). Today, the deepened riverbed poses little resistance to the incoming tidal wave. Recent hydraulic engineering works and training measures carried out in the riverbed – mainly close to the navigation channel – have hardly changed anything about this situation.

### 5.5 Storm Surge Forecasts for the Baltic Sea

The Baltic Sea water level forecasting service was integrated organisationally into BSH's ice warning service in 2006. On workdays, it is operational at least from 6:30 h to 15:00 h; outside this period it is on standby. Water level forecasts for the western Baltic are issued twice a day, at 8 and 14 h. When water levels are expected to exceed 1 m above normal, the water level forecasting service becomes the Baltic Sea storm surge warning service, which is on duty for 24 h/day.

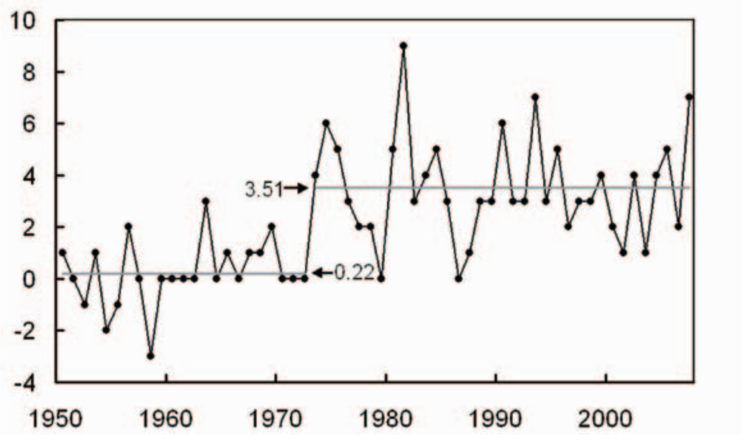



Fig. 13: Difference in the number of storm surge peaks of Δh ≥ 1.5 m above MHW at Hamburg and Cuxhaven 1950 to 2007

BSH's operational model system is the most important tool for these forecasts. In addition, current water level data from about 50 gauge stations along the western Baltic Sea coast are included in the computations. Another forecast is based on statistics in empirical methods, which establish a connection between wind data measured in certain parts of the Baltic Sea and local water levels (SCHMAGER, 1984; SAGER et al., 1956; ENDERLE, 1989). The empirical-method wind set-up of SCHMAGER (1984, Fig. 14) is based on wind data from the Arkona monitoring station, measured 6 hours before the expected peak high water. The thick line from the top to the bottom left corner in the diagram indicates the wind direction most

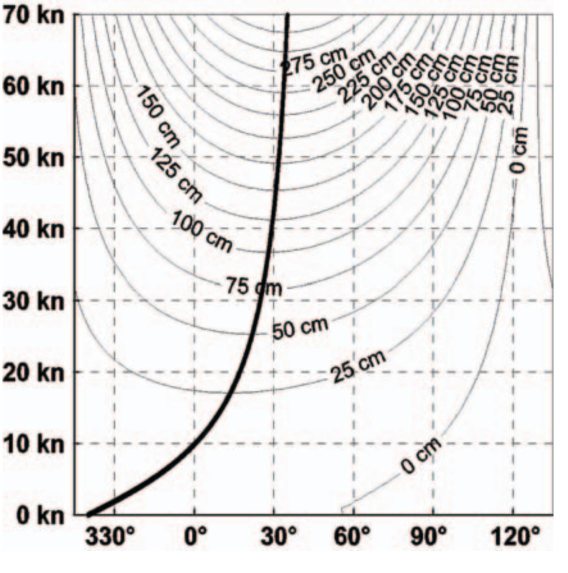



Fig. 14: Wind set-up diagram for Warnemünde (SCHMAGER, 1984)

likely to produce a set-up at Warnemünde for certain wind speeds; at 50 knots, it is 32° (NNE).

Because of the small tidal range in the Baltic Sea, storm surges in this region lack the typical tidal pattern that makes forecasts for the German Bight so difficult. Therefore, the speed at which low-pressure systems travel across the Baltic Sea area is less important than in the North Sea, and it may be quite appropriate to issue warnings early (e.g. on Friday for the following weekend). Consequently, it is not necessary to distinguish between different forecast phases. Forecasts are made rather continuously, and water levels rise more or less steadily until they reach peak level, depending on the weather situation. There are no interruptions due to low-tide phases. Storm surge warnings for the Baltic, therefore, can be issued for longer periods. They go to more than 80 recipients including many information multipliers, as is done in the North Sea region.

### 5.6 Accuracy of Storm surge forecasts

In assessing the accuracy of storm surge forecasts, the above-mentioned uncertainty of wind forecasts should be taken into account. The statistics include data on a logical linkage of forecasts with warnings. The main purpose of issuing warnings is to protect people and their property and to keep damage to a minimum. To this end, sometimes worst-case scenarios have to be assumed. This can happen when wind forecasts indicate possible wind set-ups of 4–5 metres but the corresponding temporal evolution cannot be forecasted some 18 hours earlier with an accuracy of 3 hours. Then the worst-case assumption could read that the storm will reach its highest intensity just before the computed astronomical peak level is reached. That was the situation as storm „Kyrill“ approached in January 2007, accompanied by radio and TV broadcasts which were describing a disaster scenario for days preceding the arrival of the storm. Although the weather services later evaluated the forecasts positively (DMG, 2007), it is evident that the low-pressure centre crossed Jutland about 3 hours earlier than forecasted, and thus did not have the maximum impact on water levels. Warnings nevertheless had to be issued, but the forecasted very severe storm surge did not occur (MÜLLER-NAVARRA, 2008), and the peak level forecasted 14 hours earlier was 1.75 m too high (Fig. 15, triangle top right).

The quality of forecasts can be assessed in different ways. Especially in extreme events, a number of parameters are suitable for this purpose. It is, for example, important to know whether or not a forecasted event (exceeding of a limit value) occurs at all. Another important question is how often forecasted water levels deviate by more than a fixed amount from measured water levels. This has been investigated for the North and Baltic Sea coast by perusing the examples of Cuxhaven and Warnemünde, respectively. The database used included all events during which the water level at the Cuxhaven gauge station differed more than 1 m from MHW (Fig. 15). At the Warnemünde gauge station this was more than 1 m from MW (Fig. 16). The forecasts for Cuxhaven, marked by triangles, cover periods of 6 to max. 18 hours, those for Warnemünde 6 to max. 39 hours.

Fig. 15 shows that the forecast error has decreased markedly from the mid-1990s. With the exception of storm “Kyrill”, the error has never exceeded ± 75 cm.

Probably even more important is the fact that not a single extreme event has been overlooked since then, which still happened sporadically in the early 1990s. This is attributable to several reasons. Firstly, the frequency of storms in the German Bight was higher in the early 1990s; secondly, substantially more personnel has been employed in the water fore-

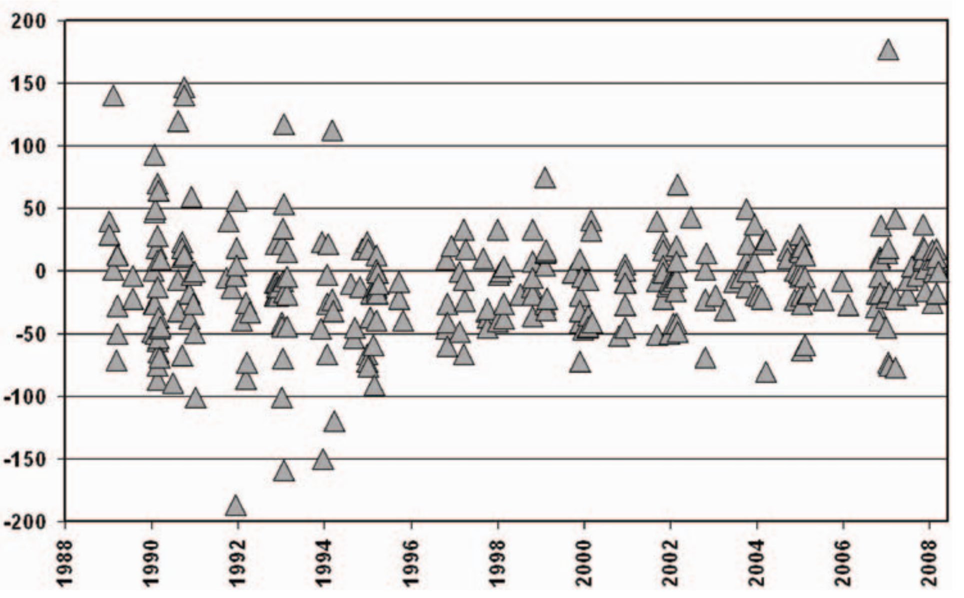



Fig. 15: Forecast error in cm (forecasted deviation from MHW at Cuxhaven minus measured deviation from MHW), all cases from January 1989 to March 2008 with observed deviations from MHW greater than 100 cm

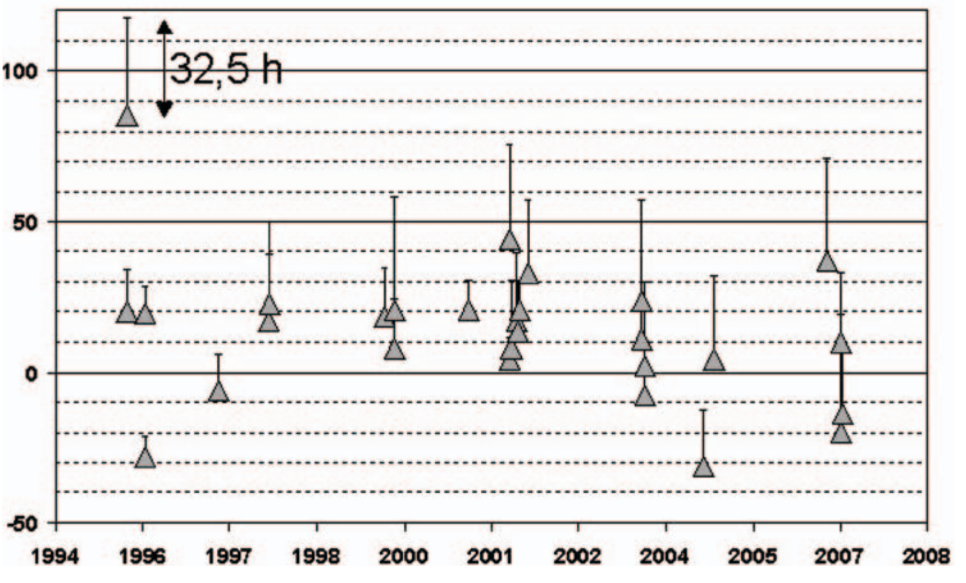



Fig. 16: Forecast error in cm (deviation from MW forecasted for the coast of Mecklenburg-Vorpommern less deviation from MW at Warnemünde) and forecast period in hours (line above triangles), all cases from 1995 to 2007 in which observed deviations from MW exceeded 100 cm

casting services since the mid-1990s; and thirdly, considerable improvements have been achieved in numerical weather and water level forecasts in the past 15 years. Nevertheless, there has been no significant reduction of the error interval in the past 10 years. Here, nature obviously is showing us current limits of predictability. Probably the meteorological observation network at sea, i.e. in the North Sea, Baltic Sea, and Northeast Atlantic Ocean, is simply too thin. In the individual case, the forecast of a storm surge peak probably has to be considered a success if it can be predicted with an error of ± 50 cm half a day in advance.

Statistics for the German Baltic coast, covering the period since 1995, only allow the conclusion that the error has been within the narrow range of ± 50 cm – with one exception. But only very few cases are documented, and forecasted values generally were not archived prior to 1995. The GDR's water level forecasting service did not routinely review and criticise forecasts made for the Baltic coastlines of Mecklenburg-Vorpommern in order not to impair the good co-operation between hydrologists and meteorologists at the Warnemünde sea weather service (O. MIEHLKE, pers. comm.).

Forecasts for the Baltic coast of Schleswig-Holstein were not routinely subjected to critical review, either. There only exist two hindcasts of KOOPMANN (1961) from 1960/61 which cast some light on forecasting problems encountered at the time.

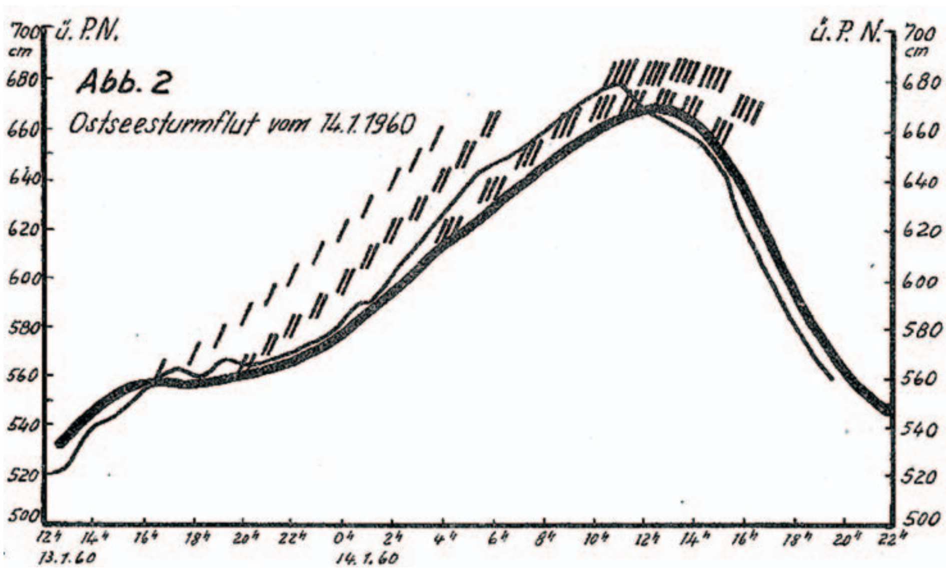



Fig. 17: Baltic Sea storm surge of 14 January 1960, water level above zero gauge (thin line: measurements; thick line: hindcast based on observed weather data. The short lines indicate water levels derived from 4 meteorological forecasts (KOOPMANN, 1961)

The example of the storm surge of January 14, 1960, shows quite nicely how the scientist on duty, taking into account latest meteorological forecasts, successively closed in on the peak water level that was eventually measured at the Kiel gauge station (about 1¾ above MW) on January 14, 1960, towards 11:00 h. The first forecast made in the late afternoon of the preceding day still was ¼ m too low and predicted the time of the peak water level 8 hours too early. It was only the third forecast (symbol "///" in Fig. 17) in the morning of January 14, 1960, which produced satisfactory results. But even the hindcast based on observed meteorological data, using an empirical method (unpublished), was not entirely convincing after all. Since the autumn of 1990, BSH has been operating a coupled model of the North and Baltic Sea, which also predicts water levels at the coasts of Mecklenburg-Vorpommern. It was instantly found to be a useful supplement to existing empirical methods. Since that time, forecasts for the German Baltic Sea coast have been based "at least at 80 % on the hydrodynamic numerical model (HN model) of the BSH" (STIGGE in: HUPFER et al., 2003, p. 54). This may also account for the fact that over-predictions have been more frequent than under-predictions (Fig. 16), because current numerical atmospheric models usually overestimate the maximum wind speeds of events that are farther ahead in the future. As the forecasted event approaches, the severity of forecasted storms in the model runs tends to decrease.

### 5.7 Open Issues and Outlook

One major future problem will be the increasing automation of the meteorological and oceanographic forecasting services in order to save costs. Automation in this context means that the human factor, i.e. the personal contact and interaction between meteorologist and oceanographer, will ultimately be eliminated from the operational forecasting process. Although acceptable results may be obtained in this way for moderate wind situations (BALZER, 2002), this method is not likely to work for storm surge forecasts because of an insufficient data availability at sea, as has been pointed out in more detail above.

Another, as yet largely unsolved, problem is the parameterisation of the atmosphere/ ocean impulse transfer during extreme storm surges. While parameterisation at wind speeds of up to approx. 25 m/s is considered to be well supported by measured data (SMITH et al., 1975), that is not the case at higher values. Both computation of the wind profile (10-m wind) in atmospheric models and of the wind stress coefficient, which depends on wind speed, are still subject to research.

It remains to be seen whether 'ensemble prediction systems' (EPS) will be capable of significantly improving the quality of storm surge forecasts. Although it will be possible using this method to allocate a probability to forecasted events (MOLTENI et al., 1996), experience has shown that the end-users of forecasts do not appreciate such information. By contrast, the forecasters consider it essential to know whether or not a high percentage of model runs have the same tracks and tracking speed. This information may help them to bring forward the decision whether or not an extreme event is about to occur.

Depending on the coastal sector affected, it may be useful for emergency response services to obtain information not only about maximum water levels but also about sea states, because dike stability may also be threatened by wave overtopping (MAI, 2004). To be able to predict wave action at shallow coasts in storm surge situations, simulation tools for wave breaking require a high resolution grid. Because of the enormous computer time needed for such simulations, operational wave forecasts of adequate quality are not yet available for the German coast. However, over the past few years, theories and a hindcast model with a horizontal resolution of just under 2 km have been developed, at BSH (MURAWSKI, 2007). The latter will be operational for wave forecasts in coastal waters in the near future. Hindcasts of extreme storm surges using this model have shown that waves breaking on the foreshore have caused a set-up of a few decimetres between and behind barrier islands.

Any uncertainties concerning wind set-up development in the Elbe estuary are to be eliminated in the coming years by the development of an operational model for the tidal Elbe estuary. The "OPTEL" project (Wind Set-up Studies and Development of an Operational Tidal Elbe Estuary Model) was started in April 2008 as a joint project of the Federal Waterways Engineering and Research Institute (BAW), the German Meteorological Service (DWD), Hamburg Port Authority (HPA), and the Federal Maritime and Hydrographic Agency (BSH). The Elbe model will complement the range of BSH's models and will include the option of an application to the other German North Sea estuaries at a later date. As soon as the Elbe model becomes operational, its data will be available to all Federal and State administrations.

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Die Küste, 74 ICCE (2008), 1-417

# Allocation of Administrative Responsibilities and Legal Framework Conditions

By Bernd Probst and Frank Thorenz

Contents



## 1. Administrative Boundaries and Legislative Competence

The Basic Constitutional Law of the Federal Republic of Germany defines the Republic as a federal system in which individual states are granted a high degree of autonomy according to the principle of subsidiarity. The consequence of this is that federal administrative boundaries in coastal regions result from historical developments and that areas of responsibility are hence non-homogeneous.

The German coastal zone comprises the federal states of Niedersachsen (Lower Saxony), Bremen, Hamburg, Schleswig-Holstein and Mecklenburg-Vorpommern. The German Federal Republic (or the federal government) is solely responsible for shipping routes in the entire coastal region of the North Sea and Baltic Sea as well as for navigation channels in estuaries. In several task areas the federal government has reserved the legislative competence for centralised framework laws, whereas responsibility is borne by the individual states on a regional level. This includes, e.g. responsibility for water resources management and nature conservation. Moreover, a range of task areas exist for which the federal government has either no legislative competence or does not assume responsibility for. The responsibility for such task areas therefore solely rests with the individual states.

The five coastal states are each responsible for coastal protection and all matters concerning state and municipal ports and harbours.

## 2. Legal Framework Conditions

### 2.1 European Legal Norms

By way of the **Directive on the Assessment and Management of Flood Risks** adopted by the European Union with effect from Nov. 20, 2007, legal provisions on flood protection have now been established which also partly apply to coastal protection. So far, however, this does not concern operational tasks but only management tasks. In the next step, a preliminary assessment of flood risk must be drawn up by December 22, 2011. Thereafter, flood hazard maps and flood risk maps must be produced by December 22, 2013.


Fig. 1: Federal states in the coastal zone of Germany

Finally, the member states must produce and publish flood risk management plans by December 22, 2015.

The member states are obliged to put into force their respective national legislative and administrative rules and regulations by November 26, 2009. Thereafter, the afore-mentioned plans and maps must be checked and updated every 6 years.

Additional important EU Directives that have been implemented in national legislation are as follows:

- *Directive for establishing a framework for Community action in the field of water policy (Water Framework Directive)*
  This directive is intended to protect the ecological systems of rivers and therefore only concerns coastal protection indirectly. There is, however, a close connection between the latter and the afore-mentioned Flood Risk Directive as far as the area in question and public information and participation are concerned.
- *Environmental Impact Assessment Directive (EIA Directive)*
- *Directive on the conservation of wild birds (Special Protection Area Directive)*
- *Flora-Fauna Habitat Directive (FFH Directive)*

### 2.2 German Federal Laws

According to the *Basic Constitutional Law of the Federal Republic of Germany* (GG), Article 74, coastal protection is subject to concurrent legislation. As the German coastal states have effectively regulated coastal protection matters by way of federal laws, there is no cause for the federal government to exercise its legislative powers except for co-financing the construction of protection structures within the framework of the common task of "Improving agrarian structure and coastal protection", as defined in the German constitution.

According to Article 91a of the GG, coastal protection is defined as one of the tasks of the states, which is realised with the involvement of the federal government "provided these tasks are important to the community at large, and involvement of the federal government is necessary to improve living conditions (common tasks)". The law governing the common task "Improvement of agrarian structure and coastal protection" particularly regulates the financial participation of the federal government in investment-related coastal protection measures: today, the federal government bears 70 % of the investment-related costs within the scope of the available budgetary funds.

According to Article 75, Paragraph 1, No. 4 of the GG, the federal government enacted the framework legislation competence for water resources, and on this authorisation basis, decreed the Water Resources Act (WRA). Although this law, as a skeleton law, does not include direct regulations for coastal protection, it must nevertheless be taken into consideration.

Importance is also attached to the intervention regulation as well as to the biotopes protected by the Federal Nature Conservation Act (BNatSchG) as a skeleton law, which is supplemented by the respective state nature conservation acts. Additional provisions of the Federal Nature Conservation Act must also be taken into consideration in individual cases, as outlined in Section 4 with regard to the protection, maintenance and development of certain parts of the natural environment and the landscape.

The layout and operation of the federal waterways as transportation routes are regulated by the Federal Waterways Act (WaStrG). The Federal Administration for Waterways and Navigation (Wasser- und Schifffahrtsverwaltung – WSV) bears responsibility for the latter. The federal government is hence responsible for the upgrading, operation and maintenance of federal waterways, which includes inland waterways, maritime navigation channels and coastal waters. The federal government is also responsible for regulating traffic on these waterways.

Among other things, the federal states are permitted to use the maritime navigation channels and adjoining estuaries of inland waterways, owned by the federal government, free of charge for coastal protection measures.

With regard to the construction and upgrading of coastal protection structures, the Environmental Impact Assessment Act (Umweltverträglichkeitsprüfungsgesetz – UVPG), which regulates the performance of environmental compatibility checks, must also be observed.

The Water Association Act (WAA) regulates matters pertaining to the water and land associations, which, as dyke associations, have cooperation obligations and duties to partly support coastal protection measures.

The Regional Planning Act (RPA) of the federal government applies to the realisation of coastal protection measures relevant to regional planning as well as to conceptual planning. This act includes provisions governing the development of state and local regional planning programmes as well as regional planning procedures.

### 2.3 German State Laws

Due to the fact that a federal law governing coastal protection is non-existent at the present time, the federal states have established the necessary legislative policies on coastal protection by way of state laws. The states of Mecklenburg-Vorpommern, Hamburg, Bremen and Schleswig-Holstein have included coastal protection alongside water resources management in their respective state water laws. Besides the Lower Saxony state water law, the Lower Saxony dyke law also exists as a special law. Additional regulations may be drawn up in ordinances (e.g. the Hamburg Dyke Ordinance).

In addition to definitions of terms, these laws include directives on the accord of classification, the specification of dyke dimensions as well as the maintenance and utilization of dykes and other coastal protection structures. They additionally include provisions on rights and obligations relating to dykes, on dyke associations, dyke authorities and dyke defence.

Further state laws which are not mentioned individually here concern nature conservation, regional planning, national parks, disaster control, checks on environmental compatibility, and legal approval procedures.

## 3. Areas of Responsibility

According to legislation, the areas of responsibility are split between the federal government and the states.

The federal government is responsible for upgrading, operating and maintaining **federal waterways**, which not only include inland waterways but also maritime navigation channels and coastal waters. The federal government is also responsible for regulating shipping traffic on these waterways. The Federal Administration of Waterways and Navigation, which is part of the Federal Ministry for Transport, Building and Urban Affairs, is responsible for technical matters. Within the scope of the above-mentioned operational tasks, the German Federal Waterways Engineering and Research Institute (Bundesanstalt für Wasserbau – BAW) is also responsible for collecting basic hydrological and hydro-morphological data in the coastal zone. Using scientific methods, planning criteria are established for larger construction measures, and these measures as well as their effects are conclusively documented.

Other federal authorities, such as the German National Meteorological Service (Deutscher Wetterdienst – DWD), the German Federal Maritime and Hydrographic Agency (Bundesanstalt für Seeschifffahrt und Hydrographie – BSH) and the Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde – BfG) contribute considerably to the latter.

Different bodies of responsibility exist for **ports and harbours:**

Ports which primarily deal with passenger traffic and the movement of goods are the responsibility of states (state ports) or municipalities (municipal ports). These include all the large German seaports such as e.g. Hamburg, Bremerhaven, Lübeck-Travemünde or Rostock. Today, the handling of cargo is carried out by private companies in several ports, especially the larger ones.

Federal ports are primarily necessary for ensuring the safety and ease of maritime traffic, e.g. as ports of refuge or operational harbours. For this reason, responsibility for these is borne by the Federal Administration for Waterways and Navigation.

The states are responsible for **coastal protection:**

In this case a distinction must be made between official and operational responsibilities. Official responsibility includes the passing of appropriate laws by parliaments, the enactment of additional directives such as ordinances or similar by administrations, the legal approval of measures, and the supervision of facilities and measures. The state governments bear sole responsibility for the latter. Apart from the supreme coastal protection authorities within the ministries responsible, lower coastal protection authorities exist on a local level. These may be state authorities, state offices, municipalities or other public corporations contracted by the state concerned.

Operational responsibility comprises the construction (including strengthening), maintenance and operation of coastal protection structures.

In *Lower Saxony*, 22 dyke boards are mainly responsible for dyke maintenance and strengthtening. Here, as in other federal states, the dyke boards, as water and land boards, are corporations under public law according to the Water Board Act. The owners of all property in dyke-protected areas who benefit from these protected locations are compulsory board members liable to contributions.

The state is responsible for coastal defence and erosion protection on the islands, storm surge barriers, state-owned dykes as well as strategic and general technical planning. In charge is the State Agency for Water Management, Coastal Defence and Nature Conservation (NLWKN – Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz) subordinated to the State Ministry of Environment and Climate Protection. In state-owned ports, the dykes are maintained by the "Nports" Company.

In the city of *Bremen*, dyke maintenance and conservation is the duty of the two dyke boards on the left-hand and right-hand banks of the Weser. Dykes in Bremerhaven and in the harbour areas of the federal state of Bremen are operated and maintained by the "bremenports" Company.

In the port area of *Hamburg*, the Hamburg Port Authority (HPA) bears responsibility under the supervision of the State Ministry for Economic Affairs and Employment while the State Agency for Roads, Bridges and Waters (LSBG – Landesbetrieb für Straßen, Brücken und Gewässer) is responsible in the remaining parts of the city.

In *Mecklenburg-Vorpommern*, the State Agencies for the Environment and Nature Conservation (StAUN – Staatliches Amt für Umwelt und Natur) are responsible for construction and maintenance work in the field of coastal protection. In the long term, it is planned to hand over responsibility for these tasks to coastal protection boards. These boards, however, have not as yet been founded. Secondary dykes are maintained by water and land boards.

In *Schleswig-Holstein*, the State Agency for Coastal Protection, National Parks and Marine Conservation (LKN-SH – Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz) has been responsible for the construction, maintenance and operation of state-owned coastal protection structures, especially state protection dykes, since Jan. 01, 2008. The water and land boards are responsible for this work on secondary dykes and a number of so-called regional dykes.

Coastal engineering is of supra-regional interest to all departments dealing with such technical matters. For this reason research on coastal engineering is carried out to a large extent on a cooperative basis. In this connection, the federal government and coastal states have set up the German Coastal Engineering Research Council (KFKI – Kuratorium für Forschung im Küsteningenieurwesen) within the framework of an administrative agreement.

The council ascertains the joint need for research, sets priorities for projects, coordinates the research carried out by its partners and makes every effort to financially support coastal research projects. An important partner in the council is the German Federal Ministry of Education and Research, which makes available and awards funds for the promotion of coastal research.

## 4. International Agreements

Several international agreements contain general specifications which might also be of importance to coastal protection. The following agreements ratified by German federal law must be observed as a law providing guidelines:

- The Ramsar Convention on Wetlands of International Importance, especially as habitats for aquatic and wading birds. The Schleswig-Holstein Wadden Sea National Park and bordering regions are registered international wetlands.

- The Bern Convention on the Conservation of European Wildlife and Natural Habitats. With regard to coastal protection, especially the habitats of certain species of coastal birds and the common porpoise might be of importance.
- The Rio Convention on Biological Diversity, which deals with the conservation and sustainable utilisation of biodiversity in sectoral schemes such as, e.g. those relating to coastal protection.

In addition to the latter, multilateral declarations of intent by the German federal government exist which are binding on administrative action:

- The declarations by the Minister of the Environment at the trilateral government conferences on the protection of the wadden sea as an ecological entity.
- The currently updated "*Stade Declaration*" of 1997 contains a wadden sea plan in the enclosure which includes guidelines for the protection of the wadden sea. Besides emphasising the basic need of the local inhabitants for protection against storm surges, care is also taken to ensure that the realisation of the wadden sea plan is not detrimental to safety standards. Recent conferences have concentrated on the realisation of the plan and the integration of those affected by way of a "Trilateral Wadden Sea Forum".
- The "*Helsinki Convention*" on the Protection of the Marine Environment of the Baltic Sea Area in the ratified version of January 2000. The Helsinki Commission established within the framework of this convention developed several recommendations aimed at this objective. In three of these HELCOM recommendations, namely: (15/1) "Protection of the coastal strip", (16/3) "Preservation of natural coastal dynamics", and (19/1) "Marine sediment extraction in the Baltic Sea Area", declarations are made which could have consequences for coastal protection. It is, however, recognised (Recommendation 16/3): "that coastal protection measures are necessary at locations where ocean currents, waves or high water levels caused by storms could threaten settlements, human life or high economic assets, or destroy cultural heritage".
- The *Unesco Programme: "Man and the biosphere*". The Schleswig-Holstein Wadden Sea National Park is a biosphere reserve.

The objectives of international agreements are sometimes formulated in more detail than other federal and state statutory provisions. The fact that the contents overlap to a large extent, however, means that no additional restrictions are necessary in relation to coastal protection.

## 5. Coastal Zone Management

A balance between the different utilisation demands placed on the coastal zone is gaining increasing importance in the European context. The aim of Integrated Coastal Zone Management – ICZM is to help preserve and develop the coastal zone as an ecologically intact and economically thriving living space for humans, fauna and flora. A framework for ICZM was established in 2002 by way of the "Recommendation of the European Parliament and Council on the realisation of a strategy for Integrated Coastal Zone Management of European coasts". A first step in this direction was realised by Germany in 2006 by way of a "National strategy involving an appraisal of the current situation". The ICZM recommendation explicitly addresses important aspects of coastal protection such as the long-term threat posed on the coastal zone by storm surges, also taking account of anticipated climate changes.

Possible conflicts of objectives include, among others, the aims of nature conservation, economic and touristic land utilisation as well as communal interests connected with coastal protection structures or proposed measures.

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# Coastal Protection along the North Sea and Baltic Sea Coasts

By Bernd Probst

## Introduction and Overview

The Mean Sea Level (MSL) has been rising at different rates over the past millennia. Inhabitants along the coast have reacted to this in different ways. As a first resource, they left the inundated areas and resettled on higher-lying ground.

For more than 1,000 years, the inhabitants of coastal regions and the shoreline zones of estuaries have protected themselves against the destructive forces of the sea by means of artificial dwelling mounds, dykes and other coastal protection structures. The choice of strategies and priorities depended on the one hand on the degree of protection necessary (the objective), and on the other hand on the technical and economic resources available for constructing coastal protection structures.

People in very early times were only concerned about protecting their dwellings from flooding. The strategy at that time was to resettle on artificial dwelling mounds. Around the 11th century, however, they also began to protect their agricultural land by means of dykes. The dyke profiles developed over the course of the centuries in response to the rise in sea level. The new dykes were built according to the previously registered highest water level plus a small tolerance height. In contrast to the strategy adopted nowadays, no account was taken of expected future conditions. Dyke construction and dyke maintenance were tasks undertaken by farmers. With an increasing awareness of the importance of dykes for the well-being of the local community, larger groups gradually took on responsibility for dyke construction and maintenance. Due to the limited technical resources then available, an enormous amount of physical effort was required to build the dykes and protection structures. Due to the fact that these structures were often destroyed by storm surges in a matter of hours, many people lost their lives or were forced to resettle.

This vacillating development of coastal protection over almost two millennia up to the present-day appearance of the coastal zone is inseparably linked to the history of the landscape. Today, this has resulted in a special relationship between the inhabitants of the lowlands and the marshes as well as the Wadden Sea and the land where their ancestors bitterly fought against and often lost their battle against the destructive forces of the sea.

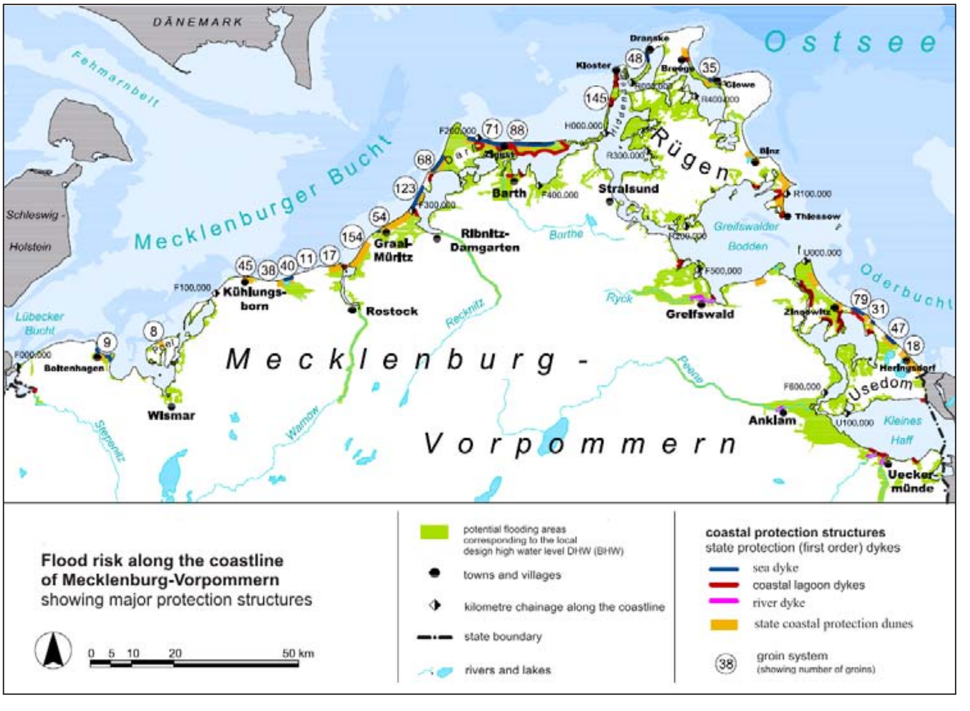
In the case of the one and only German deep-sea island, Helgoland, the original incentive for coastal protection had little to do with agriculture but was far more concerned with the strategic importance of the island and its relevance to maritime shipping. An additional concern today is the preservation of the island in the interest of its inhabitants.

Totally different bio-geographical conditions exist on the Baltic Sea coast. In contrast to the North Sea coast, the number of interconnected low-lying areas on the Baltic Sea coast is relatively small. The history of coastal protection along this coast is hence shorter. Systematic coastal and flood protection along the coastlines of the Baltic Sea only began in the first half of the 19th century.

Coastal protection is an expression of the historically-rooted and justified wish of coastal inhabitants to protect life and property against flooding and to avoid losses of land. Socio-economic utilisations such as colonisation, agriculture or industrial production in these coastal lowlands were first made possible by coastal protection and can only persist in the long-term under the precondition of a functioning coastal protection strategy. Besides flood protection, certain coastal regions are protected by means of groin construction, beach replenishment and other measures in order to avoid or reduce land losses due to erosion. Coastal protection in terms of the protection of individuals, settlements and tangible assets against sea attack does not necessarily mean, however, that every flood event or loss of land can always be prevented. The fact that absolute protection is not possible means that coastal protection measures must strike a balance between the utilities or objects to be protected.

Special problems are posed by flood protection in built-up areas directly exposed to storm surges. Due to the fact that dyke construction is often not possible in such cases due to lack of space or town-planning restrictions, alternative solutions are required.

Coastal protection is not an intrinsic task of the state. The protection of property against hazards is essentially the responsibility of the property owner himself. During the course of historical developments, however, the state or regional water and land associations have increasingly accepted this liability for coastal protection measures in so far as these are necessary in the interest of the well-being of the community at large.




Flood risk along the coastline of Mecklenburg-Vorpommern showing major protection structures

Planning practice in the field of coastal protection is based on master plans which are similar in character to special plans. These are neither binding for municipalities and districts nor for other planning bodies, but should rather be considered as programmatic statements by the Minister responsible with self-binding effect. For this reason, the coastal protection master plans do not fulfil the requirements of §§ 19a to 19d of the German Nature Conservation Law (BNatSchG). As a special plan, the master plan is therefore not subject to environmental impact assessments.

Almost all states with coastlines have drawn up a master plan. The "Lower Saxony/ Bremen Coastal Protection Master Plan – mainland –" was published as a joint master plan for these two federal states in 2007. The "Coastal Protection Master Plan – Integrated Coastal Protection Management – in Schleswig-Holstein" was published in 2001. The "Coastal and Flood Protection Master Plan for Mecklenburg-Vorpommern" has existed since 1994.

In accordance with the Hamburg "Flood Protection Construction Programme", all public dykes and flood protection walls are rebuilt, reinforced or raised as necessary. The construction programme is updated at regular intervals. In accordance with the 1976 "Framework Concept for Improving Storm Surge Protection", the public flood protection facilities in the City of Hamburg were supplemented by private flood protection facilities in the port area. The private flood protection facilities in the Port of Hamburg are mainly intended to protect valuable goods and installations.

The master plans generally include a description of the bio-geographical conditions pertaining to the respective coastal regions. This is accompanied by a documentation of the utilisation of the respective regions, which provides a basis for formulating the aims of coastal protection measures and the required safety standards. The existing coastal protection structures are represented and assessed in lists and maps. An important component consists in the dimensioning base data, which, unless pursuant to the statutory regulations, are described in detail in the master plan. The dimensioning data finally indicate which structures should be constructed or reinforced in order to guarantee the necessary safety standard for a defined future period of time.

Within the framework of this synopsis of necessary construction measures, a priority categorization is undertaken in which a degree of urgency is assigned to each construction measure depending on the extent to which the structure is under-dimensioned, its structural state and also to some extent the gross value of the land or property to be protected. A cost estimate not only permits a determination of the required overall costs of the respective master plan, but also enables an appropriate medium-term plan of action to be implemented in combination with priorities. In addition, the plans clearly indicate special features typical of the region arising from bio-geographical or administrative differences.

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# Coastal Flood Defence and Coastal Protection along the North Sea Coast of Schleswig-Holstein

By JACOBUS HOFSTEDE

Contents



## 1. Introduction and Historical Development

Schleswig-Holstein is the most northerly Federal State in Germany. It has an area of 15,731 km² and a population of about 2,700,000 (about 172 inhabitants per km²). The State is situated between two seas, the Baltic Sea in the East and the North Sea in the West (Fig. 1). As a result, a large part of the State may be characterised as coastal zone. Within this zone, most of the population is concentrated, e.g. in the harbour cities of Kiel (about 248,000 inhabitants) and Lübeck (about 217,000 inhabitants). In all, the coastline measures 1,190 km, and about 3,800 km² of flood-prone coastal lowlands exist. In these lowlands, which represent almost 25 % of total surface area, 345,000 people live and economic assets worth of 47 billion Euros are concentrated (HOFSTEDE, 2004). This chapter focuses on the North Sea coast, in-


Fig. 1: Overview of Schleswig-Holstein with State dikes (black bold lines), regional dikes (brown lines), and coastal lowlands

cluding the Schleswig-Holstein sector of the Elbe-estuary. For the Baltic Sea coast, the reader is referred to chapter 1.3.

The North Sea coast of Schleswig-Holstein is characterized by reclaimed coastal marshes, the Wadden Sea and the Elbe estuary (Fig. 1). The coastline measures 553 km, including 256 km of island coastlines and 77 km of estuarine shorelines. Of this coastline, 408 km have dikes, 105 km are occupied by sandy shorelines and 51 km are made up of soft cliffs. Approx. 1,700 km$^2$ of Wadden Sea stretch out in front of the mainland coastline. This area is a sink for coastal sediments and developed in the course of the Holocene transgression, resulting from a combination of sediment availability (mainly from the North Sea) and a hydrodynamic regime of tides and waves (HOFSTEDE, 2005). According to SPIEGEL (1997), a tidal energy input in the order of 2.2 thousand MW occurs in the Wadden Sea of Schleswig-Holstein with each flood phase. This energy input, combined with the energy impact of wind waves and storm surges, results in strong morphological processes. Outstanding are the high proportions of intertidal flats (57 %) and the 'Halligen'. These are isolated salt marsh islands in the Wadden Sea protected by low summer dikes and/or revetments. Most of them are inhabited with people living on dwelling mounds.

The history of colonization of the coastal marshlands started more than 2,000 years ago. With rising storm surge water levels, early settlers erected dwelling mounds on which they built their houses. A major change in human interference occurred at the turn of the first to the second millennium AD. At this time, farmers started to protect their cultivated land against flooding during (lower) summer storms by erecting low dikes. In the beginning, so-called "ring-dikes" were built around cultivated land. Soon afterwards, these isolated ring-

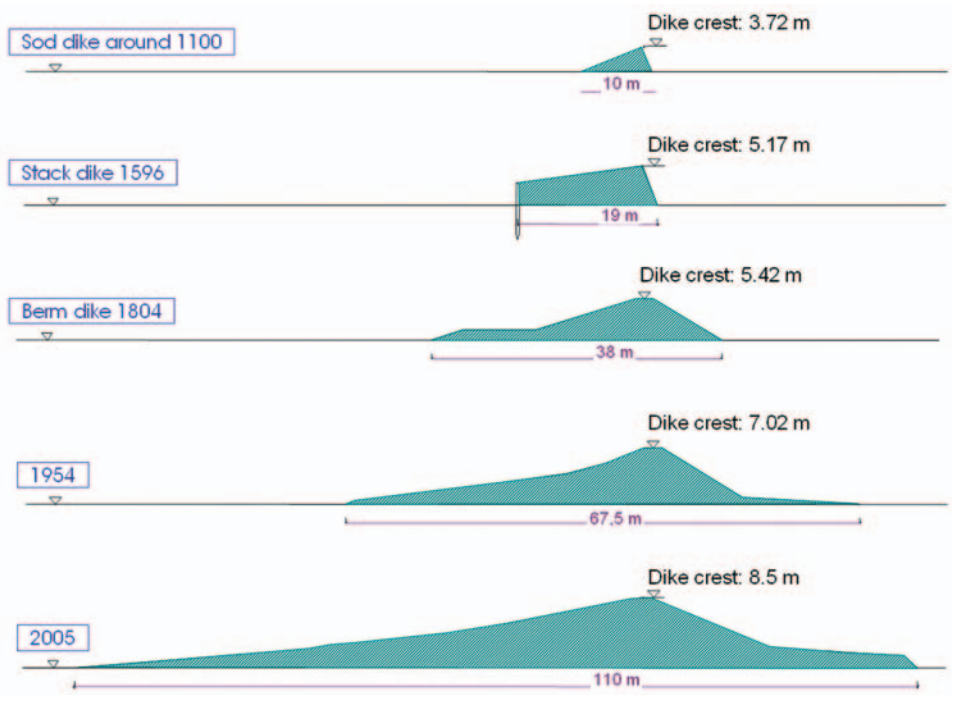


Fig. 2: Development of dikes in Schleswig-Holstein

dike systems were connected, and by the end of the 14th century, a more or less complete dike system protected the coastal marshes of the Wadden Sea. Due to the limited technical means, these early dikes were rather low and steep. Breaching of dikes frequently occurred. The following centuries were characterised by a continuous struggle of the local population against the sea. A number of catastrophic storm floods occurred in the Wadden Sea area (e.g. OOST, 1995). The greatest land loss resulted from the Second Marcellus Flood ("Erste große Mandränke") in 1362. Another catastrophic storm flood ("Zweite große Mandränke") with many fatalities occurred in 1634. During these events, thousands of people lost their lives and huge areas of marshland were permanently lost to the sea. The 'Halligen' emerged as remainders of these marshlands on the newly developed tidal flats. With increasing technical possibilities (Fig. 2), more and more salt marshes were reclaimed. Still, extreme storm surges occasionally caused the breaching of dikes, e.g. in 1717, 1825, and 1962. During the last catastrophic storm flood, in the year 1962, more than 300 people lost their lives in the greater Hamburg area.

As a result of this historical development, local population has attained a unique attitude towards their land and the sea *(trutz Blanker Hans)*. Consequently, modern coastal flood defence and coastal protection express the historically grown and justified desire of the inhabitants to protect their lives and properties from flooding and land loss. Today, the about 3,400 km$^2$ large coastal marshes are protected by a 408 km long dike line (364 km of state dikes and 44 km of regional dikes). In the protected area, more than 250,000 people live, and economic assets worth of 32 billion Euros are present (HOFSTEDE, 2004). About 2,000 km$^2$ of the coastal marshes are protected by a second dike line. The remaining area between the first and the second dike line is divided into 75 polders (Köge) by so-called middle dikes (Fig. 1). Each of these polders represents a closed 'flood unit'.

## 2. Modern Coastal Defence

### 2.1 Strategic Considerations

Under the impression of the 1962 storm flood catastrophe, in which more than 300 people lost their lives in Hamburg, the Schleswig-Holstein State Government adopted a master plan for coastal flood defence and coastal protection. It contained the technical and financial concept for improving the standards of protection in Schleswig-Holstein. The plan was updated in 1977 and 1986. One main goal was to reduce the danger of dike breaches by shortening the primary flood defence line, amongst others through the construction of tidal locks and barrages in four river mouths. Until 1986, the primary flood defence line along the west coast was reduced by about 207 km to a length of 364 km. In the year 2000, the new master plan "Integrated coastal defence management in Schleswig-Holstein" was prepared by the responsible administration (HOFSTEDE, 2004). After comprehensive public consultation, it was adopted in 2001 by the State Government. The master plan describes the midterm defence strategy and is based upon the principles of integrated coastal zone management (EUROPEAN COMMISSION, 2002). For the first time in Germany, it considers the possible consequences of anthropogenic climate change.

### 2.2 Measures and Design Parameters

Coastal flood defence and coastal protection along the North Sea coast of Schleswig-Holstein mainly consists of three techniques: (1) dikes, (2) salt marsh management techniques and (3) sand nourishment. These are described below.

**Dikes**

Dikes constitute the main coastal flood defence in Schleswig-Holstein. The marshlands are protected by an almost continuous 408 km long primary dike line (Fig. 1). About 364 km of these are so-called state dikes, the rest are regional dikes. In contrast to state dikes, regional dikes do not have fixed safety standards. The safety standard of a state dike includes a design water level, a design wave run up, and an extra safety margin of 50 cm to account for future sea level rise (Fig. 3). The design water level should meet three basic requirements (HOFSTEDE, 2004):

1) it should have a (statistical) return period of once in a century,
2) it should not be lower than the highest water level observed in the past (incl. sea level rise since than), and
3) it should not be lower than the sum of highest spring tide water level and highest observed wind set-up.

For the North Sea coast, the statistical value delivers the highest water level. In consequence, this value represents the respective design water level to which a design wave run up is added.

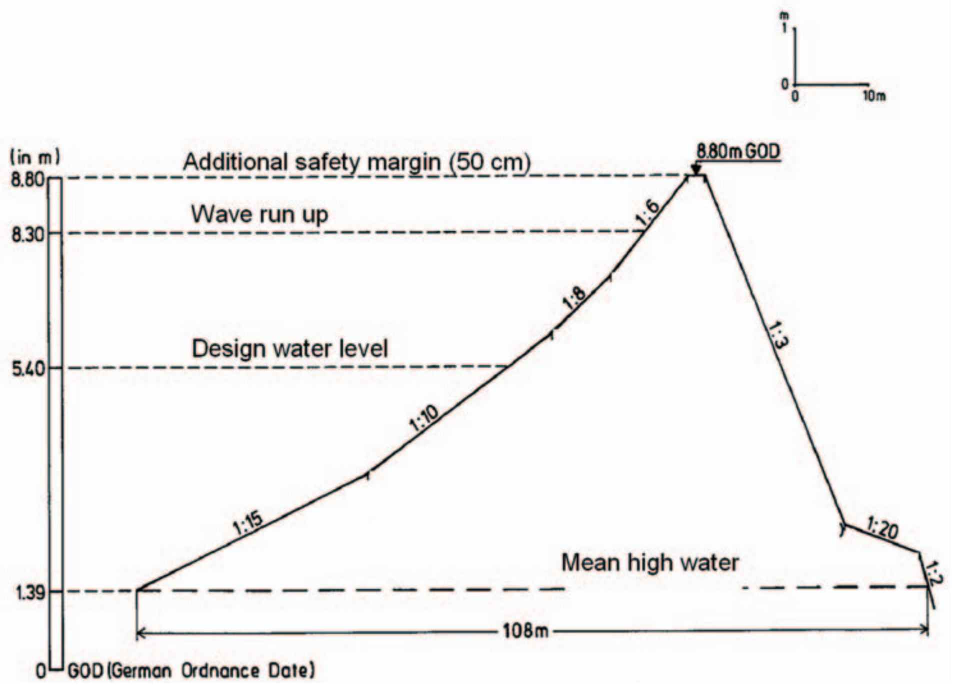


Fig. 3: Dimensions of a state dike (schematic)

With the establishment of the new coastal defence master plan, a safety check was conducted with localised values for water levels (based upon nearby tidal gauge stations) for more than 400 locations along the state dikes. Wave run up was calculated applying HUNT's formula adapted to local circumstances with empirical parameters (HUNT, 1959). If the dike is too low, wave overtopping occurs. In this case, overtopping amounts were determined using the method of VAN DER MEER (VAN DER MEER and JANSSEN, 1994). It is assumed that modern dikes are able to withstand an overflow of at least 2 l/m·s. If the calculated values exceeded this, the dike stretch was included in a priority list for dike strengthening. It turned out that, in all, 77 km of state dikes needed to be improved to meet the safety standard. From 2001 until the end of 2007, 30 km (40 %) have been enforced.

Behind the primary dike line, a 570 km long secondary dike line exists along the North Sea coast of Schleswig-Holstein (Fig. 1). These 'middle' dikes are usually older primary dikes that "shifted" into the second defence line after land reclamation. They still have a function in that they may limit the flooded area after a breach in the primary dike line occurs. The responsibility for these dikes lies with 'dike boards' (Deichverband). As with regional dikes, they do not have fixed safety standards.

On the Halligen (Fig. 4), a special form of regional dikes exists. These dikes only prevent summer floods, thereby allowing cattle grazing during summer. In winter, the 350 inhabitants on the Halligen depend on dwelling mounds for their protection. In 1962 and 1976, high storm surges caused significant damages and hazardous situations. As a consequence, all 32 inhabited dwelling mounds were strengthened between 1977 and 2007. Apart from a small ring dike around the houses, the outer slopes were flattened to reduce wave run up. Within the houses, finally, a "rescue room" was incorporated (Fig. 5). This room is deeply built into the dwelling mound, and rests independently from the house on four concrete piles. It is anticipated that, even if the whole house collapses during the surge, this one room will withstand the flood. Nevertheless, living on the Halligen remains a challenge, especially under possibly deteriorating conditions due to a climate change!

Fig. 4: Hallig Hooge

**Salt marsh management techniques**

Significant expenditures in coastal defence arise from salt marsh management techniques. With respect to coastal defence, salt marshes in front of dikes are, in the first place, a method to move the energy impact of storm waves from the dikes towards the outer edge of the salt marshes. Furthermore, after dike-breaching, a salt marsh can prevent the development and growth of a scour hole. It is also a source of material for dike repairs. Finally, it prevents damage at the seaward dike toe through tidal gullies migrating towards the dike. Thus, it could make the building of expensive slope revetments and groins superfluous. In recognition of these functions, the establishment and maintenance of salt marshes in front of dikes is a public obligation. At the same time, salt marshes have a high ecological value and are protected under the State Nature Protection Act. In 1995, the Coastal Defence and Environmental Administration, together with local water boards, adopted a salt marsh management concept to integrate both functions (HOFSTEDE, 2003). The results of management based on this concept are regularly evaluated by a technical board, working on principles of an Integrated Coastal Zone Management-ICZM'. The board consists of members from coastal defence and nature protection authorities together with representatives from local dike boards, NGOs and the municipalities. The success of the concept is demonstrated by the fact that, despite sea level rise, the salt marsh area in the Schleswig-Holstein sector of the Wadden Sea increased by about 16 % from 1995 to 2005.

The oldest technique to enhance salt marsh growth is the drainage of the salt marsh surface along with a narrow strip of the adjoining mud flat. With this reclamation technique, the aerated zone is shifted to a lower level in relation to mean high water, resulting in a horizontal extension of the salt marsh vegetation (DIJKEMA et al., 1990). In order to function, the

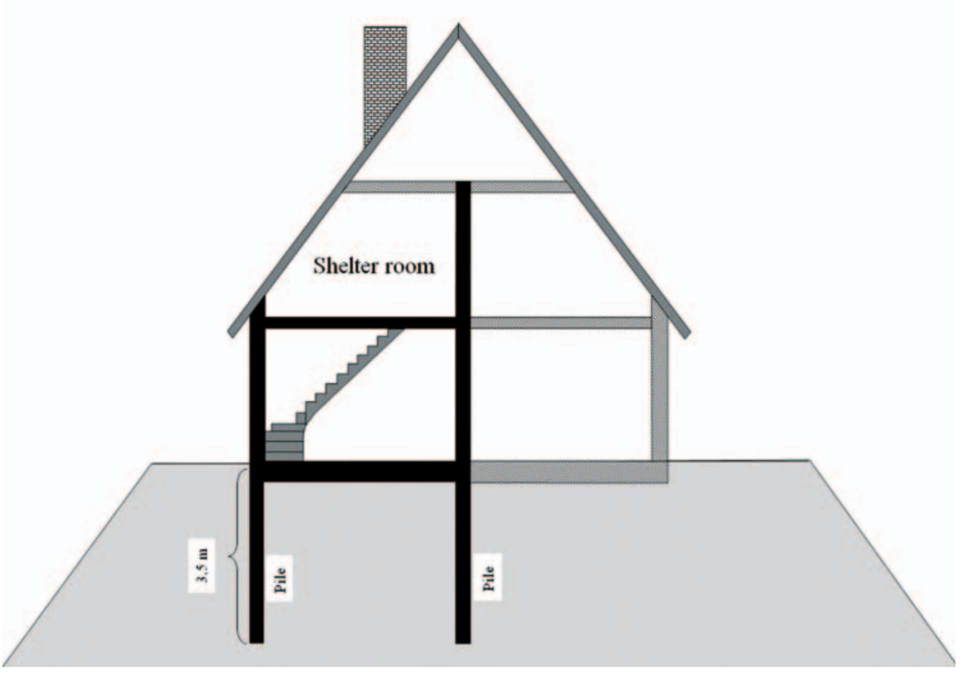


Fig. 5: Flood proof room in houses on the Halligen

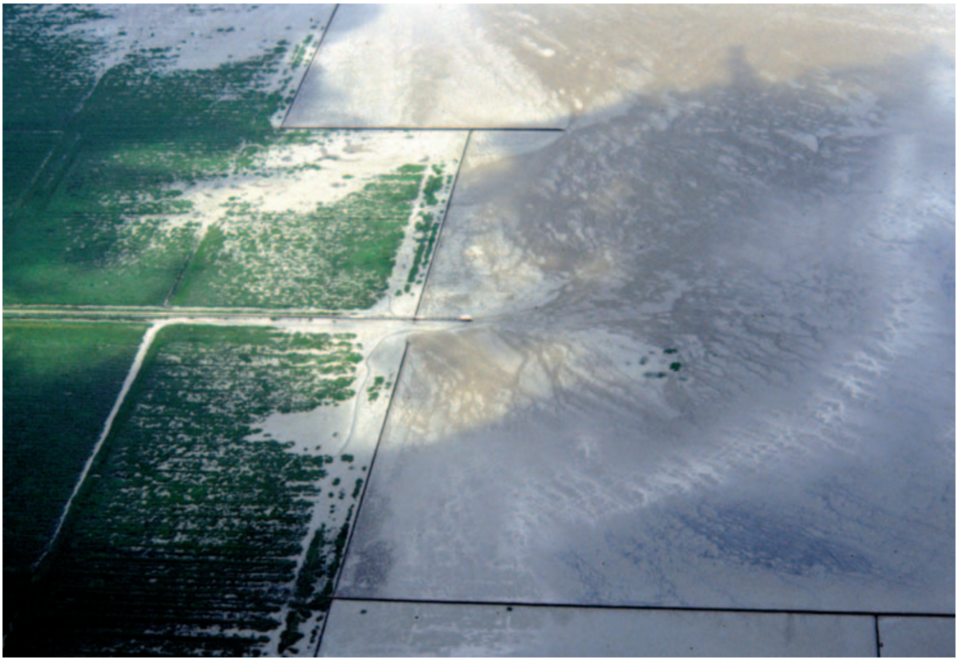

Fig. 6: Salt marsh protected by groin fields

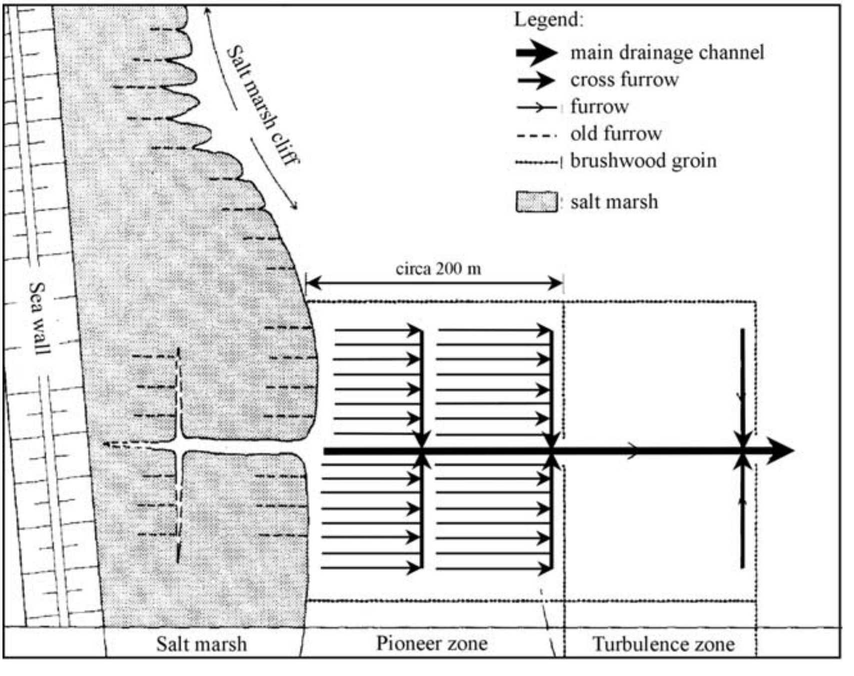


Fig. 7: Echelon system of salt marsh management

drainage needs to be cleaned on a regular basis. Another old technique is the building of brushwood groins in front of salt marshes. With this technique, wave and tidal energy, the most critical factors in salt marsh formation, are reduced significantly. As a result, sedimentation of suspended matter behind the groins and in front of the salt marsh edge is enhanced. The positive effect of the brushwood groins upon salt marsh growth is demonstrated (Fig. 6). A combination of both techniques, the so-called „Schleswig-Holstein Method“, was introduced by the Prussian government in 1900. It consists of brushwood groin fields with a size of about 200 x 200 m combined with a drainage system. The presently applied echelon system in salt marshes, as shown in Fig. 7, is based upon this Prussian method. In the turbulence zone, tidal and wave energy within the water column are reduced. Within the accretion zone, deposition of suspended matter reaches its maximum thereby stabilising the salt marsh zone (HOFSTEDE, 2003).

## Sand nourishment

Sand nourishment at the islands of Sylt and Föhr constitutes the third main aspect of the coastal defence strategy along the West coast of Schleswig-Holstein (Fig. 8). Since 1963, more than 40 million m³ of sand have been deposited at the beaches of these two islands (Sylt 37, Föhr 3.3 million m³). With this sand, shoreline retreat could be halted. Comprehensive investigations demonstrate that this technique, the results of which are sometimes questioned, is most effective for technical as well as economic and environmental reasons. For example, the application of nourishments may make ‘hard’ coastal protection structures, which can cause negative side effects such as lee-erosion, superfluous. Hence, both islands are stabilised in a sustainable manner.

Fig 8: Sand nourishment on the isle of Sylt

Traditionally, the sand is deposited directly on the dry beaches (Fig. 8). Because of the technical equipment needed, this represents a relatively expensive method to balance coastal erosion. Furthermore, although the retreat of the shoreline can be halted, the evolution of the entire coastal profile may remain negative, causing coastal profile steepening. As a consequence, higher waves may approach the beach, inducing stronger coastal erosion during storm surges. Sediment budget analyses indicate that this was the case in front of Sylt. Hence, in 2006, major foreshore nourishment was conducted. About 850,000 $m^3$ of sand were dumped directly on the outer reef. In this way, about 150,000 $m^3$ of sand more could be deposited without extra costs. A monitoring program is under way to evaluate the effect of this technique that is already routinely being applied in Denmark and the Netherlands.

## 3. Outlook

About 47 km of the State dikes along the North Sea coast of Schleswig-Holstein still need to be strengthened in order to meet the safety standards as described in the master plan coastal defence. In 2007, the 'International Panel on Climatic Change – IPCC' published its fourth report on future climate change (IPCC, 2007). Although within the range of sea level rise scenarios the expected increase was slightly diminished (18 to 59 cm until 2100), significant uncertainties remained, concerning e.g. an accelerated melting of the Greenland ice cap. However, even if the Greenland ice cap melted faster than expected, the safety margin of 50 cm adopted in the master plan would be valued as being high enough. It is concluded that the situation is (still) serious, but no adaptations to the present strategy are necessary. With respect to climatic change and increasing utilization of the coastal zones, the master plan states that coastal flood defence will never end!

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# Coastal Protection at the North and Baltic Sea: Helgoland Island

By Klaus Bednarczyk, Anne Heeling, Detlef Schaller
and Ulrich Vierfuss

Contents



## 1. Introduction

Helgoland (Fig. 1) is located approximately 60 km north-west of the Elbe mouth in the German Bight of the North Sea. Thus, it is the German island most remote from the coast. If viewed from the West in particular, its towering red rocky shore offers a unique and prominent appearance in the German Bight. Surrounding water depths are between 20 and 40 m.

The new red sandstone (bunter) core of the main island – up to 60 m high – has been enlarged by numerous harbour structures and artificially created land areas amounting to an overall length of approx. 2,200 m and a width of 800 m. Separated from the mainland by an 800 m wide roadstead, the sand island Düne ('dune') is protected by jetties and groynes.

Due to the law for the German coast, coastal protection is the responsibility of the federal state of Schleswig-Holstein, represented by the State Agency for Coastal Protection, National Park and Marine Conservation (LKN) in Husum. However, according to the Federal Waterways Act (Bundeswasserstraßengesetz) the preservation and maintenance of the main island's base is a federal obligation looked after by the regional authority (WSA Tönning) of the Federal Administration of Waterways and Navigation (Wasser- und Schifffahrtsverwaltung, WSV).

The evolution of the island of Helgoland and Düne is inextricably coupled with harbour construction. Thus, in the following, the history of harbour development on Helgoland has to be mentioned, too.

In these days, the main source of income of the approx. 1,500 inhabitants of the island is tourism. Because of the exposed location of the island, the secure protective harbour is most important for marine traffic safety in the surrounding waters. During the summer months, it is mainly frequented by pleasure craft. In addition, search and rescue as well as pollution control and marine disaster prevention units have an important base on the island.

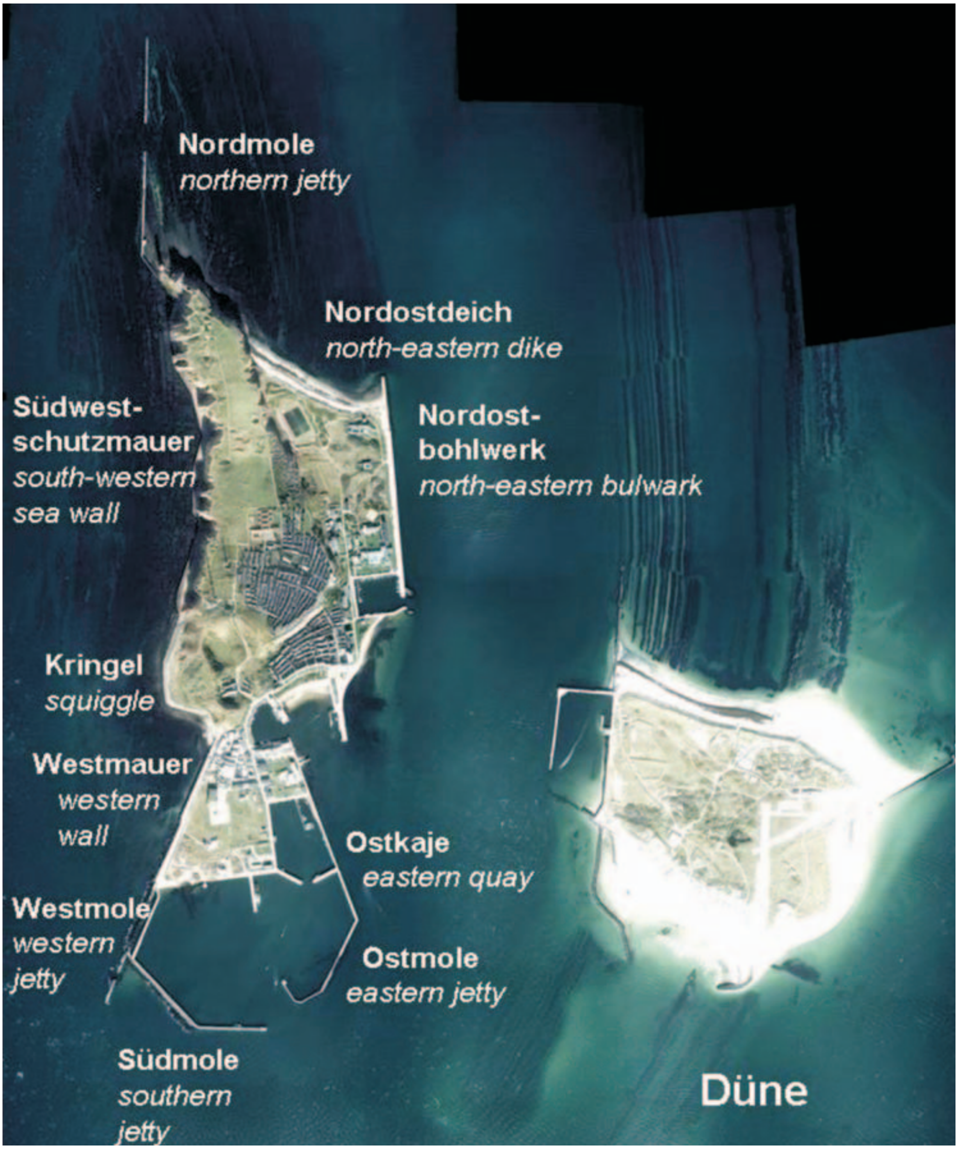


Fig. 1: The island of Helgoland and Düne ('dune') (aerial photograph © AWI, 2003)

## 2. Geology

The geological history of Helgoland starts in the Upper Permian (Zechstein) approx. 255 Mio. years ago. In an arid climate, enormous salt deposits were generated by repeated evaporation over a shallow inland lake. At that time, the present Northern Germany was located close to the equator and – as a consequence of the continental drift – migrated towards its present position only during the further course of history.

The intrinsic bedrock genesis started in the Upper Trias (Buntsandstein) some 250 Mio. years ago. Helgoland could be found at the western edge of the 'Germanisches Becken' (Germanic Basin), a long-stretched depression which extended to the present river Weichsel in the East. Coming from the southern elevated plains, immense quantities of debris (conglomerates, sandstone and mudstone) were transported by rivers and deposited in the depression. Today, these layers have a thickness of approx. 1,000 m. Fossils and fossil sediment structures (ripple marks, dry desiccation crevices, and rain drop impressions) indicate that layers were deposited while water depths varied. The red colouration of the Helgoland rock is typical for a desert-like climate and was created by iron oxide coating the sand grains as a matrix. In some locations this binding agent is missing, and white unconsolidated layers occur. In former times, this material was used by the inhabitants of Helgoland to cover the floors of their houses (Katen). Thus, it was named 'Katersand'.

During the middle Trias (Muschelkalk) the Germanische Becken turned into a shallow sea. The red desert sediments of the Buntsandstein were covered with a 300 m layer of fossil-rich grey limestone and gypsum. Even 250 years ago, the 'Wittekliff', made of Muschelkalk material, protruded about 60 m above the water surface in front of the Düne island. Muschelkalk sediments are still the base of Düne.

No depositions of Keuper, i.e. the Upper Trias, of the entire Jurassic and of Tertiary can be found in the stratigraphic sequence of Helgoland. This is possibly already an indication of the beginning of salt tectonics. In Northern Germany, the Triassic sediments – overlaid by younger layers – can normally be found in depths of several thousand metres. Only at Helgoland, they break the surface. During Cretaceous and Tertiary, the Permian salt was mobilized – due to its lesser density – under the weight of younger sediments. The salt layers became ductile, started to rise along weaker areas and lift and tilt the covering layers.

Helgoland is at the apex of such a salt dome which surfaced in the region of the submarine basin 'Görtel' approx. 1.5 km south of the island. Today, however, it is covered by a cap consisting of leaching material. From that point the rock material of Helgoland slopes down at an angle of 20° towards the East (Fig. 2). Some of the primordial layers were eroded following the lifting process: thus, the Muschelkalk sediments are directly followed by Cretaceous layers. This is a gap in the stratigraphic sequence representing a period of approx. 100 Mio. years.

The Cretaceous layers consist solely of marine sediments. Initially, approx. 40 m of ossil-rich dark clays and marl were deposited in the Lower Cretaceous. From this period come the so-called 'Katzenpfötchen' (cat's paws) which are petrified shell segments of ammo-

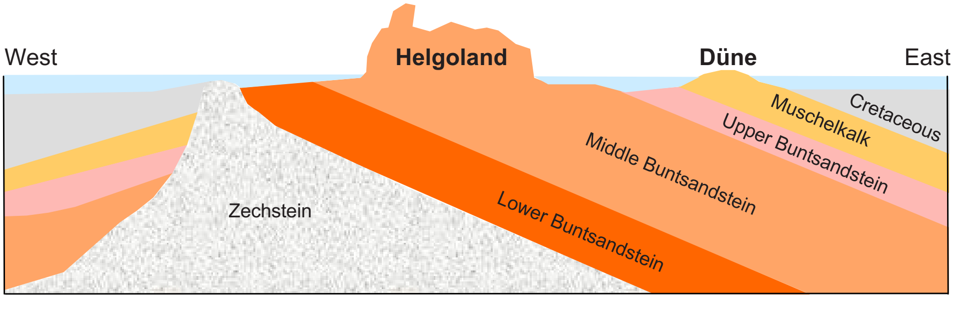


Fig. 2: Schematics of the geological structure of Helgoland (after SCHMIDTKE, 1995)

nites as well as 'Donnerkeile' (thunderbolts) which are petrified internal shells of belemnites and can be found along the shores of the Düne. On top of this, a layer of 1 m dark bituminous marl, which is rich in fossil fish and ammonites, is found: in Helgoland dialect it is called 'Kreide-Töck' (chalk-mist). The 260 m layer of Upper Cretaceous Schreibkreide (chalkstone) with intermediate layers of flint stone (remnants of diatoms) constitutes the outer eastern cliff elbow. Its red flint stones cannot be found in any other place around the world.

1.8 Mio. years ago at the start of Pleistocene, the older Quaternary, the area of Helgoland consists of mainland mountains which were covered by glaciers during the Elster as well as the Saale glacial period. This is also indicated by till from the Saale glacial period on the island top. Between 1945 and 1947, this material was largely blasted away or moved by British bombs. Following the Elster and Saale glacial periods during the Eem interglacial, Helgoland was either part of the mainland or a large wooded island with a formation of peat and limnic sediments in small depressions – the so-called 'Süßwasser-Töck'. After this period, the ice never reached Helgoland again.

The development towards the island as it is known today started with the melting of the glaciers some 10,000 years ago and the sea level in the North Sea region rising by approx. 100 m: Helgoland became an island. Today, the island is still subjected to erosion by wind and waves. The development of ledges ('Hörner') and promontories with bays ('Slaps') in between is characteristic of Helgoland. Those promontories can be ruptured by surf action to form arcs ('surf gates'). If these collapse rock towers ('Stacks') remain: the landmark of Helgoland 'Lange Anna' is such a Stack.

## 3. Historical Events

### 3.1 Events till 1890

Earliest traces of civilization (burial mounds) on Helgoland date back to the New Stone Age or Neolithic. Contemporary documents prove that Helgoland was occupied by Frisians in the 7th century. Between the 12th and 15th century, the island was under the influence of the Danish crown and became part of the duchy of Schleswig.

During this time, the main island was connected with the 'Wittekliff' by a sand spit, the 'Woal' (Fig. 3). Since medieval times, shell-limestone and gypsum had been mined on this cliff. This exploitation contributed to its rapid destruction up to a point of instability; it collapsed during the storm surge of 1711. Shortly afterwards, the 'Woal' disappeared as well. On top of the remaining cliff, the present Düne developed. The sand island is important for today's beach activities.

After Helgoland had been occupied by British troops and incorporated as a colony of the United Kingdom in 1807 the seaside resort was established in 1826. Increasing building activity on the lowlands 'Unterland' forced the people of Helgoland to carry out shore protection measures. Several construction methods were tested: vertical or inclined wooden bulwarks, bulwark racks, palisade structures and rack-trestle structures similar to a prototype developed in England. Until the end of the 19th century, the western island shore remained unprotected, and a substantial loss of land had to be registered every year.

Fig. 3: The island of Helgoland with the 'Wittekliff' and 'Woal' in the 17th century
(map by Johannes Mejer, 1694)

### 3.2 Between 1890 and Today

In 1890 Great Britain relinquished the ownership of the island to the German Empire in exchange of rights in Africa (so-called Helgoland – Zanzibar – Treaty). The emperor Wilhelm II had Helgoland turned into a navy base. Now, shore protection measures at the western part of the island were accelerated since in many places the unsecured rock cliffs threatened to collapse onto the gun emplacements, underground shelters and bunkers. Consequently, in 1903, the construction of the protective south-west beach wall began with the last gap closed in 1927. South of the rock island, the naval port with new harbour facilities and large jetties was established (Fig. 4).

During WWI, the island and the port were spared any destruction. Only due to the Versailles Treaty, military installations together with the jetties had to be blown up or stripped down. However, because of the insufficient shelter for marine traffic and for the sake of the island itself protection measures and the rebuilding of the western jetty started already in 1928.

During WWII, the 'fortress on the high seas' was considered to be of great military importance. Planning reached a climax with the harbour project 'lobster claw (Hummerschere)' triggering the construction of additional jetties and the present north-east area (Fig. 5). This project, including island and Düne, was to turn Helgoland into one of the largest ice-free harbours of Europe. Consequently, extensive beach nourishments for enlargement of the area of the Düne and the construction of embankments towards the North began. Within this project, the Düne harbour on the eastern shore of the Düne was built (1938–1941).

However, during WWII, the real military importance of the island proved to be marginal. In spite of that, the British Air Force carried out a devastating air raid on the island on April 18, 1945: 1,000 British aircraft dropped approx. 7,000 bombs within a period of 2 hours.


Fig. 4: Development of Helgoland (main island) since 1890 (after KRUMBEIN, 1975)

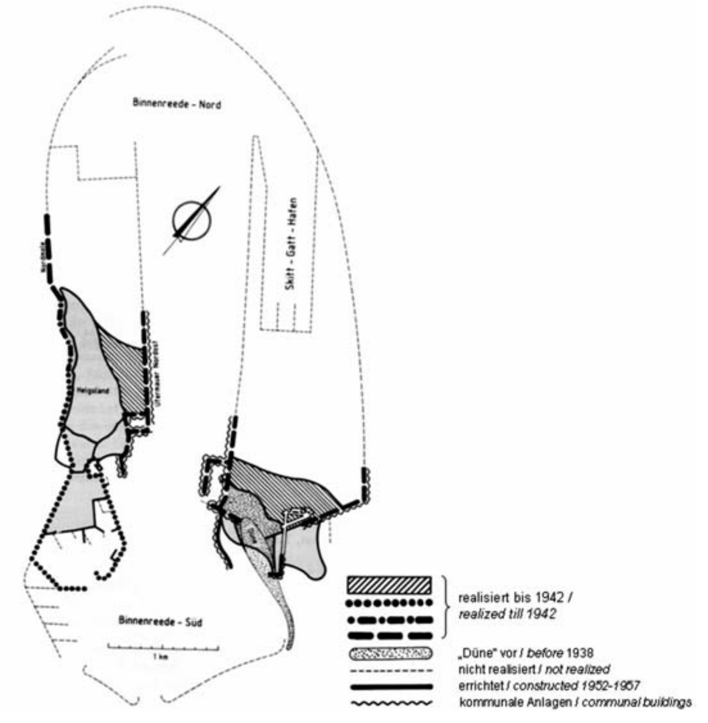


Fig. 5: Design of the mega-port 'Lobster Claw (Hummerschere)' and the realized structures (SCHINDLER and LINDEMANN, 1990)

Afterwards, the island was uninhabitable and had to be evacuated. In the following years, the island was used as a bombing target range for the British Air Force.

Two years later on April 18, 1947, a major blasting was to destroy all military installations as well as old ammunition stores in order to prevent any future military utilization of Helgoland (the greatest non-nuclear blast of history till today). The ignition of approx. 6,700 t of ammunition rocked the island down to its base at a depth of several kilometres and led to a lasting modification of its appearance.

Only on March 1, 1952, Helgoland was returned by Great Britain to the Federal Republic of Germany. The population was permitted to return to their island. Since rebuilding, the livelihood of the people of Helgoland is based on tourism and resort activities. In 1962, the island was given the official status of a North Sea Resort (Nordseeheilbad).

### 3.3 Development of Düne

In 1721, the history of Düne being an independent island begins by its separation from the main island. The breaching of the sand spit 'Woal' (Fig. 3) triggered the generation of a gully which became deeper and wider. The size of the main body of Düne decreased during the course of the centuries, and it assumed a spindle shape (Fig. 6). At its eastern end, a long-stretched flat sand and rubble spit developed. This so-called 'Aade' was continuously modified by waves and currents.

The progressing erosion of Düne had not been paid any attention. Only when – after the establishment of the sea resort – its sandy beaches became attractive for swimming and sun-bathing in 1826, people started to worry about the development. Towards the middle of the 19$^{th}$ century, double-pile tiers packed with brushwork were installed perpendicularly to the shoreline. These were only sand traps and were not capable to act as breakwaters. Thus, the area of the island above NN + 5 m was further reduced by wave action. As an example, the island's size decreased from 4.4 to 1.5 ha during the storm surge of 1894.

Based on a suggestion of Ludwig Franzius, the famous German pioneer of river engineering, a star-shaped system of groynes was built starting in 1896. The eight groynes with a length of up to 400 m and head elevations of 3–4 m below MLW were to trap the sand migrating around the Düne. However, because of the low elevation of the structures, surf-induced currents were not influenced, and wave action eroded the sediment and uncovered the groynes. Yet, the erosion of the Düne was somewhat delayed since the development of beach parallel gullies could be prevented (BAHR, 1938).

The construction of the naval port on the main island (1908–1916) provided substantial protection of Düne against waves from the South-west. Sediment dynamics were distinctly dampened, but considerable beach erosion was still recorded. However, considerations and efforts to find a solution were finally surpassed by the start of the (today unfinished) project 'Lobster Claw'. The Düne was expanded by nourishments to 3–4 times its original size. A harbour was built at its western shore, the northern jetty and the eastern dune-dam were established (Fig. 5). After the return of Helgoland to the German government in 1952, an extensive survey of Düne was carried out, followed by a hydrographical survey of the surrounding waters in 1954. Until today, the results of this survey are the basis for the evaluation of the morphological evolution of Düne. Another comprehensive survey was carried out in 1982, triggered by the severe storm surge of Nov. 11, 1981.

The development of Düne during the 30 years between those surveys was mainly characterized by a receding beach and dune erosion at the southern beach, a shortening and flat-

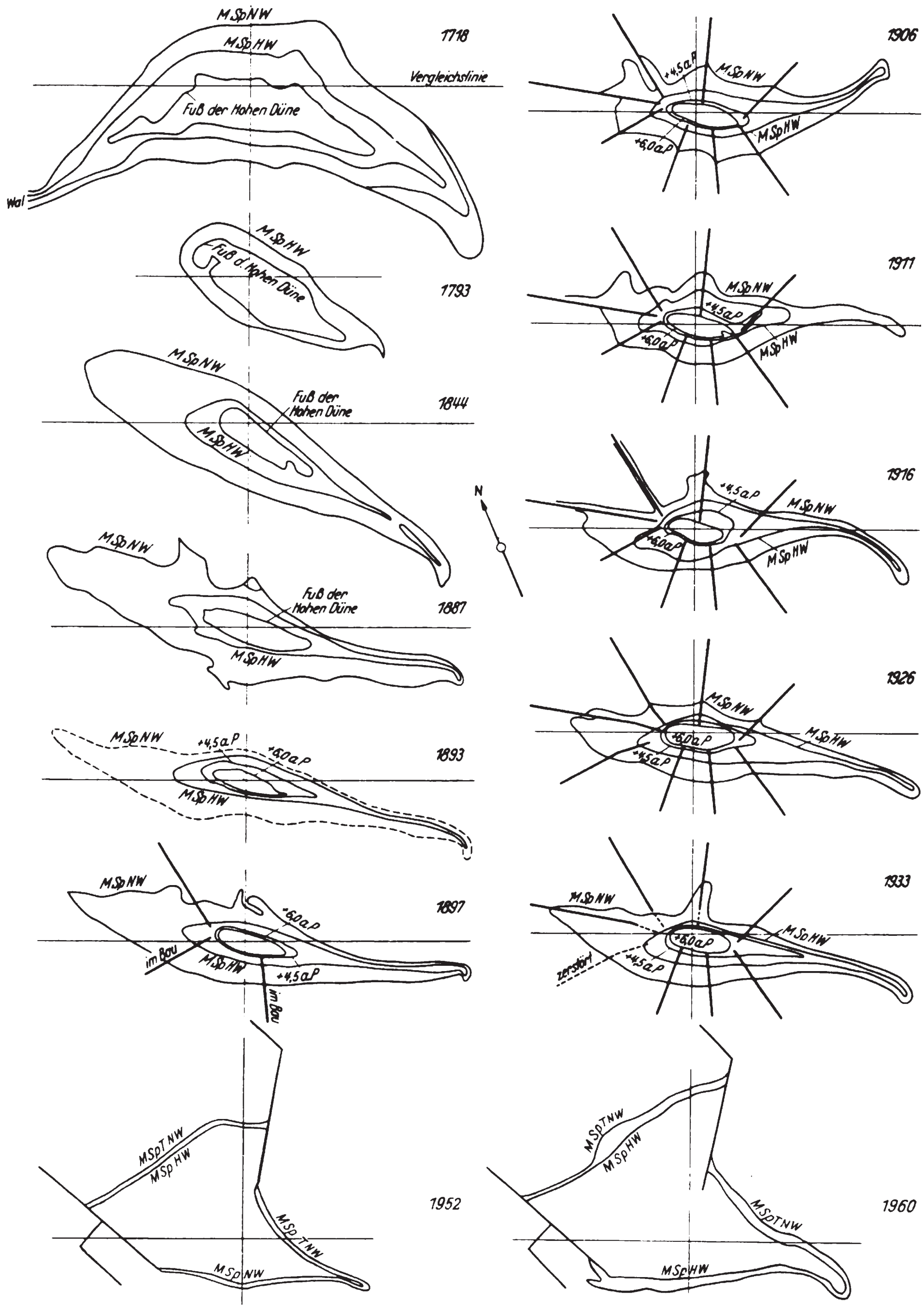


Fig. 6: Development of Düne (Spaeth, 1990)

tening of the spit 'Aade' in the South-east and a widening of the eastern beach. The northern beach remained fairly stable (FÜHRBÖTER and DETTE, 1986). The construction of the embankment dam west, built of Tetrapodes in the South-west in 1964, had a significant influence. This structure was extended to 610 m till 1976 and was accompanied by beach nourishment measures dumping approx. 240,000 m³ in 1974.

In 1979, with the receding beach front at the eastern part of the southern beach, the HW-line moved to the immediate vicinity of the runway of the little airport, resulting in a scour at the runway head. Among others, this led to a concept for the protection of the southern side of Düne and the runway. For this purpose, a 60 m Tetrapode groyne was built in early 1983 and extended to 234 m in 1987. This hooked groyne was the counterpart to the embankment dam mentioned above. The result was an increased sand deposition and the evolution of a bay ideal for swimming. This bay has been stable until now (Fig. 7).

The latest morphological development of Düne (1999–2007) is based on terrestrial surveys of the northern beach and laser-scan records from aerial surveys. They show that approx. 22,000 m³ of sand were lost at the northern beach; on the eastern beach approx. 8,000 m³ accumulated. Major erosion had to be recorded at the northern beach due to the low pressure storm system 'Tilo' (Nov. 9, 2007)


Fig. 7: The Düne of Helgoland (aerial photograph of Nov. 14, 2007)

## 4. Hydrological Parameters, Design Water Levels

Water level recordings and measurements of currents and waves are the basis for these parameters. The first water level measurements at the tide gauge on Helgoland were carried out and recorded in September 1880. After changing its location several times, the gauge has been at its current position (Fig. 1) since Nov. 1, 1961. Time series of water levels include gaps, particularly for HW, between 1911 and 1952 and during war times. Since 1952, water levels have been continuously recorded, analyzed and published in the Hydrological Year Book (Deutsches Gewässerkundliches Jahrbuch) for the North and Baltic Sea coast (ROHDE, 1990). While the annual means for the time series 1996–2005 show a HW = NN + 1.16 m, LW = NN – 1.23 m and a tidal range of 2.39 m the highest recorded storm surge at the gauge Helgoland was at NN + 3.87 m on Feb. 16, 1962. Other major storms occurred in Jan. 1976, Feb. 1990 and Nov. 1982.

Based on the 'general arrangement plan for coastal protection in Schleswig-Holstein (Generalplan Küstenschutz S-H)' of 2001, the reference water level for 2010 is at NN + 4.30 m, and the design water level 2100 is at NN + 4.50 m (MLR, 2001). In addition to the highest water level, the maximum wind set-up occurring with storm surges is important for the design of structures for coastal and flood protection. Investigations into storm surges and wind set-up in the German Bight show a maximum set-up of 3.30 m with a forward slope of 5.5 h/m. This characteristic curve can occur at HW and, therefore, be a component of a severe storm surge (GÖNNERT, 2003).

Due to its exposed location in the open North Sea, the island of Helgoland is particularly prone to wave action. During the storm surge of Jan. 28, 1994, significant wave heights of up to 6.8 m were recorded. In a research project conducted by the Federal Waterways Engineering and Research Institute (Bundesanstalt für Wasserbau, BAW), the standard wave parameters for the waters around Helgoland were determined (VIERFUSS, 2002) based on results of a comprehensive hind-cast (GKSS Research Centre) of the years 1955 to 1994. The highest significant waves can occur from WSW to NW with heights between 7 and 8 m (return interval 100 years). Wave dissipation on the rock base of the island (Felswatt) was taken into account according to the various locations of the considered structures. For the examination of the stability and structural safety of the jetties, design wave heights of up to 9.50 m with a return interval of 100 years were assumed. The functional design and dimensioning of the northern Düne embankments was carried out with the support of suitable model investigations with boundary waves coming from NW. In addition, system analyses in a 2-D current model supported determining the optimal length of the dams.

## 5. Coastal Protection Strategies and Structures

### 5.1 North-Eastern Dike and Bulwark

The obligatory coastal protection activities of Schleswig-Holstein cover the main island as well as the Düne if danger of flooding of populated areas is involved. Towards the end of the 1930s, the construction of the north-eastern bulwark made possible the raising of the north-eastern terrain by hydraulic deposition up to the rock base and the planned utilization of the newly established area. The 950 m long dike had been built from the cliff edge of the 'Oberland' to the north-eastern harbour to protect the rear area against flooding. On this terrain, important infrastructure installations such as the power station, the desalination plant, the health resort treatment facilities, the seawater pool, the sports field and a student dormitory are located.

Based on the amendment of the water laws (Wassergesetz, 1992) of Schleswig-Holstein, the north-eastern dike behind the north-eastern bulwark and the adjacent stretch joining the 'Oberland' obtained the highest status of a flood protection structure (Landesschutzdeich). Now, its average crown elevation is at NN + 5.90 m on its entire length. The reference water level 2010 for safety inspection purposes is at NN + 4.30 m (MLR, 2001). Dimensioning of this dike was done based on small-scale physical model studies to obtain the run-up height for the complex slope profiles, which are being influenced by the north-eastern bulwark, a wide shore promenade and the dike itself (Schüttrumpf et al., 1997).

The north-eastern bulwark had been fundamentally renovated in the years from 1978 to 1980. In front of the old gabion construction, a new wall of steel girders with suspended prefabricated concrete elements had been erected. A curtain of concrete foundation piles drilled into the bunter was to prevent scouring and secure the sand filled in between the old and new structure. The northern sloped cofferdam adjacent to the bulwark was armoured with 8t Dolosse (Schindler and Lindemann, 1990).

Following the upgrading of the north-eastern bulwark, the north-eastern harbour – adjacent towards the South – was improved. Its quay walls protect the near-harbour buildings and – to the North – safeguard the underground freshwater bubble. On top of the existing quay a flood retention wall with a crown elevation of NN + 4.85 m for the protection of the adjacent terrain was built.

### 5.2 South-Western Sea Wall

The most vital structure to protect the island base is the south-western sea wall – also called the Prussian wall (Preußenmauer ) – which is being maintained by WSA Tönning. It protects the rock walls and prevents wave-induced erosion processes (generation of surf grooving, surf portals and 'Stacks') at the strongly attacked western shore of the island. Moreover, it is to collect debris which is continuously generated by rain, spray, frost and wind and drops from above. Initially, this material was thought to adjust itself to form a naturally flat slope which would eventually be covered by natural growth and protect the bunter against further erosion. However wave action prevented this. Particularly during storm surges the erosion by wave overtopping is so strong that rubble and debris are carried away. Thus, the south-western wall only protects against direct wave attack.

The sea wall was erected using a combination of concrete blocks, poured concrete and a covering of natural stone blocks between 1903 and 1913 and between 1926 and 1927. It was substantially damaged by bombs during and after WWII and reconstructed in concrete between 1960 and 1963. The average crown elevation is at approx. HW + 3.50 m, and the toe of the rock slope in front of the wall is close to LW. Towards the North, the south-western sea wall merges into the northern jetty. South of the 'Kringel', which was generated by the blasting in 1947, it continues to cross over into the shore protection and jetty structures of the secure protective harbour.

Fig. 8: View of the cliff coast and a part of the south-western sea wall
(Photo: H. J. Bennöhr, 2005, Wikipedia Commons)

### 5.3 Northern Jetty

The northern jetty – also called the Island Dam North (Inseldamm Nord) – was built as part of the naval port project in 1940. As a continuation of the south-western beach wall, it extends into open water. Even though, the jetty remained a fragment. Today, the 550 m section connected with the south-western wall is followed by a gap – left for operational reasons – and another 350 m section. The jetty provides some protection for the rock terrace and the North shore against waves from westerly directions. However, the protected area is relatively small.

### 5.4 Secure Protective Harbour

The former naval port serves as a secure protective harbour (harbour of refuge) today. Even though it was never intended to be a coastal protection structure, it contributes with its outer jetties and reinforced embankments that extend the island southward to the protection of main island and Düne. The outer protective ring of the harbour is composed of the western wall, western and southern jetty, eastern jetty and quay (Fig. 1). Because of their ever-changing history of destruction and re-construction these are made up of partially very old building fabric needing substantial corrective maintenance today. Further information can be found in the relevant literature (e.g. THIEMANN, 1990; RÖBEN, 1990).

Fig. 9: View of the northern jetty and the rocky foreshore (Felswatt) north of the main island (Photo: TomCatX, 2007, Wikipedia Commons)

### 5.5 Protection of Düne

The coastal protection concept for Düne integrates all older jetties built for harbour projects and recent protective dams (cf. 3 – Historical events). The dune dams West and East – relics of the 'Lobster Claw' (Fig. 5 ) – border the northern beach and were upgraded between 2005 and 2007 to secure the island base effectively. For this purpose, Tetrapodes (single weight 6 t) taken from a dismantled revetment on the island of Sylt were used to strengthen and complement the western face of the dune dam West. The eastern side and the dune dam East were strengthened with natural granite blocks (3–6 t) placed on a doubled geo-membrane.

The counterparts of these structures at the southern side are the Tetrapode dam (1965–1974 ) and the hooked groyne (1983–1987; cf. Fig. 7). Finally, the dune harbour was protected by a new southern jetty and an offshore breakwater against wave impact. Moreover, these structures are to prevent the penetration of sediment. The harbour is an integral part of the protection of Düne.

## 6. Future Development and Research

Coastal protection on the island of Helgoland is predominantly determined by the preservation and maintenance of the sandy beaches of Düne. This requires a regular evaluation of the availability of sand at the beach, at the Düne itself and on the foreshore by means of a measurement and monitoring program. The external forces such as water levels, currents and waves are measured at representative points of a grid. The spatial distribution of these parameters is calculated using empirical formulae or numerical models.

Morphological changes of the foreshore area and of the sandy coastlines are monitored based on hydrographical, terrestrial and laser-scanning surveys supported by aerial photographs (Ortho-photos). Furthermore, terrestrial survey is used to record the actual status, changes or new additions of all coastal protection structures (dikes, revetments, bush dams etc.). The information is stored and made available in the Coastal Protection Information System (KIS) of Schleswig-Holstein.

While continuous water level data from the tidal gauge 'Helgoland' are at hand (chapter 4), measurements of waves close to the island are carried out by the Federal Maritime Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH) and data can be used as input to numerical models. These have been increasingly applied for preliminary investigations and planning during the past few years. Generally, the well-known wave model SWAN for wave investigations and various tidal 2D- or 3D-models are available to authorities or consultants. Even though several morphodynamic models have been applied to similar problems, there is still a considerable need for research and development concerning the evaluation of evolution of sandy coastlines.

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# Coastal Flood Defence and Coastal Protection along the North Sea Coast of Niedersachsen

By FRANK THORENZ

Contents



## 1. Introduction

The German Federal State of Lower Saxony (Niedersachsen) is located in north-western Germany. It is bordered in the North-west by the North Sea, in the West by the Netherlands and in the North-east by the Elbe River and the federal states of Schleswig-Holstein and Hamburg. It covers 47,625 km² with a population of 7,971,684 (Dec. 31, 2007).

The North Sea coast of Niedersachsen is lined by low lying marshlands of a width between 5 to 30 km, extending also far inland along the estuaries of Ems, Weser and Elbe and their tributaries. During the Holocene transgression, these marshlands developed by sedimentation of fine fluvial- and marine sediments and intermediate peat layers on a Pleistocene basis (STREIF, 1990). The elevation of these areas lies mainly from about NN –0.5 m to NN +1.4 m (NN = approx. mean sea level –MSL). The lowest point is located near the city of Emden with an elevation of NN –2.5 m.

About 6,600 km², 14 % of the total state area with a population of 1.2 million is prone to flooding during storm surges and is protected by coastal flood defences. Without these defences, significant parts of the coastal area would be flooded even during a normal high tide (Fig. 3).

In front of the mainland coast of Niedersachsen, the seven inhabited Eastfriasian islands are located. These sandy barrier islands, consisting mainly of dunes in the North and salt marshes in the South, are part of the Wadden Sea, which stretches from the Netherlands to Denmark. With a tidal range from about 2 to 4 m, the Wadden Sea can be classified as a mixed energy / tide-dominated tidal flat area (HAYES, 1979). Antecessors of the barrier islands are more than 2000 years old and developed during the postglacial sea level rise (STREIF, 1990). In this system consisting of islands, tidal inlets, ebb deltas and tidal flats, complex hydromorphodynamical processes occur, induced by tides, waves and storm surges.

The coastal lowlands of Niedersachsen are a settlement and economical area of great importance. The economical structure und development of the coastal area is notably influenced by harbours, maritime traffic and shipbuilding. Specific infrastructural advantages result in important specialized harbours and industrial areas such as Emden, Leer, the deep-water port at Wilhelmshaven, Nordenham and Brake at the Lower Weser as well as Cuxhaven and Stade at the Elbe estuary. Within the areas protected against flooding, several important industrial and economical sectors are represented. Agriculture and fisheries are of an above-average importance. Mainly the Eastfrisian Islands and the coastal towns form one of the most important touristical regions in Germany. Of special attraction is the unique landscape of the Wadden Sea and the marshlands as well as many cultural places of interest.

## 2. Historical Development of Coastal Defence

The history of coastal defence in Niedersachsen is characterized by a permanent struggling of man against the forces of the sea. The development of the coastline was mainly influenced by the postglacial sea level rise, trans- and regression phases and storm surges. In historical times, gradual colonization of the coastal lowlands began. Starting more than 2000 years ago, settlements were actively protected against flooding by dwelling mounds, which were erected, heightened and extended over time mainly as a reaction to flooding. Around the turn of the first millennium, the first isolated ring-dikes were built in order to protect the cultivated agricultural areas against storm surges. The existence of a complete dike defence line at the coast, resulting of the connection of these ring-dikes, can be attributed to the period of the 12$^{th}$/13$^{th}$ century. Until the end of the mediaeval times, huge land losses as a consequence of several severe storm surges can be detected in the evolution of the major bays Dollart (Ems estuary), Leybucht (East-Frisia) and Jade Bay (Jadebusen) (Fig. 1). With a reduced size due to reclaiming of parts of the lost land, these bays still exist. Around 1500, these losses of land reached their biggest extension. Since that time, the reclaiming of land prevails. The dike line was shifted seaward and straightened. Some of the old dikes still exist and have adopted a role as secondary dikes.

Examples of these catastrophic flood events are the historical storm surges of 1164, 1362, 1374, 1570, 1717 and 1825 which caused many casualties and economic losses (Fig. 2), (NLWKN, 2007). Based on experiences acquired since the beginning of dike construction, the dike profiles have been continuously optimized and crest levels have been raised.

## 3. Present Coastal Defence Strategies

As a consequence of the catastrophic storm surge in the Netherlands of February 1953, in 1955 the Lower Saxony Coastal Programme (Niedersächsisches Küstenprogramm) for the enhancement of the protection of the coastal lowlands against flooding was established. The severe storm surges of February 1962, with more than 300 casualties and huge economic losses, and of January 1976, striking the German North Sea coast were reason to intensify the programme for strengthening and upgrading the coastal defences and to improve the technical standards. In 1973, the status of execution and further needs for coastal defence works were determined in a *'coastal defence master plan'*. In 1997, this plan was updated for the Weser-Ems region.

Since 1955, 2 billion Euro were invested in coastal defence measures. The primary dike line along the mainland coast was significantly straightened and shortened from more than 1100 km to 610 km. 17 storm surge barriers had been constructed in order to cut off the tributaries of the tidal rivers Ems, Weser and Elbe from the influence of storm surges. Due

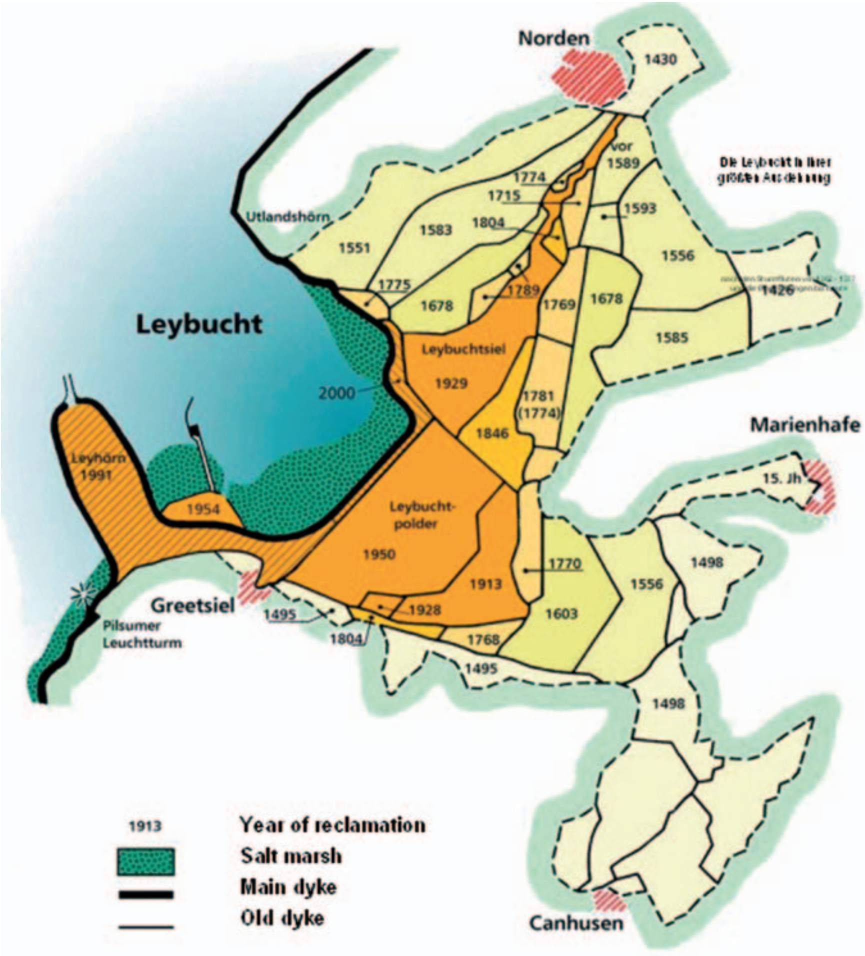


Fig. 1: Ley-Bight – History of reclamation

to historical reasons, secondary dikes exist for only 20 % of this defence line. Wide-stretching coastal areas, which are not divided into polders, are protected. Hence an equal safety standard is defined for all flood protected areas.

The Master Plan Coastal Defence for Niedersachsen issued in 2007 (NLWKN, 2007) describes the mid-term defence strategy. Primary objective of coastal defence is safeguarding of coastal areas against flooding due to storm surges and guaranteeing the existence of the inhabited islands. New embankments have not been planned. In the plan, a current inventory is given and necessary measures are described. Still, 120 km of the primary dikes on the mainland coast have to be upgraded and strengthened.

The Niedersachsen dike law (NDG, 2004) defines the type of flood defence structures as well as their function and elaborates e.g. on regulations for maintenance, utilisation, extension and inspection. 22 dike boards are in charge of maintenance and strengthening of the primary dikes on the mainland coast. Members of the dike boards are owners of flood-protected land. Storm surge barriers, selected mainland dikes and coastal defence of the islands

Fig. 2: Dyke breach during the storm surge of 1825 near Norden/East Frisia

as well as strategic planning are the state's obligation. As an important precautionary measure, the state also operates a storm surge warning service, which provides relevant information for the public and the decisions makers.

The coastal flood defence system in Niedersachsen, protecting an area of 6,600 km, comprises the following main elements:

- 610 km of primary dikes on the mainland coast,
- 17 storm surge barriers,
- salt marshes in front the primary dikes,
- secondary dikes,
- 88 km of flood protection dunes on the sandy barrier islands, partly protected by revetments, seawalls and groynes,
- 35 km of primary dikes on the islands


Fig. 3: Overview over primary dikes, storm surge barriers and flood protected area in Niedersachsen. (1) Leda barrier, (2) Ems barrier, (3) Barrier Leysiel, (4) Hunte barrier, (5) Ochtum barrier, (6) Lesum barrier, (7) Geeste barrier, (8) Oste barrier, (9) Barrier Freiburg, (10) Barrier Wischhafen, (11) Barrier Ruthenstrom, (12) Barrier Abbenfleth, (13) Schwinge barrier, (14) Lühe barrier, (15) Este barrier, (16) Barrier Seevesiel, (17) Ilmenau barrier

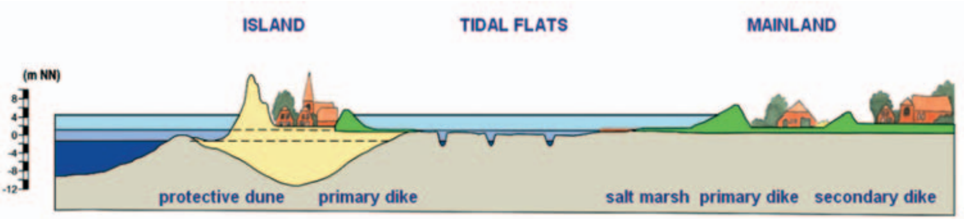


Fig. 4: Coastal flood defence system in Niedersachsen

Fig. 3 and 4 give a general overview of the flood defence system for the islands and the mainland coast.

The design height of coastal flood defences is determined by addition of the design water level and the local wave run-up. Generally, the design water level for open coastlines is evaluated by a legally defined deterministic procedure by addition of four parameters:

1. Mean high tide water level,
2. maximum spring tide influence,
3. maximum recorded surge effect (wind set-up) and
4. expected sea level rise (for 100 years) of 50 cm, including potential effects of climate change.

For the tidal rivers, hydro-numerical modelling, taking the surge effect and a design freshwater discharge into account, is applied (NLWKN, 2007). The hydraulic loads and design heights of all coastal defence structures are recalculated on a regular basis.

### 3.1 Flood Defence Structures – Primary and Secondary Dikes

The 610 km-long primary dike line begins in the Dollart Bight at the Dutch-German border and ends at the Elbe-River upstream of Hamburg at the Geesthacht barrage. Crest heights of the dikes range from NN + 5.6 m in Cuxhaven to more than NN + 9 m upstream of Hamburg and in North-west East-Frisia. Usually primary dikes have huge cross sections and basis width of up to 140 m. They are built with a sand core and a grass-overgrown clay cover of at least 1 m thickness, if the limited availability of clay permits. Functional parts of the dikes are inner and outer berms as well as drainage ditches and toe protection by revetments and groynes. Significant dike stretches are so called foreland-dikes, were a salt marsh functions as a toe protection and is, therefore, an important element of coastal defence.

For approximately 20 % of the primary dike line, secondary dikes exist. These are often former primary dikes until new land has been reclaimed by construction of a new dike. Secondary dikes can attain a breakwater function during storm surges and limit flooding and potential damage in case of failure of the primary dike line. Hence, they have to be maintained as a legal obligation.

### 3.2 Salt Marsh – Management

The salt marshes, located seaward of the primary dike line, are an important coastal defence element in Lower Saxony. Thus, their maintenance and preservation as a protective element for the primary dike is a legal obligation. A sufficiently wide and elevated salt marsh reduces the hydrodynamic load on the main dike toe and outer slope during storm surges because of their energy dissipation capacity. Therefore, they can make expensive toe protection, revetments and groynes superfluous. In case of a dike breach, a continuous in- and outflow of tidal waters will be reduced by salt marshes and summer dikes.

Most of the existing salt marshes have been artificially created for agricultural purposes by land reclamation in the past, building salt marsh groynes and applying systematic drainage of the groyne fields. Nowadays, main objectives of coastal defence are to preserve the extent of the existing salt marshes and create new ones up to a certain width and elevation, were possible and necessary. A successful technical method is the establishment of brushwood groyne fields of 200 x 400 m, which enhance the settlement of suspended sediment by reducing the effect of currents and waves. Under certain circumstances revetments may support the foreland evolution (Fig. 5). Furthermore, maintenance work such as the drainage of salt marshes and groyne fields are applied where necessary for improving the functionality and stability. To improve the stability of dikes, in parts of the salt marshes extensive livestock grazing is applied to reduce vegetation and, consequently, the amount of debris settling on the dike surface after storm surges.

Except for coastal defence, salt marshes are a valuable habitat and biotope, and they are of high importance for nature conservation. Most of the salt marshes in Niedersachsen are protected by international and national legislation (NWattNPG, 2001). To integrate the objectives of coastal defence and nature conservation, integrated salt marsh-management plans have been prepared under the participation of relevant parties from coastal defence and nature conservation. These plans are based on the principles of integrated coastal zone management (EU, 2002). Since they contain common objectives and measures for both coastal protection and nature conservation for the coming ten years, they are an important element of sustainable management of the coastal zone.

Fig. 5: Salt mashes and groyne fields in front of a primary dyke

### 3.3 Storm Surge Barriers

Storm surge barriers are a vital element of coastal flood defence in Niedersachsen. They are located in tidal rivers and/or their tributaries and protect upstream areas against storm surges. In Niedersachsen, fourteen storm surge barriers have been constructed since 1954. Three more protect Niedersachsen territory, but they are located in other federal states. Their locations are shown in Fig. 3.

The boundary conditions for operation of the barriers are dependent on expected storm surge water levels, water management, maritime traffic and nature conservation issues. The largest barrage, the Ems Barrier, was finished in 2002 and has a total width of 462 m (Fig. 6). Upstream of the barriers, dikes protect the lowlands against the retained water in case of barrier operation and provide a second security in case of barrier failure. The dike crest elevations depend on the duration of closure of the barrier, the river discharge as well as wave run-up.

### 3.4 Costal Protection for the East Frisian Islands

Length of the East Frisian barrier islands ranges from 6 to 15 km. In the past centuries, the morphodynamic processes led to significant changes of island size and shape as well as to a total disappearance. Due to erosion and flooding, many settlements, mostly small villages, were destroyed, abandoned or had to be relocated. With the start of the $19^{th}$ century, many

Fig. 6: Ems storm surge barrier

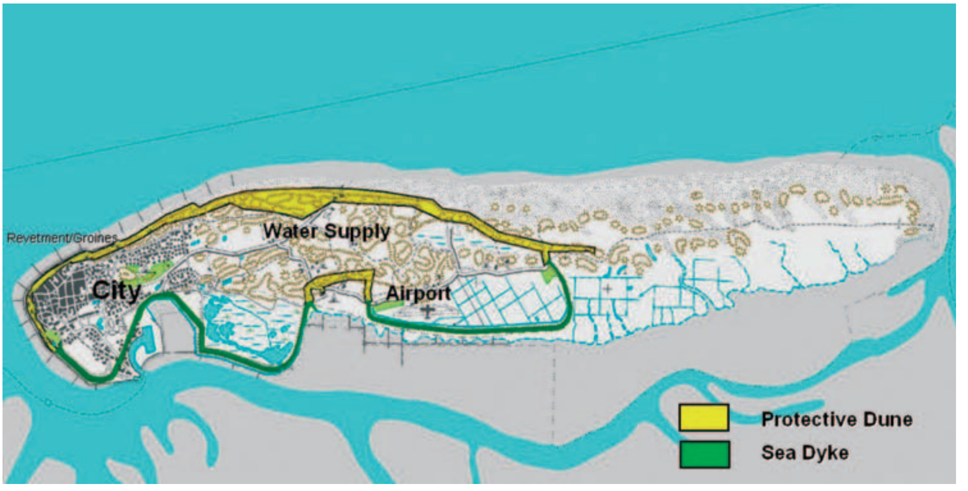


Fig. 7: Flood defence system for the island of Norderney

of the small island villages developed into health resorts of steadily growing economical importance. Nowadays, the East Frisian Islands are considered to be among the most important sea resorts along the German North Sea coast. In order to safeguard settlement areas against erosion and flooding, first revetments and groynes were mainly built at the western coastlines of all islands, except for the island of Langeoog, in the second half of the 19$^{th}$ century. These structures have been continuously extended, upgraded and strengthened to counteract erosion and damage by wave action.

Along the northern coastline of the islands, mostly natural dune chains with a width of about 200 to 400 m are to be found. Nowadays, they are defined by decree to be protective dunes. In the central as well as in the southern parts of the islands, marshlands dominate, and almost no protective dunes exist. Here, main dikes have to protect the islands. Dunes and main dikes form a ring of flood protection elements for inhabitated and economically utilized areas (Fig. 7). During storms surges, the islands also reduce the energy of waves approaching the mainland coast. Therefore, they contribute to the safety of the mainland coast and have to be preserved. The eastern shorelines of many of the islands are part of the National Park „Niedersachsen Wadden Sea". They are not protected by coastal defence structures with the objectives of nature conservation and letting natural processes prevail.

Principal coastal defence elements, functioning for prevention of flooding and for stabilisation of the islands, are:

- 35 km primary Dikes,
- 99 km protective Dunes,
- 22 km revetments and 125 massive groynes.

Parts of the coastal structures at the islands of Borkum and Wangerooge serve as stabilizing elements for major navigation channels. Therefore, they are the responsibility of the Federal Administration of waterways and Navigation (Wasser- und Schifffahrtsverwaltung – WSV).

The technical concept to guarantee the functionality of protective dunes depends on sediment supply from the beaches and specific protection objectives (THORENZ, 2006). Where massive constructions such as revetments, seawalls and groynes are present and erosion pre-

Fig. 8a: Revetment and groyne system at Norderney

Fig. 8b: Wave run-up reduction elements at Norderney

vails, the existing coastline is protected. If necessary, structures need to be upgraded or reinforced to protect the inhabited areas. Often, restricted availability of space requires cost intensive constructions if an upgrade or extension is unavoidable. E.g. in order to reduce wave run-up and overtopping at the revetment at the north-western part of Norderney, the reconstruction, carried out between 2001 and 2008, necessitated special structural elements (Fig. 8a and b).

In addition to the building and maintenance of coastal structures, beach and foreshore nourishments are executed at Norderney to protect the massive constructions against scouring. This is done, if the sediment volume of the adjacent beach falls below a critical threshold. Since 1951, eleven nourishments with a total volume of 5.0 million m³ have been executed.

Most stretches of protective dunes are not protected by revetments or groynes. If scour and erosion protection is necessary because of hinterland habitation and/or infrastructural facilities, beach and foreshore nourishments being an environmentally sound and active coastal defence method, are carried out to balance sediment deficits. The north-western beaches of Langeoog Island were nourished six times with a total amount of 2.9 million m³ sand since 1971.

Receding of the coastline due to erosion is tolerated up to a limit, as long as the required dune width to fulfil safety standards is ensured. Safety checks of the dunes are conducted by means of numerical dune erosion models in combination with a morphological trend-analysis (BLUM and THORENZ, 2005). A strengthening of dunes on their lee or a relocation by building up an entirely new naturally shaped and replanted chain of dunes to guarantee the functionality as protective structures can be considered. The latter was carried out with an extent up to 1 km at the islands of Juist and Langeoog (Fig. 9).

Fig. 9: Dune reinforcement at the island of Langeoog

Island beaches are often characterised by discontinuous sediment supply. In case of a relatively wide dune belt, limited erosion is tolerated as long as the safety standard is guaranteed and positive sediment supply can be expected to follow. The dune toe is rebuilt by use of sand-trapping fences which are to accumulate sand transported by aeolian action during phases of a positive sediment balance. This environmentally sound method is applied on all islands.

Most protective dune chains on the East Frisian Islands are relatively narrow with a maximum width of a few hundred meters. Therefore, maintenance of the dune corpus to avoid damage of the vulnerable vegetation and, consequently, aeolian erosion is therefore very important. Damage is remedied by replanting of marram grass. This is mostly gathered on natural dune sites, but for major demand may also be obtained from cultivation in a seedling nursery on Norderney (THORENZ and SCHULZE DIECKHOFF, 1998).

Continuous comprehensive information and guidance of the numerous tourists is an important part of dune management. Information display boards concerning the importance of dunes for coastal defence and nature conservation, paved and well maintained paths through the dune belt and viewing platforms on dunes in combination with inspection and information given by dune wardens are important elements of this concept. It is based on cooperation between coastal defence and nature conservation agencies as well as municipalities.

### 3.5 Island Dikes

The severe storm surges from 1962 and 1976 caused flooding of settlement areas on nearly all islands. Often the water advanced from the low lying Wadden Sea overtopping the low-crest dikes. Nowadays, 24 km of 35 km main dikes on the island have been reconstructed within a dike upgrade programme. Usually, the dike is covered and sealed by a clay layer. On the islands, no clay pits are available. As a remedy and based on a long-term management in cooperation with waterways, coastal defence and nature conservation agencies mud dredged in the course of harbour and navigation channel maintenance was stored and conditioned for later use in dike construction. Additional clay was transported from the mainland. Presently, 30 km of the island dikes are protected by salt marshes. Groyne fields shelter approx. 14 km of the foreland against erosion.

## 4. Monitoring and Research

Comprehensive hydrological and morphological monitoring programmes are being executed as a basis for the analysis of the dynamic coastal system to yield data for design, safety checks and sustainable future planning of coastal defences. Regularly monitoring actions are:

- terrestrial and ship-based survey of reference profiles,
- airborne laser-scanning of beach and dune areas, tidal flats and foreland,
- airborne photography,
- recording of hydrological data by gauges, buoys and measurement stations to be also used as basis for modelling and storm surge forecast.

Applied research in the field of coastal engineering is also conjointly organized between the Federal States and the Federal Republic and coordinated by the German Coastal Engineering Research Council – GCERC (KFKI – Kuratorium für Forschung im Küsteningenieurwesen) (KFKI, 2001).

## 5. Outlook

In Niedersachsen, flood and erosion protection is an essential basis for the utilisation of a coastal zone covering 6.600 m² with high importance as a region for habitation, recreation, economy and ecology. Since 1955, more than 2.2 billion Euro have been invested in coastal flood defence measures. However, still 120 km of the mainland dikes and several coastal defence structures on the islands have to be upgraded.

The potential effects of climate change such as an accelerated sea level rise and an increased frequency of storms will be of growing importance. Although there are still great uncertainties concerning the consequences of climate change (IPCC, 2007), the design of coastal defences in Niedersachsen already takes a safety margin of 50 cm/100 years for dikes and of 100 cm/100 years for the design of foundations and the statics of massive structures into account. Today and in the future, there is no alternative but to carry out technical measures to meet the targets of coastal defence. Hence, the continuous improvement of technical and scientific knowledge is of great importance.

The coasts are subject to continuous attack by natural forces. At the same time, the economic values in the coastal region are rising. Therefore, defence of the flood-prone coastal areas and the sandy islands can be considered a continuous challenge which has to be adapted to changing boundary conditions.

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# Coastal Flood Defence and Coastal Protection along the Baltic Sea Coast of Schleswig-Holstein

By JACOBUS HOFSTEDE

Contents



## 1. Introduction and Historical Development

Schleswig-Holstein is the most northerly Federal State in Germany. It has an area of 15,731 km² and a population of about 2,700,000 (about 172 inhabitants per km²). The State is situated between two seas, the Baltic Sea in the East and the North Sea in the West (Fig. 1). As a result, a large part of the State may be characterised as coastal zone. Within this zone, most of the population is concentrated, e.g. in the harbour cities of Kiel (about 248,000 inhabitants) and Lübeck (about 217,000 inhabitants). In all, the coastline measures 1,190 km, and about 3,800 km² of flood-prone coastal lowlands exist. In these lowlands, which represent almost 25% of total surface area, 345,000 people live and economic assets worth of 47 billion Euros are concentrated (HOFSTEDE, 2004). This chapter focuses on the Baltic Sea coast of Schleswig-Holstein. For the North Sea coast, the reader is referred to chapter 1.2.1.

In contrast to the relatively plane North Sea coast, the Baltic Sea coastline of Schleswig-Holstein was formed during the last ice age by glaciers. They left a strongly undulating relief with moraine hills and glacier valleys. In the course of the Holocene sea level rise, the valleys were inundated and a coastal landscape developed, characterised by elongated bays (Förden) and headlands. In all, the coastline measures 637 km, 162 km of which belong to the semi-enclosed Schlei-Förde and another 87 km to the island of Fehmarn (Fig. 1). About 148 km of the coastline are occupied by soft cliffs. As a result of the Holocene sea level rise and the hydrologic forcing, the long-term morphologic development is characterised by a general retreat of the headlands. For example, the headland "Brodtener Ufer" to the North of Lübeck retreated by about 6 km in 6,000 years. The material that was eroded from the headlands was partly transported into the bays (longshore drift). Here, it accumulated in spits which in some cases almost completely cut off the bay from the Baltic Sea (e.g., Schlei-Förde). Over the time period of 1872/76 to 1951/68, almost 182 km of the coastline receded, whereas 128 km moved forward. Maximum retreat rates are registered at Heiligenhafen cliff with up to 2.5 m/a, whereas the 'Graswarder' spit situated some kilometres to the East is growing by 2 to 3 m/a (Fig. 2).

The first dike at the Baltic Sea coast of Schleswig-Holstein was erected about 30 km to the East of Flensburg in the year 1581. In the $18^{th}$ and $19^{th}$ century, more dikes were built due to private initiatives. These were, however, under-dimensioned and were destroyed during storm surges. The highest storm surge in the Western Baltic Sea was registered in the year

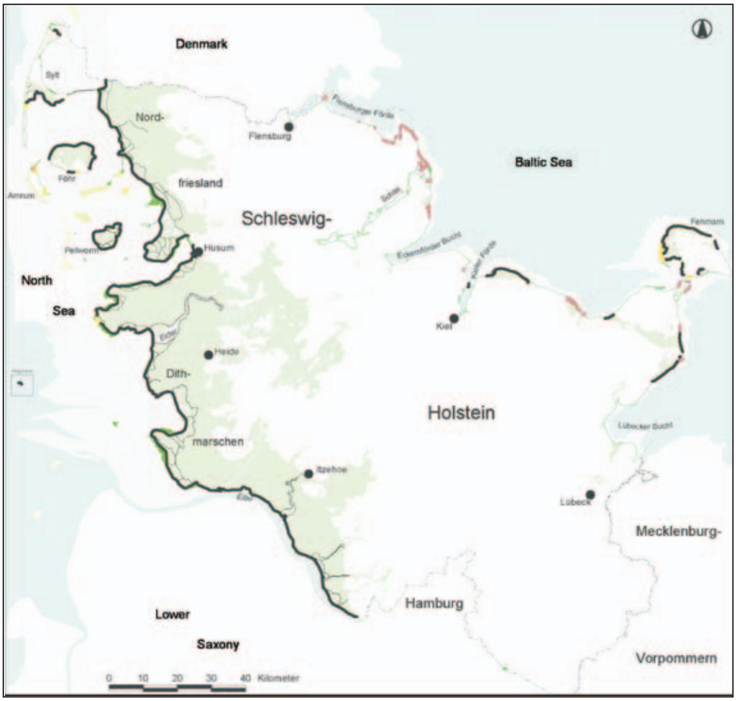


Fig. 1: Overview of Schleswig-Holstein with State dikes (black bold lines), regional dikes (brown lines), and coastal lowlands

Fig. 2: The Graswarder spit near Heiligenhafen

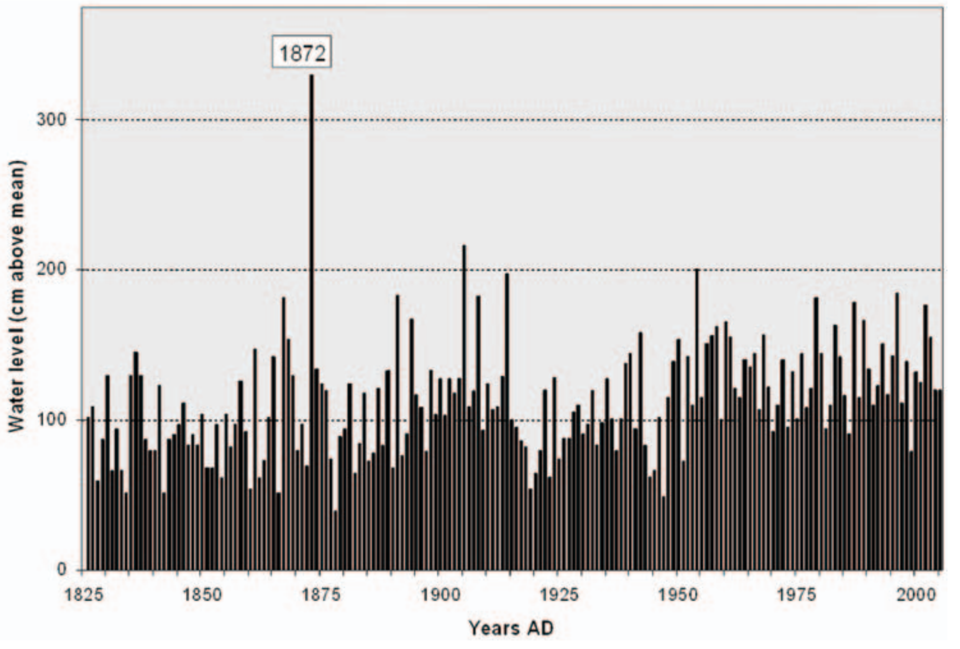


Fig. 3: Development of yearly highest water levels in Lübeck since 1826

1872. With a water level of up to 3.3 m above mean sea level, this event was almost 1 m higher than all previous and following surges (Fig. 3). This storm surge, which caused 271 fatalities, constitutes the turning point in coastal flood defence along the Baltic Sea coast of Schleswig-Holstein. From now on, the Prussian Government systematically planned flood defences. The dike profile that was developed already showed the basic characteristics of modern dikes. In the decades following 1872, the first major public defence programme was implemented.

Due to the undulating topography with bays and headlands, a large number of isolated coastal lowlands exist along the Baltic Sea coast of Schleswig-Holstein (Fig. 1). Approx. 92,000 people live in these lowlands, and economic values of 15.4 billion Euros are concentrated mainly in the port cities of Kiel and Lübeck (HOFSTEDE, 2004). Apart from the harbours, significant economic values are concentrated in a number of coastal tourist resorts such as Timmendorfer Strand (see below).

## 2. Modern Coastal Defence

### 2.1 Strategic Considerations

Under the impression of the 1962 storm flood catastrophe, in which more than 300 people lost their lives in the greater Hamburg area, the Schleswig-Holstein State Government adopted a master plan for coastal flood defence and coastal protection. It contained the technical and financial concept for improving the standards of protection in Schleswig-Holstein. The plan was updated in 1977 and 1986. In the year 2000, the new master plan "Integrated

Coastal Defence Management in Schleswig-Holstein" was prepared by the responsible administration. After comprehensive public consultations, it was adopted in 2001 by State Government (HOFSTEDE, 2004). The master plan describes the mid-term defence strategy and is based upon the principles of Integrated Coastal Zone Management (EUROPEAN COMMISSION, 2002). For the first time in Germany, it considers the possible consequences of anthropogenic climatic change.

### 2.2 Measures

Coastal flood defence along the Baltic Sea coast of Schleswig-Holstein mainly consists of sea dikes. In the Lübeck Bay, a flood defence scheme (sheet pile wall) of about 10 km length is presently being established. Both techniques being used are described below.

**Sea dikes**

In contrast to the North Sea coast of Schleswig-Holstein, a large number of isolated coastal lowlands exist along the Baltic Sea (Fig. 1). Most of these are protected by dikes. In all, 117 km of dikes protect the lowlands from flooding: 67 km are State dikes (Fig 4; Probstei), the rest are regional dikes. In contrast to State dikes, regional dikes do not have fixed safety standards and are mostly within the responsibility of dike boards. The safety standard of a state dike includes a design water level, a design wave run up and an extra safety margin to account for future sea level rise (Fig. 5). The design water level should meet three basic requirements (HOFSTEDE, 2004):

1) it should have a (statistical) return period of once in a century,
2) it should not be lower than the highest water level observed in the past (incl. sea level rise since then), and
3) it should not be lower than the sum of highest spring tide water level and highest observed surge.

For the Baltic Sea coast, the storm surge water level of 1872 represents the highest water level and, consequently, the respective design water level (incl. sea level rise since then), on top of which a design wave run-up is calculated.

With the establishment of the new coastal defence master plan, a safety check was conducted with localised water level values based on nearby tidal gauge stations. It turned out that, in all, 35 km of state dikes needed to be upgraded to meet the safety standard. From 2001 until the end of 2007, only 3.5 km (10 %) have been strengthened. This low achievement is a result of complex local situations and a focus on the North Sea coast (see page 134).

**Other flood defences**

Not in all flood prone coastal settlements along the Baltic Sea dikes are appropriate, especially in tourist resorts. Hence, alternatives have to be found. One example is the Lübeck Bight. Here, in the coastal resorts Timmendorfer Strand and Scharbeutz, almost 6,000 people live less than 3 meters above mean sea level (MSL). Capital values amounting to 1.75 billion Euros, mainly tourist infrastructure, are situated in this area. The existing flood defence for the coastal lowland is a barrier beach system with a mean elevation among 2.5 and 3.0 m above MSL. Hence, from a flood defence point of view, the situation is rather critical. It is estimated that a breaching of the barrier will occur with a water level of about 2.1 m above MSL. Fig. 6 displays the frequency distribution of the highest annual water levels for the time period between 1921 and 1996 at the gauge station Neustadt, situated about 10 km to the North.

Fig. 4: State dike with T-groins about 25 km to the Northeast of Kiel

From this diagram, it can be seen that, statistically a water level of 2.1 m above MSL has, in the present situation, a return interval of about 100 years. If MSL rises by 0.5 m, the statistical return period would be reduced to about 10 years. Considering the high capital values and human lives at stake and the long-term increase in flooding probability, it becomes evident that a sustainable flood defence solution is urgently needed.

With the last catastrophic storm surge about 135 years ago and an economic dependency on tourism (broad beaches), it is evident that the local population was rather sceptical towards coastal flood defence ("dike on the beach"). However, since the municipalities are responsible for flood defence they decide whether and what kind of sea defence is implemented. The coastal defence administration has an advisory function and may contribute to the costs. Hence, an appropriate coastal defence solution for the area can only be achieved with active involvement of and acceptance by the local population. To find a sustainable and integrated solution, an active participation procedure was conducted by external moderators (HOFSTEDE, 2001). Coastal administration did not interfere with this process; they only presented and illuminated the problem (Fig. 6). Based upon the systems theory, citizens of the two municipalities developed a model of their region. With this model and based on several coastal flood defence scenarios (e.g., "do nothing"/ "dike on the beach"), they simulated possible future developments. The model was "activated" by a step-by-step MSL rise (i.e., increase in the probability of flooding; Fig. 6). The main outcome of this procedure was:

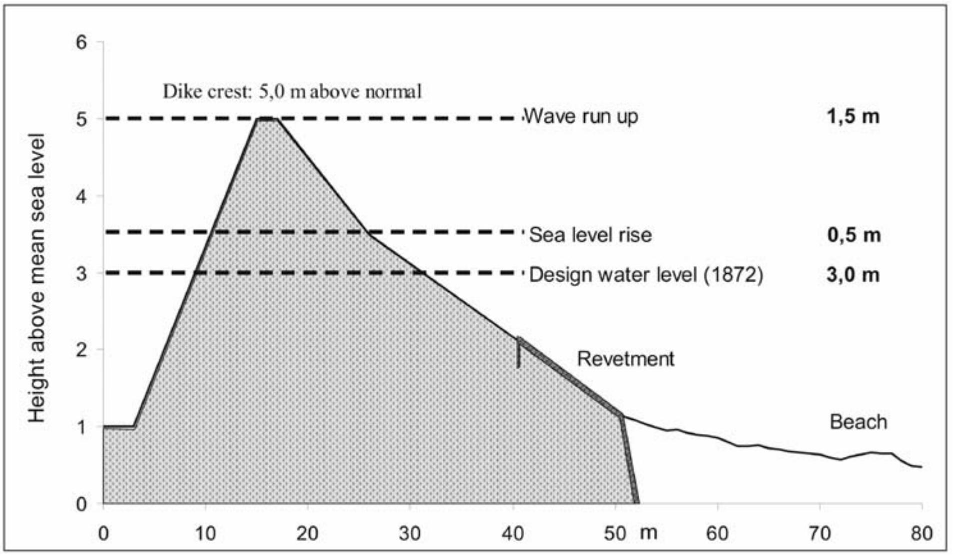


Fig. 5: Dimensions of a state dike along the Baltic Sea (schematic)

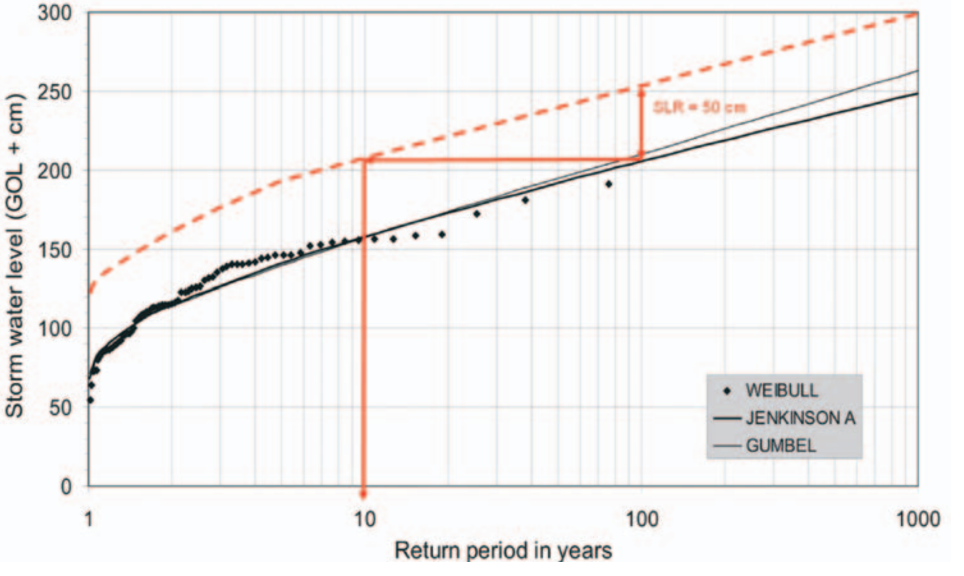


Fig. 6: Frequency distribution of the yearly highest high water levels at gauge station Neustadt for the period 1921–1996. Depicted also is the situation for a 50 cm higher sea level and its consequences for the occurrence probability

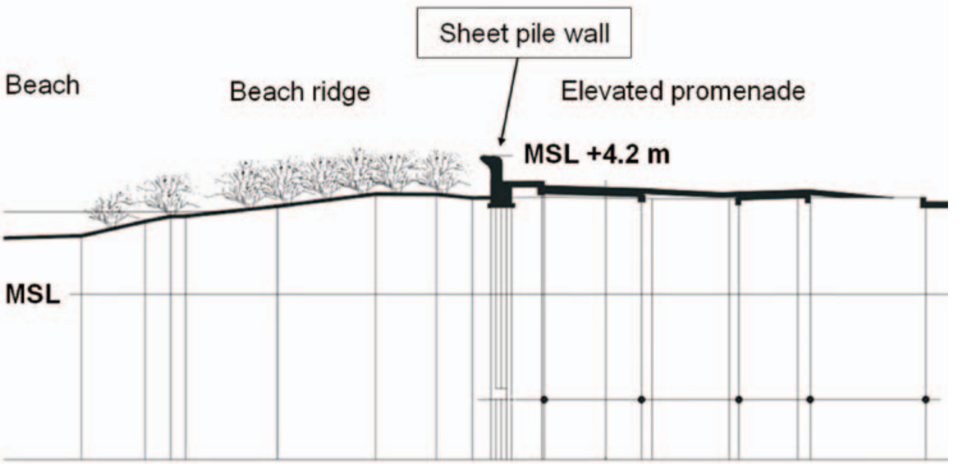


Fig. 7: Flood defence scheme for Timmendorfer Strand and Scharbeutz

Fig. 8: Sheet pile walls mounted with concrete holms and fronted by sand containers

Fig. 9: Flood defence scheme "hidden" under sand and marram grass

- the participants recognised the long-term risk for their coastal lowlands,
- they accepted their responsibility to anticipate this risk, and
- they evolved from sceptics to advocates of an integrated coastal defence concept that "fits" into the coastal landscape.

For a comprehensive description of the procedure, the reader is referred to HOFSTEDE (2001). With the basic requirement of an integrated solution, an ideas competition between selected consultants was conducted. The winning scheme is presented in Fig. 7. It consists of a sheet pile wall with concrete top rails, installed behind or within the natural beach ridge. As a toe protection, sand containers will be placed in front of the wall. Different stages of implementation are shown on Figs. 8 and 9. After completion, the structure will be buried under the beach ridge or camouflaged as a promenade wall. It should be emphasized, that the scheme does not guarantee protection against a storm surge event of 1872 dimensions (see Fig. 3). After long discussions, the municipalities decided that the costs of such a solution would be too high. Further, the interference with tourism was judged to be too intense. Thus, the citizens accepted the risks present without further protective structures.

**Coastal protection**

Due to its advantageous orientation to the dominant wave directions, the Baltic Sea coast of Schleswig-Holstein is, relatively stable (EIBEN, 1992). However, local erosion problems have resulted in a number of protective measures, mainly groins. The first groins were constructed in the years 1878/79. In the 1980s, 43 so-called T-groins were built near Kiel as foot protection for the new sea dike (Fig. 4). Finally, toe protection revetments were built in two locations in front of a coastal cliff and of a regional dike. These examples show that the Baltic Sea coast of Schleswig-Holstein is rather free from protective structures.

## 3. Outlook

About 32 km of the State dikes along the Baltic Sea coast of Schleswig-Holstein still need to be upgraded to meet the safety standards as described in the Coastal Defence Master Plan. Due to a low risk awareness of the local population and often complicated local situations, the strengthening of these dikes remains a challenge for the responsible administration. In 2007, the International Panel on Climatic Change-IPCC' published its fourth report on future climate change (IPCC, 2007). Although within the range of sea level rise scenarios, the expected increase was slightly diminished (18 to 59 cm until 2100), significant uncertainties remained, concerning e.g. an accelerated melting of the Greenland ice cap. At present, no acceleration in regional sea level rise can be deduced from the records. Over the last 100 years, the mean sea level along the coasts of Schleswig-Holstein rose by about 0.15 cm per year. On medium-term, however, a doubling and tripling of the present rates should be accounted for. This will have serious consequences for the sandy coasts of Schleswig-Holstein. Coastal stretches that are now stable or even accreting may become erosive. Considerations on how to adapt to this challenge are needed urgently. With respect to climate change and increasing utilization of the coastal zones, the master plan states that 'coastal protection will never end'!

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# Coastal Protection along the Baltic Sea Coast – Mecklenburg-Vorpommern

By BIRGER GURWELL

Contents



## 1. Geological and Physical Characteristics

The coast of Mecklenburg-Western Pomerania (Mecklenburg-Vorpommern) with an overall length of 1,945 km is highly structured as a result of primal glacial shaping. The coastal equilibrium processes which still persist today have resulted in extensive cordoning-off of the shallow coastal lagoons and backwaters from the Baltic Sea. The length of the external coastline is 376 km whereas the length of the coastal lagoon and backwater coastlines is 1,569 km. Especially the external coastline, which frequently alternates between steep cliff sections (128 km) and flat coastal sections (248 km), is highly dynamic. Approx. 70 % of the external coastline is in a state of recession with an average recession rate of 34 metres in 100 years, while only 7 % is subject to accumulation. The present-day coast of Mecklenburg-Vorpommern is comprised of three large morphological sections:

- The large bays of Holstein-West Mecklenburg (running from Priwall to the north-east beach of the Wismar Bight)
- Mecklenburg equilibrium-state coastline (Bugspitze to the Rostock Heath)
- Coastal lagoon equilibrium-state coastline of West Pomerania (Rostock Heath up to and including the island of Usedom/Odra bay [Oder Bucht])

Coastal evolution along the south-west coast of the Baltic Sea began about 8000 years ago following flooding of the deeper-lying glacial drift landscapes and valleys and the commencement of shoreline erosion during Litorina transgression. It was only after the cessation of the pronounced rise in sea level about 6000 years ago that a new phase with only slight sea level fluctuations began. This phase, which still persists today, was accompanied by enhanced coastal equilibrium processes. Coastal shaping and reshaping depends decisively on the already existing topography as well as on wind conditions and the resulting wave and current climate.

The present cliffs, beaches and shores of the coastal lagoons in our federal state are essentially in a delicate state of geo-morphological balance. With different objectives in mind, natural coastal equalization processes along many stretches of coastline are influenced by coastal and flood protection measures (e.g. groin construction, construction of sea walls, beach replenishment, dyke construction). This primarily concerns the external coastline, which is strongly affected by coastal dynamics. Public awareness has been and continues to be aroused by the recent dramatic changes along the steep coastal stretches of our state, especially the cliff falls on Rügen. Although the call for an effective coastal protection strategy along the cliff coastlines is understandable, these one-sided demands disregard the delicate balance between the three types of coast. It is therefore necessary to make the public aware of a coastal protection strategy which incorporates the entire coastline of the state.

## 2. Historical Events

Storm surges along the German Baltic Sea coast are outstanding natural events. These develop as a result of the coincidental combined action of a number of meteorological and hydrological processes which are mainly influenced by the configuration of the Baltic Sea as an elongated shallow sea with relatively narrow connections to the North Sea and the world's oceans. The reasons for the processes which may contribute to the development of storm surges in the south-western part of the Baltic Sea are low pressure regions of the westerly wind drift (storm depressions, intense low-pressure systems) which cross the Baltic Sea along characteristic paths, and especially in winter, result in strong winds with the above-mentioned consequences. Almost all storm surges, therefore, also occur during the winter months from October to March. The major factors which contribute to the development of storm surges are the degree of fill of the Baltic Sea, the setup due to seiches, and wind setup, which significantly affects water levels. In the case of small-scale domains in the form of bays, the effect of setup in bays is also of importance.

| | Event | Wismar | Warnemünde | Greifswald |
|---|---|---|---|---|
| Heights of extreme storm surges based on historical records and geological findings (metres above the average water level at the time in question) | 1044 | 3.35 | 3.15 | 3.35 |
| | 1134 | 2.85 | 2.45 | 2.55 |
| | 30. 11. 1320 | 2.80 | 2.65 | 2.65 |
| | 16. 10. 1449 | 2.60 | 2.50 | 2.70 |
| | 10. 02. 1625 | 3.80 | 3.60 | 3.80 |
| | 11. 01. 1694 | 3.38 | 3.01 | 3.08 |
| Peak water levels of the highest measured storm surges from 1872 up to the present day (metres above NMW*) | 13. 11. 1872 | 2.83 | 2.70 | 2.81 |
| | 31. 12. 1904 | 2.26 | 1.88 | 2.41 |
| | 30. 12. 1913 | 2.06 | 1.89 | 2.26 |
| | 02. 03. 1949 | 1.78 | 1.52 | 1.82 |
| | 04. 01. 1954 | 2.14 | 1.72 | 1.84 |
| | 03. 11. 1995 | 2.02 | 1.60 | 1.79 |
| | 21. 02. 2002 | 1.98 | 1.58 | 1.78 |

*) NMW = Present-day normal average water level along the coast of Mecklenburg-Vorpommern (MWP)
= 5.00 m at the tide gauge or 5.00 m above gauge datum
= 0.14 m below HN (HN = official levelling datum in the state of MWP)

The height, form and duration of storm surges depend on which of the above-mentioned factors are involved and how they are superimposed. In the most unfavourable case, i.e. when all factors coincide with their respective maximum possible increases in water level, it must be assumed that storm surge peak values of about 4.0 m above the normal average water level may result along the German Baltic Sea coast. Although such values have not as yet been measured, historical records handed down over the past 1000 years as well as the geological findings of the University of Greifswald derived from core samples of coastal and seabed deposits as well as shingle deposits on Rügen indicate that such extreme storm surges are indeed possible, as is also evident in the included table. The upper part of this short list contains the highest storm surges on the Baltic Sea coast of Mecklenburg-Vorpommern over the past 1000 years (1044 up to and including 1872) while the lower part of the list contains the highest storm surges accurately measured along our coast since 1872.

## 3. Design Water Level

The design high water level DHW (BHW) of a stretch of coastline is the high water level according to which the coastal protection structures for the stretch of coastline concerned are dimensioned. This constitutes the basis or fundamental base parameter for all design work in connection with coastal protection structures and also represents the safety level considered by the state as necessary and realisable in order to protect its citizens and material assets at risk in the coastal zone.

A basis for defining the BHW is the most severe storm surge of 1872 in the southern part of the Baltic Sea, as verified by measurements. The maximum water level (peak value) which occurred at that time has been scientifically checked in recent years by detailed investigations. The data recorded for the storm surges of 1625, 1872, 1874, 1904 and 1913 have also been discussed in detail, evaluated, and included where appropriate.

In Mecklenburg-Vorpommern the BHW is determined by means of the comparative value method, i.e. the secular sea level rise over two centuries subsequent to 1872 is added to the peak value up to about 2070, which corresponds to the end of the anticipated service life of many coastal protection structures. Forecasts of the relative secular sea level changes along the coast of MWP are possible due to the existence of tide gauge recordings over a period of 100 years as well as the monthly average and extreme water levels determined in recent years from a time series analysis of these data.

The past assumption of a linear change in sea level rise has been verified by investigations. The results of these investigations yield values ranging between 6 cm and 15 cm in 100 years. These results are significantly lower than those given by the scenarios of the Intergovernmental Panel on Climate Change (IPCC). The application of the IPCC values would lead to considerably higher water levels.

BHW values along the external coastline of Mecklenburg-Vorpommern are found to lie between 3.35 m below HN (Priwall) und 2.2 m below HN (North Rügen).

Based on an evaluation of recent geological data, it appears probable that the water level of the Baltic Sea along the coast of Mecklenburg-Vorpommern will rise by about 20 to 30 cm by the end of this century (2100). This will affect the external coastline as well as the coastlines of the coastal lagoons. This demands the basic continuation and upgrading of the existing "Coastal and Flood Protection Master Plan for Mecklenburg-Vorpommern" of 1994. The major work in connection with the latter may now be regarded as being completed.

## 4. Coastal Protection Strategy

The coastal protection strategy in Mecklenburg-Vorpommern is based on natural conditions and coastal protection engineering traditions. As far as protection requirements are concerned, the preservation of natural coastal dynamics is of top priority. Environmentally-compatible methods such as sand replenishment as well as the preferred use of natural construction materials, such as wooden posts in groin construction and natural stone in breakwater and revetment construction, are in keeping with the recommendations of the Helsinki Baltic Marine Environment Protection Commission as well as with (OK) the beach utilisation requirements posed by tourism.

Based on the state water law, the strategy is aimed at the protection of interconnected developed areas. A differentiated strategic approach is adopted according to the utilisation of those areas which are at risk of flooding or recession.

The rule along the flat stretches of the external coast is <u>defence</u> along the existing defence lines close to the shoreline. This also includes protection of the defence lines themselves against coastal recession. Besides the direct protection of towns and villages along the external coast, continuous chains of dunes and sea dykes prevent breaches into coastal lagoons and backwaters during storm surge events. Consequently, lower design high water levels and reduced wave loading can be applied here. Where continuous defence lines are not necessary, ring dykes are also constructed around towns and villages (adaptation) while undeveloped areas are left to the vagaries of the natural flooding process.

The realisation of coastal protection as a public obligatory task only applies to steep coasts if inner-town areas are acutely at risk due to coastal recession and/or if cliff falls are likely in the event of a design storm surge. If this is not case, the strategy of <u>retreat</u> is followed in order to retain the function of the cliffs as suppliers of sediment. Excluded from the latter are selected, exposed steep coastal sections which must be stabilised because of their far-reaching support function for neighbouring coastal sections.

Besides <u>defence</u> <u>along existing lines,</u> a strategy of <u>retreat</u> is also followed along the shorelines of backwaters and coastal lagoons, especially in the case of under-dimensioned and fairly long dykes at remote locations. If engineering efforts and costs for the upgrade and maintenance of old defence lines, intended to withstand the BHW, are not justified, these are replaced by considerably shorter new dykes in the proximity of towns. In this connection, the aim is to renaturate dyked-in areas for various reasons, e.g. as a compensation for unacceptable encroachments due to coastal protection measures. If required, the old dykes are retained in order to reduce loading on the new structures or sustain agricultural utilisation.

Special demands are posed by the necessary protection of port towns at risk of flooding, where high damage potential exists and where protection structures are often absent or inadequate at the present time. This requires intelligent solutions which suitably blend in with the urban environment. Shortened defence lines in the proximity of the coast are only possible and appropriate in exceptional circumstances, as illustrated by the storm surge protection measures for Greifswald, in which a tidal barrier in the Ryck river is planned as the central component. As this will lead to an increase in the availability of relatively flood-secure areas suitable for building development, this is in a certain sense equivalent to <u>advancement.</u>

The rule in urban areas is rather a <u>strategy of adaptation</u>. Besides the construction of linear defence structures, especially sea and embankment walls, this also includes the raising of ground levels and the construction of DWH-safe storey heights as well as suitably adapted utilisations within the framework of urban and town planning. Mobile elements should only be used in exceptional cases or for the protection of objects. The number of operational openings should be minimised.

## 5. Coastal Protection Structures

Coastal protection dunes constitute the major coastal protection element over a length of 106 km of coastline in the state of MWP. Along 2/3 of this length, dunes alone must be capable of withstanding storm surges without backup by dykes. For this reason, sand replenishment is a dominant coastal protection method along these stretches of coastline. During the period 1990–2005, 13 million m³ of sand were used for dune, beach and backshore nourishment. A major component of the coastal protection system along the external coastline consists of groins (Fig. 1), whose task is to reduce natural recession or stabilise replenished sand. The total number of groins amounts to 1,129. The major proportion of these consists of single-row wooden-post groins. These are incorporated into 12 groin systems over 81 km of coastline. Exposed and heavily-loaded steep stretches of coastline which border acutely endangered inner-town areas or which have a support function for neighbouring flat coasts are nowadays effectively stabilised locally by beach-parallel breakwaters (Figs. 2, 3, 4). Rubble mound structures or sea walls in the proximity of cliffs were used for his purpose in earlier times. The total length of the state's coastal protection dyke system (1$^{st}$ order dykes) is 150 km. Of this total, 107 km consist of coastal lagoon and backwater dykes, while 43 km consist of sea dykes (Fig. 5). These provide flood protection over a length of 33 km in combination with load-reducing dunes or rubble mound banks along the foreshore. In the event of the design storm surge, an area of about 105,000 ha is at risk of flooding because of the low natural terrain level. Without effective protection structures, about 8.7 % of the population of Mecklenburg-Vorpommern would be thereby be affected.

Over the past 15 years, the costs for the new construction and strengthening of coastal protection structures as well as for preserving their performance capability amounted to 249 million €. The relative costs for the various protection measures are shown in Fig. 6.

## 6. Traditional Coastal Protection System in Mecklenburg-West Pomerania: Dune – Coastal Protection Woodland – Dyke

Following the storm surge of 1872 and the subsequent storm surge events of 1904, 1913 and 1954, sea dykes were constructed on the Fischland-Darß-Zingst peninsula and the island of Usedom at a distance of 100 to 200 m from the shoreline. The purpose of these dykes was to damp waves in the foreshore zone. In order to provide continued protection in the event of dune breaching and subsequent levelling of the surrounding terrain, an additional damping element was necessary. For this reason, trees were planted on the foreshore between the dykes and the dunes in order to create so-called coastal protection woodland.

During the years 1994/95, the effectiveness of coastal protection woodland as a damping element was scientifically investigated. This investigation revealed that the wave-damping action of woodland had been overestimated in the past. Besides the roughness geometry (dependent on the woodland configuration) and the initial wave parameters, particularly the residual dune height following overtopping as well as the foreshore level were found to have a significant influence on wave heights at the dyke. Woodland widths of < 30 m, which still


Fig. 1: Groins in Rostock-Warnemünde

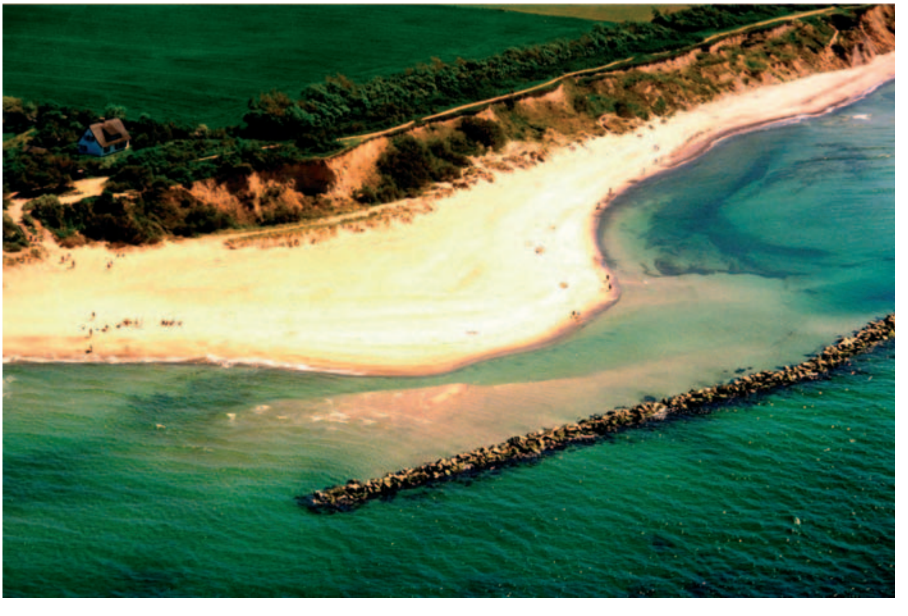

Fig. 2: Breakwaters in Ahrenshoop

Fig. 3: Breakwaters and sea bridge in Wustrow

Fig. 4: Breakwaters and sea wall on the Island of Usedom


Fig. 5: Groins, beach nourishment, dyke and steel wall in Markgrafenheide

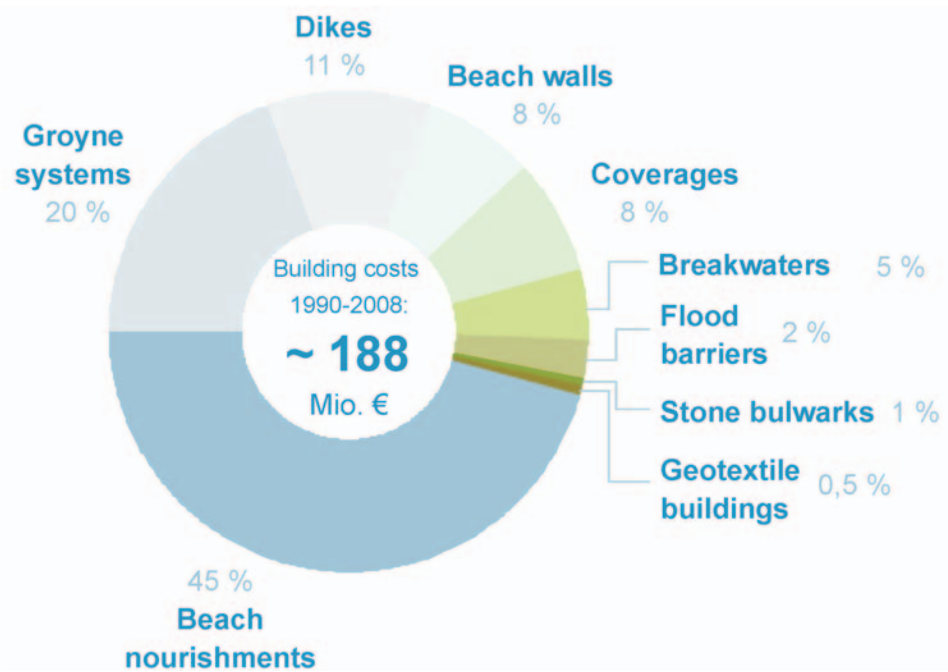


Fig. 6: Compilation of costs for coastal protection measures during the period 1990–2008

partly exist today, are unable to provide the necessary damping action. With the exception of widths > 100 m, coastal protection woodland is not included in dyke dimensioning calculations even though it is still retained as an additional wave-damping element.

The woodland does have positive functions, however, such as the promotion of aeolian dune development and preservation as well as armouring of the foreshore terrain.

## 7. Future Developments, Research

### 7.1 Continuation of the Master Plan

The Coastal Division of the State Agency for the Environment and Nature Conservation in Rostock (STAUN – Staatliches Amt für Umwelt und Natur Rostock) is currently working on the update of the existing master plan in the form of guidelines. Besides cataloguing the measures implemented so far, projects to be undertaken in the coming years have also been earmarked. At the same time, the currently valid methods applied for designing coastal protection structures are also being examined. Extensive investigations have been carried out for this purpose in recent years.

The previously adopted principle of applying a design standard for all coastal protection structures along the external coastline as well as backwater coastlines has now been formulated more flexibly: the design water level for a particular coastal section is now specified within a prescribed tolerance range, whereby economic and ecological criteria as well as communal interests are taken into account in a risk analysis.

The upper bound of the tolerance range is defined by the values corresponding to the storm surge of 1872, i.e. values based on actual measurements in the case of the external coastline, and values based on the results of numerical modelling at the University of Dresden for backwaters and coastal lagoons, taking into consideration the secular changes in sea level in each case.

### 7.2 Coastal Spatial Information System (Coastal SIS)

Work has now begun on the complete changeover from the ArcView projects to ArcGIS, including the conversion of all data to the official height and position reference system ETRS89/DHHN92. Further development of the present coastal SIS is also planned. Key aspects of the latter include public-relevant possibilities of presenting the results and complex intersection possibilities between the different databases of the Coastal Division and the existing spatial base data.

### 7.3 Coastal Digital Terrain Model (Coastal DTM)

The existing DTM has aroused a great deal of public interest in the past two years and has become an important tool for planning work in the coastal zone. Casting our sights beyond the initial versions, however, plenty of work is still necessary to update and maintain the ArcGIS-based and html-based versions of the digital terrain model "Endangerment of the Mecklenburg-Vorpommern Coast", taking into consideration different BHW levels, setup heights and flooding scenarios over a potential flooding area of about 6,500 km². This will primarily involve the development of new methods for computing realistic flooding areas for new coastal protection concepts as well as for computing the consequences of damage events.

### 7.4 Partly-Automated Dune Register (PADR)

Dunes are an essential element of the coastal protection strategy in Mecklenburg-Vorpommern. The purpose of the PADR is to promptly quantify dune break-offs following storm surge events. This involves a comparison of surveyed dune profiles (actual dune profiles) with nominal dune profiles, taking into consideration changes in the shoreline and scarps. This will permit the development of partly-automated routines, i.e. routines for incorporating new dune surveys with wide area coverage, e.g. by means of airborne laser scanning following a storm surge event.

### 7.5 Measurement Surveys

Land and sea surveys along the shoreline and the backshore as well as at sand extraction points will be extended by measurements using side scanners, fan echo-sounders, boomers and ammunition detectors. The survey results will provide input data for problem-oriented morphological, sedimentary and biological monitoring programmes, taking special account of the dynamics/variability of the coastal zone. With regard to the design and planning of coastal protection structures, the results of these monitoring programmes will serve to indicate the effects of coastal protection structures on the nearshore zone, thereby providing a sound basis for forecasting the influence and mode of action/effectiveness of these structures in the coastal defence system.

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# Sea Dikes in Germany

By HOLGER SCHÜTTRUMPF

Contents



## 1. Introduction

Sea dikes (Fig. 1) and estuarine dikes represent the main coastal defence structure in Germany and protect low lying areas in Lower Saxony, Schleswig-Holstein, Bremen, Hamburg and Mecklenburg-Vorpommern. More than 2,400,000 people and an area of more than 12,000 km² are protected by more than 1,200 km of sea dikes and estuarine dikes in Germany (Tab. 1). The protected economic values are high. In Hamburg, the protected value by estuarine dikes is more than 10,000 Millions of Euro, in Schleswig-Holstein more than 47,000 Millions of Euro.

Tab. 1: Overview of dike lengths, protected area and population in German ferderal states

| Federal state | Length of Dikes (primary flood defence line) | Protected area | Protected population |
|---|---|---|---|
| Lower Saxony (incl. islands) | 645 km | 6,600 km² | 1,200,000 |
| Schleswig-Holstein | 527 km | 3,800 km² | 345,000 |
| Bremen | 74 km | 360 km² | 570,000 |
| Hamburg | 77.5 km | 270 km² | 180,000 |
| Mecklenburg-Vorpommern | 150 km | 1020 km² | 90,000 |

Sea dikes have a very long history in Germany. A first citation of seadikes can be traced back to the year 10 (GARBRECHT, 1985). The construction and maintenance of seadikes was firstly organised and managed from around 1150 as a joint agreement between landlords. The history of sea dike design in the mediaeval times was mainly influenced by severe storm surges and the reconstruction after frequent dike failures. The consequences of extreme storm surge disasters and dike failures can still be observed at many locations along the German coast. The islands along the north-frisian coast result from storm surge disasters in 1362 and 1634 and many lakes behind the present dikes have developed due to the scouring process of a breaching dike. Therefore, the crest levels in former centuries correlate well with the

Fig. 1: Modern sea dike in Germany (photo: SCHÜTTRUMPF)

maximum storm surge levels in that times. The memory of the severe storm surges in the past and the consequences is still fresh and not forgotten. As a result of this historical development, the local population has a special attitude towards the safety of sea dikes and the importance of coastal flood defences and coastal protection is well accepted. Nowadays, maintenance and construction of sea dikes are performed by the German Federal States Lower Saxony, Schleswig-Holstein, Bremen, Hamburg and Mecklenburg-Vorpommern. Each state has a master plan for coastal flood defence and coastal protection to prioritize and to indicate dike reinforcement tasks for the future.

## 2. History of Sea Dike Design

During the last millennium, many severe storm surges occurred and are reported in several historical chronicles (e.g. BRAHMS, 1754; WOEBCKEN, 1924). The number of fatalities after storm surge disasters in the middle age was high and the consequences for those who survived the flood were severe (Tab. 2). Large areas were flooded, houses and farms destroyed and the fields were rendered useless for agriculture and stock farming. These fatalities, damages and economic losses were caused by flooding through dike breaches. The resistance of dikes in the middle ages and in later centuries against wave attack and high storm surge water levels was low, and many dikes were even overflowed. First dike breaches along the German North Sea Coast with about 20,000 fatalities are reported from a storm surge in 1164. Even if the number of fatalities is uncertain, the importance of this event is obvious for that time.

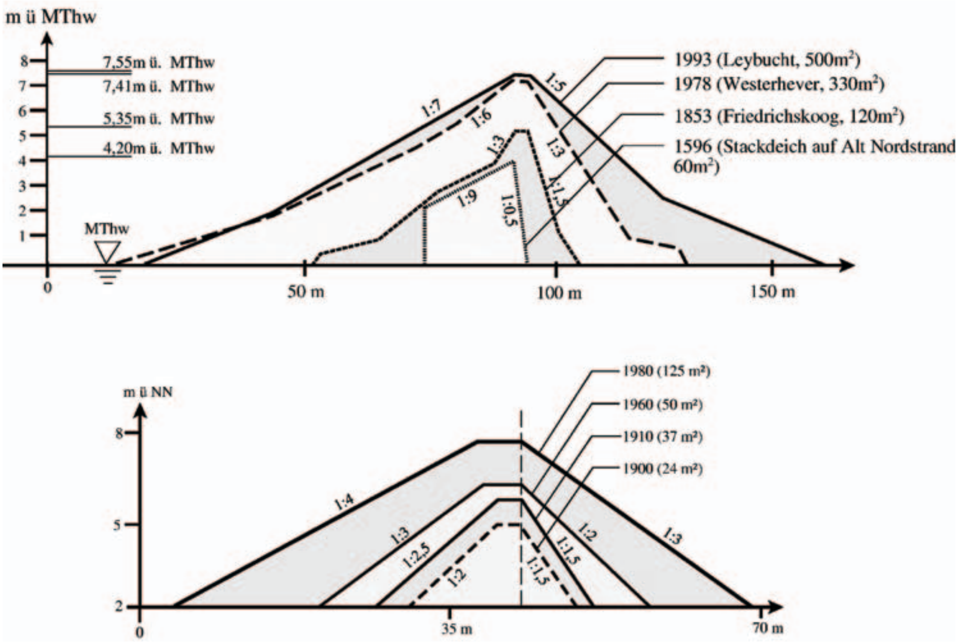


Fig. 2. Evolution of dike profiles in the past (SCHÜTTRUMPF and OUMERACI, 2002)
(upper part: sea dikes, lower part: estuarine dikes)

For the years 1362, 1634, 1717 and 1825, more historical storm surge disasters are reported for the Belgian, Dutch, German and Danish coasts. They triggered the development of sea dikes along the coastlines in these countries. Essentially based on experience, sea and estuarine dikes became higher and broader (Fig. 1) over the centuries. First dikes – called 'Stackdeich' (Fig. 2) – were very steep and sometimes vertical on the seaward slope and consisting of a wooden front face.

Compared to modern sea dikes, the crest level was low and able to resist only summer storms. People settled on artificial dwelling mounds to be protected against high winter storms since the sea dikes were not strong enough to protect houses and farms. Observations of the failure mechanisms led to a better understanding of the processes and a better design of sea dikes. Therefore, sea and estuarine dikes became smoother and higher over the centuries. First distinctions between dike failure mechanisms due to breaking wave impacts and dike failures due to wave overtopping are reported from a storm surge in February 1825 (WOEBCKEN, 1925). In addition, unfavourable factors like animal activities in the dike were identified for the first time as a negative effect; burrow animals decrease the stability of the dike under breaking wave impacts or wave overtopping. This knowledge enhanced the design and the maintenance of seadikes. The crest level itself was still designed by experience.

During the storm surge disaster in the Netherlands in 1953, many dike failures and dike breaches occurred (about 139 km of damaged dikes). In 1962 and 1976, about 600 km of damaged dikes and several dike breaches and dike failures along the German coastline, respectively, resulted from severe storm surges in Germany. Fig. 4 shows a breaching estuarine dike near Hamburg during a storm surge in January 1976. A detailed summary of dike failures and dike breaches in Germany is given by SCHÜTTRUMPF and OUMERACI (2002). The

Fig. 3: Stack dike (about 1600) at the dike museum in Büsum (photo: MEIER, 2006)

Fig. 4: Breaching dike (photo: SCHOLZ, 1976)

coastal disasters in recent times changed the design philosophy of sea dikes in Germany. Before 1950, the crest level and the slopes of sea dikes were designed by experience. After that, the crest levels of sea dikes were designed deterministically based on a statistically determined design water level and a corresponding wave run-up height. Experimental investigations were applied to determine the wave run-up height (1$^{st}$ experimental investigation in Germany by HENSEN, 1954) and the wave overtopping rate (1$^{st}$ experimental investigation in

Germany by TAUTENHAIN, 1981). Other failure mechanisms of sea dikes such as the landward slope were considered by experience without taking the individual failure processes into account. Nowadays, it is the objective in Germany to improve the scientific knowledge concerning the probabilistic design of seadikes (KORTENHAUS, 2003). However, the probabilistic design has not found its way into practice yet.

Tab. 2. Storm Surge Disasters in the Southern North Sea (WOEBCKEN, 1924; KRAMER, 1992; JENSEN, 2000)

| Date | Area | Remarks | Date | Area | Remarks |
|---|---|---|---|---|---|
| about 340 B.C. | Cimbrius Flood | | 26.2.1625 | Total Southern North Sea Coast | Shrove Tuesday flood. Ice flood |
| 17.2.1164 | Total Southern North Sea Coast | First Julianen-flood. One of the first severe storm surges after construction of the first seadikes. About 20 000 fatalities between Rhin and Elbe river | 11.10.1634 | West coast of Schleswig-Holstein | Very severe storm surge and many eye-witness reports. At least 8 000 fatalities |
| 16.1.1219 | West- and East Frisia (The Netherlands) | First Marcellus-flood. About 36 000 fatalities. An eye-witness report exists. | 22.2.1651 | | Petri-flood |
| 14.12.1287 | Total Southern North Sea Coast | Lucia-flood. Creation of the Dollart between the Netherlands and Germany. 50 000 fatalities | 12.11.1686 | The Netherlands and Germany | Martin-flood |
| 23.11.1334 | From East Frisia to Flanders | Clemens-flood | 24.12.1717 | Total Southern North Sea Coast | Christmas flood. 6 000 km² land flooded |
| 16.1.1362 | Total Southern North Sea Coast | Second Marcellus-flood. Creation and Extension of Jadebusen, Dollart, Harle, Ley-bay. End of north-frisia – mainland is transformed into an island area in the wadden sea. About 100 000 fatalities | 31.12.1720/ 1.1.1721 | Total Southern North Sea Coast | New Year Flood |
| 9.10.1374 and 1377 | East Frisia, Oldenburg | First and Second Dionysius-flood. | 3./4.2.1825 | Total Southern North Sea Coast | February Flood. Large areas flooded. About 800 fatalities. Many eye-witness reports |
| 1400 | Frisia | Frisia Flood | 1./2.1.1855 | Total Southern North Sea Coast | January Flood |
| 18.11.1421 | East England and The Netherlands | Elisabeth-Flood | 13.3.1906 | East Frisia, Oldenburg | March Flood |
| 1.11.1436 | Total Southern North Sea Coast | All Saints Flood | 1.2.1953 | The Netherlands and England | Netherlands Flood. Very Severe Flood in the Netherlands with about 1850 fatalities, many dike breaches and large flooded areas |

| | | | | | |
|---|---|---|---|---|---|
| 6.1.1470 | Total Southern North Sea Coast | Epiphany Flood | 16./17.2.1962 | Total Southern North Sea Coast | Second Julianen-Flood. Many dike failures and dike breaches. Heavy damages in Hamburg. About 315 fatalities in Hamburg |
| 26.9.1509 | East Frisia, The Netherlands | Cosmas- and Dami-anflood | Nov./Dez. 1973 | Total Southern North Sea Coast | 5 severe storm surges in a short time |
| 16.1.1511 | East Frisia, Oldenburg | Antonius-flood. Ice-Flood | 3.1.1976 | Total Southern North Sea Coast | Many Dike Failures but no severe consequences |
| 31.10/ 1.11.1532 | Total Southern North Sea Coast | Second All Saints Flood. Several thousand fatalities. The height of this strom surge is delivered. | 24.11.1981 | Elbe and west coast of Schleswig-Holstein | November Flood |
| 1.11.1570 | Total Southern North Sea Coast | Third All Saints Flood. Between 9 000 and10 000 fatalities between Ems and Weser | 4.12.1999 | Elbe, west coast of Schleswig-Holstein and Denmark | Dike Breaches in Southern Denmark |
| 1572 | | Grain Flood | | | |

## 3. Modern Sea Dikes in Germany

The construction of sea dikes in Germany differs from federal state to federal state resulting from the local topography, from the availability of different soils, from the local sea states and experiences. A comparison of the different dike elements for the different federal states is shown in Tab 3.

Tab. 3: Typical values for dike elements in the different German states (EAK, 2002)

| | Lower Saxony (North Sea) | Schleswig-Holstein (North Sea) | Hamburg (Elbe estuary) | Schleswig-Holstein (Baltic Sea) | Mecklenburg-Vorpommern (Baltic Sea) |
|---|---|---|---|---|---|
| Seaward Slope | 1:6 | 1:6 to 1:10 | 1:3 | >1:6 | 1:3 to 1:6 |
| Thickness clay (Seaward slope) | 1.3 to 1.5 m | 1.0 m | 1.5 to 2 m | 1.0 m | 0.5 to 1.2 m |
| Crest width | 3 m | 2.5 m | 3 m | 2.5 to 3 m | 3.0 to 3.5 m |
| Landward Slope | 1:3 | 1:3 | 1:3 | 1:3 | 1:2 to 1:3 |
| Thickness clay (Landward slope) | ≥ 1.0 m | 0.5 m | > 1.3 m | ≥ 0.5 m | ≥ 0.5 to 0.7 m |

Two different types of sea dikes can be distinguished (Fig. 5). Type 1 has a wide foreland at an elevation above MHW to protect the dike toe. At storm surge water levels, the high foreland reduces the incoming wave parameters by wave breaking. The width of the foreland can reach several hundred meters. At normal tides, no water, waves or currents affects the dike toe. Thus, no revetment is needed to protect the dike toe. If a smooth slope is not possible due to place constraints, a light revetment is recommended. If no foreland protects the dike, a heavy revetment at the toe of the dike is recommended (Type 2). These revetments are often constructed with a slope 1:3, a toe embedded in the sea bed to avoid scouring and a crest reaching a height of about 1.50 m to 2.0 m above MHW. Usually, an asphalt or concrete berm is located landward of the crest of the revetment. Berms constructed 1.0 m to 2.0 m above MHW with a width of up to 3.0 m often serve as service roads.

The seaward slope of a dike can differ between 1:3 (some estuarine dikes and Baltic Sea dikes without heavy wave loads) and 1:7 (at very exposed locations along the North Sea coast). In general, a grass- covered 0.5 m (Baltic Sea) up to 2.0 m (North Sea dikes) thick clay layer is preferred to avoid erosion and scouring due to wave loading. The quality of the clay is defined in EAK (2002) and in Tab. 4. Some dikes are protected by asphalt or concrete layers, but, generally, grass covered dikes merging into the landscape are preferred. Nowadays, the core of a dike consists of sand with a drainage system towards a trench at the landward toe.

Tab. 4: Critical limits for clay for cover layers of dikes (EAK, 2002)

| **Soil properties** | **limits** | | |
|---|---|---|---|
| | **Well suited** | **suited** | **Limited** |
| **Type of soil** | **Clay** | **Sandy clay** | **Very sandy clay** |
| **Percentage of clay** | 20–40 | 15–20 | 10–15 |
| **Percentage of sand** | 10–40 | 25–50 | 30–50 |
| **Flow limit** | 35–70 | 30–55 | 25–40 |
| **Plasticity index** | 20–45 | 15–20 | 10–15 |
| **Water content** | 25–60 | 25–50 | 25–45 |
| **Dry bulk density** | 1.10–1.45 | 1.15–1.50 | 1.25–1.55 |
| **Undrained shear strength** | ≥ 25 | ≥ 30 | ≥ 40 |
| **Organic matter** | ≤ 10 | ≤ 10 | ≤ 5 |

The crest of a sea dike or an estuarine dike in Germany has a width of 2.0 m to 3.5 m to allow vehicles or pedestrians traffic. The crest is slightly sloped to enable overtopping water or rain to flow landwards or seawards without infiltration.

The landward slope has to fulfil geotechnical aspects (no sliding) and erosion or infiltration due to wave overtopping should be avoided. Besides, harvesters should be able to drive on the landward slope. Therefore, landward slopes range between 1:2 and 1:5, but most of the existing slopes are constructed with a gradient of 1:3.

A berm with a width of up to 10 m with a 3 m to 4 m wide road is situated at the toe of the landward slope. This permits heavy vehicles to drive along the dike even during very severe storm situations. The landward berm is located about 0.5 m to 1.0 m above MHW to ensure trafficability even when the low lying areas are flooded during extreme situations.

Finally, an inner ditch is constructed at the toe of the landward berm to collect drained water or rain.

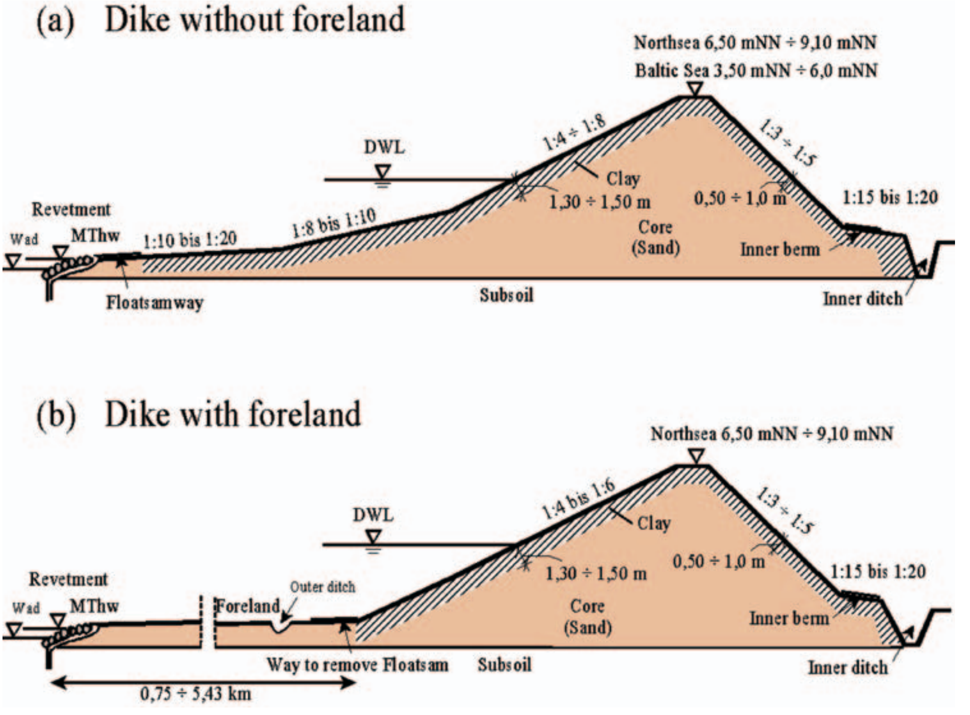


Fig. 5: Typical dike profiles in Germany (SCHÜTTRUMPF, 2001)

## 4. Crest Level Design of Sea Dikes

Different design philosophies are practised in the German federal states (Fig. 6). Lower Saxony and Bremen have adopted the a-b-c-d-method for seadikes. The design water level is calculated based on the mean tidal water level (a), the difference between the highest spring tide water level and mean high water level MHW (b), the difference between the highest water level (HWL) and MHW (c) and the sea level rise (d). This water level is compared to a water level based on the reference method. The water level based on the reference method is the highest ever observed water level plus a safety margin. The maximum of both methods is used as the design water level for sea dikes in Lower Saxony and Bremen.

This method, however, cannot be used for estuarine dikes in Lower Saxony nor in Bremen and Hamburg because of the influence of the river discharge (Weser and Elbe), a number of construction measures along the estuary (e.g. dikes and barriers) and fairway adaptations in the past. Due to the inhomogeneity of the water level records in the estuaries, the design water level for estuarine dikes in Bremen, Hamburg and Lower Saxony is calculated based on numerical simulations for an undisturbed reference gauge. Finally, a wave run-up height is added to the design water level for sea dikes and estuarine dikes in Bremen, Hamburg and Lower Saxony.

Different methods to determine the design water level are also used along the west coast of Schleswig-Holstein. The design water level should fulfil three conditions. It should (a) have an occurrence probability of 1 in 100 years with respect to the year 2100 (statistical method), (b) not be lower than the ever observed highest water level (reference method) and (c) not be lower than a water level calculated from the a-b-c-d-method. In general, the statistical method gives the highest value for the west coast of Schleswig-Holstein.

Along the east coast of Schleswig-Holstein the reference method is adopted based on an extreme storm surge in 1872 which has never been exceeded. Therefore, the water level from 1872 plus 0.5 m to account for sea level rise is used along the east coast or Baltic Sea coast of Schleswig-Holstein. Finally, a design wave run-up height is added to the design water level along the west and the east coast of Schleswig-Holstein. In addition, a critical mean overtopping rate of 2 l/(sm) should not be exceeded.

The reference method with respect to the extreme storm surge in 1872 is also used along the Baltic Sea coast of Mecklenburg-Vorpommern. An additional value with a range between 0.15 m and 0.25 m, which is to account for sea level rise, is considered. The wave run-up height is added to determine the crest height.

The wave run-up height is calculated in all Federal States according to the "Guidelines and Recommendations for the Design of Coastal Structures" (EAK, 2002).

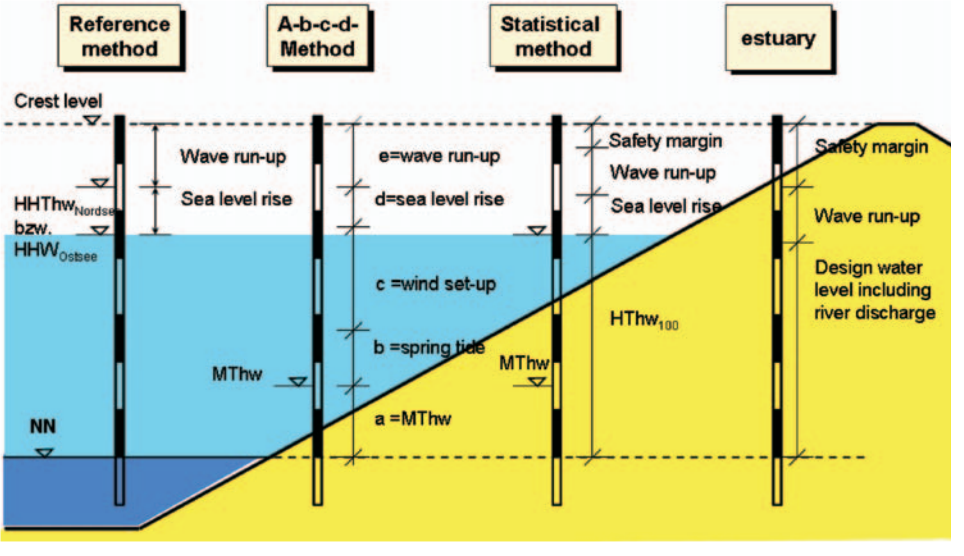


Fig. 6: Methods to calculate the design water level in Germany

Nowadays, it is recommended to apply the European Overtopping Manual (PULLEN et al., 2007) for wave overtopping analysis, which has been set-up in a joint project between the Netherlands, United Kingdom and Germany.

## 5. Future Aspects of Sea Dike Design in Germany

Thirteen working groups were set up by the German Society of Port Engineering (HTG) to identify important research topics for coastal and estuarine areas. Two of these working groups are related directly to sea and estuarine dikes and some important research topics for sea and estuarine dikes were identified. PETERS et al. (2008) highlighted further research topics concerning the geometry of dikes, the interaction of the hydrodynamic processes and the soil properties, the design of seadikes, the monitoring of sea and estuarine dikes and new strategies for a better coastal and storm surge protection of low lying areas. A number of research topics were also identified by KORTENHAUS et al. (2007) related to the probabilistic design of seadikes. KORTENHAUS et al. identified further research related to a better description of the failure mechanisms and the uncertainties for coastal structure design. More sophisticated probabilistic models are required to keep simulation time manageable. These aspects must be included in a software which is easy to use and considers a database of all relevant information. Finally, critical failure probabilities are required.

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# Storm Surge Protection Walls in Germany

By Andreas Kortenhaus, Thomas Buss, Oliver Sulz, Jeff Marengwa and Hans-Andreas Lehmann

Contents



## 1. Introduction

Storm surge protection walls (SPW) are vertical or almost vertical walls used to prevent flooding of low-lying areas during storm surges with extremely high water levels. They are often built on top of revetments, sea dikes or simply as plain vertical walls in harbour areas. Hence, both their utilization and type of construction is manifold. Next to the classic green dikes, SPWs are considered fundamental storm surge protection measures in Germany many of them can be found in Lower Saxony, Schleswig-Holstein, Bremen, Hamburg and Mecklenburg-Vorpommern.

In Mecklenburg-Vorpommern, 27 assets with a total length of 9.5 km (sheet pile walls, cantilever retaining wall and gravity walls) can be found. The longest construction is about 1.2 km and 6 gates are also part o the defence line. In Lower Saxony there are no figures at hand to provide an overview of these constructions since numerous walls may be found along the major estuaries of the rivers Ems, Weser and Elbe. Additionally, sea wall constructions with vertical walls are also used as coastal protection schemes on some of the major East Frisian Islands.

In Hamburg, there are two storm surge protection units which are the public storm surge protection installations and the private protection assets (private polders in the harbour). The total length of the public storm surge protection assets is about 103 km, 25 km of which are built as protection walls. Additionally, 33 gates, six sluices, and six barriers can be found in the public storm surge protection area. The total length of the private polder protection walls in the harbour is about 100 km. The walls are disposed in 45 assets. For operational harbour business reasons 886 gates are also part of the private storm surge protection system.

This chapter provides an overview of the various types of vertical storm surge protection assets which can be found in the various states along the North and Baltic Sea coast in Germany. The chapter starts with some examples of typical vertical wall constructions, illustrated by photos and cross sectional drawings. Furthermore, some details of the history of this type of wall are given before a summary of the main design steps for assessing wave overtopping and wave loading at these walls is given. Finally, maintenance aspects of vertical walls are briefly discussed and some future design aspects for an improved stability and safety of these structures are introduced.

## 2. Types of Vertical Coastal Defence Structures in Germany

Numerous types of vertical wall constructions are being used for coastal or harbour protection in Germany. In this chapter, some typical examples of structures – recently built or renewed and with the associated documentation available – are shown. They are of the following type (Fig. 1 to Fig. 4):

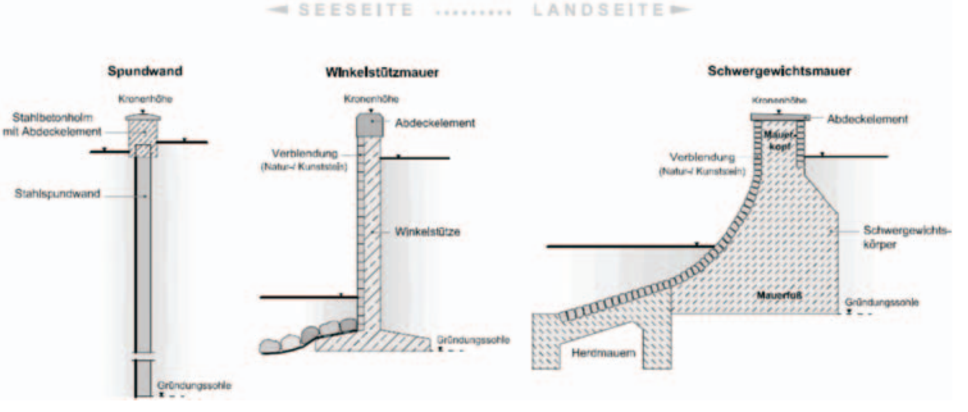


Fig. 1: Examples of storm surge protection walls

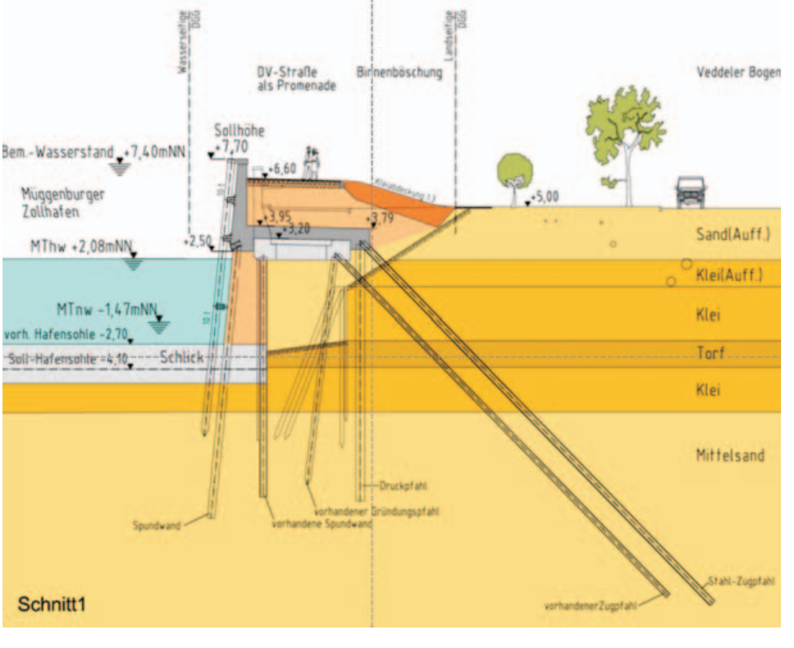


Fig. 2: Example of combined cantilever retaining wall (Hamburg)

Fig. 3: Typical example of a gravity type wall in Nienhagen (Baltic Sea)

Fig. 4: Sheet pile wall with concrete cap (Karlshagen, left; length: 183 m) and cantilever retaining wall (Heiligendamm, right)

- sheet pile walls (with or without concrete caps) (Spundwände);
- gravity walls (Schwergewichtsmauern);
- cantilever retaining walls (Winkelstützmauern);
- brick and stone walls (Steinmauern)
- combined cantilever retaining walls on sheet-pile foundations (Winkelstützmauern auf Spundbohlen), primary defence type in Hamburg

There is a wide spectrum of functionality of these walls comprising flood and storm surge protection, mooring abilities for ships, stability for embankments or revetment constructions and many more. Moreover, flood gates can be also considered as vertical walls. This may also include existing mobile flood protection walls such as stop-logs or bulkheads which need to be designed in a similar way. Size and length of these constructions may vary substantially, depending on where they were built and which purposes they serve. Usually, their height ranges from some decimetres to several meters, whereas lengths may be between a couple of meters and several kilometres.

A typical gravity wall may be found in Nienhagen (Baltic Sea coast), as shown in Fig. 3. Other examples in Fig. 4 show a sheet-pile wall with a concrete cap (left) and a cantilever retaining wall (right). All examples were taken from the Baltic Sea coast.

A new and innovative vertical storm surge protection wall is being built in Hamburg St. Pauli (Fig. 5). Due to space limitations, limitations of inclination of the access bridge and other restrictions, the existing building on the right hand side of Fig. 5 (Brückenhaus) serves as an elevated part of the storm surge protection scheme. The extension above the design water level is partially made of armoured glass in order to provide the public with a view from the building onto the harbour area.

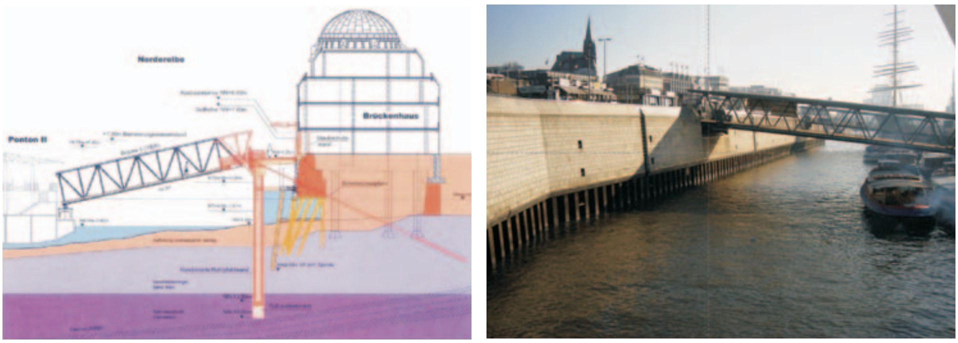


Fig. 5: Cross-section and photo of the public storm surge protection wall at 'Landungsbrücken, St. Pauli' Hamburg (photos: LSBG)

A major reconstruction of storm surge protection walls was built in 2003 at Großmarkt in Hamburg. Fig. 6 shows the overall extension of this wall of Großmarkt (left). The right side of Fig. 6 shows the storm surge protection wall from the water side. It can be seen that these walls are massive constructions which may reach considerable heights.

Fig. 6: Public storm surge protection wall at Großmarkt in Hamburg (left: aerial view; right: wall as seen from the water) (photos: LSBG, 2003)

Fig. 7 shows part of the Bostelbeker main dike which comprises a sheet-pile wall integrated in the dike line. The construction combines a classical green dike (seen from the landside in the left part of Fig. 7) with a vertical sheet-pile wall on top. Usually, space limitations and/or shortage of building material such as sand and clay are the key reasons for building vertical walls rather than sloped dike structures. Although the construction is relatively simple, other possible problems such as the structure's life time, deterioration maintenance

Fig. 7: Public storm surge protection: Bostelbeker main dike (left, length: 770 m) and sheet pile wall section at Bostelbeker main dike (right) (photos: HPA, 2007)

problems, ecological aspects, and costs have to be considered when selecting the type of protective structure. Other examples of sheet-pile walls can be found downtown in the city of Hamburg and near Finkenwerder (newly built sheet-pile walls protecting the Airbus production facility against storm surges).

In addition to vertical walls, Hamburg and other cities along the North and Baltic Sea coast maintain various other structures (gates, weirs, sluices) to prevent inhabited areas from being flooded. Examples of such structures are given in Fig. 8 with both, a mobile lift gate

Fig. 8: Use of a flood protection lift gate (left side) and a flap gate for flood protection (right side) as part of the public storm surge protection (photos: LSBG, 2007)

Fig. 9: Use of different protection gates (bulkhead gate in front and revolving gate, rear) at Dradenau main dike along the northern head of the port railway station "Alte Süderelbe" as part of the public storm surge protection (photo: HPA, 2006)

(left side) and a permanently installed flap gate (right side). In Fig. 9, another two types of gates (bulkhead and revolving gate) are depicted. Gates and mobile walls are also considered to be flood or storm surge protection structures.

All gates in Hamburg as part of the public flood protection are built following the "double safety/redundancy" concept which means that (i) there are two gates behind each other; (ii) there is always an alternative possibility to close the gate; and (iii) there are additional mechanical tools to open and close the gates. For gates, this usually means that they can either be operated by usual machinery or hydraulic engines but also by hand or emergency operation systems.

A standard type wall as part of the private flood protection has been constructed at Köhlfleet (Fig. 10). It shows an anchored sheet-pile wall with a vertical front and a back side construction with two pedestrian walkways and housing in the immediate vicinity.


Fig. 10: Public storm surge protection wall 'Köhlfleet', Hamburg (graphics and photo: HPA, 2002)

In the private polders in the harbour, a multitude of types of storm surge protection wall is being used at various locations such as Predöhlkai (sheet-pile wall, also used as a quay wall) or Köhlfleethafen (cantilever retaining wall, Fig. 11). In the right part of the figure, the SPW is shown during construction. The different crest elevations illustrate the difference between old (crest elevation at NN + 7.50 m) and new design (crest elevation at NN + 9.50 m), which was derived from wave overtopping considerations for this part of the harbour.


Fig. 11: Private storm surge protection in Köhlfleethafen: (left: new cantilever retaining wall; right: difference between old SPW at NN + 7.50 m and new SPW at NN + 9.30 m) (photos: HPA, 2008)

## 3. History of Storm Surge Protection Wall Design

Whereas the history of dikes, being earthen structures, in Germany and The Netherlands is rather long (see chapter on sea dikes in this book) references to the design of storm surge protection walls are scarce, since most of these structures are either built of concrete or steel. On the other hand, there is proof that sea walls in the UK and elsewhere are dating back until Roman times and even earlier (see e.g. THOMAS and HALL, 1992). Ancient sea walls were built back to Egyptian and Constantinople times where rudiments these walls are still visible today. While these structures were made of brick or big stone blocks, modern walls use steel and reinforced concrete.

In Germany, the storm surge of 1962 has caused many dike breaches and more than 300 casualties, particularly along the Elbe estuary and in Hamburg. However, in the harbour of Hamburg where the storm surge reached NN + 5.70 m, old wharf-type structures that were built up to the same elevation were not severely affected by the storm surge. The catastrophe of 1962 triggered intensive re-design and construction of new and adapted public storm surge protection schemes, including new dikes and protection walls. The latter, rather unknown until then, were built at high speed, including the existing quay structures. It was only after the storm surge of January 3, 1976, where the highest water level ever was recorded in Hamburg (NN + 6.45 m), when the intensive design and construction of private storm surge protection walls started in the harbour of Hamburg. The private storm surge protection facilities had been previously designed for a height of NN + 7.50 m and protected major parts of the city against flooding.

At present, the public flood protection walls are being re-designed and adapted to new design water levels. Hence, the crest elevation of most of these walls is being increased or the structures are completely being replaced by new ones. New crest elevations of those structures in Hamburg are between NN + 7.50 m and NN + 9.25 m, depending on the design water level and the wave climate at the respective location. Costs for a storm surge protection wall in Hamburg may range from 20.000 to 50.000 €/running meter.

## 4. Present Design Practice

Presently, storm surge protection walls are being designed regarding the following parameters:

- wave overtopping over the wall crest to determine its height;
- wave induced loads on the walls;
- geotechnical aspects for wall stability.

While the geotechnical aspects of the subsoil are not considered here, both wave overtopping and wave induced loads will be briefly discussed in the following:

The crest elevation of walls is usually determined by a maximum acceptable overtopping rate under wave attack. This may be either defined based on the maximum volume of water which can be drained free of damage in the rear of the wall or on the stability of the wall or its foundation under overtopping waves. Recommendations for assessing the overtopping quantity are given in the 'Recommendations for Storm Surge Protection Walls in Hamburg' (Freie und Hansestadt Hamburg, 2007) or in the new 'Wave Overtopping Manual' (http://www.overtopping-manual.com/manual.html).

Considering wave induced loading on such walls, there is a range of different design method for a specific type of wall, none of which is really 'globally' accepted. Possible sources to design storm surge protection walls based on other parameters of influence are as follows:

- Empfehlungen des Arbeitsausschuss Ufereinfassungen (EAU, 2004 or EAU, 1996)
- Design method for vertical walls (GODA, 2000)
- Zusätzliche Technische Vertragsbedingungen – Wasserbau (ZTV-W) der Wasser- und Schifffahrtsverwaltung des Bundes

While the EAU contains design recommendations for different types of walls (e.g. sheetpile walls and gravity walls), including some recommendations for different types of wave loading and soil failures, GODA (2000) proposes design loads for vertical wall breakwaters, a method which has been found to be transferable to other vertical structures (KORTENHAUS et al., 2001). The design recommendations for storm surge protection walls in Hamburg (Freie und Hansestadt Hamburg, 2007) comprise different methods for different types of loading of the wall. They also propose different measures on how to reduce the wave overtopping such as parapets and underwater sills, and they discuss the consequences of using such measures.

In addition to these general design recommendations, some of the following more practical design rules might apply:

- There should be infrastructural installations for the inspection and defence of the wall such as a road as a direct access (Deichverteidigungsweg). Elevation of the road should such as to overview the wall.
- The type of structure should be planned according to various aspects such as vibrations, noise, available space, material and equipment supply, etc.

- It might be advantageous to include in the design an option of raising the wall crest in the future.
- The use of wave dissipation systems in front of the wall should be considered in order to reduce wave heights and, consequently, loads.
- Open chambers or cavilties underneath the structure should be avoided since they have to be inspected frequently. If unavoidable, inspection possibilities have to be provided in the design.
- If sheet-pile walls are in contact with air, corrosion protection should be applied up to 0.50 m underneath soil surface. Locks should be sealed to avoid corrosion.
- To avoid erosion behind storm surge protection walls, the surface behind the wall should be armoured.
- Cable crossings should be arranged above the structure, if possible. Wherever this is not possible, cables should be bundled and pipelines carrying fluids should be equipped with additional valves.

## 5. Maintenance Aspects of Storm Surge Protection Walls

Storm surge protection structures are exposed to exceptional conditions under which they are required to perform their protection function, whilst they are continuously exposed to deteriorating processes. The technical demands on such structures are compounded by economic pressures and constraints on their maintenance. Since their proper functioning is not directly related to operational requirements, the allocation of sufficient budgets and resources for maintenance is problematical.

The effects of deterioration are structure and site specific. Concerning structural strength, the main deterioration processes are corrosion and fatigue. Typical indications of deterioration are spalling, cracking, and degraded surface conditions. A majority of concrete structures in the marine environment under hydraulic loads shows signs of degradation due to corrosion of the reinforcement. Beside the influence of the marine environment, other factors are responsible for the corrosion, such as: poor construction quality, inadequate standards based on prescriptive measures; and poor design as a result of insufficient information about the most important parameters that influence the degradation process.

Maintenance may be defined as "all activities aimed at retaining an object's technical state or at reverting it back to this state, which is considered a necessary condition for the object to carry out its function." This definition includes the repair of the structural strength, back to the starting level, and also any inspections. The following types of maintenance can be distinguished (JCSS, 2001):

- Corrective maintenance: there will be no inspection and repair is done after failure has occurred (this will be done if the cost of failure is low and the inspection costs are high);
- Preventive maintenance: no inspection but maintenance (repair) is done at a time no failure has occurred (this will be done when failure costs are high and failure is predictable;
- Condition based maintenance: inspections are planned and some measurable parameters are no longer fitting specific maintenance criteria (inspection intervals are fixed or depending to measured conditions)

There are two phases of a structure's life cycle in which it can be useful to apply maintenance optimisation techniques: the design phase and the serviceability phase. In the design phase, one might obtain an optimum balance between the initial costs of a structure and the future costs of maintenance and failure. In the serviceability phase, it might be possible to minimise the costs of inspection, repair, replacement, and failure. In Germany, responsibilities for maintenance works are usually laid down in the state regulation plans for the German coastal states (NLWKN, 2008; BEZIRKSREGIERUNG WESER-EMS, 2002; MLR, 2001).

To manage flood defences and structures, the maintenance has to be optimised and renewal and replacement of assets should be based on performance and effectiveness. That encourages maximum return on investment through whole-lifecycle costing. Based on such a "Performance-Based Asset Management System", critical assets will be protected from breakdown. Such a management system will lead to the following benefits:

- Asset management activity can be focused on priority areas (in terms of flood probability and consequences);
- It will enable the Authorities to assess flood risk arising from a range of asset management options, and to select cost effective maintenance/repair options;
- It will limit or stop activities that are not justified, in terms of reducing flood risk;
- Assets will be managed based on evidence of their performance and risk, accounting for climate change;
- Risk and uncertainty-based approach will allow better planning for future uncertainties.

Performance based management should be applied to all flood defence assets like embankments, walls, rivers, and tidal and sea defences. It also should be applied to structures which have a primary flood defence function such as gates, locks, sluices and pumps.

The following key problems will need to be addressed by further research (MARENGWA, 2007):

- The flood defence system is complex, with multiple components contributing to the structure's performance (or reliability) during a flood event.
- It is difficult to obtain meaningful indicators of asset performance by visual inspection alone.
- Assessing the improvement in performance resulting from management interventions (ranging from routine maintenance to major renovations) is difficult.
- Whole life asset management will need closer integration of maintenance and capital decision-making with good representation of performance over the asset's life.

## 6. Future Aspects of Vertical Wall Design in Germany

There is still a fundamental gap in understanding the physics of wave impacts on vertical and/or almost vertical walls (BRUCE et al., 2007). A consistent method is needed to distinguish the key loading cases for vertical or almost vertical walls (standing, slightly breaking, impact, already broken waves). Even though, after having solved this, the design for wave loads is still not simple and straightforward. So far, the key recommendation is to avoid direct wave impact on walls whereever possible. However, where that is unavoidable, a system analysis should describe the interactions between waves, structure and soil and the dynamic amplification factors for the time-dependent wave loads to be determined on this basis (CUOMO, 2005).

A new design of storm surge protection walls might be devised and considered for practical applications. This should not include the use of parapets (PEARSON et al., 2004, for a start), but also consideration of new shapes and mobile elements or even entire mobile walls.

Advantages and disadvantages of these new types of walls should be drafted and further discussed.

Further research on storm surge protection walls should deal with uncertainties related to wave loads and the methods used for design. Presently, recommendations on how to use uncertainties in design are elaborated on within a working group of EAK. Further research has also been recommended recently (KORTENHAUS et al., 2007).

## 7. Acknowledgements

The major part of the information and photos used in this paper have been provided by the 'Hamburg Port Authority' (HPA), the 'State Agency for Roads, Bridges and Waters' in Hamburg (LSBG – Landesbetrieb für Straßen, Brücken und Gewässer), the 'State Agency for the Environment and Nature Conversation Rostock' (StAUN – Staatliches Amt für Umwelt und Natur Rostock), and 'Der Senator für Bau und Umwelt', Bremen. This support is gratefully acknowledged. Furthermore, Volker Barthel provided very valuable comments on the manuscript which have significantly improved the paper. This support was also very gratefully received.

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# Tidal Barriers at the North and Baltic Sea Coast

By HANS-ANDREAS LEHMANN and HEINZ JASPER

## Contents



## 1. Introduction

The German North and Baltic Sea Coast being an integral part of the Federal provinces (Länder) Lower Saxony, Bremen, Hamburg, Schleswig-Holstein and Mecklenburg-Vorpommern was shaped by the last ice age. Under the influence of the external forces of the sea it evolved to be a continuously changing boundary line between land and water.

Approximately 2,500 years ago, man began to colonize the coastal zone. Subsidence of the coastal area as well as the melting process of the polar ice led to gradually rising sea levels and, consequently, more frequent flooding of coastal areas. In order to protect themselves against rising water levels the coastal people started building earth mounds (Warften, Wurten) some 2000 years ago. The further rise of the mean sea level necessitated a continuous raising of these mounds. For a more efficient protection of houses and arable lands the construction of dikes started some 1,000 years ago.

While initially low elevation 'summer' dikes were sufficient for protection increasing tidal levels and storm surges required structures with higher crown elevations. Thus, dikes were strengthened and raised in the course of time. In the following centuries, dike design and construction evolved to create the present efficient flood protection system.

Two main tasks have developed from human habitation of the coastal zone:

- Coastal protection – stabilization of the coastline (prevention of loss of land/receding of the coastline)
- **Flood protection** – prevention of flooding of lowlands during storm surges.

**Flood protection is generally defined as the sum of all measures for the protection of the population and material goods against flooding.** The protection is provided by flood protection structures (Hochwasserschutzanlagen HWS). This does not only include dikes but particularly artificial structures such as protective walls, sluices, pumping stations and **barrages/tidal barriers**.

## 2. Barrages, their Development and Operation

In Germany, the planning and design of barrages to dam off entire river regimes and estuaries started about 100 years ago. Initially, their main task was to obstruct storm surges and, thereby, prevent the intrusion of large water masses into river regimes and estuaries and the adjacent fertile lowlands. Thus, barrages provided the basis for a full utilization of those areas for agriculture and habitation. In 1936, the first Eider barrage was completed, followed by the Leda Barrier in the Ems estuary in 1950.

The severe storm surges in the Netherlands in 1953 and at the German North Sea coast in February of 1962 were catastrophic events necessitating the strengthening and raising of crown levels of existing dikes as well as the design and construction of tidal barriers. Another storm surge in 1976 affected particularly the Hamburg harbour region. Based on the experience of these events, major efforts have been undertaken to improve coastal and flood protection. This required major financial investments into the improvement and completion of all protective (HWS) structures.

Often, the construction of tidal barriers results in a shortening of the dike defence line. Consequently, the placing of a barrage close to the river mouth seems to be reasonable. Because of their location barrages would also meet important requirements of water management such as drainage of lowlands, maintaining inland water levels during dry periods and/or maintaining or improving the navigability of a main navigation route and/or tributaries by impounding water.

## 3. Barriers/Barrages in Germany

The following table deals solely with storm surge barriers. Sluices and locks are not included, even though they can function as barriers dependent on their location. Along the German North Sea coast and in the estuaries, we can find 32 barrages which have to ward off storm surges.

While the Eider Barrier with a discharge width of 200 m used to be the largest and most impressive German tidal barrage at the North Sea coast, in the meantime this claim has been taken over by the Ems Barrier with a passage width of more than 400 m.

Table 1: German tidal barriers

| lfd. Nr. | Sperrwerke | Inbetriebnahme | Kennzeichnende Größen | Ansprechpartner |
|---|---|---|---|---|
| 1 | Leda-Sperrwerk | 1954 | Durchflussweite: 70 m<br>Öffnungen: 5 × 14 m<br>Verschlüsse: Hubtore | WSA Emden |

| | | | | |
|---|---|---|---|---|
| 2 | Ems-Sperrwerk | 2002 | Durchflussweite: 414 m<br>Öffnungen: 7<br>(60 m, 2 × 50 m, 4 × 63,5 m)<br>Verschlüsse: 1 Drehsegment,<br>1 Segment, 5 Hubtore<br>(1-fache Sicherheit) | NLWKN<br>Betriebsstelle Aurich |
| 3 | Sperrwerk Leysiel | 1991 | Durchflussweite: 30 m<br>Öffnungen: 3 × 10 m<br>und Seeschleuse<br>Verschlüsse: Hubtore | NLWKN<br>Betriebsstelle Aurich |
| 4 | Hunte-Sperrwerk | 1979 | Durchflussweite: 92 m<br>Öffnungen: 4<br>(2 × 26 m und 2 × 20 m)<br>Verschlüsse: 2 Stemmtore und<br>2 Segmenttore | NLWKN<br>Betriebsst. Brake-Oldenburg |
| 5 | Ochtum-Sperrwerk | 1979 | Durchflussweite: 20 m<br>Öffnungen: 2 × 10 m und<br>Schleuse<br>Verschlüsse: Hubtore | NLWKN<br>Betriebsst. Brake-Oldenburg |
| 6 | Lesum-Sperrwerk | 1979 | Durchflussweite: 60 m<br>Öffnungen: 4 × 15 m<br>und Schleuse<br>Verschlüsse: zweiteilige Hubtore | Bremischer Deichverband<br>a. r. Weserufer/Bremen |
| 7 | Geeste Sturmflutsperrwerk | 1961 | Durchflussweite: 31 m<br>Öffnungen: 1 × 24 m<br>und Spülöffnung<br>Verschlüsse: Stemmtore und<br>Rollschütze | Bremenports GmbH & Co<br>KG/Bremerhaven |
| 8 | Sperrwerk Schleusenpriel | 1979 +<br>2009<br>n. Umbau | Durchflussweite: 19 m<br>Öffnungen: 1 × 19 m<br>Verschlüsse: Stemmtore | NLWKN<br>Betriebsstelle Stade |
| 9 | Sperrwerk Alter Fischereihafen | 2009<br>(geplant,<br>nach<br>Neubau) | Durchflussweite: 14 m<br>Öffnungen: 1 × 14 m<br>Verschlüsse: Stemmtore | NLWKN<br>Betriebsstelle Stade |
| 10 | Oste-Sperrwerk | 1968 | Durchflussweite: 110 m<br>Öffnungen: 5 × 22 m<br>Verschlüsse: 1 × Stemmtore<br>und 4 × Segmenttore | WSA Cuxhaven |
| 11 | Freiburg-Sperrwerk | 1967 | Durchflussweite: 8 m<br>Öffnungen: 1 × 8 m<br>Verschlüsse: Stemmtore | NLWKN<br>Betriebsstelle Stade |
| 12 | Stör-Sperrwerk | 1975 | Durchflussweite: 130 m<br>Öffnungen: 4<br>(2 × 22 m und 2 × 43 m)<br>Verschlüsse: 2 × Stemmtore<br>und 2 × Segmenttore | WSA Hamburg<br>Außenbezirk Glückstadt |

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|---|---|---|---|---|
| 13 | Sperrwerk Wischhafen | 1978 | Durchflussweite: 30 m<br>Öffnungen: 3<br>(1 × 20 m und 2 × 5 m)<br>Verschlüsse: 1 × Stemmtore und 2 × Hubtore | NLWKN<br>Betriebsstelle Stade |
| 14 | Sperrwerk Ruthenstrom | 1978 | Durchflussweite: 14 m<br>Öffnungen: 2 × 7 m<br>Verschlüsse: Stemmtor (vorn) und Hubtor (hinten) | NLWKN<br>Betriebsstelle Stade |
| 15 | Sperrwerk Abbenfleth | 1971 | Durchflussweite: 13,5 m<br>Öffnungen: 1 × 13,5 m<br>Verschlüsse: Stemmtore | NLWKN<br>Betriebsstelle Stade |
| 16 | Krückau-Sperrwerk | 1969 | Durchflussweite: 44 m<br>Öffnungen: 3<br>(1 × 20 m und 2 × 12 m)<br>Verschlüsse: 1 × Stemmtore und 2 × Hubtore | WSA Hamburg |
| 17 | Pinnau-Sperrwerk | 1969 | Durchflussweite: 36 m<br>Öffnungen: 3<br>(1 × 20 m und 2 × 8 m)<br>Verschlüsse: 1 × Stemmtore und 2 × Hubtore | WSA Hamburg |
| 18 | Schwinge-Sperrwerk | 1971 | Durchflussweite: 16 m<br>Öffnungen: 1 × 16 m<br>Verschlüsse: Stemmtore | NLWKN<br>Betriebsstelle Stade |
| 19 | Lühe-Sperrwerk | 1959 | Durchflussweite: 10 m<br>Öffnungen: 1 × 10 m<br>Verschlüsse: Stemmtore | NLWKN<br>Betriebsstelle Stade |
| 20 | Sperrwerk Este-mündung | 2000 | Durchflussweite: 40 m<br>Öffnungen: 1 × 40 m<br>Verschlüsse: Stemmtore | HPA<br>Hamburg |
| 21 | Baumwall-sperrwerk | 1969 | Durchflussweite: 7,30 m<br>Öffnungen: 1 × 7,30 m<br>Verschlüsse: Stemmtor (vorn) und Segmenttor (hinten) | LSBG<br>Hamburg |
| 22 | Nikolai-sperrwerk | 1969 | Durchflussweite: 10 m<br>Öffnungen: 1 × 10 m<br>Verschlüsse: Klapptore | LSBG<br>Hamburg |
| 23 | Sperrwerk Billwerder Bucht | 1966 + 2002 n. Umbau | Durchflussweite: 128 m<br>Öffnungen: 4<br>(2 × 34 m und 2 × 30 m)<br>Verschlüsse: Klapptore (oben gelagert) | HPA<br>Hamburg |
| 24 | Sperrwerk Veringkanal | 1965 + 2003 n. Umbau | Durchflussweite: 12 m<br>Öffnungen: 1 × 12 m<br>Verschlüsse: Stemmtore | HPA<br>Hamburg |
| 25 | Sperrwerk Schmidtkanal | 1966 + 2002 n. Umbau | Durchflussweite: 12 m<br>Öffnungen: 1 × 12 m<br>Verschlüsse: Stemmtore | HPA<br>Hamburg |

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|---|---|---|---|---|
| 26 | Sperrwerk Müggenburger Durchfahrt (privater HWS) | 1978 | Durchflussweite: 41,90 m<br>Öffnungen: 1 × 41,90 m<br>Verschlüsse: Klapptor<br>(1-fache Sicherheit) | HPA<br>Hamburg |
| 27 | Sperrwerk Marktkanal (privater HWS) | 1978 | Durchflussweite: 18,70 m<br>Öffnungen: 1 × 18,70 m<br>Verschlüsse: Klapptor<br>(1-fache Sicherheit) | HPA<br>Hamburg |
| 28 | Sperrwerk Peutekanal (privater HWS) | 1978 | Durchflussweite: 41,90 m<br>Öffnungen: 1 × 41,90 m<br>Verschlüsse: Klapptor<br>(1-fache Sicherheit) | HPA<br>Hamburg |
| 29 | Sperrwerk Seevesiel | 1966 | Durchflussweite: 15 m<br>Öffnungen: 3 × 5 m<br>Verschlüsse: Schlagtor (vorn) und Hubtore (hinten) | NLWKN<br>Betriebsstelle Lüneburg |
| 30 | Ilmenau-Sperrwerk | 1974 | Durchflussweite: 36 m<br>Öffnungen: 3<br>(1 × 16 m und 2 × 10 m)<br>Verschlüsse: 1 × Stemmtore und 2 × Hubtore | NLWKN<br>Betriebsstelle Lüneburg |
| 31 | Eider-Sperrwerk | 1973 | Durchflussweite: 200 m<br>Öffnungen: 5 × 40 m + Schleuse<br>Verschlüsse: 5 Segmentverschlüsse | WSA Tönning |
| 32 | Sperrw. Greifs-wald-Wieck | in Planung | Durchflussweite: 21 m<br>Öffnungen: 1 × 21 m und 2 × 17 m<br>Verschlüsse: 1 Drehsegment (1-fache Si.)<br>und je Uferseite 2 Schiebetore | Staatl. Amt für Umwelt und Natur/Ueckermünde |

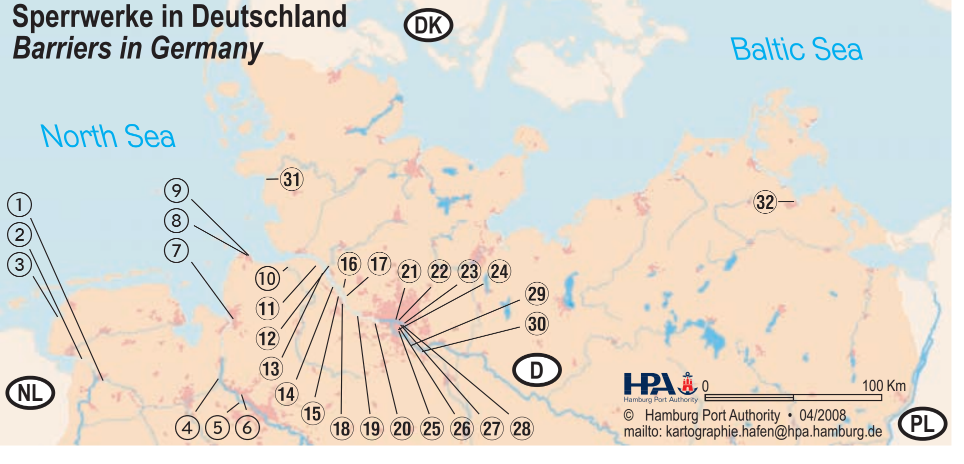


Fig. 1: Location of the German tidal barriers at the North and Baltic Sea coast

## 4. Layout and Concept of the Barrages

Planning and design of a tidal barrier requires a conception aimed at the particular location and its requirements as well as establishing the compatibility between the manifold operational tasks of the barrier with the various local and boundary conditions. Due to this, safety is of the utmost importance. Along with the standard principle of doubled safety for the gates the redundancy of technical systems plays an important role nowadays. The insertion of spare elements (e.g. two independent power supplies, doubled instruments or modules) serves to increase the reliability of technical systems in case of failures or break-downs and, thereby, guarantees a higher likelihood of uninterrupted operation.

### 4.1 Gates and Other Closure Devices

Mitring, radial, flap and vertical lift gates are the most common gate types which have evolved for barrages. Main advantages in comparison to other gate types are their economical design, the sturdiness, operational safety and the possibility of closing them even when the drives have failed. Moreover, they are easily maintained and repaired.

However, the choice of a suitable type of gate always depends on the particular case. Technical, operational and economical conditions always influence this decision.

### 4.2 Drives

While in the past mechanical drives using chains, steering racks and steel cables have been deployed generally hydraulic drives can be found nowadays. Mainly, they stand out because of simple maintenance and can be easily steered and monitored from a control centre.

### 4.3 Scour Protection

At the bottom of a river in front of and behind a barrier scouring can occur at different degrees. Particularly affected areas are to be protected against erosion. The extent of the scour protection is not only dependent on the local conditions (e.g. external forces, properties and stability of the bottom of the river or estuary). The Eider Barrier was built in a wadden sea environment in contrast to other barrages built in the course of a river or channel. Experience and practical knowledge derived from its operation have clearly indicated that the currents occurring under these particular conditions as well as the operation of the barrage substantially influence the development of scour. Therefore, and under these particularly difficult conditions, the execution of model tests is highly recommended. Because of still remaining imponderables the extent of the scour protection should not be designed too sparingly in order to prevent costly supplementary protection measures afterwards.

### 4.4 Additional Installations

To guarantee the operational safety of barrages in the cold season at low temperatures **electrical heating and air bubblers** are part of the standard equipment. They are to prevent icing around the seals, the gate stop faces and recesses.

In order to increase operational safety in case of a power failure, many barrages include an **auxiliary power generator**. For this purpose major barrages usually have a permanently installed diesel generator in a special casing or room. Smaller barrages have a mobile power generator or can be easily connected to an auxiliary power network.

For the purpose of inspection, repair and maintenance **auxiliary gates** can be inserted for drainage and dry access to the barrier gates. They are usually stop-logs, needle dams and gate boards. In case of a storm surge and for the replacement of entire gates the single auxiliary gate is not sufficient. Today, for that purpose barrages maintain a so-called double-safety standard, i.e. two gates arranged behind each other. Both are not necessarily of the same type.

An essential element of a functioning disaster control in case of a storm surge is a well maintained and open dike defence road. Thus, all barrages can be crossed on **bridges** which also may be part of major traffic arteries. Often, these are bascule or swing bridges which are only opened for the passage of ships if the barrage is connected with a lock.

### 4.5 Secondary Installations

If barrages have to be kept closed for a longer period the reservoir capacity between the river dikes may not be sufficient to store the fresh water discharge. This can be compensated for by coastal pumping stations and/or storage polders.

To enable navigation into and out of the rivers or estuaries at all times, the passages for maritime traffic of some barrages are designed as locks.

## 5. Design and Construction

The main issue of storm surge and flood protection is the safeguard of human lives and material values. However, the task of nature and landscape protection is to also maintain the bases of all animal and plant life. According to the present legislation the construction or improvement of a barrage represents an encroachment on nature and landscape. Thus, each and every case has to be examined and evaluated meticulously to arrive at a decision – even though the protection of human lives has priority. Aspects of nature and landscape protection have to be considered in the design of the planned structure in the sense of an encroachment minimization. Should, however, the project prove to be an encroachment on nature and landscape, compensatory measures have to be taken.

### 5.1 Legal Principles

Coastal and flood protection are the responsibility of the federal provinces (Länder) within the legal framework of the federal Water Management Act (Wasserhaushaltsgesetz).

Additionally, the European Community Law (EU) supersedes the national legislation. The single citizen, however, has no legal claim to flood protection and/or a certain type of protection measures. Coastal and flood protection structures or installations (HWS-Anlagen) require a project approval procedure (Planfeststellungsverfahren). The so-called dike regulations (Deichordnung) include restrictive bans on the utilization of such installations.

### 5.2 Owner Functions and Control

Coastal and flood protection installations, if not in private hands, are generally federal or provincial property unless a dike association (Deichverband) owns it. The supervisory authority – usually called water authority (Wasserbehörde) – has to control the status of the installation and carries out inspections on a regular basis. This does not apply to private installations, unless they are subjected to legal regulations such as the polder regulation in Hamburg. Areas in the harbour of Hamburg which are not protected by the public main dike due to their location are secured by polders. This private initiative was established after the storm surge of 1976.

## 6. Operation and Maintenance

The operation and maintenance of barrages are the responsibility of the owner. Independent of the mentioned mandatory control regulations, the owner checks and monitors his installation on a regular basis, thereby ensuring its operational safety and readiness. In addition to the daily visual check a regular preventive maintenance provides the essential basis for a safe and reliable operation.

Based on the present equipment of barrages with hydraulic drives and modern control technology, the operation of barrages could not be spared the current reduction of personnel. In modern barrages all functional and operational processes are automated. Within the framework of dike strengthening and crown elevation measures of the last few years the electrical control of older barrages has been adapted to modern standards. Steering, control and visualization on electronic monitors, alarms and recordings of all states of operation and messages are carried out by programmable-storage modules (SPS = Speicher programmierbare Steuerung) for the support of operating staff in the control centre.

## 7. Future Prospects

Coastal and flood protection is an everlasting task of generations. Predictions of future development prove to be difficult since the extent and evolution of climatic changes with their consequences for the German coastal zone are difficult to determine. In the foreseeable future, increasing design levels can be still counterbalanced with strengthening structures and raising their top levels. Moreover, these measures can be accompanied by a flood risk management. Decisions for further investment, however, need a reliable database. Should, therefore, the global sea level rise take on greater dimensions one would have to consider the design and construction of new and even larger barrages. Scenarios resulting in a sea level rise of several meters let us only guess the effects on the German North and Baltic Sea coast – a withdrawal of the inhabitants from the coastal regions could be the final consequence.

## 8. Description of Selected Barrages

### 8.1 Ems Barrier in Lower Saxony

With an overall width of 476 m the Ems Barrier is the largest and most modern barrage in Germany. After a construction period of four years, the barrage went into operation in September 2002. This was a delay of one year since construction had been brought to a halt by a court order in November 1998, just 2 months after the first pile had been driven. Quarrelling in court concerning the legality of the barrage had accompanied the project for several years. In a court settlement, the province of Lower Saxony committed itself to a payment of altogether 9 Million € for compensation measures along the river and estuary of the Ems.

Main functions of the barrage are on the one hand the improvement of the storm surge protection along the Ems and its tributaries. On the other hand the weir function would increase water levels to NN + 2.70 m and ensure navigability between Papenburg and Emden. Moreover, the safe transfer of larger vessels with a draught of up to 8.5 m was made possible.

The barrage has been planned for a design water level of NN + 6.4 m with a single safety. The second safety level is being provided by the existing dikes along the Ems (crown elevation NN + 8.0 m).

**Technical data:**

- Size of the barrage approx. 476 × 56 m
- 7 passage gates, with 1 main navigation opening (HSÖ) B = 60 m, 1 navigation opening for barges (BSÖ) B = 50 m, 5 secondary openings (NÖ): 1 × 50 m and 4 × 63.5 m wide
- Entire flow passage width: 414 m
- Water level during closure: NN + 3.5 m
- Clearance of the BSÖ = 5.25 m above MHW. Barges with a draught of up to 4.5 m can pass the opening
- Elevation of the threshold of HSÖ: NN – 9.0 m, BSÖ: NN – 7.0 m, NÖ: NN – 7.0 m and NN – 5.0 m
- Flood gate safety: single
- Type of gates: revolving sector gate (HSÖ), radial gate (BSÖ), lift gates in all NÖ
- Drives: hydraulic with two lifting cylinders at each gate
- In addition to the operations and information building the structure includes service bridges and tunnels (accessible sills in three northernmost openings) as well as a service pier
- Closing of all gates of the barrage takes approx. 30 minutes
- Overall costs of the project were more than 215 Million €

Fig. 2: Aerial photograph of the Ems Barrier/© NLWKN Aurich

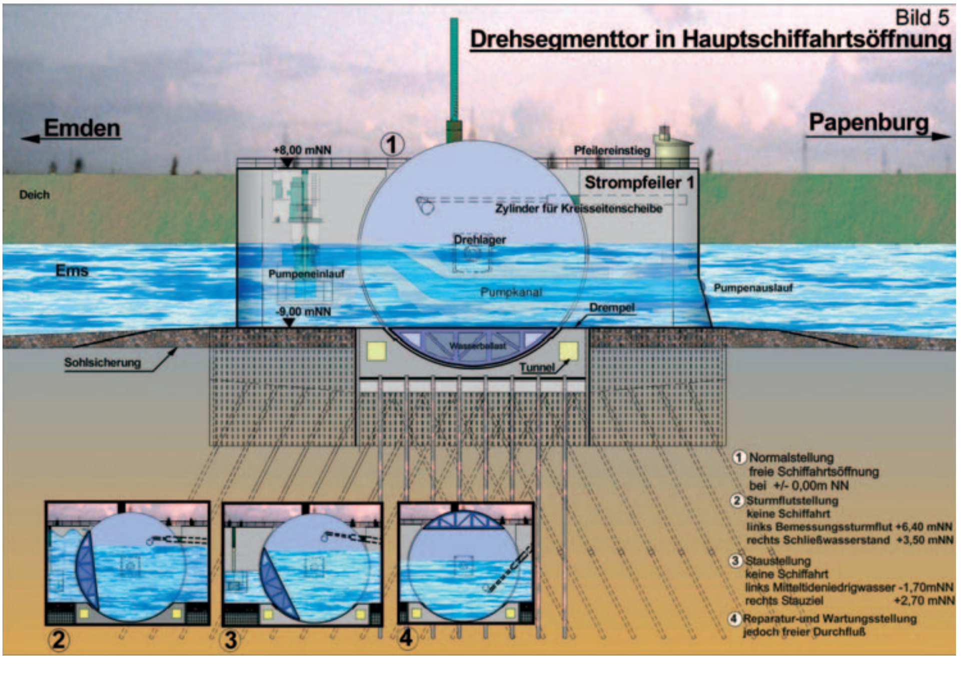


Fig. 3: Cross-section of pier No. 2/© NLWKN Aurich

**Construction procedure:**

The structure was built in a trench. Construction began with dredging works to move the main navigational channel. Securing the river bed with bush mattresses covered with armour stones was carried out before starting work on the bridge piers and sills. For the construction of the bridge piers sheet pile boxes were installed whose piles had to be driven through the river bed fortification. After driving the foundation piles, the sheet pile boxes were sealed on the bottom by underwater concrete. Thereby, bridge piers could be erected in dry building pits. After finishing the piers, the emplacement of the pre-fabricated sills with a single weight of up to 1,000 t were carried out. Only the sill of the HSÖ was cast in site-mixed-concrete in a dry building pit. Afterwards, service bridges and vertical lift gates as well as the sector gate and the service bridge of the BSÖ were installed. The revolving sector gate of the HSÖ was lowered onto its hinges. In March 2002, the HSÖ was opened for navigation – the outer geometry of the barrage was finished. The completion of the service building followed, and transformers and the electrical, hydraulic and machinery equipment were installed.

## 8.2 Lesum Barrier in Bremen

To achieve a comprehensive solution of coastal protection problems on the Lower Weser, the provincial government of Lower Saxony and the Senate of the Free and Hanseatic City of Bremen decided on the erection of three tidal barrages in the river mouths of Hunte, Lesum and Ochtum, tributaries to the Weser. At that time, this solution seemed to be the most economical way to guarantee storm surge protection within a short time span. Because of their influence on the tidal water levels downstream these three barrages could only start to operate conjointly and after the completion of all other flood protection installations along the Lower Weser. This condition was finally met in 1979, even though the construction of the Lesum Barrier had been completed in 1974.

Based on the results of hydraulic model tests carried out by the Franzius Institute of the University of Hannover the barrage was built with four flood gates. The bridge spanning the barrage serves as the connection between the district of Grohn (Bremen-Vegesack) and Werderland (Lesumbrock) in Bremen-Burglesum.

**Technical data:**

- Size of the barrage approx. 118 × 35 m
- 4 passage gates with 15 m width each (60 m passage width overall)
- 1 lock, clear dimensions: B × L = 14 × 30 m
- Backwater level: NN + 2.50 m
- Bridge: solid road bridge across the passages and a balanced bascule bridge across the lock. Overall length: 120 m
- Clearance at bridge closed: NN + 7.0 m (lower edge of bridge)
- Sill elevation of passages and lock: NN – 3.3 m
- Gate safety: doubled safety
- Type and drive of the gates: Split lift gates with mechanical drives with pivoted chains for the flow passages and hydraulically driven mitring gates in the lock
- Secondary installation: pumping station with three pumps, capacity: 3 × 15 $m^3/s$


Fig. 4: View from downstream/© Bremischer Deichverband am rechten Weserufer, Bremen

**Construction procedure:**

The Lesum Barrier was erected between 1971 and 1974 in three stages in a trench. Because of favourable subsoil conditions, a low-cost spread-foundation could be chosen. Phase I: lock with two adjacent passage openings and river training measures on the right Lesum embankment. Phase II: passage openings 3 and 4 . Phase III: pumping station and shore connection to the left Lesum embankment.

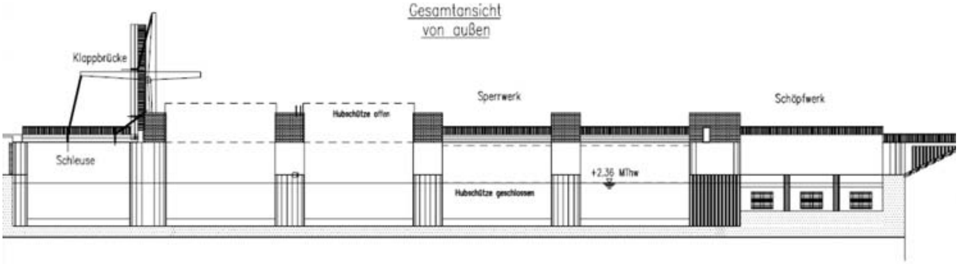


Fig. 5: Cross-section of the barrage/© Bremischer Deichverband am rechten Weserufer, Bremen

### 8.3 Eider Barrier in Schleswig-Holstein

The Eider Barrier was completed in 1973 and is part of the dike defence line of the North Friesian coast. For almost 30 years, the Eider Barrier could claim to be the largest coastal protection structure in Germany. Only in 2002, this 'title' had to be handed over to the Ems Barrier. Planning for the construction of an Eider barrage already started in 1957. First suggestions for its location and alignment and hydraulic model investigations at the Federal Waterways Engineering and Research Institute (Bundesanstalt für Wasserbau – BAW) followed. Construction started on March 29, 1967.

The Eider barrage is composed of several structures: the tidal gates, the bottom foundation plate, the lock and the 5 km Eider causeway. The tidal gate structure has an overall flow passage width of 200 m. The openings are framed by piers and bridged by pre-tensioned concrete girders. These so-called weir trusses (Wehrträger) have a length of almost 43 m and an elliptical cross-section. The hollow interior serves as an auto tunnel for the coastal road connecting the regions of Dithmarschen and Eiderstedt. Radial type steel gates are used for closure. They are pivoted on the weir trusses. The bottom foundation of the passage openings is a reinforced concrete slab of 0.8 m thickness which connects on both sides to the 150 m long rigid bed protection. The navigation lock is equipped with 5 pairs of steel mitring gates. The two pairs of gates in the outer sluice head represent the two-fold safety. The lock is bridged by a balanced bascule bridge.

**Technical data:**

- Size of structure approx. 240 × 65 m (without lock)
- 5 sluice gates with 40 m passage width each
- Sluice sill elevation: NN – 4.6 m
- Weir trusses above the flow passages
- Bottom edge of weir trusses: NN + 2.0 m; top edge: NN + 10.35 m
- Sector gates, 2 for each flow passage, pivoted at the weir truss; weight 250 t each, drives: 2 oil-hydraulic cylinder-plunger-aggregates for each segment

Fig. 6: Aerial photograph of the Eider Barrier, © Raabe, Friedrichstadt

Fig. 7: Lock chamber with bascule bridge/© WSA Tönning

Fig. 8: View of the Eider Barrier/© WSA Tönning

- Lock: (effective chamber dimensions: L = 75 m, B = 13.5 m) with 5 pairs of mitring gates; drives: oil-hydraulic lift cylinders; auxiliary gates: needle weirs with floatable supports (needle beams)
- Sluice sill elevation: NN – 5.6 m
- Gate safety: two-fold
- Road connection (two lanes) goes through the weir truss (236 m tunnel roadway)
- Balanced bascule bridge (width between supports: 18.6 m) spanning the lock with a width of 12.15 m
- Operation: tidal and storm surge barrier

**Construction procedure:**

The sluice structure, lock and building harbour were constructed within a protective ring dike erected by way of the build-up of an embankment on a sandbank in the wadden area. Material transport was carried out over a 1 km long, one-lane auxiliary bridge connecting to shore. After the construction of the lock on a pile foundation and of the sluice structure, the longer Eider causeway of approx. 4 km length was built towards the North. After removal of the construction island and start of the operation of the sluice and the lock the improvement of the navigational channel and the build-up of the southern Eider causeway was carried out. The construction of the elliptical weir truss represented a special feature of the project. Because of the exterior shape and the interior design as a road tunnel the pre-tensioned concrete modules were fabricated in several phases in a pulsing procedure. This required sophisticated and expensive tooling and formwork.

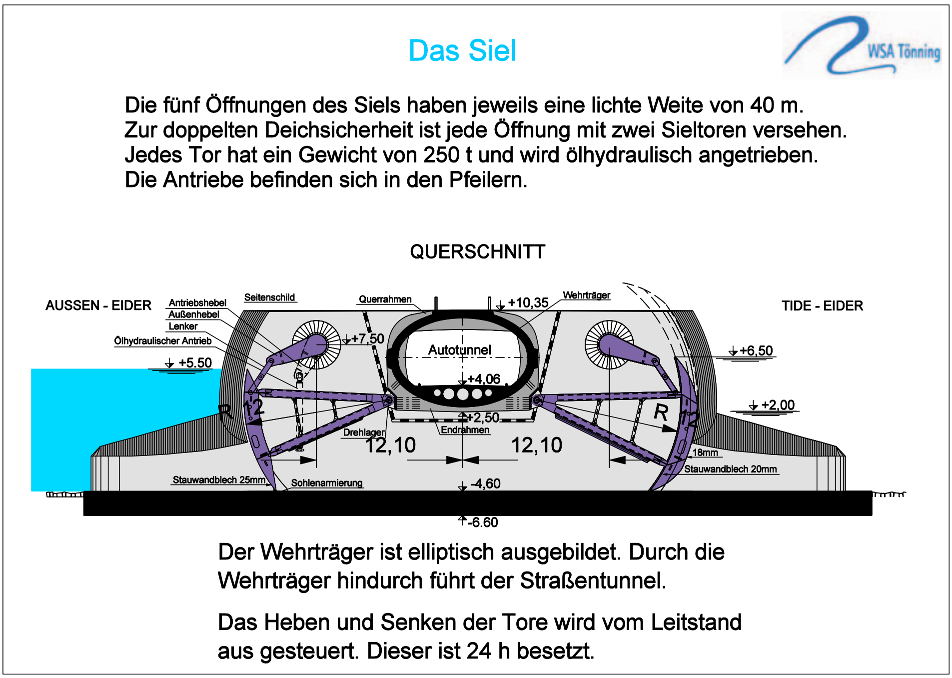


Fig. 9: Cross-section of the barrage/© WSA Tönning

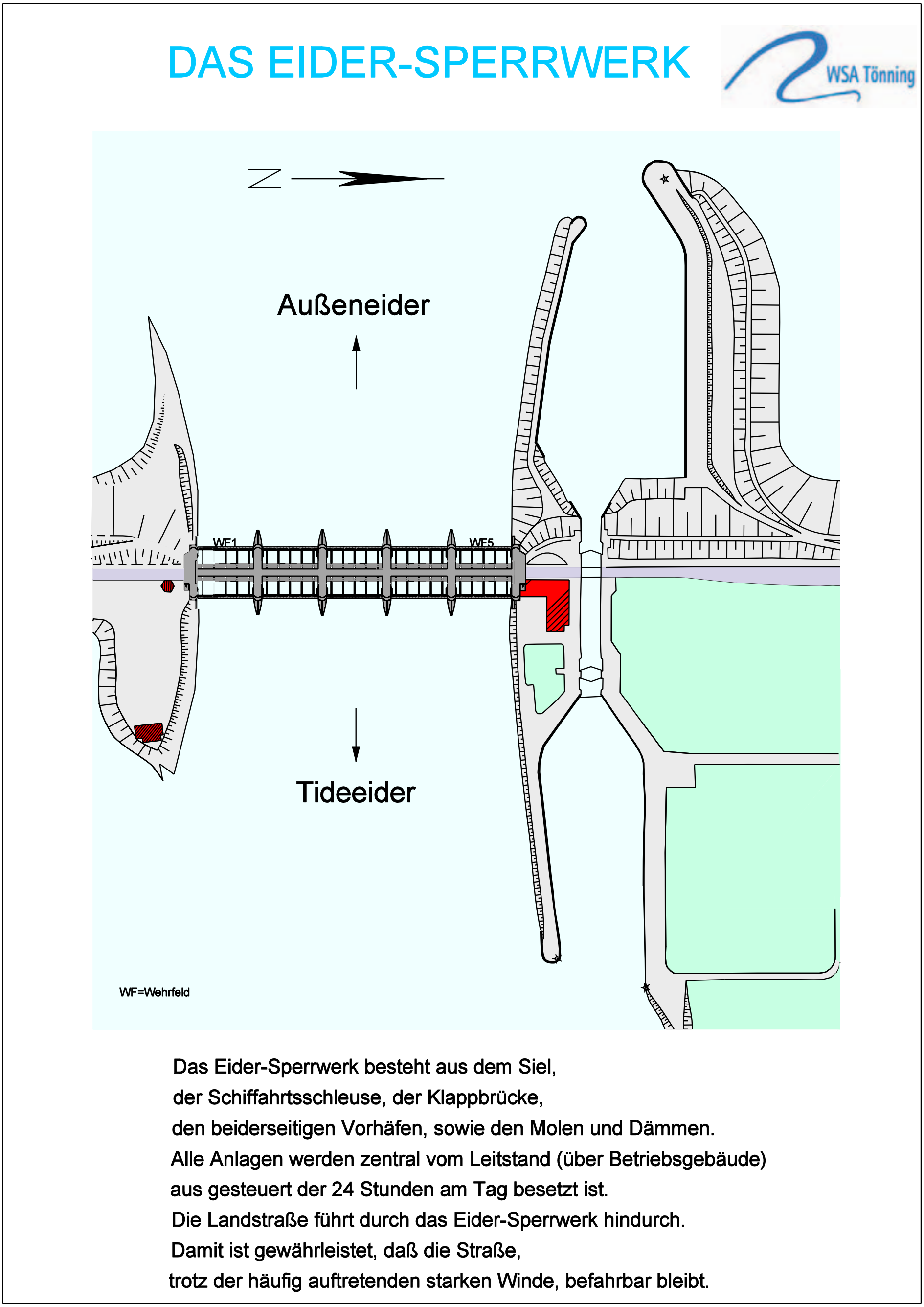


Fig. 10: Layout plan of the barrage/© WSA Tönning

The sector gates were transported to the construction site on waterways and were assembled and paint-coated on site.

### 8.4 Barrage Billwerder Bucht in Hamburg

The barrage Billwerder Bucht is the third-largest barrage in Germany. It was erected for the protection of the region of Billwerder Bucht and its adjacent industrial canals between 1964 and 1966. Thereby, it became part of the main dike defence line of the City of Hamburg, which was drawn up after the storm surge of 1962. Between 1999 and 2002 the barrage was rebuilt within the framework of the Hamburg Construction Programme for the adaptation of all storm and flood protection structures to the new design water level. The reconstruction was tantamount to a new construction since the barrage was not only raised by 1.2 m to a new crown level of NN + 8.2 m, it also added a second defence line of equal elevation behind the first one.

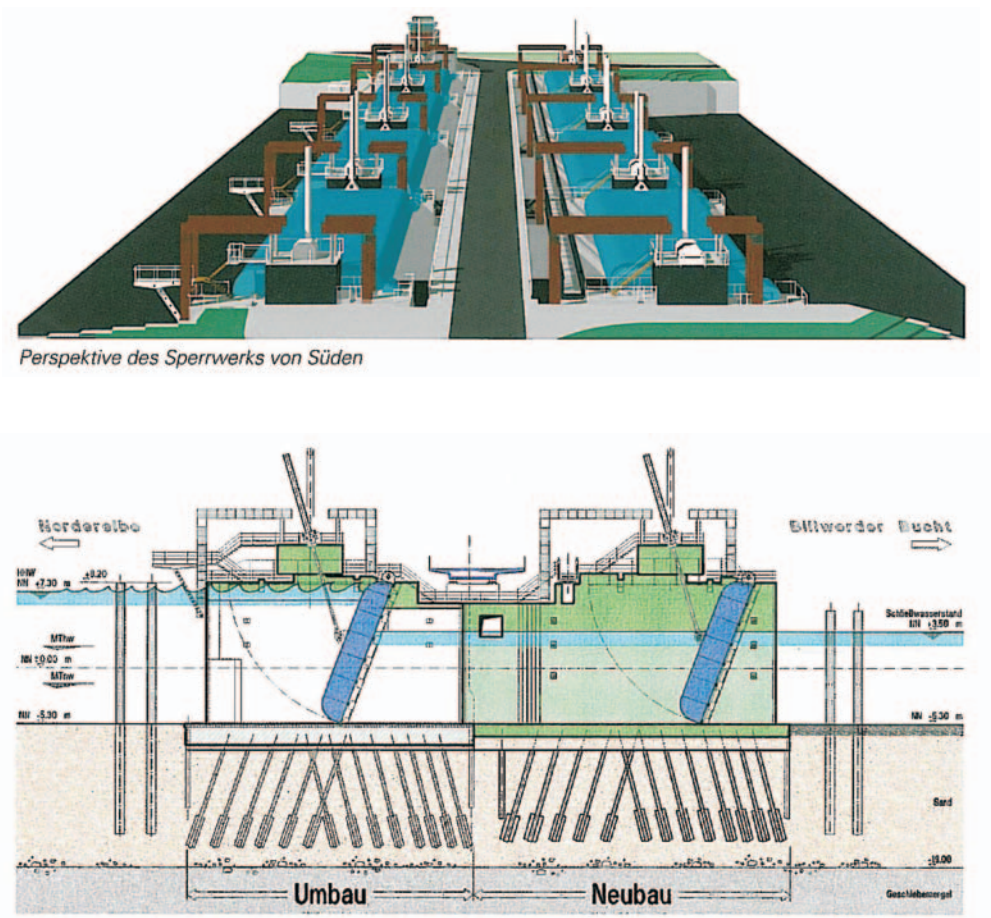


Fig. 11: Cross-section of the Billwerder Bucht Barrier/© HPA Hamburg

**Technical data:**

- Size of structure approx. 150 × 55 m
- 4 flood passages, of which two are navigable with a width of 34.5 m each, and 2 secondary passages with 30 m width each
- Overall passage width: 128 m
- Backwater level: NN + 3.5 m
- Passage clearance for navigation: NN + 8.05 m (bottom edge of the bridge/flap gate)
- Top of sluice sill: NN – 5.3 m (navigable passages) and NN – 4.2 m (secondary passages)
- Gate safety: two-fold
- Type of gates: steel flap gates (on upper mountings) built as girder grids with a steel-plate cover
- Drives: hydraulic, with two hydraulic jacks per flap gate
- Road bridge: 1 steel box girder as a 4-field continuous system with an orthotropic two-lane carriageway plate and a cantilevered sidewalk; overall width approx. 9.0 m
- Control building and machine house; housing for the diesel-operated auxiliary hydraulic power aggregate
- Architecture: 8 welded brackets per pier (powder-coated aluminium caskets with float glass at the front); upper edge of the bracket: NN + 15.5 m

Fig. 12: Aerial photograph of the Billwerder Bucht Barrier/© HPA Hamburg

**Construction procedure:**

1966: step-by-step construction of the first barrage in a trench in sheet-pile boxes

1999 – 2002: new construction of the eastern defence line with subsequent reconstruction of the previous line (dismantling of the old flap gates, demolition of the 5 machine houses, heightening of the existing piers, lifting of the road bridge by approx. 1 m and shifting towards the East by 3.15 m); new construction of the control building.

The construction sequence was carried out under the following boundary conditions:

- Guarantee of full flood protection at all times
- Maintenance of navigation operations
- Maintenance of road traffic to a large extent
- Avoidance of reduction of the flow passage

The construction of the piers was carried out in sheet-piling pits; the sluice sills were exclusively poured in underwater concrete. The gate bed-stop rail was designed as a 1 m wide pre-fabricated concrete slab commensurate with the passage width.

### 8.5 Barrage Greifswald-Wieck in Mecklenburg-Vorpommern

The danger of flooding the downtown region of the Hanseatic City of Greifswald and townships in the lower Ryck (Ryckeniederung) area is met by this barrage and the adjacent dikes. The province of Mecklenburg-Vorpommern will invest approx. 25 Mio. € into the project 'Storm Surge Protection Greifswald' and, thereby, reduce the flood defence line by 3.5 km. The barrage is located in a cross-section of the Ryck close to its mouth at the 'Dänische Wiek', Baltic Sea.

Within the planning framework, special attention was paid to the design and integration into the urban development around the harbour of Wieck. Thus, a structure evolved which – because of its low constructional height – blends into the coastline very well. The 21 m wide navigation passage with a revolving sector gate element is the core of the installation and the most modern type that water engineering has to offer presently. On each side of the main passage a 17 m wide secondary opening in the dike is arranged as an aperture for the shoreline promenade. Both sliding gates designed for the secondary passages have been invisibly arranged inside the adjacent dikes. The secondary passages in the coffer dams have been dimensioned for taking the discharge of the Ryck should the main passage have to be closed for a longer period due to severe icing or ice drift.

Start of construction: planned for 2010

Beginning of operation: planned for 2012

**Technical data:**

- Size of structure: width of barrage incl. piers: 30 m; incl. coffer dams: 53 m, length of piers: 32 m
- 1 navigation passage (SÖ) with a width of 21 m; 2 secondary passages as dike openings with a width of 17 m each
- Overall passage width: 21 m
- Backwater level: NN + 3.0 m (= design high water level)
- Top of bottom sill: NN – 4.0 m
- Type of gates: revolving sector gate in the SÖ, sliding gates in the secondary passages
- Gate safety: single safety for the SÖ and in the secondary passages in the dikes
- Drives: 2 hydraulic cylinders for the SÖ

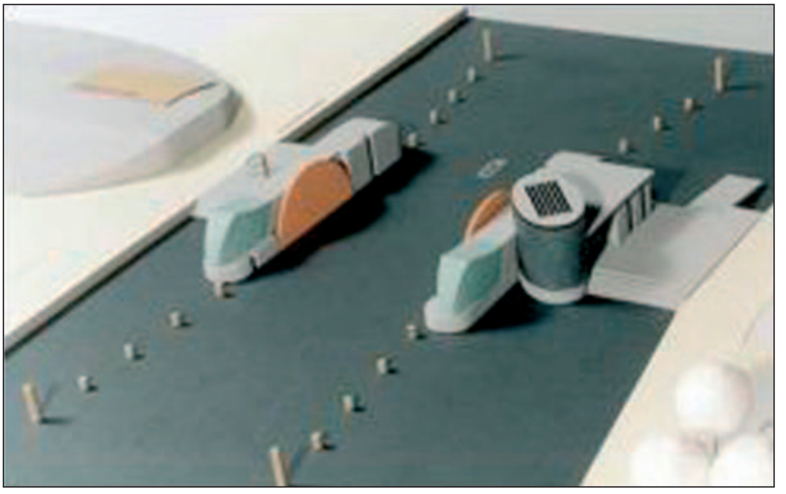

Fig. 13: Model of the barrage Greifswald-Wieck/© Staatl. Amt für Umwelt und Natur/Ueckermünde

Fig. 14: Mouth of the Ryck in Greifswald-Wieck (planned location)/© Staatl. Amt für Umwelt und Natur/Ueckermünde

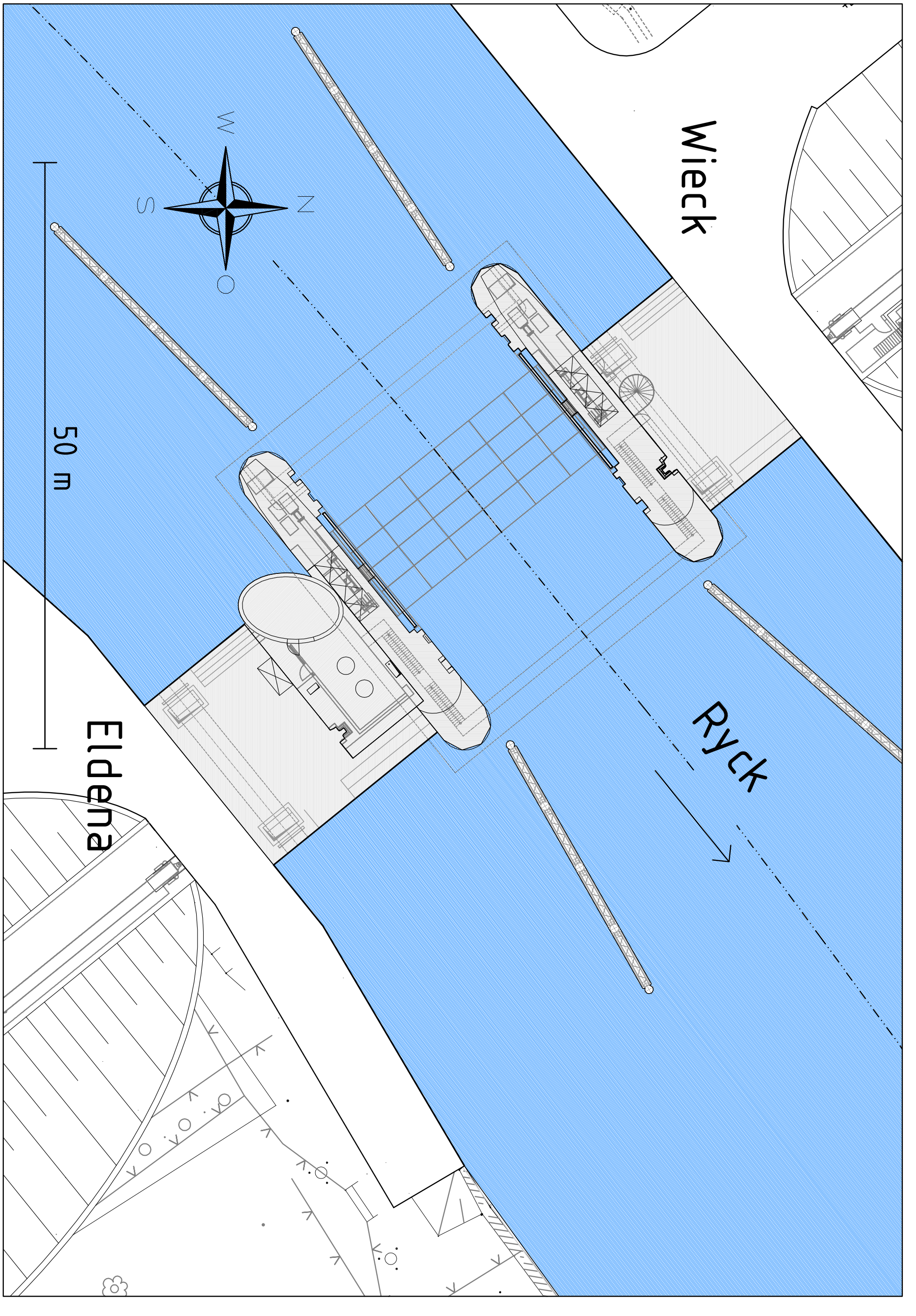


Fig. 15: Layout plan of the barrage Greifswald-Wieck/© Staatl. Amt für Umwelt und Natur/Ueckermünde

- In addition to the control building, the barrage is equipped with inspection hatches for the main passage, as well as two independent drive aggregates with auxiliary power supply
- Control by programmable-storage modules (SPS) from the control room

## 9. Acknowledgements

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Staatliches Amt für Umwelt und Natur Rostock, Rostock;
Wasser- und Schifffahrtsamt Tönning, Tönning.

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# Detached Breakwaters

By Peter Fröhle

Contents



## 1. Introduction

In Germany, detached breakwaters have been constructed only at the Baltic Sea coast of Mecklenburg-Vorpommern up to now. Here, they are used for the protection of eroding sandy coastal stretches since 1978. Today, 23 detached breakwaters are installed in 8 systems along the Baltic Sea coast (Fig. 1).

Detached breakwaters for coastal protection are constructed using rubble and/or natural rocks. Their layout is nearly homogeneous with no core or filter layer. The weight of the natural rocks used for the breakwaters is in the range between 2t and 7t, depending on the local wave forces. In a construction the heaviest blocks are used for the armour layer and the crown of the construction, since there normally the loads are concentrated. A typical cross section of a detached breakwater used in Mecklenburg-Vorpommern is given in Fig. 2.


Fig. 1: Systems of detached breakwaters in Mecklenburg-Vorpommern, Baltic Sea coast

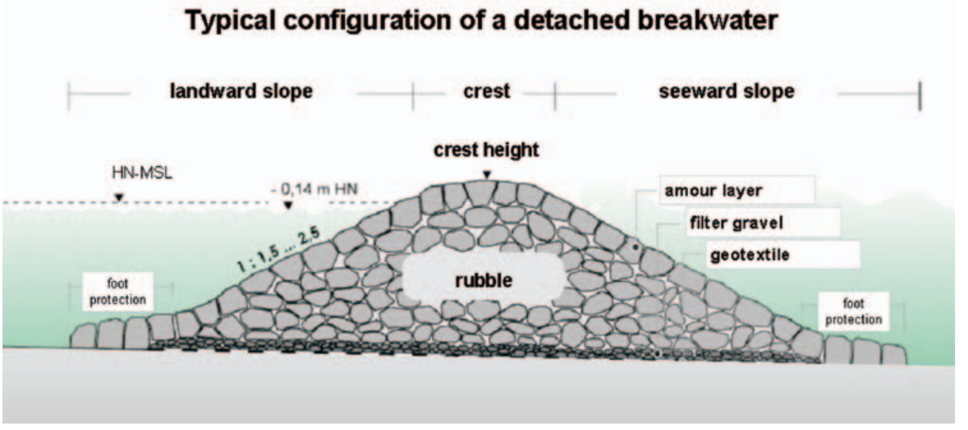


Fig. 2: General layout of detached breakwaters in Mecklenburg-Vorpommern (StAUN Rostock)

Detached breakwaters are used as single breakwaters or in systems with up to 4 units. Their length is typically between L = 50 m and L = 200 m, the distance to is between 70 m and 200 m and the crest elevation between $H_c$ = 0 m and $H_c$ = 2 m above mean sea level. In systems, the gap width is between Lg = 50 m up to Lg = 100 m (CARSTENSEN, FRÖHLE, JÄGER and SOMMERMEIER, 2004).

The ratio between length, distance to shore and gap width is normally selected in a way that a stable salient can be expected. The development of a complete tombolo is normally not the aim of the detached breakwaters built in Mecklenburg-Vorpommern. To support the development of stable salients in the wave-shadow of the detached breakwaters, the construc-

Fig. 3: System of detached breakwaters at Sellin/Rügen (Google Earth)

tions are normally combined with initial beach nourishments. An example for a constructed project which consists of a system of 2 detached breakwaters is given in Fig. 3.

## 2. Design of Detached Breakwaters

The general function and the general influence of detached breakwaters on the sediment budget and on the morphological development of a coast area are shown in Fig. 4. The principles of the physical processes dictate that all hard structures can provide local protection, only. The evolution of a coastline shows the desired accretion in the protected area behind the breakwater. However, one usually must expect downdrift-erosion on the lee-side of the detached breakwater.

The design of detached breakwaters is normally separated into a functional and a constructional part. The functional design ensures the performance, namely the development of a salient or tombolo, of the breakwaters/breakwater systems. The constructional design ensures that the designed cross section of the breakwater is statically and/or dynamically stable for the selected design parameters.

The functional design of detached breakwaters is normally based on numerical simulation of the sediment transport in the project area to determine the influence of the structure on the local and wide area sediment transport and, hence, the future morphological development of the area. The numerical simulation includes an assessment of the long term behaviour of the affected area. An example of such an assessment is given in Fig. 5.

In order to assure the results of the numerical simulations, they are double-checked based on nomograms and empirical and/or analytical solutions (Fig. 6). For details see e.g. POPE and DEAN, 1986 or SILVESTER and HSU, 1993.

The structural design of the breakwaters is often performed based on the research work on the stability of rubble mound structures by HUDSON (1954) and VAN DER MEER (1991). Since breakwaters are used to direct the morphological development of a coastal stretch, the probability of occurrence of the design parameters (wave height, etc.) is selected to be comparatively high, e.g. in the range of p = 0.05 to p = 0.02.

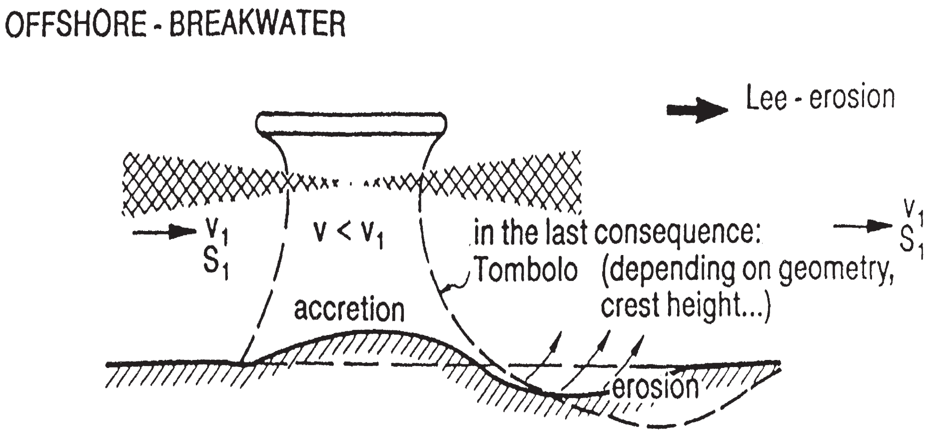


Fig. 4: Influence of a detached breakwater on sediment transport and coastline development (schematic, after KOHLHASE, 1991; KOHLHASE, 2004)

Fig. 5: Numerical modeling of shoreline evolution using Genesis (general example)

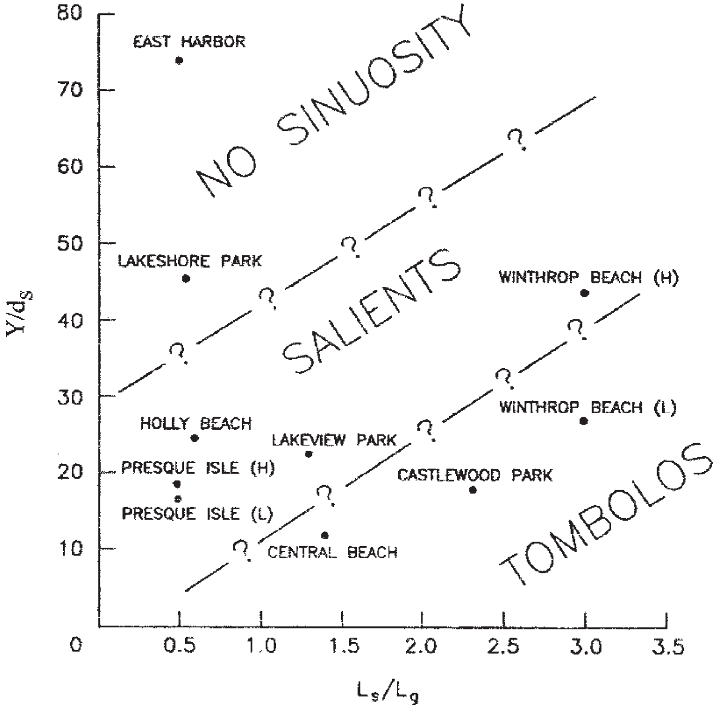


Fig. 6: Effect of breakwater layout on the morphological response of the coast (POPE and DEAN, 1986)

## 3. Breakwater System Streckelsberg

The Streckelsberg (Fig. 1, No. 8) is located in the middle of the NE-coast of the island of Usedom, Mecklenburg-Vorpommern. This part of the island is extremely exposed to waves. The Streckelsberg is an erosive cliff of up to 50 m height consisting of glacial sandy deposits. The length of the area in question is approximately 500 m. South of the Streckelsberg the coast is formed by active cliffs (boulder clay). North of the Streckelsberg, the coast changes from an (partly) active cliff (boulder clay) to the typical low lying sandy coasts with dunes and comparatively wide beaches. This low-lying area forms a narrow border – sometimes less than 50 m – between the open Baltic Sea and the coastal lagoon (Bodden) of the Achterwasser. Consequently it is very vulnerable to breaching caused by high water levels and strong wave attack.

This vulnerability is the main reason for the protection of the Streckelsberg cliff, being an anchor for the development of the entire surrounding coastal area. Loosing ground here would also cause retreat of the adjacent coastlines north and south of the Streckelberg and would, finally, result into a breaching of the narrow stretch coast and the separation of the island of Usedom.

For more than one century the Streckelsberg has been protected by a beach wall (Streckelsberg Wall), which was destroyed over time (Fig. 7). Due to the negative sediment budget in the area, the beach in front of the Streckelsberg Wall has eroded completely.

After a detailed investigation of the problem, one decided that a system of detached breakwaters could be seen as the only effective protection of the Streckelsberg cliff. The layout of the breakwater system was optimized using a numerical model, in which a wide

Fig. 7: Destroyed Streckelsberg Wall

variety of systems-layouts, transmission-coefficients of the structures and distances to shore have been analyzed. The assessment of the situation was based on long-term wave information covering a period of 5 years. Criteria for the layout were mainly the formation of a stable salient in front of the Streckelsberg Cliff without a tendency towards a complete tombolo and, on the other hand to minimize negative downdrift effects.

Investigations resulted in the design of a system of 3 detached shore parallel breakwaters with a length of approx. 190 m each, and a gap width of approx. 50 m. They were to be built at a maximum distance of approx. 200 m from the shoreline, considering the construction costs. In addition to the detached breakwaters, a new beach wall was built to protect the Streckelsberg Cliff against extreme high water levels. Shore perpendicular groyne systems south and north of the completed detached breakwaters system were installed to minimize negative effects. An aerial photo of the detached breakwater system is shown in Fig. 8.


Fig. 8: System of detached breakwaters at Streckelsberg/Usedom

Detached, shore parallel breakwaters have been used successfully for the protection of sandy, erosive coasts at several locations in the German Baltic Sea. At the German part of the North Sea the mainland coast is normally protected against high wave attack by the shallow areas of the Wadden Sea. Hence, a protection using detached breakwaters is normally not useful.

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# Coastal Groynes in Germany

By Frank Weichbrodt

Contents



## 1. Introduction

Coastal groynes represent one of the oldest coastal protection structures in Germany. Since a wide beach is by far the best form of coastal protection at a sandy coast, the coastal engineer uses groynes for beach management or control. Today, coastal groynes are frequently used in combination with beach nourishment. Groynes are designed in such a way, that long-shore sediment transport is locally influenced in order to increase the persistance of sand at natural or artificially nourished beaches.

In the available literature, different definitions of groynes can be found. Generally, groynes are slender structures built to protect beaches, forelands, coast-parallel structures and other objects at the coast. They are arranged more or less normal to the coastline to influence near-shore currents and, thus, the sediment transport process in the littoral zone. Considering the function there is a differentiation between beach groynes influencing mainly

Fig. 1: Wooden single-row pile groynes at low water at the Baltic coast near Warnemünde (photo: Weichbrodt, 2006)

wave caused currents and groynes located at islands and tidal inlets mainly acting at the tidal currents. The latter are named 'stream groynes' in German textbooks (EAK, 1993).

At the German Baltic Sea beach groynes still represent an important part of the coastal protection scheme. The groynes are mostly deployed in entire groyne systems (Fig. 1) to influence the movement of sediments along the shoreline as a result of wave-induced longshore currents. Most of these groynes are built as permeable groynes consisting of wooden piles.

At the German North Sea coast, groynes are often installed as stream groynes, especially at islands and estuaries, to protect sandy coasts against erosion caused by tidal currents. These groynes are mostly constructed using rock and concrete because of usually heavy loads (Fig. 2).

Despite extensive national and international investigations having been carried out in the past including hydraulic/numerical model tests and field investigations, the effectiveness of coastal groynes is being controversially discussed in literature and by public authorities. However, many single groynes and groyne systems exist and have to be maintained at the German coast and new groynes are still built. Therefore, there is a need for a safe and efficient design.

Tab. 1 gives an review of the actual number of groynes at the coast of Germany broken down to the three federal coastal states with a coastline.

Fig. 2: Rock groyne at 'Hallig (holm) Südfall' (photo: HINRICHSEN, 2005)

Table 1: Number of groynes in Germany

| Federal state | Number of groynes |
| --- | --- |
| Lower Saxony | 262 (North Sea) |
| Schleswig-Holstein | 1245 (North Sea)<br>1143 (Baltic Sea) |
| Mecklenburg-Vorpommern | 1129 (Baltic Sea) |

In the following, some information on the history, the functional and constructive design and future aspects of groynes in Germany are given.

## 2. Review of History of Groyne Construction in Germany

Between 1815 and 1821, first simple groynes were built at the Island of Wangerooge in the North Sea for the purpose of protecting a lighthouse. The groynes were built of brushwood material without additional rubble protection. Due to information given by FÜLSCHER (1905), these first groynes were already seriously damaged in the winter of 1821/22. Nevertheless, more groynes of this simple design were built at Wangerooge in 1832 and 1834, but they had to be abandoned around 1850 because of destruction by currents and waves.

Starting 1843, further simple bush groynes were constructed on the Island of Norderney. Just like the first groynes built to protect the coastline of Wangerooge, these groynes were destroyed shortly after completion.

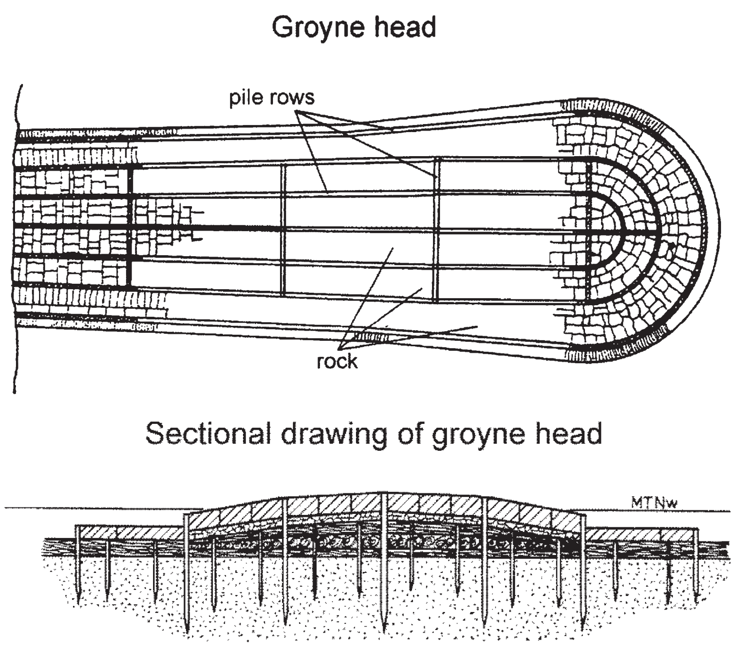


Fig. 3: First rock groynes on Norderney, 1861 (TRITT and ALTEMEIER, 1987; after FÜLSCHER, 1905)

Table 2: Year of first construction and type of groynes at the German North Sea islands

| Island | Year of first groyne construction | Type of groyne |
|---|---|---|
| Borkum | 1869 | Rock groynes |
| Juist | 1914 | Pile groynes |
| Norderney | 1843 | Bush groynes |
| Baltrum | 1873 | Rock groynes |
| Langeoog | no groynes | – |
| Spiekeroog | 1873 | Rock groynes |
| Wangerooge | 1815 | Bush groynes |
| Amrum | 1895 | Rock groynes, Pile groynes |
| Föhr | 1895 | Pile groynes |
| Sylt | 1872 | Rock groynes, Pile groynes |
| Helgoland | 1897 | Fascines, fascine raft, Rock |

Using this experience, coastal engineers began constructing various types of groynes from rubble or broken rock on the North Sea islands. The first seven solid groynes were installed at the western part of the Island of Norderney between 1860 and 1867. They were built with a length between 190 m and 215 m using layers of fascines, wooden piles and an cover of rock or rubble, as shown in Fig. 3. Only little damage was detected after this modification of groyne construction. Until 1877, five more of these groyne constructions were placed at the west side of Norderney.

Following the positive experience of groyne construction at Norderney, more groynes of this type were built on the other German islands in the North Sea, e.g. Borkum, Baltrum, Spiekeroog, Sylt and Wangerooge. Tab. 2 presents the year of construction and the type of groyne built along the North Sea island coasts. In Figs. 4 and 5, satellite views of the East and North Friesland islands are shown to illustrate the situation.

At some locations on the North Sea islands, wooden pile groynes were built as well. Since 1906, they were established on Borkum, Juist, Norderney, Sylt, Föhr and Amrum using various designs and were constructed both as permeable and as impermeable groynes. As a special construction, wooden pile boxes filled with rubble or concrete blocks (called box-type-groynes), were introduced for the first time in 1925.


Fig. 4: Satellite view of the East Friesland Islands (photo: Nasa World Wind – Wikipedia)


Fig. 5: Satellite view of the North Friesland Islands (photo: Nasa World Wind – Wikipedia)

Starting in the middle of the 1920s, different construction materials such as steel, concrete, reinforced concrete and asphalt were increasingly used for groyne construction. In the 1930s single wall groynes made of steel sheet piling were built. Later on, box-type-groynes made of two rows of sheet piling filled with sand, rubble or broken rock with or without a concrete armour layer became common along the coast. Combinations of various constructions methods and materials in one groyne were tested and very long submerged groynes were built.

However, wooden pile groynes became generally not too popular at the German North Sea islands although they seldom sustained any damage by currents and waves according to FÜLSCHER (1905). This may be also due to the fact that wooden constructions in sea water is susceptible to infestation by the shipworm *(teredo navalis)*. Today, one will mostly find natural stone (e.g. basalt columns), concrete, steel and asphalt as construction material for groynes at the German North Sea coast.

Following recommendations of HAGEN (1863), the first groynes at the German Baltic coast were tentatively installed at the Island Ruden (near Usedom at the border to Poland) in 1843. Similar to those first ones at the North Sea coast, these groynes were very simple constructions consiting of two rows of piles entwined with pine branches. Compared to present groynes, they had small dimensions. With a length of 4 to 8 Ruthen (a Ruthe is an old dimension unit – 1 Ruthe = approx. 3.77 m), they were built in water depths of not more than 1.0 m. These groynes were destroyed by waves and scouring some years after completion. Over the years, advanced structural design and construction methods were introduced. Figs. 6 and 7 show some examples of groyne construction in the 19$^{th}$ century using fascines and rock armouring.

With the invention of pile drivers, the embedding length of piles in the ground could be remarkably increased. Thus, groynes were more stable and could better resist wave and ice forces. The length of groynes was increased and groynes were built up to a water depth of 3.0 m.

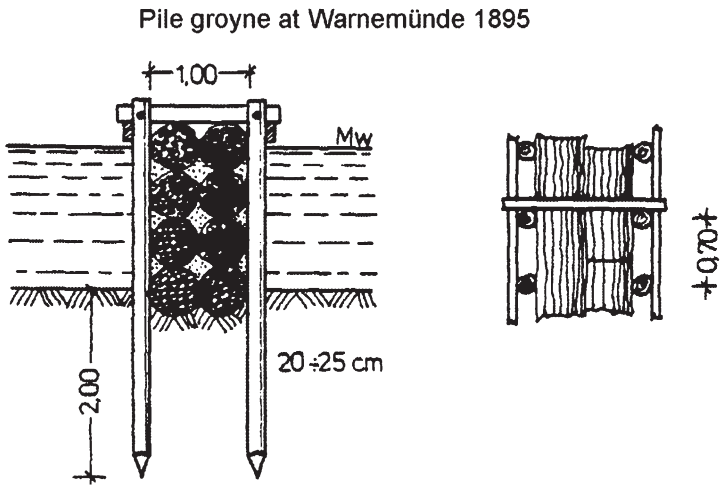


Fig. 6: Wooden groyne construction at the Baltic coast near Warnemünde, 1895
(TRITT and ALTEMEIER, 1987; after FÜLSCHER, 1905)

Before World War II, some groynes were built with steel sheet piling. However, substantial corrosion problems were encountered and groynes caused a risk for tourists at sandy beaches. Since they do not well merge into the environment as do the more naturally looking wooden stone or wooden groynes, they were not very popular and are not accepted today, in addition.

By comparing experience and practical knowledge from the construction of groynes, POPPE (1942) wrote: "among the simple groyne constructions, the wooden single-row pile

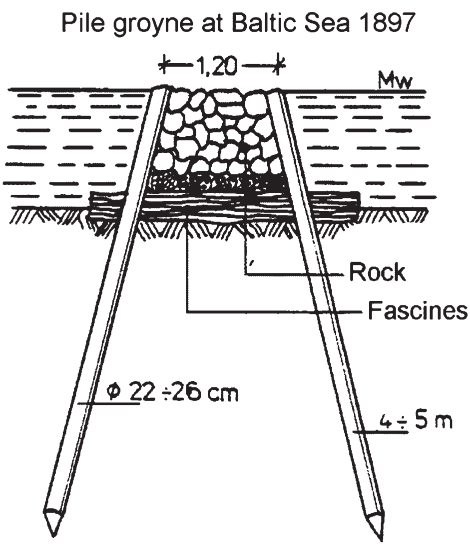


Fig. 7: Wooden groyne construction at the Baltic coast, 1897 (TRITT and ALTEMEIER, 1987; after FÜLSCHER, 1905)

groyne has proven best, despite some faults". At the Baltic coast of Germany and at the coast of Mecklenburg-Vorpommern in particular, the wooden single-row pile groyne became most accepted and has been the favoured design from World War II until now. Reasons are also the lower costs compared to double-row pile or stone groynes as well as the option to build the groyne with a varying permeability depending on its intended function.

In this contribution, it is not possible to describe the design details of all groynes which were established along the German coast during the last 200 years. Numerous examples from the history of groyne construction can be found in KRAMER and ROHDE (1992), the old literature cited above and others. A good overview of German publications on groyne construction, with a focus on the effectiveness of beach groynes, from the beginning until 1961 is given by PETERSEN (1961).

## 3. Design of Groynes

First papers on the experience with the functional and structural design of groynes were published by PLENER (1856), HAGEN (1863) and FRANZIUS (1884). Based on practical knowledge and field and model investigations, recommendations, design formulae or even manuals for the design of groynes were offered in the 'Shore Protection Manual' by CERC (1984), the 'Guide on the use of groynes in coastal engineering' by CIRIA (1990) and the 'Recommendations for Coastal Protection Structures' (EAK, 1993 and 2002). Further interesting publications are listed under references.

As mentioned before, many investigations were performed on the effectiveness of groynes at sandy beaches. Quite a few different recommendations for the length, the crest elevation, the inclination of the crest, the spacing between two neighbouring groynes in a system and the layout of a groyne can be found. Some detailed recommendations for the functional design of beach groynes in Germany are offered in EAK (1993).

Generally the crest elevation for North Sea groynes should be between 0.5 and 0.75 m above the planned beach level. The crest elevation should be >0.5 m above MThw (mean tidal high water) at the groyne root and 0.5 m above MTnw (mean tidal low water) at the head. Along the Baltic Sea coast, the crest elevation of wooden groynes is determined to be 0.5 m above mean water level. That ensures its functioning during events with elevated water levels. Groynes should be arranged normal to the coastline. The crest level is chosen to be horizontal or parallel to the beach slope.

With a focus on the Baltic coast, some diagrams can be used to determine groyne length, spacing within a system and its permeability. The groyne length can be determined as a function of local wave parameters (wave length) and beach slope. The spacing depends on its length, permeability and category of wave load at site.

Today, usually permeable single-row pile groynes with a permeability >20 % are used at the German Baltic coast for water depths > 1.0 m at the seaward part of the groyne. In a groyne system, the permeability is increased towards the end of the groyne field in order to avoid downdrift erosion effects at the beach.

The first concept for the functional design of a single groyne or a groyne system is often obtained by numerical model tests. Experience with existing groynes in the vicinity of the proposed construction site are included in the functional and structural design.

Another important issue of the engineering process is the structural design of a groyne. Papers published before 1945 present a lot of practical knowledge and information on damage sustained at existing groynes. Both, national and international investigations carried out after 1945 are focused mainly on the functional design of beach groynes. Even though it may seem trivial to perform research on such a simple structure as a groyne, the lack of information for an economical structural design of groynes is evident. This may also be due to the lack of processes in the near-shore zone, which are complex and not yet fully understood.

Design methods used for breakwaters can be applied to groynes made of stone, rubble or concrete armour units. For steel or concrete sheet piling structures, design approaches for vertical walls are being used today. However, no special design methods for cost effective groyne constructions are available. Considering groynes at the German Baltic coast we find predominantly wooden single-row pile structures. They have a length between 50 and 90 m, where corresponding ramming depths of wooden piles are determined by an old empirical approach only based on water depth and experience. This approach uses a ratio of water depth to ramming depth of 1/3 to 2/3 for non-cohesive subsoil and 2/5 to 3/5 for cohesive subsoil respectively.

In 2001 the German Ministry for Research and Education (BMBF) approved and funded a research programme aiming at the development of a more scientific approach to design wooden groyne piles. The project focused on the load on piles induced by wave impact as well as vertical and horizontal ice forces. Holding forces depend on type of subsoil and dynamic effects. From existing publications, we could not find satisfactory information about wave induced pile movements and the possibility of ensuing liquefaction effects in the surrounding soil. Existing methods for the calculation of vertical loads and holding forces of piles gave differing results.

Therefore, the actual investigations, carried out between 2001 and 2005 were focused on wave induced pile movements, vertical ice forces and holding forces. This included possible

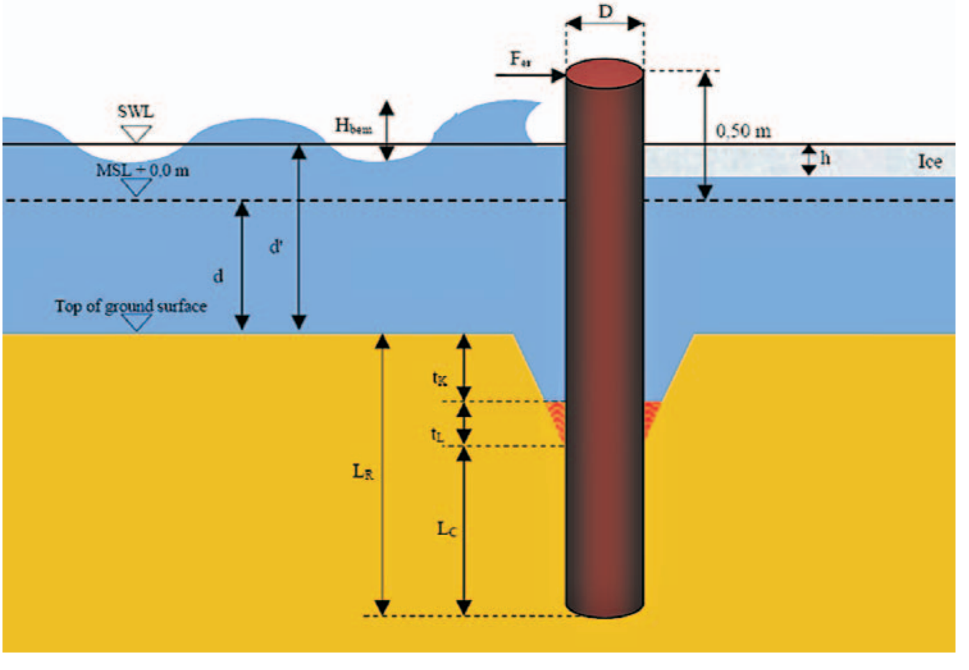


Fig. 8: Sketch for definition of parameters used in the recommendations (WEICHBRODT, 2008)

liquefaction effects of the surrounding soil. The research project was based on analysis of data from field measurements, experiments and laboratory tests (WEICHBRODT et al., 2004, 2006).

Based on results from this project and accepted methods, recommendations for the dimensioning of the ramming depth of groyne piles as a function of local wave loads, ice loads, water depth, pile diameter and type of subsoil were developed. In this publication, it is not possible to describe all recommendations in detail. Reference is made to the literature mentioned before and the dissertation of the author. An outline of the dimensioning procedure will be given in the following. Fig. 8 shows the definitions for the following explanations.

The investigations show that possible scouring effects around the piles due to waves and currents have to be considered. Safety supplements to pile length for scour and changes of the bottom surface are defined with $t_{KN}$ = 1.5 m for a non-cohesive upper soil layer and with $t_{KB}$ = 0.25 m for a cohesive upper soil layer. For periods with a closed ice cover, loads by waves and currents are reduced. Thus, for the calculation of the necessary ramming depths with respect to ice forces, reduced values for $t_{KN}$ and $t_{KB}$ are recommended.

Based on the investigations of pore water pressure and liquefaction effects, a second safety supplement for liquefaction is recommended for practical applications. This supplement is defined as $t_L$ = 0.50 m at sites with non-cohesive upper soil layers. Organic soil layers and soil layers with thicknesses smaller than 0.2 m should not be considered for the calculation of holding forces.

All horizontal loads, vertical loads and holding forces are compiled in tables as a function of water depth or clamping depth $L_C$ for practical use (see Fig. 8 for differentiation between clamping depth $L_C$ and ramming/embedding length $L_R$). The horizontal wave loads were calculated based on the approach of MORISON et al. (1950) and the respective recommendations of the EAK (2002).

The calculated wave induced moment at the pile (related to the sea bottom) is converted into a concentrated load at the top of the pile, which is given in a table for various water depths. Depending on the safety supplements and the type of subsoil, the planning engineer can calculate a moment at the theoretical centre of rotation of the pile. This moment has to be compared with the resisting moment of the holding forces, which is given in a table depending on the clamping depth $L_C$. Thus, the required clamping depth for the pile to counteract horizontal loads is found. The flexural strength of the pile itself, depending on pile dimensions and material properties, must be checked to determine the necessary pile diameter.

The design ice thickness h, which is necessary for determining horizontal and vertical ice loads was found by using a statistic analysis of ice data at the German Baltic coast. Values range between 0.25 m and 0.40 m depending on the location at the coast. Horizontal ice loads were calculated according to accepted methods by HIRAYAMA et al. (1974). Based on the performed laboratory investigations, recommendations focused on using Russian Standards to calculate the vertical ice loads on groyne piles. Respective tables for practical applications were established. By comparing the ice loads to the vertical holding forces, the clamping depth of the pile can be calculated easily. The tensile strength of the pile is given in a table, too.

The necessary ramming depth $L_R$ of the pile can be calculated from the clamping depth $L_C$ and the safety supplements defined before. The results allow the determination of the ramming depth of wooden piles in shallow water as a function of wave loads, wave induced pile movements, possible resulting liquefaction effects, ice loads, water depth and various subsoil conditions.

## 4. Future Aspects

Groynes can be found at the North and Baltic Sea coast in significant numbers and will continue to be important elements of coastal protection schemes in Germany. Even though the efficiency and value of beach groynes is controversially discussed, groynes have been used to increase the retention period of sand at eroding shorelines. In particular, beach groynes are being used and will be used in future in combination with beach nourishment. Until now, no generally accepted tool exist to predict long-term morphological changes near groynes or groyne systems in detail. There are still various questions considering both hydraulic and numerical modeling.

Cost-benefit analysis will must be an important aspect in planning and design in future. With a view at the defined value of a coastal region (habitation, industry, natural resources, effect on neighbouring areas etc.) the question about coastal protection or not is easily answered. For that, the efficiency and sustainability of the various available coastal protection methods and structures must be compared (e.g. groynes versus beach nourishment or a combination of the two). Interesting cogitations and investigations about this topic can be found already in very old publications and historic documents found at archives or coastal authorities.

A scientific method for the structural design of groyne piles is available for wooden single-row pile groynes. However, additional research is recommended e.g. to study the effect of pore water pressure on the stability of oscillating piles or other structures in the nearshore zone.

Because of the danger of infestation of wooden constructions with the shipworm *(teredo navalis)* in the North Sea as well as in the western part of the Baltic Sea, only lumber which is resistant against *teredo navalis* should be used. However, to avoid the use of tropical hard wood, an interesting new development to protect wooden constructions with geotextiles is introduced (KOHLHASE, DEDE, 2006). This method might be a possibility for other wooden constructions in coastal engineering practice.

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# Ems-Dollart Estuary

By Martin Krebs and Holger Weilbeer

Contents



## 1. Introduction

The Ems is Germany's most north-westerly river, rising near the town of Schloß Holte-Stukenbrock in Westphalia 134 m above sea level and – after 370 km – flowing into the North Sea near Borkum. Its largest tributaries are the Leda (tidal Ems) and the Hase. From Herbrum, the Ems and the Dortmund Ems Canal (DEK, 1st stage 1899) are influenced by the tide. Protection from storm surges and support for the transfer of newly-built ships has been provided by the Ems Barrier near Gandersum (Ems kilometre 32.2) since 2002.

The Ems serves as a drainage canal and shipping route, and its embankments offer space for habitation and agriculture. In its lower reaches, locks and pumping systems drain whole regions that are only very slightly above sea level and in some cases even below. The approach depth to Emden's sea port is guaranteed for shipping by maintaining the fairway depth at chart datum (LAT) – 8.5 m. Depending on the tide, ships can reach Emden with a draught of up to approx. 10.5 m. Inland navigation vessels up to the Europe ship class (length 85 m, width 9.5 m, draught 2.5 m) can travel through the Dortmund Ems canal to the Ruhr (Rhine region) or through the Mittelland canal to the waterway network of the rivers Weser and Elbe. The economic significance is defined primarily by the sea ports. Here worth mentioning vehicle transhipment with the VW works in Emden, major shipyards (Cassens, Nordseewerke, Meyer) and the handling of wood, paper and liquid chalk are worth mentioning. The handling of wind turbines is increasing, together with the significance as an energy hub, particularly on the electricity and gas sector. At the same time, the ecological significance of the Ems Estuary as a habitat for flora and fauna brings out competing uses. Tourism is assuming an increasing economic significance in the economically underdeveloped East Friesland. This is due to its high natural value, particularly with the extensive and specially protected Wadden Sea, the low population density and the authentic character of the East Frisian population. Fishing among others for shrimp also plays a role here. The fish stocks in the Ems Estuary can even be said to be good according to the so-called COFAD study.

In ecological terms, the Ems is a lowland river that flows essentially through low populated areas and bears great significance for animals and plants, providing a habitat for many protected species. The extensive marshlands and Estuary mudflats offer significant avifaunistic resting and breeding areas. As far as planning proceedings are concerned, it is significant that extensive areas are protected under the FFH Directive (Directive 92/43/EEC) as well as under the regulations of the Lower Saxony National Park Wadden Sea (1986) and the Lower Saxony Biosphere Reserve Wadden Sea (1992).

The Ems Estuary is particularly relevant on account of its significance as being a frontier region to the Netherlands (STEEN, 2003). The exact course of the national frontier has still not been established. Thus, a treaty (Ems-Dollart treaty of 1962 and supplementary treaty of 1962) on the existence of so-called "disputed territory" had to be concluded between the Netherlands and the Federal Republic of Germany. This treaty stipulates in general the use of the Estuary, maintenance and participation of both parties in cross-frontier projects (referring to the disputed territory). The Ems Commission meets regularly for discussions.

## 2. Geomorphology of the Ems Estuary

In terms of its historical origins in the context of the continental shelf in the North Sea, the Ems Estuary is a relatively young hydro-morphological system (just a few thousand years old) which, therefore, has a highly dynamic character. The appearance of the present coastline, which is dominated by the East Frisian Islands, developed by transgression following an increase in sea level about 10,000 years ago. The oldest reliable charts of the region (sailing instructions) date back to the 1630s.

One striking morphological element is the Dollart, a bay to the south of Emden with an extension of about 100 km² today. The Dollart most probably resulted from the so called Marcellus Flood in 1362. It reached its largest expanse after the heavy storm tide of 1509. Around the same time, the Leybucht was created by the storm tides of 1374 and 1378 (MEYER, 2006) to the north-east of Pilsumer Watt and north of Greetsiel. A further major morphological effect of the storm tide of 1509 was the formation of the island "Nesserland". The "old Ems" ran in a northerly loop straight past Emden, while the new branch of the river at Pogum drained the water due westwards. As a result, the "old Ems" at Emden was subject to increasing aggradation, which several attempts to keep the old fairway close to Emden failed to prevent. At this point in time, the main fairway ran to the west of Termunten through the bay of Watum. But the East Frisian Gatje, a branch of the river to the North-east of the bay of Watum, grew increasingly stronger as a result of the current forces. Consequently, in this period, the shore was subject to noticeable erosion, necessitating dyke realignments on both the German and the Dutch side. Numerous settlements had to be given up. At this point in time, the Western Ems was the main fairway, with maritime traffic being advised not to use the passage through the Hubertgat, the channel located to the South of the Western Ems on the same latitude with Borkum. Later, the channel through Hubertgat was partly used as the main fairway.

From the $16^{th}/17^{th}$ century up to recent times, an expansion of the Dukegat and East Frisian Gatje channels can be observed, which would appear to be coming to an end through the almost complete aggradation of the bay of Watum. A map by LANG (1954) shows the situation around 1860 when the old loop of the Ems near Emden had disappeared completely, with an access channel connecting the port of Emden with the river Ems (later Emden fairway). The bay which had formed to the South of Emden on the one hand sedimented up on the other hand was part of land reclamation later on.

Fig. 2 shows present cross-sectional areas between Herbrum and the mouth to the North Sea (data from 2005), calculated for water levels approximately at LW (NN –1.5m), at NN and at HW (NN +1.5m). The significant break at Ems kilometre 48 appears due to the transition to the Emden fairway. The areas of the Dollart are not taken into account.

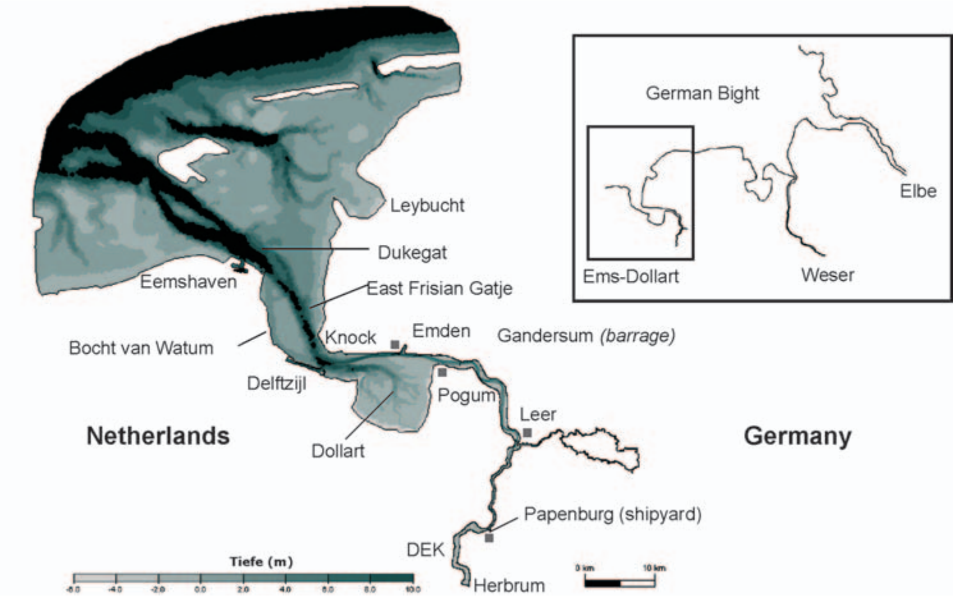


Fig. 1: Ems-Dollart Estuary

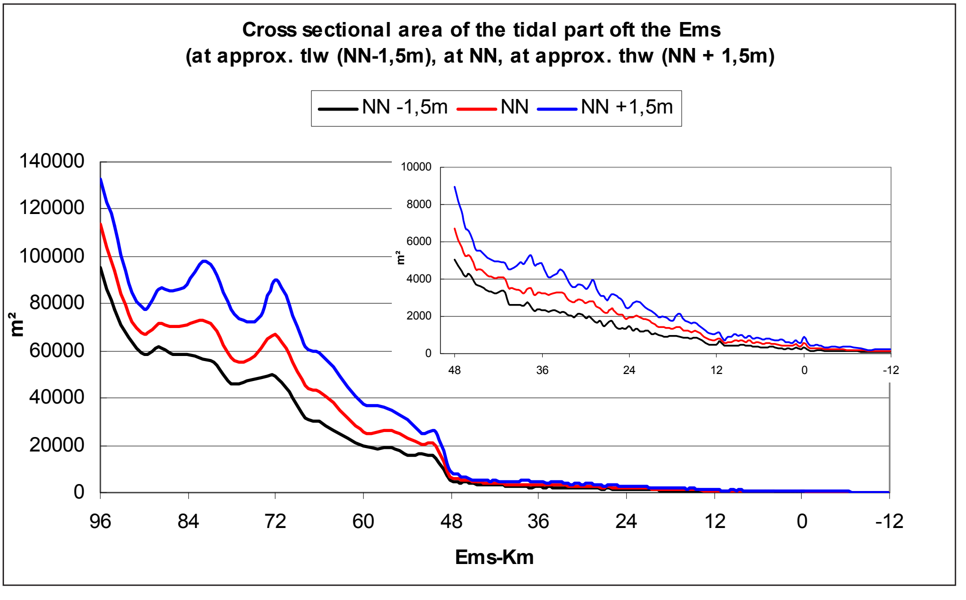


Fig. 2: Present cross-sections in the Ems Estuary as a function of the distance to the geographic origin of the system (tidal boundary)

## 3. Hydrological Characteristics

The catchment area of the Ems is 17,934 km² and thus less than 10 % of the catchment area of the Rhine or about 40 % of the catchment area of the Weser. The small size of the retention area means that there are phases with low freshwater discharge for six months in the summer. For the years 1941/2003, the maximum freshwater discharge (HHQ) is 1,200 m³/s (Feb. 12, 1946), the mean high value (MHQ) is 378 m³/s and the average discharge (MQ) 80.8 m³/s. The mean low-water discharge is 15.6 m³/s and the lowest value (NNQ) 5.2 m³/s (Aug. 01, 1947).

Statistics show that the large freshwater discharges occur frequently in the period without vegetation i.e. in the months from January to April, followed by a transition to a disctinctly smaller discharge during the summer months, as a rule. Mean monthly discharge values below 20 m³/s were only reached in 4 months over the last 20 years (towards the end of the 1980's and beginning of the 1990's). The median value (most frequent freshwater discharge) is approx. 60 m³/s.

The influence of upgrades of the navigational channel of the Ems on the tidal range (Thb), HW (Thw) and LW (Tnw) can be clearly demonstrated with the development of water levels at the tidal gauges Borkum Südstrand and Papenburg, shown in Fig. 3. The development of the mean annual tidal range for the seaward water gauge Borkum Südstrand in the mouth of the Ems shows a uniform variation through the Saros cycles (nodal tide: 18.61 years). The long-time mean of the tidal range is 225 cm, with a linearly increasing trend with a rate of currently 15 cm per century. Between 1958 and 1996, the tidal range at Borkum increased by 7 cm and at Papenburg by 165 cm. The development in water levels at Borkum is due to natural influences, while the increaseat Papenburg is primarily influenced by construction measures. The time series show various trends; e.g. the tidal high water shows

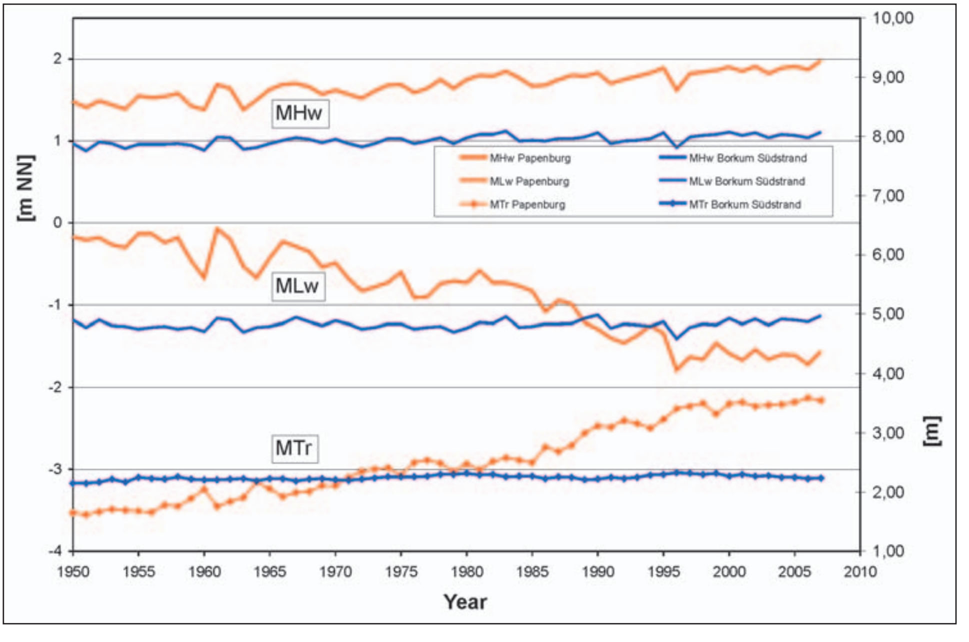


Fig. 3: Development of MLW, MHW and mean tidal range for selected water gauge sites

a greater increase at Papenburg than at Borkum. LW elevations at Borkum range between –1.5 m and –1.0 m (gauge ref. datum) for the period from 1950 to 2005. The curve for Papenburg gauge is subject to greater fluctuations than at Borkum because of the deformation of the tidal wave by the narrowing river cross-sections and freshwater discharge from upstream. There is a striking decrease in LW during the observed period.

The Ems is characterized by a large gradient in salinity reaching a maximum in the vicinity of Emden with a mean freshwater discharge. The variation of discharge and tidal current means that the conditions in the brackish water zone are subject to constant change. For mean conditions, a salt level of less than 0.5 PSU (PSU almost equivalent to ‰) can be found near Papenburg and Weener, less than 3 PSU for Terborg (Ems kilometre 24.5) and 7 PSU for Gandersum. At Gandersum (Ems kilometre 32), it is possible for salinity levels to exceed 16 PSU at slack water during longer periods with low discharge volumes during the summer. In 1951/1952, comparative measurements of salinity showed a very low level of approx. 2–3 PSU for a discharge of 30 $m^3/s$ at the Terborg water gauge, and about 10–12 PSU at Gandersum (slack water on the surface and on the bottom of the river). Today, comparable marginal conditions show a salinity level of about 6–8 PSU for Terborg and 14–16 PSU for Gandersum, indicating an increase of 4–6 PSU (SPINGAT, 1997).

One particular phenomenon can only be detected by special measurements (MAUSHAKE, 2003 and TALKE, 2006). These are situations where close to the river bed lower salinity concentrations than in the layers above can be found. Fig. 4 shows salinity concentrations measured during one tide, clearly indicating the time phases of instable salinity stratification. Sometimes, the vertical gradient in salinity concentration is more than 3 PSU. The cause of this is to be found in the interaction of the prevalent extremely high particulate matter concentrations and the resulting current and turbulence conditions.

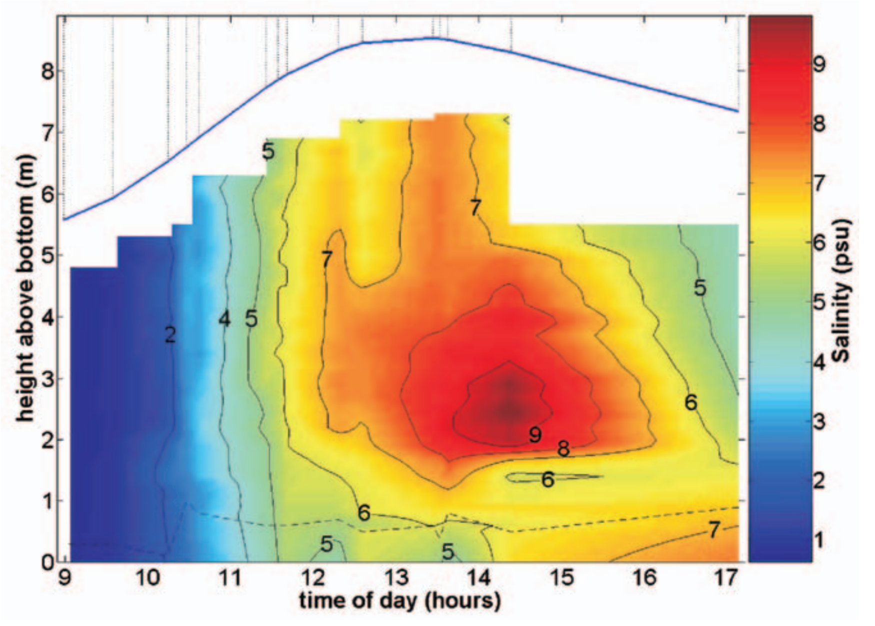


Fig. 4: Salinity concentrations measured during one tide (TALKE, 2006)

Typically current velocities are recorded by continuous measurements in one location, at a constant distance either to the water surface or to the river bed. The velocity measurements are made at the edge of the fairway and are therefore only conditionally representative for the current regime in the cross-section. It is presumed that the maximum current velocities in the fairway will be around 20–30 % larger than the measured values discussed below. Comparative statements for the Ems can be made on the basis of continuous current measurements carried out since 1986.

For Papenburg measuring station, the maximum flood current velocity values averaged over the year 2000 were approx. 1.2 m/s; ebb currents were 0.7 m/s. On the other hand for 2007, the flood and ebb values were between 0.8 and 1.0 m/s. Both periods are outside any dredging activities and in a phase with a freshwater discharge of less than 50 $m^3/s$. In the year 2000, maximum flood and ebb current velocities of about 1 m/s were measured at Leerort, without any change until 2007. The measurements near Weener and near Terborg typically show higher flood than ebb current velocities.

These statements can be confirmed by an analysis of characteristic tidal values obtained from a calibrated three-dimensional model of the Ems-Dollart-Estuary. The results of a model run for time periode in May 2005 were stored for cross-sections at each Ems kilometre and analyzed in several post-processing steps regarding characteristic ebb and flood quantities. Fig. 5 shows calculated mean maximum ebb and flood current velocities and their ratio. The dominance of the flood current, which was already found in the measurements, is clearly visible. Due to the relatively small cross-sectional areas in the upstream part of the Ems, this ratio is strongly dependent on the prevailing freshwater discharge.

Fig. 6 shows suspended matter concentrations measured at various stations of the Ems. The data are from 2004 but can be considered representative for the Lower Ems. Discharge

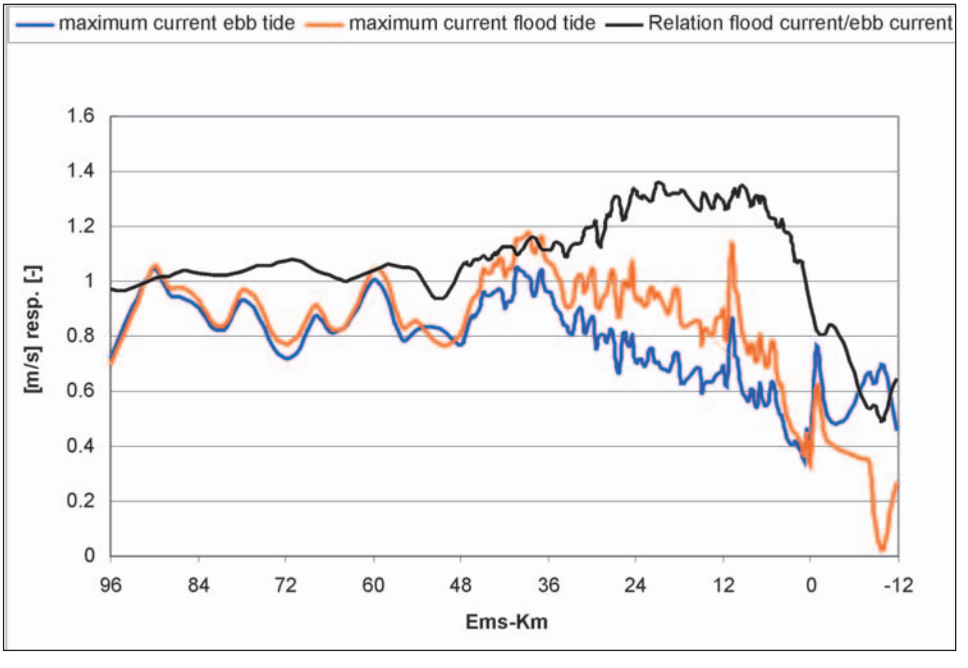


Fig. 5: Flood and ebb current velocities, mean values for cross-sections (model results)

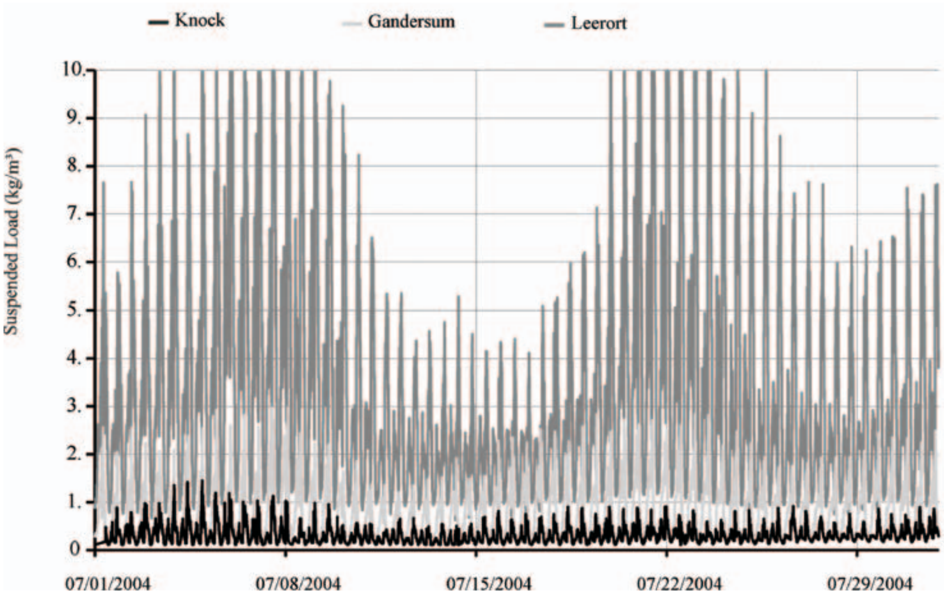


Fig. 6: Suspended matter concentrations measured at the Knock, Gandersum and Leerort stations in 2004 (WEILBEER, 2005)

volumes and tidal conditions are seen to have a particularly clear influence in the area of the Lower Ems. At Knock station (mouth of the Dollart) the concentrations are below 1 g/l. Further upstream near the Ems Barrier at Gandersum, the particulate matter concentrations reach values of approx. 3 g/l. The influence of the 14-day neap/spring tide cycle is also clearly apparent at this station. During the spring tide, concentrations reach far higher values than during the neap tide. Another 18 kilometres upstream at Leerort station, the same pattern can be seen in even greater clarity, with concentrations exceeding 10 g/l during the spring tide.

Fig. 7 shows suspended matter concentrations in the Ems resulting from measurements in a longitudinal profile in the Lower and Outer Ems. These measurements were carried out at low freshwater discharge ($Q = 20\ m^3/s$) in August 2006 (TALKE, 2006). There is a significant transition to higher concentrations in the Lower Ems. Concentrations exceeding 10 g/l can already be found in a medium level of the water column and increase further towards the river bed. At this point in time a distinctive "fluid mud" layer along the entire Lower Ems exists.

## 4. Structural Measures to Adjust the System

After the Second World War, inland navigation increased with an even greater increase in ocean-going shipping, the latter using the river Ems primarily from Emden to Leerort. Water depths in this stretch were 4.80 m below mean HW (MThw). Overseas maritime traffic calling the port of Papenburg had to lighten their load in the port of Emden or Leerort above the Jann-Berghaus Bridge, with part of their cargo being transhipped to inland navigation vessels.

In the section Leerort-Papenburg, depth of the fairway was only 4.0 m below HW. Dredging was necessary at a few points to maintain these depths. The work was carried out

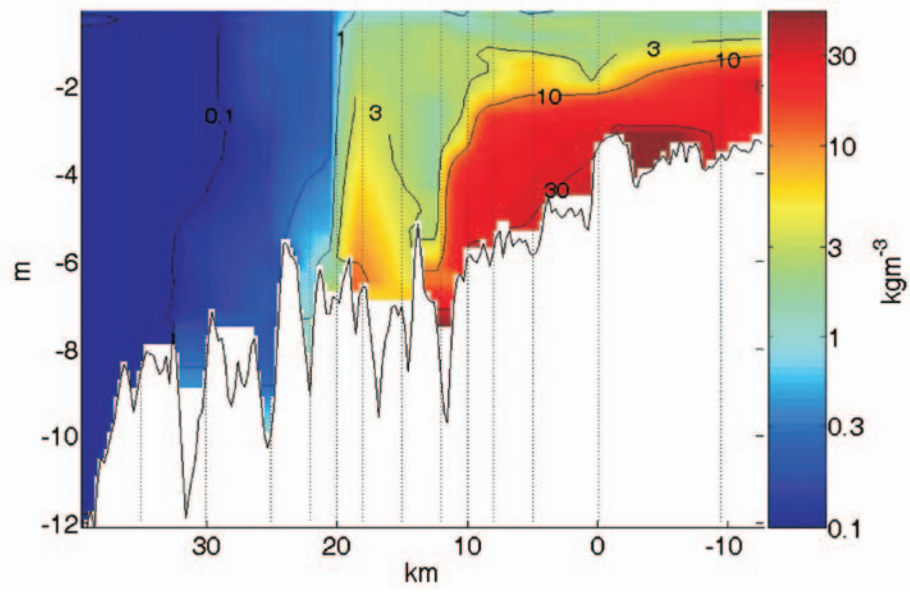


Fig. 7: Suspended matter concentrations (field measurements) in a longitudinal profile in the Lower and Outer Ems at low freshwater discharge (Q = 20 m³/s) in August 2006 (TALKE, 2007). The kilometres refer to Papenburg (Lower Ems KM 0)

with chain-and-bucket dredgers, and the dredged soils were loaded into barges to be transported to the old river branches resulting from breakthroughs made between 1911 and 1928. Here, they were dumped or flushed ashore.

In February 1962, the German North Sea coast suffered from a heavy storm surge. Consequently, all dykes along the Ems had to be reinforced and raised, starting in the mid 1960's. The design of new dykes was modified to consist a sand core covered with clay. Today, crest elevations of the dykes along the lower Ems are between NN + 6.60 and 7.30 m. The necessary sand was mined in the lowlands behind the dyke, resulting in large lakes along the river Ems. On the other hand, approx. 4.5 million m³ material was taken by hopper dredgers along various sections of the Lower Ems where insufficient fairway depths prevailed. These measures also supported the necessary maintenance measures up to the early 1980's, when the depth of the navigational channel had to be adapted to the growing drafts of vessels.

The main river and coastal engineering measures changing the appearance and system behaviour of the present Ems-Dollart Estuary are listed in a chronicle below:

| | |
|---|---|
| 1872 | Start of river construction work in the Ems to erect groynes, among others on the Geise near Emden |
| 1901 | Emden sea port is opened as the terminal point of the Dortmund Ems Canal, Dredging of the Gatjebogen and deepening of the East Frisian Gatje to improve access from the sea to Emden |
| 1914–1923 | Dyke construction Knock – Emden West Mole for fortifying Emden's fairway |
| 1930–1932 | Construction of the Knock training wall (later also boundary of former containment areas) |

| | |
|---|---|
| 1930–1939 | River structures to strengthen the Gatjebogen and construction of Geise staging to straighten Emden's fairway and achieve a depth of 7 m below chart datum |
| 1958–1964 | Regulation of Emden's fairway and deepening to 8 m below chart datum. Construction of the Geise training wall and sea dyke training wall; fairway of the Outer Ems deepened to 8.5 m below chart datum |
| 1971/72 | Approach from offshore deepened to 12.5 m below chart datum |
| 1973–1977 | Sea locks in Papenburg and Leer widened from 18 to 26 m |
| 1976 | Fairway moved from the Old Ems to the Randzelgat |
| 1983/84 | Lower Ems deepened for ships with 5.70 m draught |
| 1988/89 | Fairway moved from Hubertgat to the West Ems |
| 1991–1994 | Lower Ems deepened (temporarily) for ships with a draught of 6.30 m (basic depth) or 6.80 m |
| 1994/95 | Lower Ems deepened (temporarily) for ships with a draught of 7.30 m. |

The currently planned measures (as of 2nd quarter 2008) are listed in the following table.

| Section | Measure | Status |
|---|---|---|
| Lower Ems | Adaptation of parts of the federal waterways river Ems and Dortmund Ems canal | Planning approval procedure in progress |
| Lower Ems | Creation of summer dykes near to the shore to make the summer backwater flexible | Feasibility study |
| Lower Ems | Ems action campaign | Conceptional considerations |
| Outer Ems | Deepening the approach to Emden port | Feasibility study |
| Outer Ems | Deepening the approach to Eemshaven | Ongoing process |

## 5. Maintenance of the Fairways

As far as dredging in the Ems Estuary is concerned, a distinction must be made between dredging the Lower Ems and the Outer Ems. The reason for this distinction consists primarily in the use of the waterway and what to do with the dredged material. While the Outer Ems has to be maintained for uninterrupted maritime traffic to Emden, the maintenance of the Lower Ems is geared primarily to the transfer of ships from the shipyard in Papenburg. The boom in the cruise business has intensified the depth requirements and the intervals between necessary dredging measures in recent years. Since September 2002, the storm surge barrage at Gandersum has been in operation; the passage can be used for the transfer of large ships from the shipyard and the weir as a water retaining structure. It is operated by the Lower Saxony State Agency for Water Management, Coastal Defence and Nature Conservation (NLWKN).

In the course of fairway deepening work in the early 80's, quantities of up to 200,000 m³ p.a. were dredged at some points in the Lower Ems. In some years no dredging was carried out at all. Given the restricted conditions in the Lower Ems, only small dredgers can be used. In 1995, work was carried out for the last time with chain-and-bucket dredgers during deepening the river for ships with a draught of 7.3 m. Nowadays maintenance dredging is carried out by hopper dredgers. The machines have a hold capacity of between 800 and 1,000 $m^3$. It is worth mentioning that presently the fairway of the Lower Ems has to be maintained for the transfer of ships from the shipyard with draughts of up to 8.0 m (regular-traffic vessels have draughts of up to 5 m). The possibility of increasing the water depth for ship transfers due to the Ems Barrier has resulted in considerable reductions in the dredging quantities necessary for such large ships.

Until 1978, maintenance dredging in the Outer Ems was carried out with chain-and-bucket dredgers, usually with several units operating at the same time. As from 1978, the federal hopper dredger "Nordsee" operated in the Ems Estuary. The "Nordsee" was redeployed in 1995 and was replaced by comissioned dredgers.

In the period between 1965 and 1980, material dredged from the Lower Ems was used primarily for dyke construction; because dredged soils consisted of approx. 80 % sand, another area of utilization for road and settlement area construction was opened up in 1984, with the corresponding share declining successively since 1995. The sand was hydraulically washed onto areas near the river Ems, and containment areas were raised up to 6 m. After drying up, the material was removed and used for various applications, thus fulfilling both economical and ecological aspects. This permitted good synergetic effects between the Life-Cycle Resources Management Act and utilization of dredged material.

Today the dredged material from the Lower Ems, consisting almost completely of silt and clay, is pumped into former gravel and quartz sand pits. It is too expensive to transport the material to dumpsites of the Outer Ems because of the long transport distances and time involved. Since 2006, several hundred hectares of land for containment areas have been made available to the North of Papenburg where dredged soils can be deposited.

Between 1954 and 1994, dredged material from fairway maintenance in the Outer Ems, primarily for Emden's fairway and the port of Emden, was dumped on agricultural areas to the North-east of Emden. This, however, soon became subject to criticism because of the high costs involved as well as nature protection aspects. Until the end of the 1980's, sandy dredged material was hydraulically washed onto "Rysumer Nacken". Meanwhile all the material dredged from Emden's fairway and from the Outer Ems is transported to dumpsites in the Estuary, based on sustaining the natural material cycles.

Dredging quantities in the Ems Estuary are caused by the different structures of the Outer Ems and the Lower Ems. Particularly, in the Lower Ems, not only the dredged volumes but also the quality of the sediments has changed drastically over the last three decades (considerable share of silty sediment).

## 6. Ongoing Activities for Observation and Analysis of the System

Long-term observations include the ongoing registration of water levels at the gauges at Papenburg (since 1895), Weener (since 1899), Leerort (since 1895), Terborg (since 1899), Pogum (since 1923), Emden New Sea Lock (since 1919), Knock (since 1970) -site has been moved; originally Fiscal Lock (since 1907) and Borkum Fischerbalje (since 1961); former landing stage (from 1907 to 1959). Moreover, echosoundings for the morphology supplemented by additional permanent current measuring devices and secured in the context of the data gathering required for preserving the evidence for the structures in the Lower Ems were carried out. Furthermore, since 2004 regular sediment studies have been conducted in the Lower Ems and in Emden's fairway. The evaluations yield important findings about the physical changes of the system. All data were transferred to databases to permit decentral evaluation.

At present, tidal gauge locations are being investigated under the aspect of long-term geological movement in the context of the IKÜS research project. This has revealed initial indications of significant geogenic or anthropogenic effects (such as extraction of natural gas) and will have to be given some consideration in the future.

Some German and Dutch institutes maintain and run hydrodynamic-numerical models covering partial areas or the entire Ems-Dollart Estuary to study the hydrodynamic processes and ecological issues (HARTSUIKER et al., 2007). For several years, the Federal Waterways Engineering and Research Institute (Bundesanstalt für Wasserbau – BAW) has been operating 2D and 3D models with high local resolutions to examine the effects of upgrade measures in the Ems on water levels and currents, salinity and sediment transport. The corresponding model technology is subject to ongoing developments in order to include relevant physical effects within the simulations to predict the movement of dumped soils and long-term morphodynamic development.

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# The Jade

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## Contents



## 1. Introduction

The Jade stands out against other estuaries such as Ems, Weser, Elbe and Eider by its different geological development and the fact that it does not have a significant freshwater discharge.Therefore, it is considered a tidal bay rather than an estuary.

The geography of the Jade comprises the Outer Jade, Inner Jade and the Jade Bay (Fig. 1). The tidal flat area known as *Der Hohe Weg* separates the Jade from the Weser estuary.

The eponym Jade, a small, non-navigable river, enters the 'Jade Bay' (Jade Bay) through the sluice 'Wapeler Siel' into a system of tidal creeks and gullies at the southernmost point of the bay.

Wilhelmshaven, the main town of this region, lies at the south-western end of the Inner Jade. It was founded as a naval port in 1869 and still shelters a naval base of the Bundeswehr in its inner harbour separated from the Jade by a sea lock. This also houses transhipment facilities that are important for the region's economy. On the west bank of the Inner Jade, four transhipment piers located along the deep Jade fairway, and the industrial zones that stretch along the shore constitute the outer harbour. This is Germany's only deep water port with an access channel for very large sea-going vessels with an unrestricted draught of up to 16.5 metres. Tide-dependent access is possible for 250,000 TDW tankers with a maximum draught of 20 metres.

## 2. Geomorphology

Between the 11th and 15th century, the Jade Bay developed at the Frisian marsh coast as a result of storm tides in the North Sea and cuts deeply into the mainland. The fairway was developed and is being maintained as far as Wilhelmshaven. Upstream, it branches into several channels (Ahne, Vareler Fahrwasser and Stenkentief), which lead into the Jade Bay and, with diminishing cross-sections, merge into tidal creeks. They are used as fairways in the tidal flats.

The morphology of the Jade dates from the Ice Age with Holocene and Pleistocene sediments. Today, the spatial structure is dominated by the navigational and other deep channels, sandbanks and extended tidal flats. The regime is governed by natural forces (tidal currents and waves) as well as man-made activities (dyking, fairway maintenance and improvement and river training works).

Hydrological investigations (LANG, 2003; FRELS, 1995) indicate a positive material balance of sediment transport for the Jade. Due to various physical features, such as the dominance of flood tides, a residual flow via the 'Hohe Weg' tidal flats into the Weser estuary, lack of freshwater discharge and the shape of the Jade Bay, flood currents transport more sediment into the Jade Bay than ebb currents can take out again. This emphasizes the centuries-old

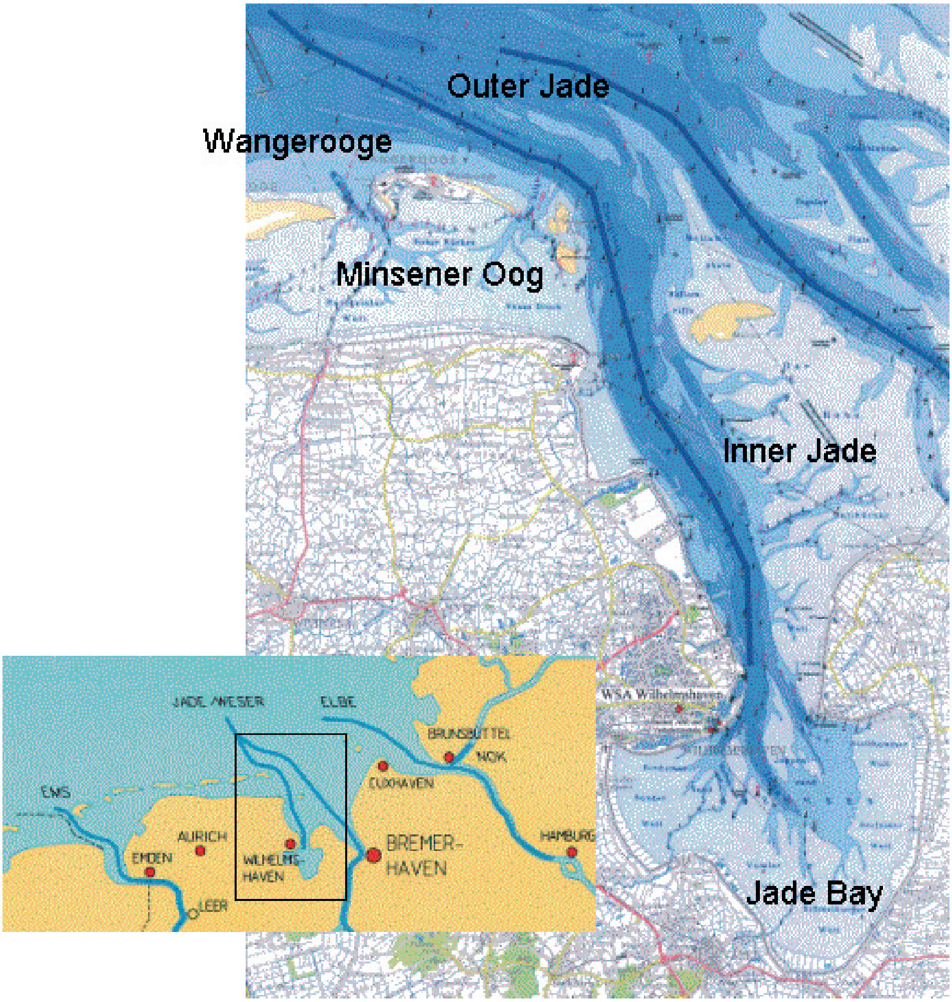


Fig. 1: General plan of the Jade

significance of the self-maintaining character of the main Jade channel. According to the investigations of LANG (2003) the reason for this behaviour is to be found in reflection properties of the tidal wave in the Jade Bay with a low dissipation of energy and an increase in the tidal range caused by resonance.

In the Jade, the tidal current moves in weak meanders. In the Inner Jade and in the Jade Bay, the incoming and outgoing tides sometimes follow different tracks. As a result, in these regions modifications of varying intensity to the morphology are caused above all at the undercut and slip-off slopes and in the areas of divergence (cf. chapter 5). Various river engineering structures, such as the groyne system on Minsener Oog and the training wall on the Schweinsrücken (cf. Figs. 1 and 5), guide and bundle the flow to prevent local sedimentation in the fairway and to facilitate maintenance.

## 3. Hydrological Parameters

### 3.1 Fresh Water Discharge

A unique feature of the Jade is its expansive tidal bay character with almost no fresh water discharge. The drainage sluices in the Jade Bay make an almost imperceptible contribution to the total volume of around 400 million cubic metres that flow in and out of the Jade Bay with every tide. The freshwater discharge has also little influence on the salinity in the Jade. This varies between 2.9 and 3.2 % and a brackish water zone does not develop.

### 3.2 Water Levels

Measurements of hydrological parameters can be traced back to the founding of Wilhelmshaven as a naval port. Water levels were recorded at the gauge station 'Alter Vorhafen' starting in 1853. At the harbour of the island of Wangerooge, records have been kept (with some interruptions) for about 100 years. Additional tidal gauges were installed after the storm surge of February 1962. However, due to dike construction (gauge station Voslapp) or sedimentation (gauge station Schillig) they were frequently moved in the early years. Long-term time series of water levels are therefore only available from the gauge stations 'Alter Vorhafen' and at the Mellumplate lighthouse (beginning in 1943). These stations were additionally used to collect data for the preservation of evidence after improvement measures in the Jade carried out between 1960 and 1976.

An overview of the mean high water levels along the navigation channel for the hydrological year 2007 is depicted in Fig. 2.

The increase of 44 cm in MHW from the sea to the Inner Jade can be clearly recognized. The opposite effect can be observed for MLW: from Wangerooge to the entrance of the Jade Bay, the low water level decreases by 56 cm. The data from the 10-year time series from 1998 to 2007 (see Tab. 1) confirm the mean conditions of the year 2007.

In the Jade Bay, the mean high water levels are a little higher than at the gauge station 'Alter Vorhafen', as the tidal wave spreads out into and is partially reflected in the Jade Bay. The mean low water levels in the Jade Bay show little difference in comparison with those of 'Alter Vorhafen'.

The water level dynamics vary due to astronomical and meteorological influences. The highest high water level was observed at 'Alter Vorhafen' to be NN + 1022 cm on 16.2.1962.

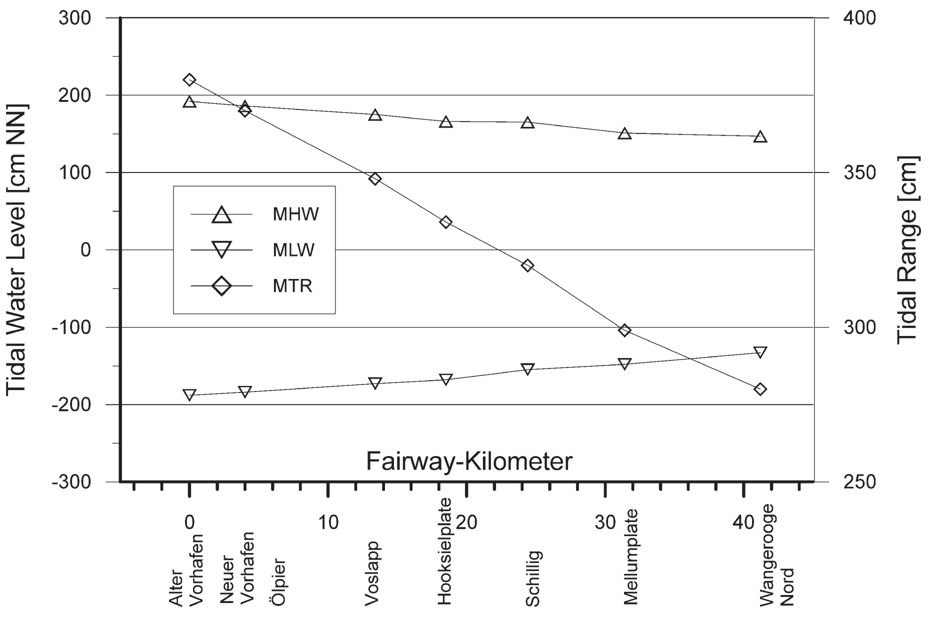


Fig. 2: Mean high and low water levels (MHW, MLW) and mean tidal range along the navigational channel of the Jade in the hydrological year 2007

In contrast, the lowest recorded low water level was NN + 59 cm on 16.02.1900. Water levels measured at the seaward gauge stations show the same relation (see Table 1).

Table 1: Mean and extreme water levels in the Jade

| Gauge station | Gauge datum cm below NN | MHW 1998–2007 | MHW 2008 | MLW 1998–2007 | MLW 2008 | Mean Tidal Range | Mean Tidal Range 2008 | Highest HW | | Lowest LW | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Wilhelmshaven Alter Vorhafen | 502 | 686 | 684 | 305 | 302 | 381 | 382 | 1022 | 16.02.1962 | 59 | 16.02.1900 |
| Wilhelmshaven Neuer Vorhafen | 500 | 678 | 677 | 307 | 304 | 371 | 371 | 965 | 01.11.2006 | 103 | 02.03.1987 |
| Ölpier (Oil pier) | 500 | 676 | 677 | 302 | 298 | 374 | 375 | 961 | 10.01.1995 | 154 | 14.02.1994 |
| Voslapp | 502 | 671 | 670 | 322 | 318 | 349 | 352 | 950 | 21.01.1976 | 161 | 14.02.1994 |
| Hooksielplate | 502 | 662 | 661 | 327 | 325 | 335 | 336 | 925 | 28.01.1994 | 167 | 14.02.1994 |
| Schillig | 500 | 655 | 654 | 335 | 330 | 320 | 324 | 913 | 01.11.2006 | 180 | 14.02.1994 |
| Mellumplate | 502 | 646 | 645 | 345 | 342 | 301 | 303 | 930 | 16.02.1962 | 124 | 02.03.1987 |
| Wangerooge Nord | 503 | 643 | 642 | 361 | 358 | 282 | 284 | 907 | 03.01.1976 | 134 | 02.03.1987 |
| Wangerooge West | 503 | 647 | 647 | 361 | 358 | 286 | 289 | 915 | 21.01.1976 | 144 | 02.03.1987 |

Fig. 3 shows a time series of MHW and MLW at 'Alter Vorhafen' since 1905. The slope of the regression line over a period of 100 years yields a mean increase of MHW of 37 cm while MLW is almost unchanged. Consequently, the tidal range has increased by 33 cm during the last 100 years. An influence of the deepening of the Jade fairway (cf. chapter 4) cannot be discerned in this almost linear development. However, channel improvement resulted in an increase in the velocity of the tidal wave progression (Fig. 4). This was due to deepening the navigation channel with a concentration of the currents, an increased hydraulic radius and a correspondingly reduced frictional resistance of the bed.

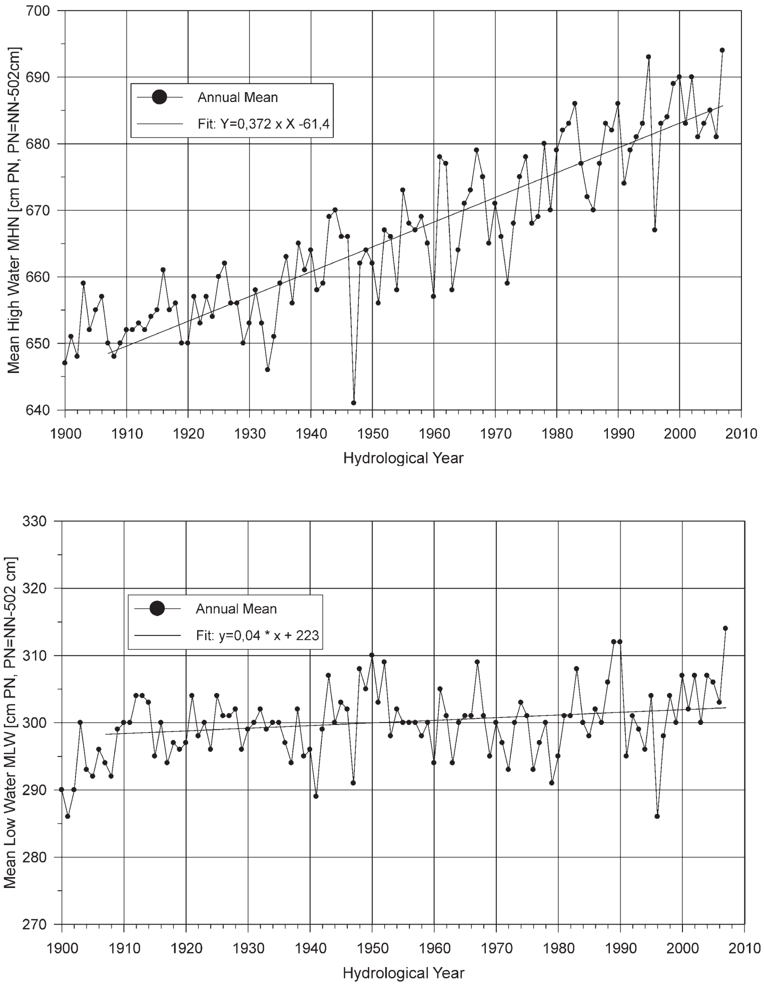


Fig. 3: Tidal peaks (MHW, MLW) at the gauge station Wilhelmshaven Alter Vorhafen since 1905

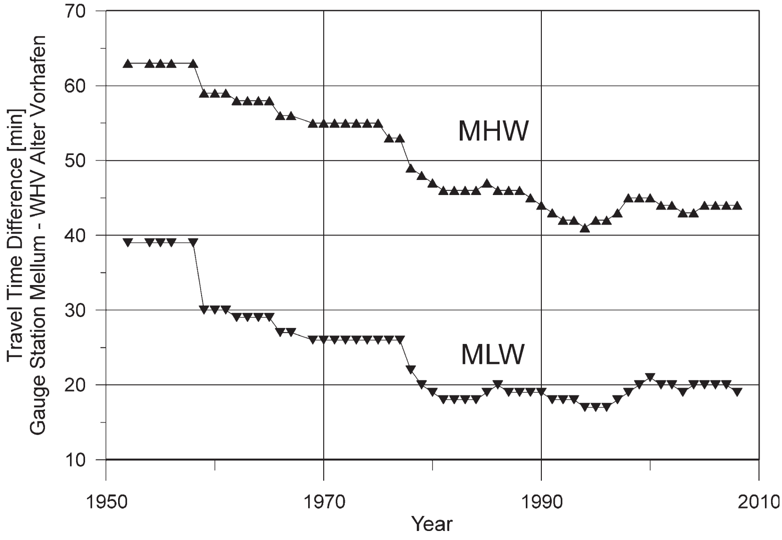


Fig. 4: Development of the travel times of the tidal peaks MHW and MLW between Mellumplate and Wilhelmshaven Alter Vorhafen

## 3.3 Current Velocities

The tidal current conditions in the fairway are being monitored all year round by means of measuring campaigns at various locations. The centre channel is exempted because of shipping traffic. Since 1998, four permanent measurement stations with another two added in 2006, have monitored the current regime in the Inner Jade. At present, the chain of measurement points stretches from the Varel fairway (Vareler Fahrwasser) to a point on a level with Horumersiel.

Table 2: Mean current velocities in the Jade

| Station | Flood tide $v_{mean}$ [cm/s] | Flood tide $v_{max}$ [cm/s] | Ebb tide $v_{mean}$ [cm/s] | Ebb tide $v_{max}$ [cm/s] |
|---|---|---|---|---|
| D0 Jade Bay | 46 | 96 | 53 | 113 |
| D1 Steenkentief | 46 | 97 | 49 | 95 |
| D2 Neuer Vorhafen | 52 | 97 | 47 | 88 |
| D3 Niedersachsen-Brücke | 50 | 94 | 48 | 104 |
| D4 Hooksiel | 58 | 106 | 63 | 115 |
| D5 Horumersiel | 58 | 109 | 58 | 110 |

Characteristic parameters can be seen in Table 2. In addition, Fig. 5 shows the distribution of the surface current velocities as calculated by the mathematical tidal model for the Jade-Weser Estuary operated by the German Federal Waterways Engineering and Research Institute (Bundesanstalt für Wasserbau – BAW).

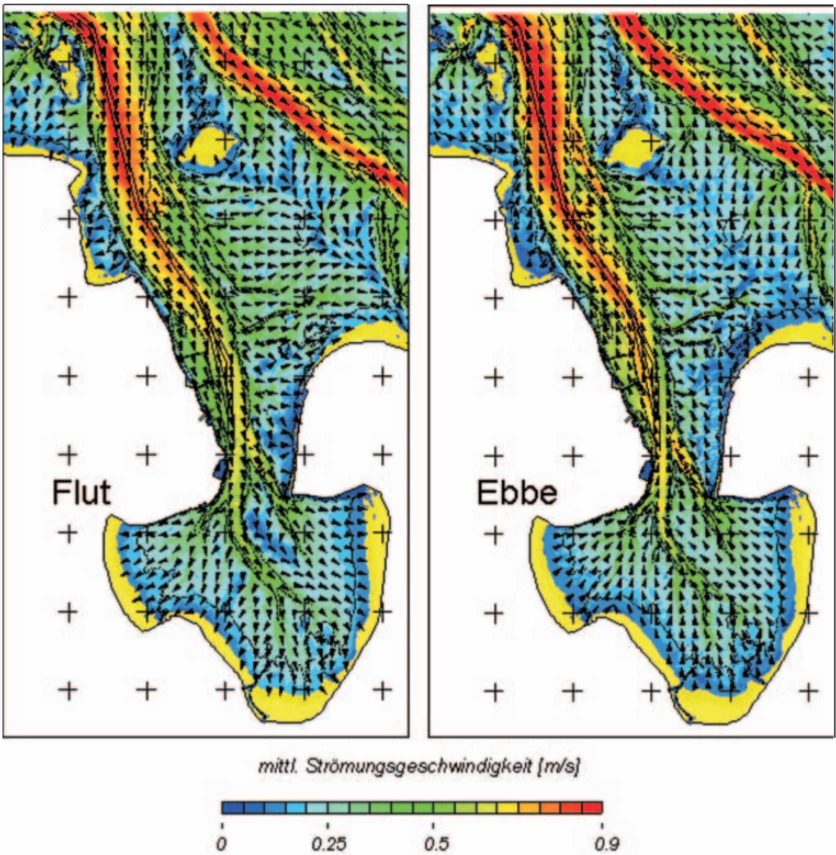


Fig. 5: Flood (right) and ebb (left) current velocities averaged over a neap-spring cycle obtained from a 3D-HN simulation with the model UnTRIM3D (BAW, 2003a)

### 3.4 Waves

Only sporadic information is available on the sea state in the Jade. The only wave information is based on measurements carried out for the planning and design of port facilities in the Inner Jade and as input values for various modeling and measuring techniques (IM+P, 2003). The following wave phenomena were deduced from the bathymetric and topographical conditions (BAW, 2003b):

- As a result of the large flow cross sections and very deep water of the Jade, swell can penetrate far into the Inner Jade, depending on the phase of the tide. It may be generated far away in the North Sea and arrives from a northerly to north-westerly direction.

- As a result of long fetches and deep water, locally generated waves in the Inner Jade will be intensified and can – dependent on the tidal phase – have a particular impact on the higher eastern tidal flats and coastal sections.
- The Jade Bay is characterized by extensive tidal flat areas. Waves entering through the 'Vareler Fahrwasser' and the 'Ahne' from the Inner Jade are transformed in shallower water by processes such as shoaling, refraction, diffraction and breaking. In addition, local wind effects modify the sea state depending on the tidal phase.

The results of a numerical spectral wave model for the rare extreme event "storm tide with ebb current" (BAW, 2003b) indicate that incoming offshore waves with a significant wave height $H_S = 6$ m and a peak period of $T_P = 15$ s will be already reduced to a $H_{Smax} = 3.5$ m at the level of Schilling by the influence of shallower water. Further south, in the Inner Jade towards Wilhelmshaven, significant wave heights decrease to values of 2 to 3 metres. The spatial distribution of the wave heights depends on the topography. Depending on the location of the deep channels, the larger wave heights are concentrated in the western part of the Inner Jade. In the southern channels with a greater water depth (Stenkentief, Vareler Fahrwasser, Ahne), waves with a height $H_S = 1 – 2.5$ m can penetrate more easily into the Jade Bay. In the shallow regions of and on the tidal flats of the Jade Bay and on 'Hohe Weg Watt' only waves with heights of $H_S < 1.5$ m occur.

### 3.5 Turbidity and Suspended Matter

As it requires considerable effort, the direct measurement of suspended load is only carried out in exceptional cases for the calibration of turbidity measurements. Annual turbidity measurement series are available from the permanent measuring points along the Inner Jade. The mean values range from 50 NTU in the region of Hooksiel to 80 NTU in the Jade Bay. The high values in the Jade Bay are caused by turbulent flow action and resuspension of fine matter on the tidal flats. In the Inner Jade region, ebb currents from the wadden area at 'Hohe Weg' occasionally cause turbidity peaks. Otherwise, the transportation of fine sand in the form of large dunes at the bottom is dominant here. Suspended load concentrations of between 200 and 2,000 mg/litre have been measured.

## 4. Construction Measures – Review and Outlook

With the last dyking in 1854, the Jade Bay was largely given its present shape. In the early 20th century, the inner harbour at Wilhelmshaven was extended southwards. The first interference with the dynamics of the Jade through construction activities, namely the building of the approx. 5.8 kilometre-long training wall on 'Schweinsrücken in the Jade Bay', started from 1893 to 1897. This structure regulates the tidal flow along the entrances to the Innenhafen (inner harbour) at Wilhelmshaven and in this form has ensured their accessibility until today.

In the transition zone between the Outer Jade and the Inner Jade, the littoral drift from West to East interferes with the maintenance of the Jade fairway. With the construction of the approx. 10.5 kilometre-long groyne system of 'Minsener Oog' between 1909 and 1936, an important contribution to stabilising the fairway was made. Migrating sandbanks and bars (so-called Platen) were kept away from the fairway.

The development of the Jade, which had formerly been characterised by river bifurcations, began in 1957 and lasted, in various phases, until 1974. Natural channel depths of between 10 and 12 m below sea chart datum were developed into a navigation channel for deep-drawing vessels with a guaranteed depth of 17.60 m below $SKN_{LAT}$ and a width of 300 m. At the same time, the embankment of wadden and marsh areas (Groden = polders) on the west shore of the Inner Jade and their development for the establishment of harbour facilities for mineral oil and chemical industries, as well as for power generation was carried out. It started with 'Heppenser Groden' in 1940, followed by 'Rüstersieler Groden' in 1960 and 'Voslapper Groden' in 1970. In addition, four transhipment piers were constructed on the west shore of the Inner Jade, the first being completed in 1958 and the last in 1980. Since the completion of the engineering works for the relocation of the Jade fairway near Hooksiel in the year 1987, no major encroachment on the Jade has taken place. Dredged spoils from the construction works of approx. 500 million m³ were removed from the hydraulic regime of the Jade and dumped or washed into marginal areas outside the main tidal flow (cf. chapter 5).

After construction works were completed, a natural adaptation of the morphodynamic conditions in the Jade followed, continued even until after completion and required extensive maintenance dredging until the mid 1990s. As the western Inner Jade is partially obstructed with the transhipment piers resting on a trestle structure, the tidal currents have lost some of their strength in this zone. The main current moved eastwards, resulting in a shallower western shore. At the eastern embankment slope, the depth contours are fairly stable. This stability applies also to the tidal creek system east of the fairway. Following the completion of the major interventions in the mid 1980s, a slow-down in the sediment relocation process has been observed since the early 1990s. Consequently, a modified dredging strategy and management by the regional authority (WSA Wilhelmshaven) of the Federal Administration of Waterways and Navigation (WSV) could be introduced, resulting in a decline of dredged volumes in the Jade fairway.

The deepwater container terminal JadeWeserPort, which is currently under construction, and the partial relocation of the fairway between km 6 and km 14 will affect the transport regime of the Inner Jade again and are expected to trigger sedimentation in the shallow water areas at the western shore up- and downstream of the JadeWeserPort for a period of years.

## 5. Maintenance of the Navigation Channels

One of the two main dredging areas is located between kms 41 and 49 of the Outer Jade. Here, a guaranteed water depth of 17.60 m below $SKN_{LAT}$ is provided. In the zone close to the fairway, extensive sedimentation has become apparent at the northern edge of 'Langes Riff'. Compensation of this progressing sedimentation emanating from the southern edge of the navigation channel can be seen in the erosion by tidal currents along the northern edge of the undercut slope. Apart from the need to occasionally remove sediment around groyne A at 'Minsener Oog' (Km 35–36), which was transported by sand bars migrating through 'Blaue Balje', the remaining fairway section is practically maintenance-free.

The second major dredging area is located in the Inner Jade between kms 6 and 13. The cause for the sedimentation of primarily silt material in this zone is the dominance of the flood currents. The weaker ebb currents are not able to completely remove all solids deposited by the incoming tide. Another reason is the ebb current from the 'Ahne' obliquely crossing the navigational channel and thereby dropping material. Only a very small proportion of the sediments that are carried in twice each day with the flood tide remains in the fairway (and in the deeper mooring basins provided in front of the piers) in the Inner Jade zone. In total, however, there are considerable volumes that must be removed from the system.

According to the guidelines of the German Navy (Bundesmarine), in the entrance of 'Neuer Vorhafen' a water depth of $SKN_{LAT}$ –9.60 m[1] and in the remaining areas $SKN_{LAT}$ -8.00 m has to be provided by means of maintenance dredging. The three deep channels 'Steenkentief', 'Vareler Fahrwasser' and 'Ahne' in the Jade Bay are not part of the Jade federal waterway, but form the southern end of the Jade Bay. For this reason, no fairway maintenance work is carried out here.

Fig. 6 shows the annual maintenance dredging volumes since 1905. Since 1997, the majority of this volume of dredged spoils has been processed by the WSV-operated own hopper suction dredger "NORDSEE" (capacity: 5,650 m³).

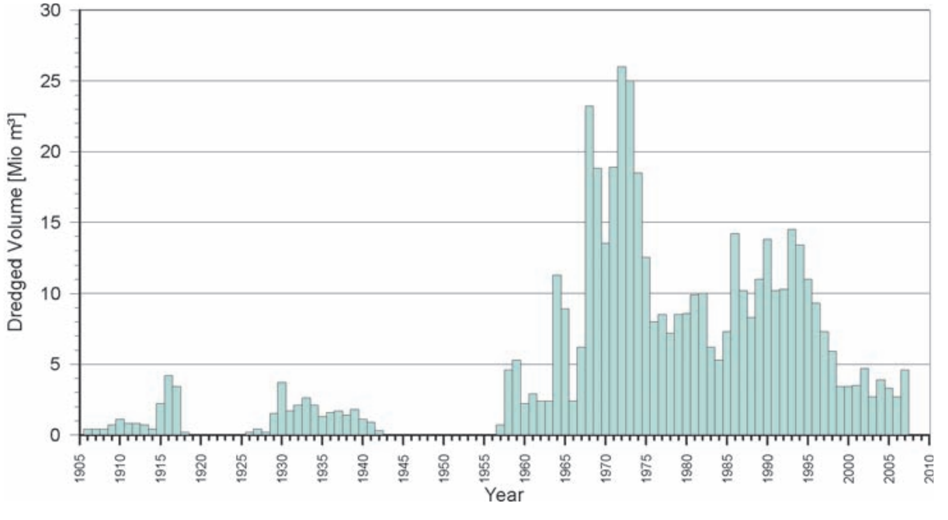


Fig. 6: Annual dredged volumes in the Inner Jade and Outer Jade
(without dredging of the outer harbour)

The total volume of material dredged from the Jade fairway is dumped on five offshore sites.

| Dumpsite | Location |
|---|---|
| "01" | north of the Outer Weser fairway |
| "Jade-Weser" | between the fairways of the Outer Jade and Outer Weser |
| "Mellumplate" | near Mellumplate lighthouse |
| "Südreede" | at the southern end of the Inner Jade |
| "Vareler Fahrwasser" | in the Jade Bay |

[1] SKN = sea chart zero

## 6. Monitoring and System Analysis

### 6.1 Hydrological Measurements

Nine gauge stations and six permanent measuring points form the basic monitoring network. They serve to improve the dredging and dumping strategy and the general information on the prevailing hydrological parameters of the system.

The dredging and dumping activities are assessed regularly. The first study of this kind was completed in 2003 (BfG and WSA Wilhelmshaven, 2003). Since then, more detailed studies have been carried out at selected dumpsites, and in the year 2008, a comprehensive examination of the statements of the initial study will be commissioned by the responsible regional authority, i. e. WSA Wilhelmshaven.

In the context of the construction of the JadeWeserPort, extensive measures for the preservation of evidence have been agreed on with the project manager. They include all hydrological parameters (water levels, currents, turbidity etc.) and the observation of morphological changes through regular surveys based on echo-soundings.

At present, preliminary investigations are taking place regarding the distribution of heat in cooling water from planned power station enlargements or new constructions on 'Voslapper Groden'.

### 6.2 Model Studies

In addition to and in support of field investigations, various mathematical models for the simulation of the physical processes in issues of water quality, concerning the ease and safety of maritime traffic and water engineering problems, are being used. The German Federal Waterways Engineering and Research Institute (BAW) in Hamburg, the advisory federal authority of WSV, is participating in the development of these state-of-the-art hydrodynamic and morphodynamic numerical tools for the simulation of tidal dynamics, waves, transport of sediments (bed and suspended load), dissolved substances (salt) and heat. The BAW operates a model for the Jade-Weser-Estuary with a high spatial and time resolution on its own compute servers based on the following methods:

- UnTRIM3D for tidal dynamics, sediment (suspension, salt) transport and heat transport
- SediMorph for bed load transport and morphodynamics
- K-model for wave transformation

In addition, a model using the Delft3D method is operated. The model was used for the environmental impact assessment studies in the approval procedure for the construction of the JadeWeserPort, for the fairway adaptations of the Outer and Lower Weser and for the expansion of the Wilhelmshaven power plant capacities. The validation of the model was done on the basis of comprehensive field measurements. With the BAW software for post-processing, further parameters (e.g. duration of flooding, tidal range, mean and maximum ebb and flood tide velocity, residual flow etc.) were generated in a so-called tidal parameter analysis and permit a substantiated description of the behaviour of and/or any changes within the hydrodynamic and morphodynamic system. This also includes visualization and animation of results (e.g. water level and flow velocity in the tidal dynamics).

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# The Weser Estuary

By Dietrich Lange, Helmut Müller, Friederike Piechotta
and Reiner Schubert

Contents



## 1. Introduction

After the Elbe, the Weser is the second-largest river in Germany discharging into the North Sea. Its origin is the confluence of the rivers Werra and Fulda at Hannoversch-Münden. After cutting through low mountain ranges it flows in northerly direction through the Northern German lowlands. It can be subdivided into the sections Upper Weser (Oberweser: Hann. Münden – Minden), Middle Weser (Mittelweser: Minden – Bremen), Lower Weser (Unterweser: Bremen – Bremerhaven) and Outer Weser (Außenweser: Bremerhaven – open sea) (Fig. 1). The barrage in Bremen-Hemelingen defines the tidal boundary. While the bottom of the Upper Weser is characterized by rubble sediment of the overlying rock, the Middle Weser carries the gravel sediment of the lowlands. Bottom sediments of the Lower and Outer Weser consist mainly of medium and fine sands.

The entire length of the Weser is classified as a federal waterway (Bundeswasserstraße) for the transport of goods by barges and sea-going vessels. The 'Mittellandkanal', an artificial inland waterway intersecting the Weser near Minden, connects the waterway Weser in East-West-direction with the rivers Elbe, Ems and Rhine. Inland navigation vessels can directly go from the Lower Weser to the Ems, via the river Hunte and the 'Coastal Canal (Küstenkanal)'. Sea-going vessels can call on the Lower Weser ports Bremen and Bremerhaven (City of Bremen) as well as Nordenham and Brake (Lower Saxony).

Bremerhaven is the site of one of the most important Container terminals of the world. After completing construction works in 2008, the river-parallel container quay has an overall length of 5.4 km. Improvement and deepening of the navigation channel and the most modern quay equipment enable the currently largest container ships to call on Bremerhaven.

Turnover figures in **Bremen/Bremerhaven** had two-digit growth rates during the past few years and amounted to approximately 5,000,000 TEU in 2007. In addition to containers, cars are the most important cargo handled in Bremerhaven. In 2007, a turnover of 2,000,000 cars has been exceeded the first time.

The privately managed port of **Nordenham** excels in bulk goods. Mainly coal is transhipped here (import); iron and steel are growing factors. The growth rate of exported goods amounted to 8 % in the years 1998–2005.

The port of **Brake** is a hub for the import and export of animal feed and grain. A strong

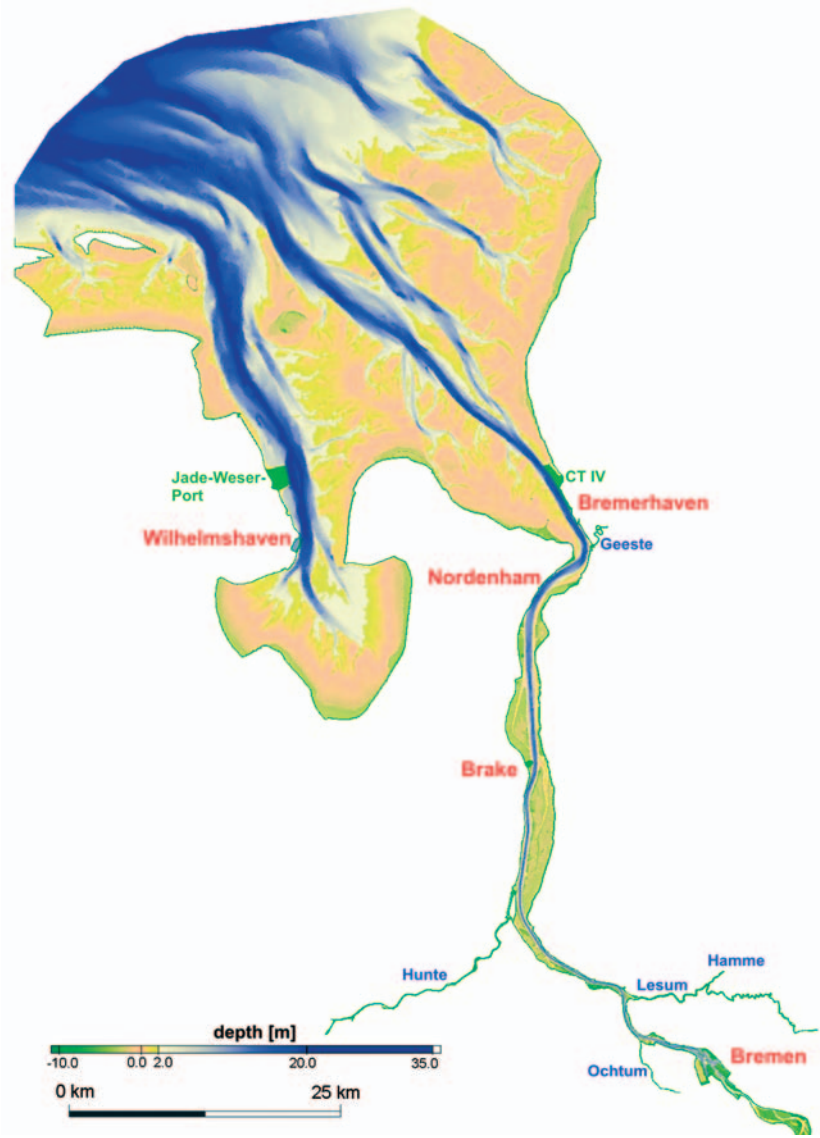


Fig. 1: General plan of the Weser estuary

increase can be noticed with lumber export and steel turnover. The growth rate for outgoing traffic was at approx. 6 % in the years from 1998 to 2005.

In addition to the utilization of river and estuary as a traffic artery, fisheries out of the small coastal harbours, energy production (wind power stations and cooling water for power stations) and an increasing tourism are other economical sectors. In spite of its high degree of improvement for navigation purposes, the Weser also represents a natural habitat for numerous species of animals and plants. Moreover, it is a region of recreation and repose for the population.

## 2. Geomorphology of the Weser Estuary

The bed material of the Lower Weser is mainly composed of fine and medium sands. Under the influence of changing water depths, tidal currents and fresh water discharge, pronounced bed forms (dunes superimposed by ripples) are created. They occur with 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, the bedforms disappear. In this area the centre of the brackish water zone with high turbidity is located, leading to an accumulation of very fine sediments (silt and mud) on the bottom.

The funnel-shaped estuary of the Outer Weser, opening up towards the North Sea in north-westerly direction, is characterized by two main channels, several secondary channels, tidal gullies and extensive tidal flats. The topography and bathymetry of the system is subjected to continuous changes. Before the establishment of the main navigational channel in the inner estuary and its fortification by groynes and training walls at the beginning of the 20$^{th}$ century, cyclic variations led to an alternating preference of the western (Fedderwarder Arm) or eastern (Wurster Arm) channel. The sophisticated system of river training structures in combination with continuously necessary dredging keeps the main navigational channel in its present position. Fig. 2 shows the development of the cross-sectional underwater profiles.

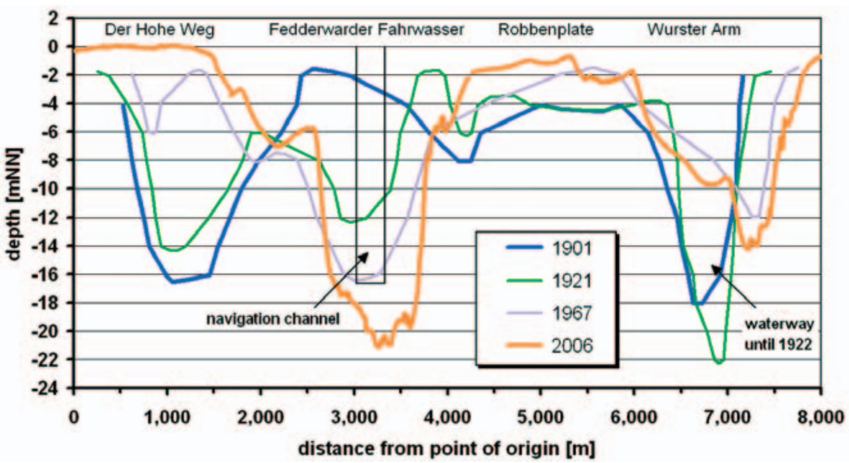


Fig. 2: Cross-sectional profiles at km 91 of the Weser estuary

The morphology of the surrounding wadden areas is still subjected to continuous changes. Tidal gullies and sand banks can move up to 100 m/a. Sediments of the channels of the Outer Weser are mainly fine and medium sands. Depending on the location, one can find sand, silt and all other sediment mixtures typical for tidal flats in the wadden areas and its gullies and streams (Fig. 3). The topology of the bottom of the navigation channel is shaped by extensive flat reaches interrupted by scoured areas or stretches with long dunes whose crest heights reach 5 m, interspaced at up to 480 m.

After the Weser estuary had attained its present shape in the Middle Ages, fortified embankments and dikes were the first man-made encroachments on the natural state (see

GRABEMANN et al., 1999). Purposeful regulation of the course of the river and its flow cross-sections began during the first correction of the Lower Weser (1. Unterweser-Korrektion) from 1887 to 1895. By damming up tributaries, straightening the river bed and establishing a defined navigation channel with a minimum depth for sea-going vessels with a draft of min. 5 m, a cross-section with a continuously decreasing area from open water up to Bremen, was aimed at. Now, the tidal wave could penetrate almost unimpeded till Bremen; the new depth of the navigational channel could be maintained with the aid of an improved flushing ability of the tidal currents. The island of Harriersand at the right-hand shore with its length of 16 km and a size of 6 km² is one of the longest river islands of Europe. Together with the 6 km-island of Strohauser Plate at the left-hand shore, it is a stabilizing factor in the river regime of the Lower Weser.

Offshore of Bremerhaven at the Outer Weser, the first river training measures for a sufficient water depth for the emerging trans-atlantic steam ship traffic were carried out. In order to adapt to increasing ship sizes and to the reaction of the estuary system to the man-made intervention, additional changes and improvements of Lower and Outer Weser were made in the 20th century. More training works and walls, jetties and groynes were built, to stabilize the course of the river and protect the embankments and shorelines (HOVERS, 1973).

Deepening the channels did not only result in a better penetration of the tidal wave and concentration of the currents. Due to the lower level of the LW and an improved discharge of freshwater from upstream the danger of lowering the ground water table upstream of Bremen arose. This was compensated by the construction of a tidal barrier and weir in Hemelingen between 1906 and 1911. Towards the end of the 1970s, the storm surge barriers

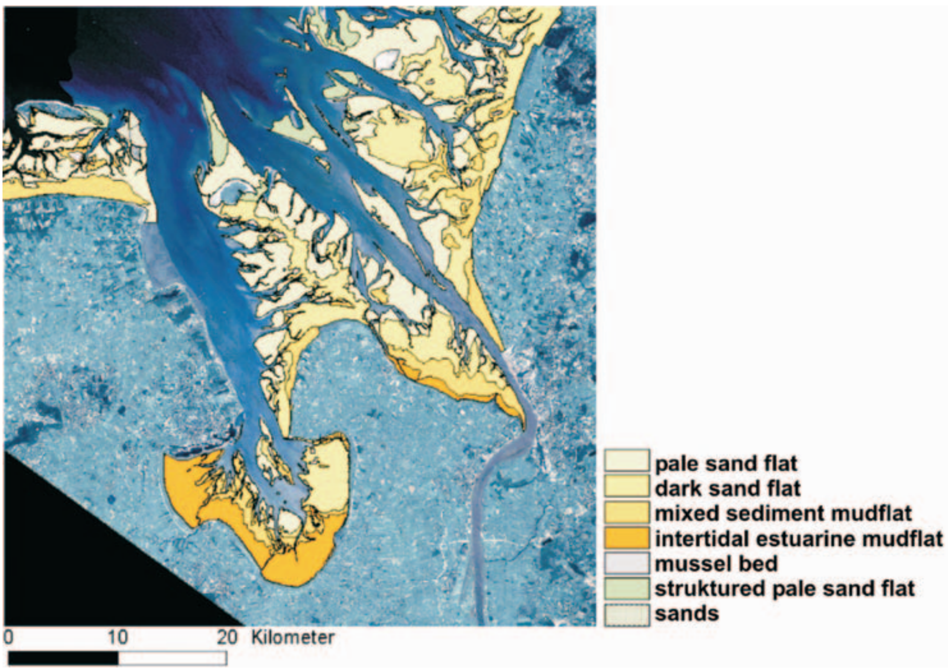


Fig. 3: Types of tidal flats around Jade and Weser estuaries (NLÖ, 1999)

at the mouth of the tributaries Hunte, Lesum und Ochtum were built. Additional man-made encroachments on the shape of the river bed and the embankments were the construction and further improvement of the harbours and quays at Bremen, Brake, Nordenham and Bremerhaven as well as the establishment of sluices and drainage canals. In the case of Lunesiel, this also led to the relocation of the mouth of the tributary Lune. For the compensation of construction measures, flood plains have been created along the foreshores of the Lower Weser.

Table 1: Compendium of river deepening and correction measures of Lower and Outer Weser (SKN = Seekartennull = nautical chart datum)

| | |
|---|---|
| 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 |

Today, the river system of the Lower Weser is still governed by the principles of the 1st Weser correction (1. Weserkorrektion). The flow cross-sections below SKN have been designed to increase in size towards Bremerhaven and, thereby, match is the increasing water flow (Fig. 4).

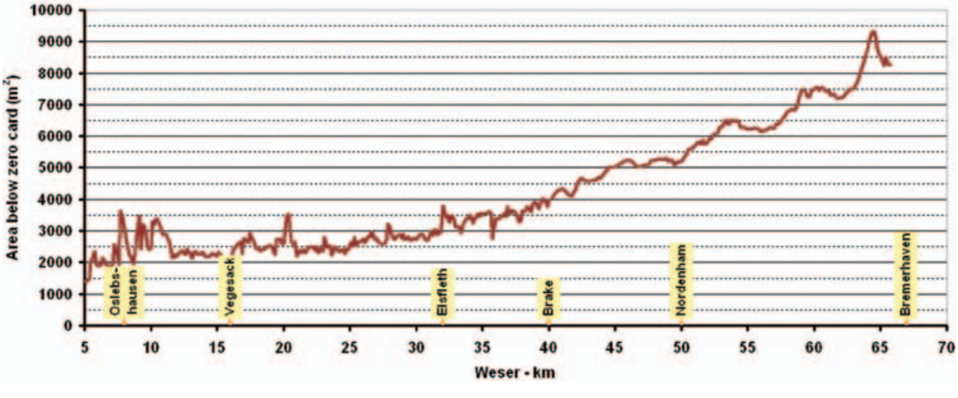


Fig. 4: Cross-sectional area below reference datum along the Lower Weser

The evolution of depths of the navigation channel of the Lower Weser as a consequence of river improvement measures is shown in Fig. 5. Channel widths were increased from 80 m (5 m-correction) to 150–200 m today.

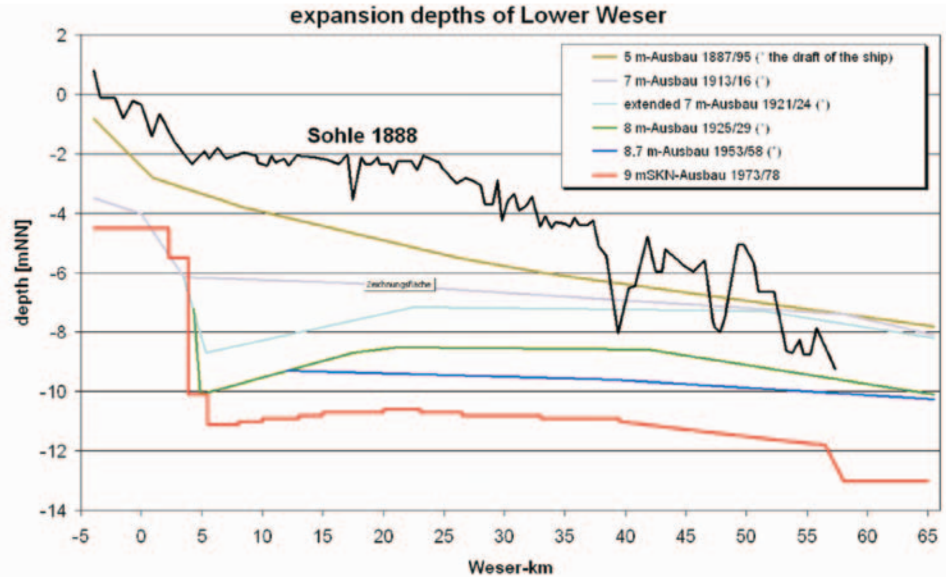


Fig. 5: Development of the navigational channel of the Lower Weser

## 3. Hydrological Parameters

The entire catchment area of the Lower Weser – a composition of those of the source rivers Werra and Fulda and of the Weser itself – adds up to Bremerhaven to be approx. 46,000 km². The catchment area of the Outer Weser is difficult to define, because of the surrounding flat landscape with some areas below NN.

In the following Table 2, the hydrological discharge values of the Lower Weser have been compiled (source: Gewässerkundliches Jahrbuch, 2004). These data were collected at the gauge Intschede, which is located at Middle Weser km 331.1, some 30 km upstream of the tidal barrier in Bremen-Hemelingen.

The wide range of discharge values between approx. 60 and 3,500 m³/s places a high demand on water management of the Upper and Middle Weser. For once, navigability has to be guaranteed for low discharges; and high discharges have to be dissipated without causing damage. Fig. 6 shows the time series of discharge between 1985 and 2005. One can see that values of more than 1,000 m³/s occur only for short periods during winter months. During summer months, lower discharge values between 100 and 200 m³/s prevail.

High fresh water discharge values have no significant influence on the dike safety along the Lower Weser. Here, a real threat is presented by increased water levels during storm surges, combined with strong winds from westerly directions.

Tidal elevations in the Weser estuary are influenced by the distribution and spreading of

Table 2: Discharge values of the Middle Weser at gauge Intschede

| | Abbr. | unit | year 2004 | Period 1941/2004 |
|---|---|---|---|---|
| Lowest discharge | NQ | $m^3/s$ | 119 | 59,7 |
| Mean lowest discharge | MNQ | $m^3/s$ | | 124 |
| Mean discharge | MQ | $m^3/s$ | 280 | 326 |
| Mean highest discharge | MHQ | $m^3/s$ | | 1270 |
| Highest discharge | HQ | $m^3/s$ | 831 | 3500 |
| | | | | |
| Annual peak | $HQ_1$ | $m^3/s$ | | 963 |
| Mean five-year peak | $HQ_5$ | $m^3/s$ | | 1640 |

the tidal wave in the North Sea (cf. Tide Tables for European Waters, BSH, 2008) and its modification by partial reflexion and shoaling effects etc. in the estuary. This results in a semi-diurnal tide with a tidal range of 2.8 m in the northern part of the Outer Weser. On the way towards Bremerhaven the mean tidal range increases to 3.8 m to attain 4.1 m in Bremen (5-year average 2003/2007). Running time from the gauge Alte Weser at the mouth till Bremen (115 km) is approx. 3 hours. Due to the various upgrading and construction measures with deeper channels and more regular cross-sections, carried out since the end of the 19th century, friction losses were reduced, and the influence of the tide is greatly enhanced.

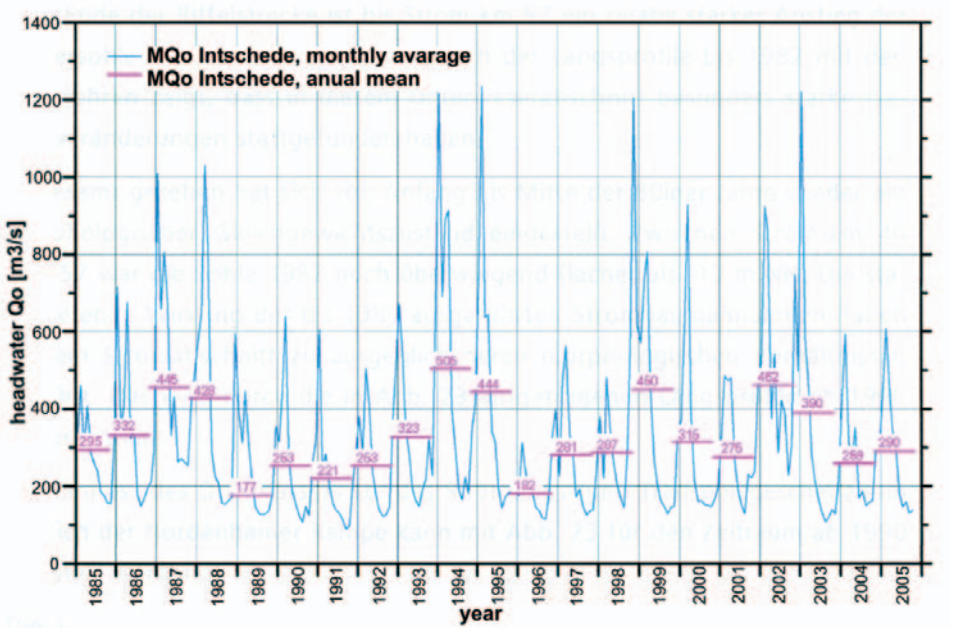


Fig. 6: Weser freshwater discharge at gauge Intschede from 1985 to 2005 (Hochschule Bremen, 2006)

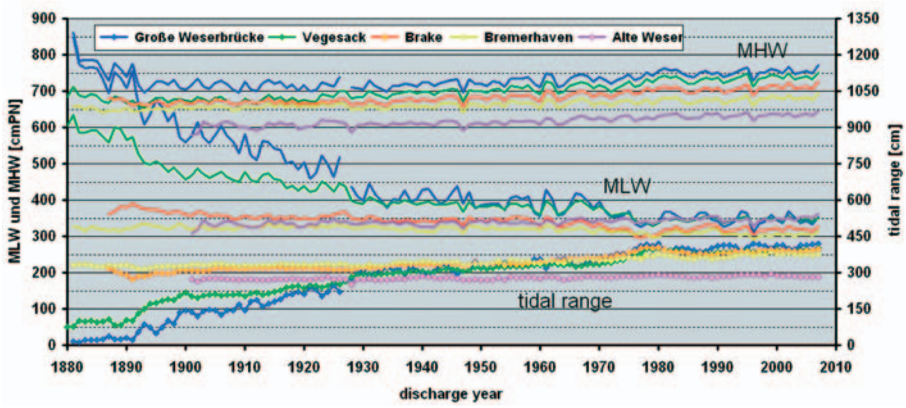


Fig. 7: Development of mean high water (MHW) and mean low water (MLW) between 1880 and 2007 (WSA Bremerhaven, 2008)

The increase of the tidal range is the most obvious indication of changes: the initial 20 cm in Bremen grew to a range of more than 4 m, mostly attributed to a drop of the mean low water (MLW) (Fig. 7). Upgrading and deepening are reflected more or less strongly in changes of the running time as well as in the flood and ebb duration.

Fig. 8 illustrates a time series of salinity values at high slack water (max. salinity) and at low slack water (min. salinity) obtained from measurements in the years of 1998 to 2005. As a consequence of discharging caustic potash solution coming from mining activities, the Lower Weser has an initial level of **salinity** of 0.5 to 1 ‰. With a classification of the brackish water zone as the region with salinity values between 2 and 20 ‰, it extends from km 45 to 70 at high slack water and from km 60 to 92 at low slack water on a long-standing average. Even though the location of the brackish water zone is also influenced by the freshwater

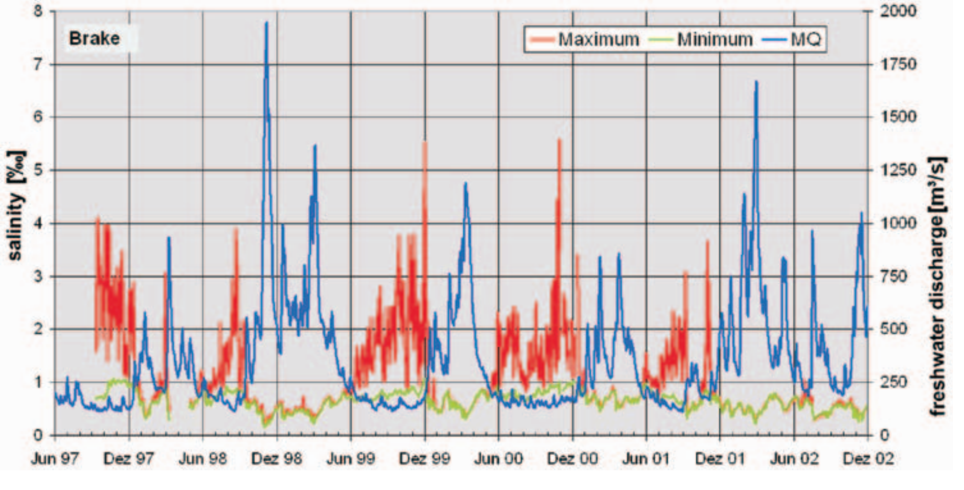


Fig. 8: Long-term time series of salinity and discharge at gauge Brake (WSA Bremerhaven, 2004)

discharge, the decisive factor for peak values are the tides. If during a succession of several tides LW increases, i.e.storm tides push seawater into the estuary, an increase of salinity intrusion into Lower Weser can be noted. During such extreme situations, the brackish water influence can be felt up to Brake and beyond.

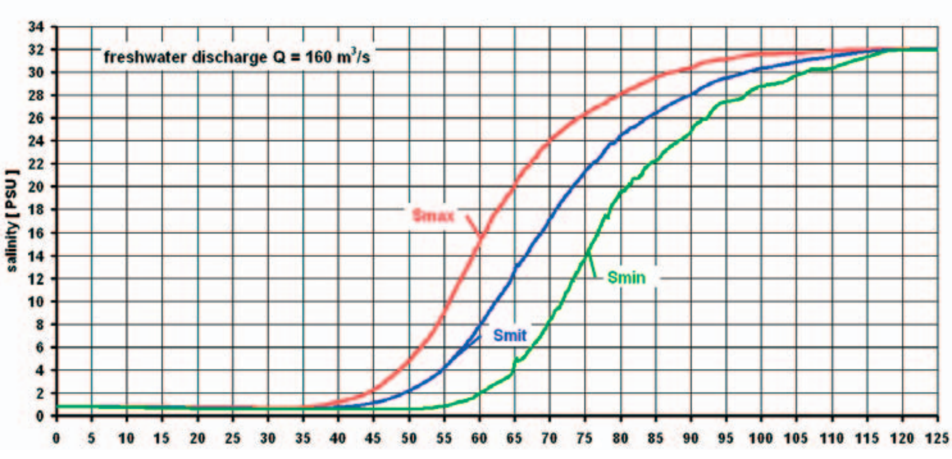


Fig. 9: Location of the brackish water zone at a discharge of 160 m³/s
(num. model investigations BAW)

For further clarification of the local salinity variations during one tide, Fig. 9 depicts the extreme salinity values along the longitudinal section of the Weser estuary ($Q_o$ = 160 m³/s) obtained from a numerical tide model.

The local and time-dependent horizontal and vertical distribution of current velocities and directions in the tidal Weser is dependent on many factors. Apart from tidal and discharge conditions, especially the bathymetry of the river bed and water density play an important role. Fig. 10 shows the vertically averaged ebb and flood current velocities in the centre of the navigation channel of Lower and Outer Weser. Values have been obtained from a three-dimensional numerical model for a spring-neap tidal cycle. Moreover, residual currents and the ratio of flood-to-ebb current have been calculated for the evaluation of the current regime. Field investigations as well as the model results indicate that in most stretches of the navigation channel of Lower and Outer Weser vertically averaged ebb currents are stronger than flood currents. There are, however, typical stretches, such as the reach between km 80 and 95, where the flood stream prevails due to strongly diverging currents in the centre channel. Due to these 'current discontinuities', shoals develop in the navigation channel requiring a high maintenance effort.

During the 1980s, measurements in the turbidity zone of the Weser (projects MASEX '83 and MASEX '85) were carried out. The results of the analysis have been published in various articles (see FANGER et al., 1985 and NEUMANN et al., 1985). Only recently, in a pilot project of the Federal Institute of Research and Coastal Engineering (BAW), new measurement methods were deployed to obtain a cross-sectional image of suspended matter at Nordenham for the duration of one tide.

These measurements confirm that in the brackish water region of the Lower Weser

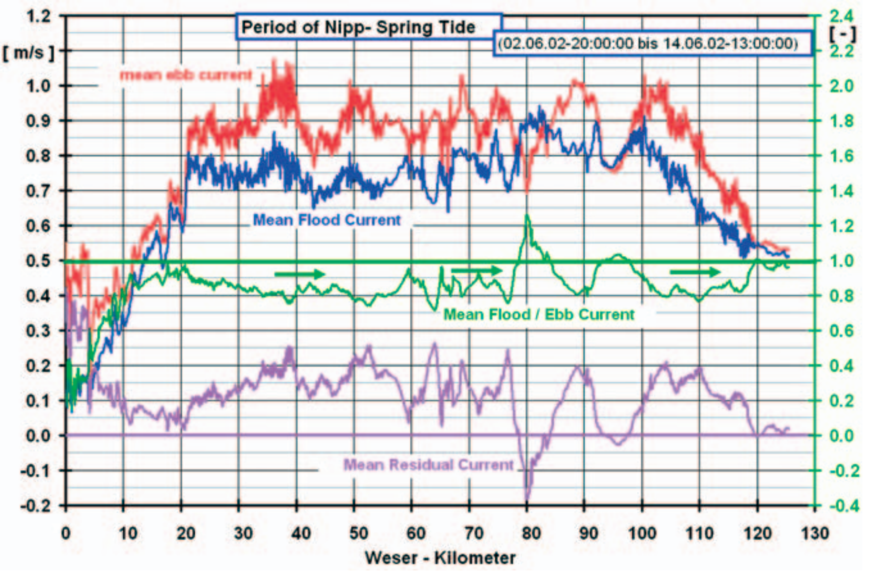


Fig. 10: Longitudinal section of vertically averaged flood and ebb currents during a spring-neap-cycle, of residual currents and of the ratio of flood and ebb current velocity (num. model investigations BAW)

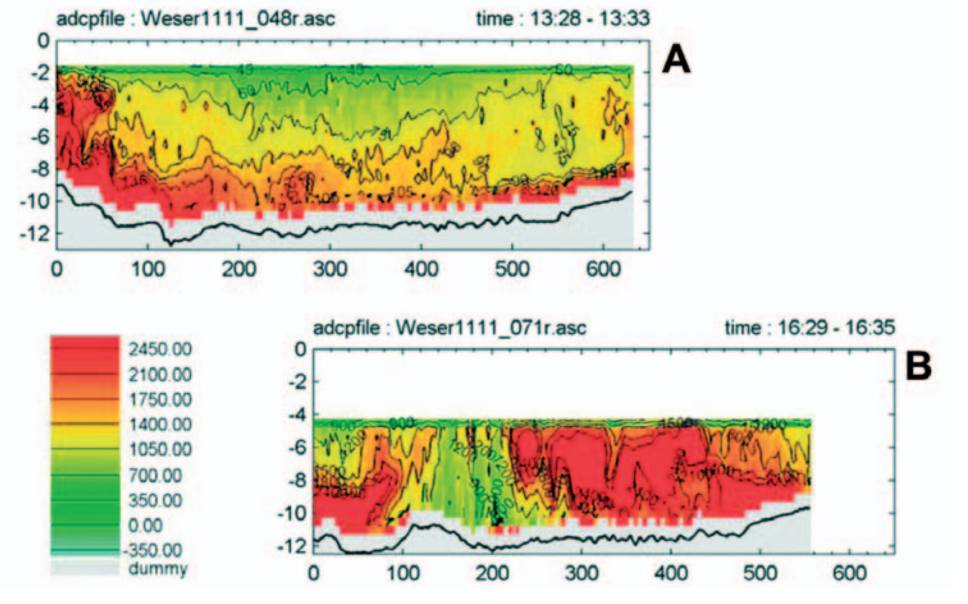


Fig. 11: Concentrations of suspended matter in the Lower Weser at ebb currents (A – beginning ebb currents, B – full ebb currents) (AQUA VISION, 2004)

concentrations of suspended matter between 300 and 600 mg/l in the water column can occur. At particular tidal phases, these values can go up to 2000 mg/l close to the bottom.

Fig. 11 shows these concentrations of suspended matter at the beginning and during full ebb currents. It is obvious that concentrations are stronger close to the embankments as compared to the centre channel.

## 4. Measures for the Improvement of the Weser Estuary

Past improvement and deepening measures in Lower and Outer Weser (Tab. 1) have been accompanied by river training works such as training walls and groynes, in order to stabilize projected water depths in the fairways and secure the embankments and shores. Today, the managed and maintained river training system extends from km 90 in the Outer Weser till km 42 near Brake. Upstream of Brake, the embankments of some river stretches are being secured by heavy revetments.

Presently, the projects '*adaptation of the navigation channel of the Outer Weser to the development of marine traffic and depth adaptation of the port-related turning circle*' as well as '*adaptation of the navigation channel of the Lower Weser to the developing marine traffic*' are being prepared in working groups. The public can follow the procedure at http://www.weseranpassung.de.

The access channel from the open sea (Outer Weser) to the Container terminal Bremerhaven is to be adapted to the foreseeable development of sizes of modern container vessels. The tide-independent accessibility of CT Bremerhaven for large container vessels with a maximum draft of 13.50 m – this is equivalent to a future-oriented degree of a lading draft of 93 % of the construction draft of vessels of the S-class – is supposed to maintain and strengthen the medium and long-term competitive position of the Container terminal Bremerhaven.

To secure and improve the competitive position of those ports along the Lower Weser and to avoid disadvantages because of an insufficient depth of the navigation channel, the adaptation of the Lower Weser between Nordenham and the ports of Brake und Bremen is scheduled. This was done considering new requirements of port enterprises and shipping companies. Deepening the Lower Weser for vessels to reach the port of Brake tide-dependent with a lading draft of max. 12.80 m would secure the future competitiveness of the port for the bulk goods animal feed and grain. A future accessibility of the port of Bremen for vessels with a lading draft of max. 11.10 m particularly ensures and improves the economical transport of iron ore and coal.

## 5. Maintenance of the Fairways

To guarantee the ease and safety of marine traffic, a sufficient water depth has to be established and maintained. Dredging works in the estuary are contracted out in close cooperation between the regional water and shipping authorities (Wasser- und Schifffahrtsämter) Bremen and Bremerhaven. In the Lower Weser, maintenance dredging in the sandy reaches between Bremen and Nordenham is carried out by water injection dredgers; between Nordenham and Bremerhaven, the prevailing silt is dredged by hopper dredgers which are also mostly deployed in the Outer Weser.

The dredged spoils transported by hopper dredgers is generally dumped on sites in or close to the navigation channel. Sometimes, suitable dredged material is also used for beach nourishment to secure the embankments of the Lower Weser and for construction measures of third parties.

In the fairways of Lower and Outer Weser and in the turning circles, the water and shipping authorities and third parties dredge approx. 4–8 Mio. m³ of sand and silt, annually. The development of quantities of dredged material in various reaches of Lower and Outer Weser can bee seen in Fig. 12. The capital investment of the Federal Administration of Waterways and Navigation (Wasser- und Schifffahrtsverwaltung, WSV) for maintenance dredging in the Lower and Outer Weser has amounted to approx. 8–18 Mio. €/a since 1999.

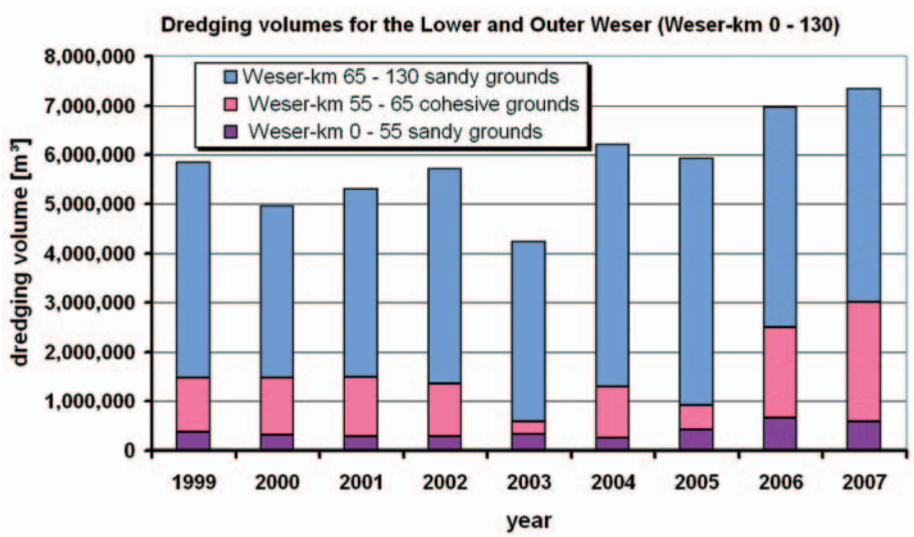


Fig. 12: Quantities of dredged spoils at the Weser estuary (WSA Bremerhaven)

## 6. Monitoring and Analysis of the Weser Estuary

Due to the complex dynamics of the Weser estuary, continuous maintenance of the navigation channel and river training works as well a new improvement projects always trigger new questions. These have to be answered based on general water engineering expertise, local knowledge and long-term experience of the estuary. Consequently, the spectrum of tasks in water engineering at the water and shipping authorities (WSÄ) of Bremen and Bremerhaven is fairly broad.

Recording and analyzing water level data is a focal point of hydrological tasks. Its importance is underlined by more than 30 water level gauges along the Lower and Outer Weser and their tributaries. These gauges are continuously maintained by WSV or provincial authorities. Abiotic parameters such as conductivity, temperature and partly turbidity are recorded by WSV on 13 locations along the Outer and northern Lower Weser.

Data are used among others for preservation of evidence. This is done with the intention to determine – from time series of various parameters – modifications induced or triggered by improvement or upgrading projects. Long-term measurements are required from before (status-quo) as well as from after construction works have been finished.

The extension of the present preservation of evidence is anchored in the 'plan approval order' for the '*improvement of the Federal Waterway Weser between km 65 and 130 to establish a minimum water depth of 14 m below SKN*', Jan. 30, 1998, paragraph A.II.3. Preservation of evidence investigations for water levels, conductivity, morphology and ship-induced waves have been identified to be carried out. The entire extent and contents of the programme and first results can be inspected at the given internet address: http://www.wsv.de/wsa-bhv/weserausbauten/14m_Ausbau/beweissicherung/index.html.

In various institutes, hydrodynamic-numerical models representing partial areas or the entire investigation area of the Weser estuary are deployed and maintained for the investigation of water engineering and ecological questions. Provincial authorities run their own numerical models in order to simulate natural conditions and investigate dike safety und storm surge conditions. Commissioned by WSV, university institutes are investigating questions concerning currents and sediment transport. BAW is looking at matters of the adaptation of the Weser to the requirements of marine traffic using numerical models with a locally increased grid resolution. These are to simulate the effect of deepening fairways etc. on currents, sediment transport and morphology. Modelling methods are permanently being improved to include morphodynamic simulations of dredging and dumping as well as long-term development of the bathymetry.

Another challenge is the simulation of the historical development of the estuary to also permit the analysis of improvement measures of the last decades. This requires an intimate knowledge of the estuary, of water engineering methods and the cooperation of all persons and institutions involved.

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# The Elbe Estuary

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Contents



## 1. Introduction

The River Elbe has its source 1,386 m above sea level in the Giant Mountains and reaches the North Sea at Cuxhaven, after 1,094 km. The entire catchment basin of the Elbe (Fig. 1) covers 148,268 km², which makes it the fourth largest river in Central Europe after the Rivers Danube (817,000 km²), Vistula (194,112 km²) and Rhine (183,800 km²). The Elbe Estuary is comprised of the lower reaches between the weir at Geesthacht (Elbe-km 588) and the transition to the North Sea (Elbe-km 760). As long as no storm-tide conditions prevail, the tidal influence of the Elbe estuary is limited by the Geesthacht weir.

From the Geesthacht weir to Bunthaus, which is situated 20 km further downstream, the Elbe has a typical width of 300–500 m. This area is called the "Upper Tidal Elbe". At Bunthaus (Elbe-km 609), the River branches out into the Northern and Southern Elbe. Each of these branches is initially only 200 m wide. However, these widths increase continually, so that at the point where they merge again (Elbe-km 626), the Northern Elbe is around 400 m and the Southern Elbe around 300 m in width. The reunited Elbe continues as a river measuring around 500 m in total width. Seven kilometres further downstream (Elbe-km 633), the river abruptly widens to 2.5 km at the Elbe bay called Mühlenberger Loch.

From here, the navigation channel of the Elbe runs in a river bed that continuously alters its form and width with the islands of Hans-Kalb-Sand/Schweinsand/Neßsand, Lühesand, Drommel/Auberg/Bishorster Sand, Pagensand, Schwarztonnensand and Rhinplatte forming numerous side channels. At low tide, some sand bars such as the Brammer Bank, the Böschrücken and the Medem-Sand appear as visible elements. Downstream of Brunsbüttel (Elbe-km 695), the Elbe widens to become a funnel-shaped estuary mouth, with a maximum width of 17.5 km between Cuxhaven and the Trischen Dam. Only 1.5 km remain water-bearing at low tide, while the major part of the funnel-shaped Elbe estuary falls dry. The northern limit of the Outer Elbe seawards of Cuxhaven is not clearly defined in literature but, according to the authors, lies close to the great beacons A and Z north of the Scharhörnriff, where a lateral separation is formed by the drained sandbanks at low tide end.

Table 1: Tributaries of the Elbe Side channel (modified in accordance with IKSE, 2005)

| Body of Water | Elbe-km | Catchment Basin area (CA) [km²] | Medial Stream Flow (MQ) [m³/s] |
|---|---|---|---|
| Ilmenau River | 599.0 | 2 852.0 | 17.7 |
| Seeve River | 604.9 | 471.1 | 4.71 |
| Bille River | 615.3 Northern Elbe | 506.4 | 3.99 |
| Alster River | 622.4 Northern Elbe | 580.7 | 5.80 |
| Este River | 634.4 | 364.2 | 3.21 |
| Lühe River | 645.5 | 216.7 | 2.51 |
| Schwinge | 654.8 | 215.7 | 2.62 |
| Pinnau River | 659.7 | 367.0 | 3.46 |
| Krückau River | 664.9 | 275.7 | 2.42 |
| Stör River | 679.3 | 1 780.5 | 21.7 |
| North-to-Baltic-Sea Canal (Nord-Ostsee-Kanal NOK) | 696.0 | 1 536.7 | 19.1 |
| Oste River | 707.0 | 1 711.1 | 17.7 |
| Medem and Hadelner Canal | 712.6 | 482.8 | 7.81 |

The regional offices of the Federal Administration for Waterways and Navigation (Wasser- und Schifffahrtsverwaltung – WSV) at Cuxhaven, Hamburg and Lauenburg are responsible for the tidal river Elbe. Very uncommon is the delegation of maintenance of this federal waterway within the state boundaries of Hamburg by the Federal government to the Free and Hanseatic City of Hamburg.

The economic importance of the Elbe Estuary is mainly due to its role as the most important shipping route for international maritime traffic. In 2006, 12,400 seagoing ships (of which 7,560 were container ships) undertook the 70-sea-mile-long estuary journey up to the Port of Hamburg. Other seagoing vessels called at the ports of Cuxhaven, Brunsbüttel and Bützfleth, all situated at the Lower Elbe.

Cuxhaven is located in the immediate vicinity of the Elbe Mouth at the North Sea. Since 1997, the deep-sea port CuxPort (Elbe-km 724, Fig. 2) has been available for RoRo traffic. It is designed for container-cargo handling, storage and shipment of new vehicles, as well as general cargo handling. The Seaport of Brunsbüttel is the most important port in Schleswig-Holstein. It is comprised of the Elbe harbour, the oil harbour and the Ostermoor Harbour. The Glückstadt harbour is considered to be an outer harbour. The harbour at Stade/Bützfleth, Lower Saxony ranks among the 8 most important German seaports by turnover volume (data from 2006). Vessels of up to 150 m in length and 10.40 m draft can call at this harbour, which has been operating since 1972. Today, the Port of Hamburg is the largest Harbour in Germany, the third largest in Europe and ranks ninth among the container harbours world-wide. In 2007, the port handled a total of 140.4 million tons, of which 95.8 million were handled in 9.9 million Twenty-Foot Equivalent Units (TEU). Container-handling terminals and docks equipped to deal with general cargo, RoRo-traffic, suction goods, grab goods, foods and edibles, as well as liquids and chemicals are available. The continuously


Fig. 1: Position and catchment area of the Elbe (IKSE, 2005)

increasing container turnover is handled at four container terminals. The container terminal at Altenwerder, operating since 2002, is considered to be one of the world's most modern cargo handling facilities.

The Port of Hamburg is privileged mainly because of its eco-geographic location. It is the main hub for overseas traffic and the most important transhipment port for middle and eastern European countries as well as Baltic States in Northern Europe. It possesses an excellent infrastructure and the best interconnections to national and international transport networks.

The maritime waterway Elbe is connected to a well equipped network of mostly artificial waterways, which offers optimum conditions for an economically efficient and ecologically preferred further distribution of goods. The Kiel Canal *(Nord-Ostsee-Kanal)* connects the Elbe estuary between Brunsbüttel with the Baltic Sea near Kiel. It is the most navigated artificial maritime waterway of the world. Another link to the Baltic Sea is the 94-km long Elbe-Trave-Canal *(Elbe-Trave-Kanal)* between Lübeck and Lauenburg, linking the rivers


Fig. 2: Lower and Outer Elbe

Elbe and Trave. Today, this inland waterway is used mainly to transport bulk goods. The Elbe Side Canal *(Elbeseitenkanal)*, which is 115 km in length, connects the Elbe upstream from the Geesthacht weir between Artlenburg (Elbe-km 572) and Edesbüttel, near Wolfsburg to the Midland Canal *(Mittellandkanal)*, which is the East-West connection between the Ruhr and Berlin. The Elbe Side Canal, which has been in operation since 1976, provides a navigable link for inland vessels between Hamburg and the Elbe near Magdeburg at low water periods.

Next to its importance for commercial navigation, the Elbe is of economic relevance for other uses. Thus, various industrial facilities draw their process water – and power-station operators their cooling water – from the Elbe. Fishery plays an important role mainly in the area of the mouth of the Elbe and just outside of the Port of Hamburg. Because water quality has noticeably improved since the German reunification, commercial and sports fishing are being successfully practised again. There are a total of seven sewage treatment plants, which discharge into the Elbe estuary. Furthermore, seventeen industrial direct dischargers, ten of them in Greater Hamburg, are situated along the estuary.

Finally, the economic utilisation of the Elbe interacts with human habitat, animal and plant life. The Elbe River and its tributaries as well as the river floodplains, which are still left, influence the groundwater level of wide stretches of land and play an important role in the renewal of ground water and water extraction for drinking purposes. They guarantee drainage of most of the areas inland of the dike, which are used for agriculture and absorb smaller storm flood incidents until the storm-surge barriers are closed and cut off the retention areas. The flora and fauna along the Lower Elbe is of special importance, too. Some animals and plants occur exclusively in this catchment area, which makes them worthy of protection. The tidal influenced alluvial forest is a very characteristic form of vegetation with reeds and soft- and hardwood, which especially develops under the semi-diurnal flooding, thereby creating a habitat with a highly specialized fauna. With the integration of large parts of the Elbe Estuary and adjacent hinterland areas into the Natura 2000 Network (largest coherent EU-network of protected areas to safeguard biodiversity), important impulses are also given to tourism.

## 2. Geomorphology of the Elbe Estuary

Major geological alterations have occurred in The Lower Elbe, which has been subjected to major geological changes and, at a smaller time scale, to anthropogenic and natural alterations. The latest ice age formed the glacial valley, which is still visible today. The water from the melting ice cleared a glacial valley with an average width of 10 km, while at the same time the sea level rose. Areas of swamps, forests and moors were covered by marine sediments. Consequently, different horizontal and vertical layers of alluvial mud, sand and moor deposits can be found. Today, the Lower Elbe lies above Pleistocene sand deposits and the Holocene sediments of the river itself. Every now and then, glaciation relics in the form of large boulders surface along the lower stretch of the Lower Elbe.

The banks of the Elbe first formed a swampy, reedy landscape, which subsisted until the beginning of our era. During the Iron Age and its increasing demand for timber used for iron smelting, vast expanses of forest along the Middle and the Upper Elbe were deforested, triggering widespread soil erosion. The sediment load transported by the river attained such great quantities that the lower reaches of the Elbe virtually choked in mud. The river banks, which had been overgrown with common and giant reed, were covered with sediments, their surface level depending on the sediment amount available and the frequency of storm surges. This generated the typical marshlands of today. The course of the Elbe estuary has been constantly changing not only along the embankments which are visible to the human eye, but also under water. Apart from those obvious visible changes such as the erosion and sedimentation along the river banks the course of the channels beneath the water surface has always varied to different extents.

The development of the embankment has either been very slow as a result of erosion or sedimentation, or very abrupt, when for example large chunks from the edges broke off under the impact of high waves and strong currents. Natural alterations of the river bed morphology are still happening today depending on local currents and varying flow velocities. A rough morphological classification of the Lower and Outer Elbe can be made as follows:

From the Geesthacht Weir up to Bunthaus, where the Elbe splits into Northern and Southern Elbe, the estuary is restricted in its course. The bottom is made up of coarse sand and pebbles. In the Port of Hamburg itself, the river is enclosed by harbour installation, sheet pile walls and revetment slopes. Natural embankments are rather seldom. The river bed of the navigation channel is sandy, silt is more common in the port basins. From Blankenese to Glückstadt, several islands – some of them protected by revetments – divide the current into main and secondary channels. The river bed within the main channel is sandy, while the lateral zones are partially sandy but mainly muddy. From Glückstadt down to Brunsbüttel, the northern embankment is almost completely protected, while mudflats and salt marshes are typical features on the south side. From Brunsbüttel to Cuxhaven, the Lower Elbe considerably widens, and the deep channel runs mainly close to the southern embankment. To the North of the fairway, extensive mud-flats line the shore. They are part of the National Park "Schleswig-Holsteinisches Wattenmeer". Beyond Cuxhaven, the lateral boundary to the Outer Elbe is only visible around low tide. It is formed by the tidal flats of Duhnen, Neuwerk and Scharhörn to the South. To the North of the channel, a chain of connected sands existed 30 years ago. Since around 1990, the erosion of the "Großer Vogelsand" *(Great Bird Sandbank)* and losses of the western part of the "Gelbsand" *(Yellow Sand)* can be observed. Thus, no clearly recognisable northern limit of the Outer Elbe exists any more, today. The river bed, cutting through the shallow littoral zone, is mainly made up of middle and coarse sands. In deeper areas, alluvial mud also occurs.

## 3. Hydrological Key Parameters

The tidal wave propagates from the mouth of the river up to the tidal boundary; its progression speed depends mainly on the water depth. Unlike in the deep ocean, the water depth in the tidal river is at the same order of magnitude as the amplitude of the tidal wave. This means that the river flows in a significantly different bed at low tide than at high tide. This is particularly obvious beyond Elbe-km 715, where the cross-section is 75 % larger at high tide compared to low tide (see Fig. 3). As a result of these conditions, the crest of the tidal wave (high water) progresses faster than the trough (low tide). This leads to a deformation of the tidal curve with a relatively long period of tidal fall and a correspondingly shorter time of tidal rise.

The discharge measured at the gauge at Neu Darchau reaches the Tidal Elbe over the Geesthacht Weir (tidal) with a time delay of 1–2 days as fresh water inflow.

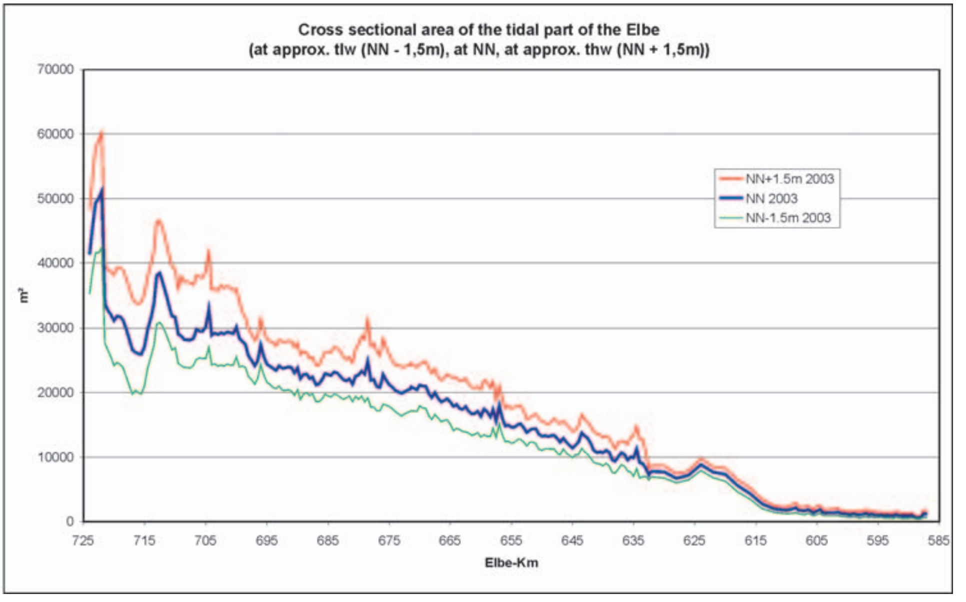


Fig. 3: Cross sectional area of the tidal part of the Elbe

Table 2: Freshwater discharge at gauge 'Neu Darchau' (source: HPA, 2007)

| | |
|---|---|
| Lowest observed discharge | 145 $m^3/s$ |
| Lowest median discharge | 278 $m^3/s$ |
| Median discharge | 713 $m^3/s$ |
| Median highest discharge | 1920 $m^3/s$ |
| Highest observed discharge | 3620 $m^3/s$ |

Coming from the sea, the mean low tide (MLW) rises by approximately 25 cm up to Glückstadt and then drops again towards Hamburg. During the past 30 years, the difference between MLW at Cuxhaven and Hamburg has continuously decreased to almost zero today. MHW along the tidal Elbe shows a different development: coming from the sea till Glückstadt, the MHW rises only insignificantly. From there a rise of approximately 0.5 m to Hamburg can now be observed (Fig. 4). This gradient has increased by approximately 0.25 m during the past 30 years as a consequence of changes of the river bed as described above.

Fig. 5 and Fig. 6 show tidal wave profiles at spring- and neap tide. They provide information on the water level situations as well as the rates of increase and decrease of the water level during regular tides. Tidal wave profiles which are close together reflect small increment and decrement rates; if they are further apart, these rates are high. Although the water-level gradients from sea to Hamburg are nearly equal during high and low tide, the maximum currents in the navigation channel from Hamburg towards the open sea continuously increase. Ebb currents become stronger compared to the flood currents. Due to the sudden change in width and depth of the cross-section at Bunthaus as well as at the tidal boundary at the Geesthacht weir, the tidal regime has been significantly transformed: While the tidal wave profiles downstream of Hamburg have nearly the same magnitude of inclination, the profiles

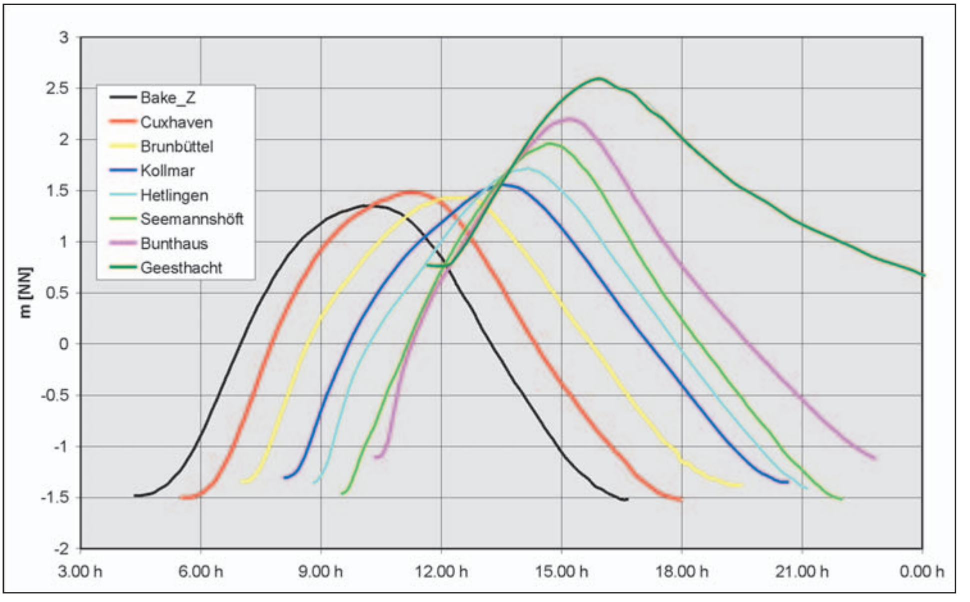


Fig. 4: Development of the tidal curve in the Elbe

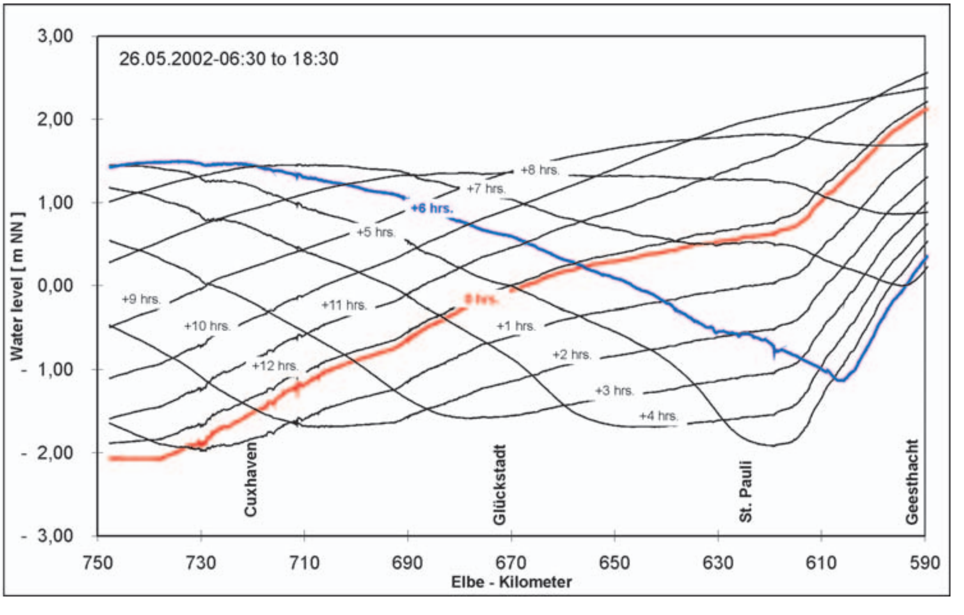


Fig 5: Tidal wave profile at spring tide

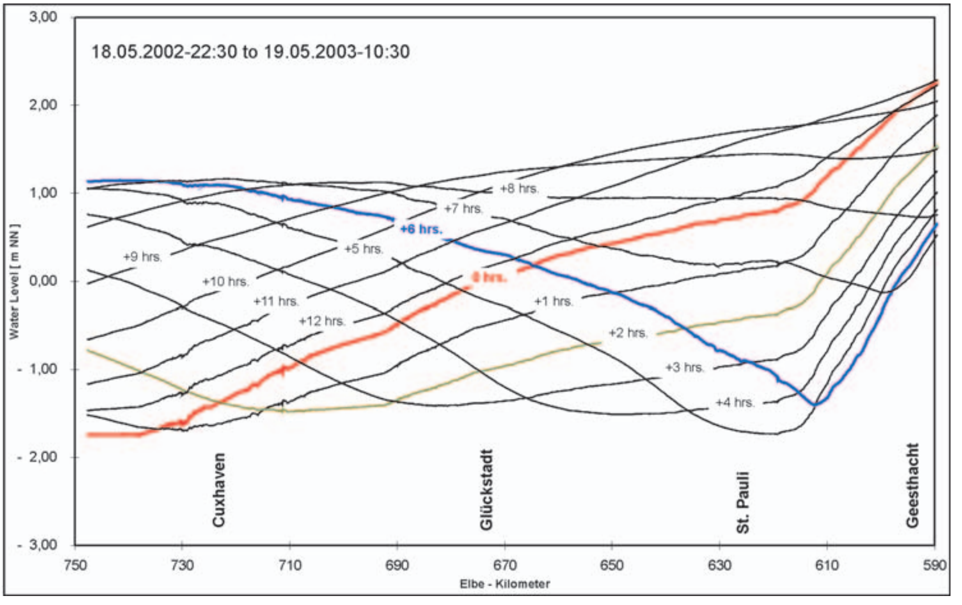


Fig. 6: Tidal wave profile at neap tide

upstream from Bunthaus show a much smaller gradient at high tide than at low tide, which is caused by the deformation of the tidal wave along this stretch.

Fig. 4 illustrates how the tidal wave is deformed on its way from the North Sea to further upstream. This originally almost sinusoidal wave is transformed due to the different propagation velocity of crest and trough. The flood gradient becomes steeper and the ebb gradient flattens. Both, the bed friction, which affects the currents, and the freshwater discharge contribute to this phenomenon. The following Tab. 3 clearly shows decreasing flood tide duration towards the upstream while the ebb-tide duration increases.

Table 3: Tidal duration asymmetries

| Tide Gauge | Mean High-Tide Duration (Min.) | Mean Low-Tide Duration (Min.) |
|---|---|---|
| Helgoland | 341 | 404 |
| Cuxhaven | 337 | 408 |
| Glückstadt | 327 | 418 |
| Schulau | 322 | 423 |
| Blankenese | 314 | 431 |
| St. Pauli | 303 | 442 |
| Zollenspieker | 265 | 480 |

Furthermore, the tidal curve is also considerably modified by the amount of freshwater discharge. This is illustrated by Fig. 7, which shows the duration of flood and ebb periods of the Elbe estuary as a function of discharges of 300 m³/s and 2000 m³/s. The higher the fresh-

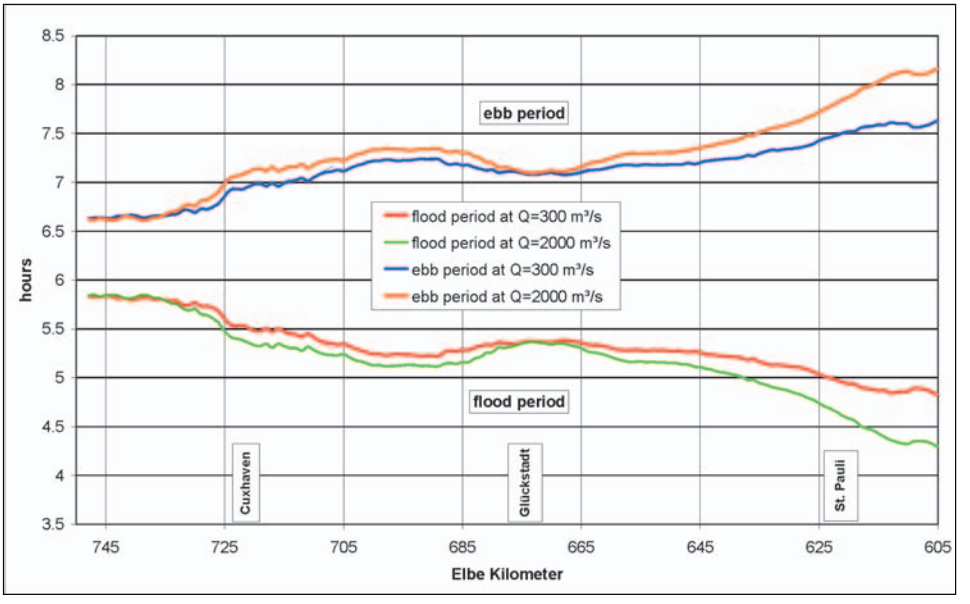


Fig. 7: Dependency of flood and ebb periods on the fresh water discharge

water discharge, the longer is the duration of the ebb tide while the flood tide duration becomes even shorter. This effect subsides towards downstream. That this phenomenon cannot simply be explained by the total volume of water, since it also linked to resonance and reflection, shows its minimum effect at Glückstadt: there is nearly no change in the duration of the ebb- and flood periods as a function of the freshwater discharge.

Similar to an inland river, the freshwater discharge affects the mean water level dependent on the river width. Moreover, upstream of St. Pauli, an increase of the discharge leads to a reduced tidal range. In this area, the reduction can reach 2 m if the discharge increases from 300 m³/s up to 2000 m³/s at the Geesthacht weir.

The influence of wind during a storm event with winds from a north-westerly direction leads to considerable increases in the tidal high water level along the Elbe, often even to storm surges. The fact that gale force winds and storms from the east also lead to significant changes in the water levels is not considered alarming for the population but, for navigation purposes, it is an unwelcome aggravation. Fig. 8 shows what moderate gale force winds at force 7, blowing from easterly directions for several days, can achieve: Compared to the normal water levels, the tidal high water level drops by up to 1 m, and the tidal low water level also decreases by around 0.5 m. This wind-generated effect appears, just as it is the case during a storm surge, virtually without any time lag and quickly abates.

Fig. 9 shows the development of the monthly averages of MHW and MLW at the tidal gauges Cuxhaven Steubenhöft and St. Pauli. While values obtained from gauge Cuxhaven only show a slight positive trend in the development of MHW and no significant trend regarding MLW, the gauge at St. Pauli shows a different water level development. During the past 50 years, MLW has decreased by nearly 1 m, while MHW has increased by around 0.5 m. Dependent on the type of deepening the fairway, past upgrades of the navigational channel have certainly influenced this development. For example, a reaction to the end-to-end fair-

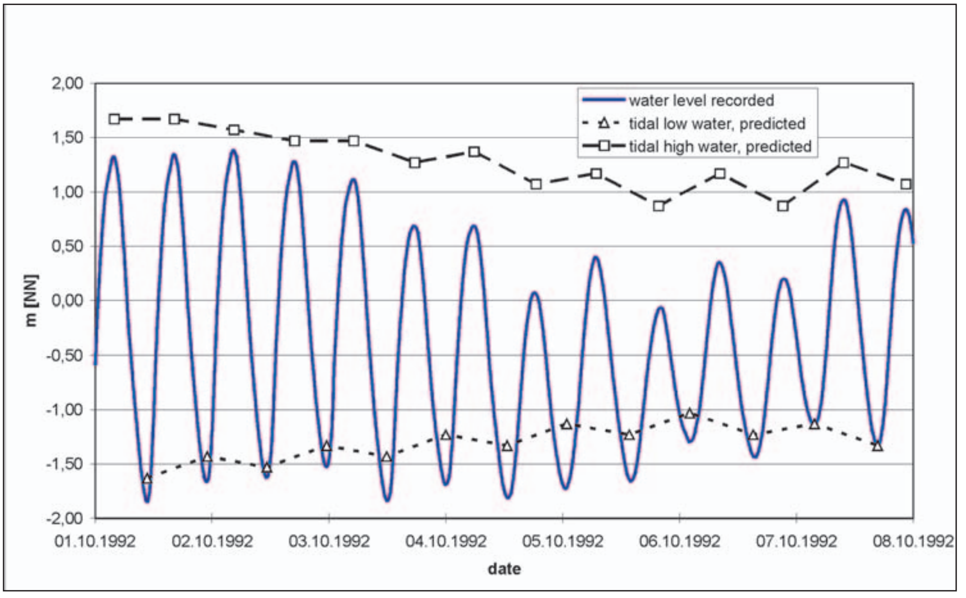


Fig. 8: Water level at Cuxhaven, predicted and recorded

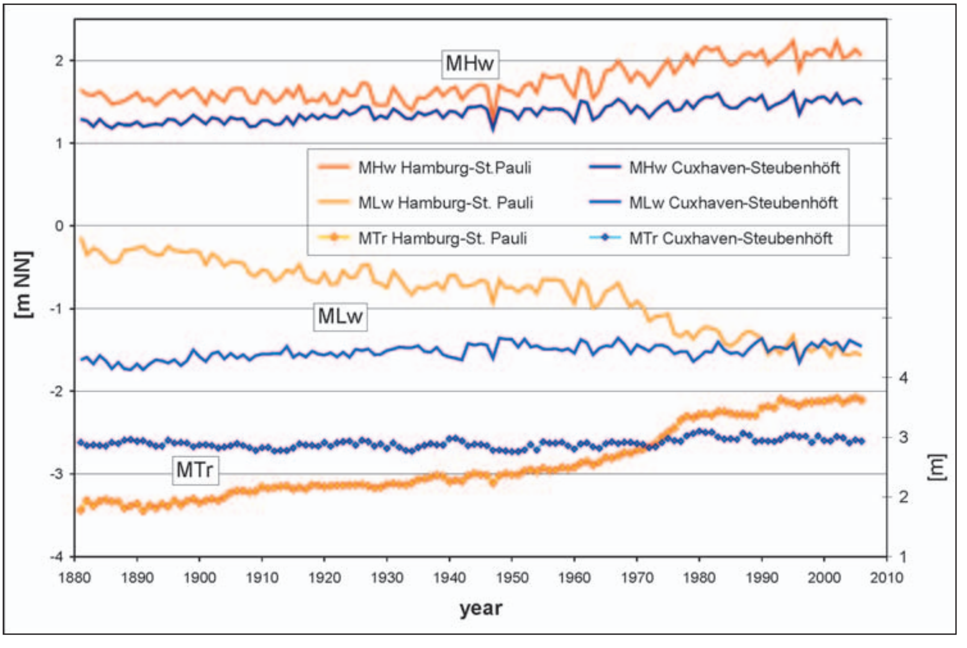


Fig. 9: Development of the mean high water, low water and the tidal range since 1880

way improvement to a depth of 13.5 m Chart Datum (*Karten Null* KN) in 1976 can be clearly seen in the MHW and MLW-levels. A similar effect to the deepening works in 1999 has not been observed, yet. Also the loss of water volume within the tidal prism due to the change of harbour basins into footprints for containers in the port of Hamburg has an influence on the tidal range in the same direction. Investigations carried out by the Federal Waterways Engineering and Research Institute *(Bundesanstalt für Wasserbau Dienststelle Hamburg – BAW)* have indicated that major naturally caused sediment movements in the Outer and Lower Elbe have generated equally strong effects on the water level, comparable to those induced by deepening measures. Examples are the shifting of the Medem Channel *(Medemrinne)* and the breakthrough at the "Lüchter Loch" during the past 20 years.

The salinity in the tidal Elbe ranges from pure fresh water to sea water with a salinity of around 32 PSU at the point where the Outer Elbe meets the German Bight. The location and extent of the brackish-water zone is considerably determined by the volume of the freshwater discharge, by the mean water level of the North Sea and by the tidal range. Under average conditions, the brackish water zone extends to Elbe-km 660 until flood slack water ($K_f$) and to Elbe-km 680 at ebb slack water ($K_e$) (Fig. 10). If minor freshwater discharges last for several days, the upper limit of the brackish-water zone can, according to BERGEMANN (1995), move upstream to Elbe-km 645. Furthermore, higher water levels in the North Sea due to meteorological circumstances can generate higher salinity levels compared to the mean values of the Lower Elbe.

The effects of high freshwater discharge values at the position LZ4 at Elbe-km 731.1 are represented in Fig. 11. In August 2002, the discharge at Neu Darchau increased from 500 m³/s to nearly 3,500 m³/s. As a result, the salinity which had oscillated between 14 and 26 PSU in rhythm with the tides, now varied between 3 and 26 PSU. The brackish-water zone not only

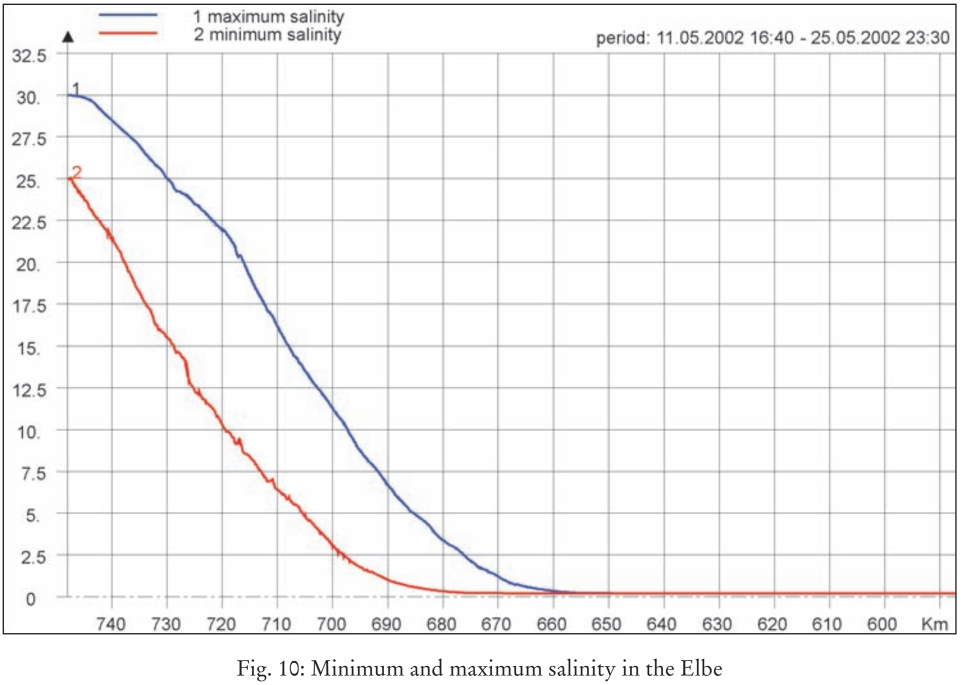


Fig. 10: Minimum and maximum salinity in the Elbe

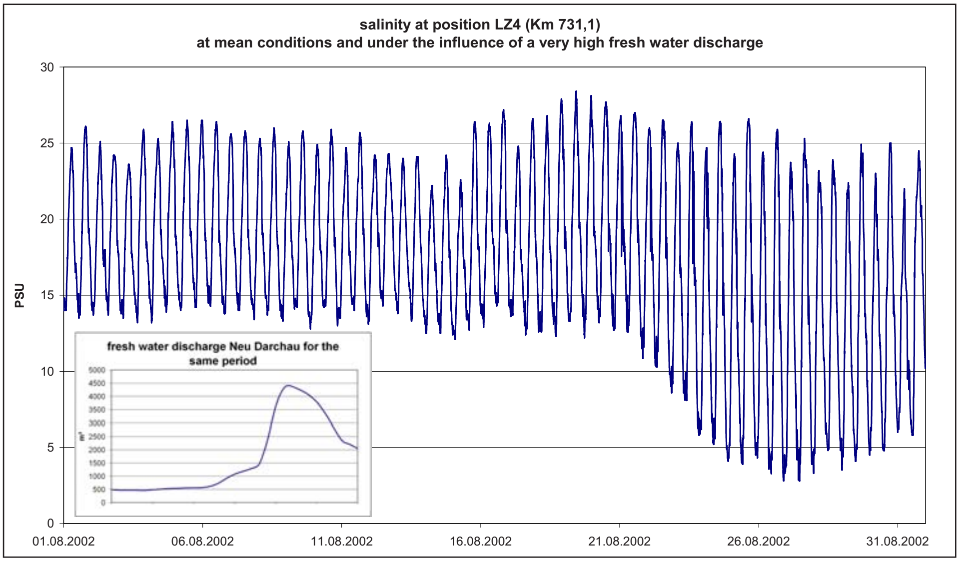


Fig. 11: Salinity at position LZ4 at Elbe-km 731.1

shifts towards the sea in such an incident, but it becomes much shorter, while the amplitude of the salinity can considerably increase at one location.

While the water level and the salinity in an estuary have a uniform large-scale distribution, the current velocity is a parameter, which varies strongly with space and time. This is what Fig. 12 and Fig. 13 clearly shows: it depicts maximum flood- and ebb velocities in the middle of the navigation channel of the Lower and the Outer Elbe. Furthermore, distinctive flood dominance from upstream of Glückstadt to Hamburg can be seen. This condition existed already around 1970, but only in a reduced form upstream of Lühesand and not as significant as today. This factor leads to the "Tidal Pumping" of sediments from the lower reaches of the Elbe to areas further upstream, resulting in insufficient water depths in the navigation channel and the harbour basins.

An overview of the concentrations of suspended matter and the behaviour of the turbidity zone in the Elbe Estuary has to be composed of single measurements carried out by various authorities and institutions (KAPPENBERG, 1996; ARGE ELBE, 2000). The shape and location of the turbidity zone change, depending on the freshwater discharge. The maximum concentration of suspended solids during periods of higher fresh-water discharge ($Q > 900$ m³/s) can reach around 0.35 kg/m³. The maximum is then found at Elbe-km 690, and the turbidity zone is more compressed than during an average discharge of 500 m³/s. In this case, the maximum concentration is at approx. 0.6 kg/m³ and lies about 10 km further upstream at Elbe-km 680 (FHH, 1997).

Results of the 3D-Elbe Model of the BAW-DH are substantiated in Fig. 14. Here the calculated cross-sectionally averaged results are represented, which were computed for a constant freshwater discharge of 350 m³/s (red lines) and a variable freshwater discharge of around 800 m³/s (black lines). The model shows not only the seaward shift of the turbidity zone at higher discharges but also flood-tide induced transportation (net transport > 0) upstream of the turbidity zone depending on the freshwater discharge.

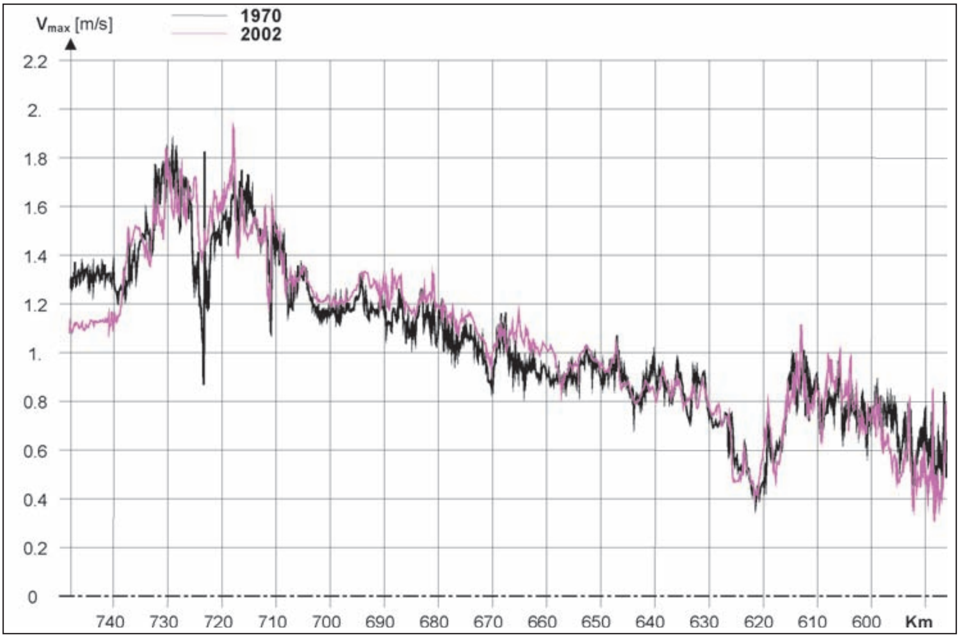


Fig. 12: Maximum current of the ebb tide 1970 and 2002 in the Elbe river

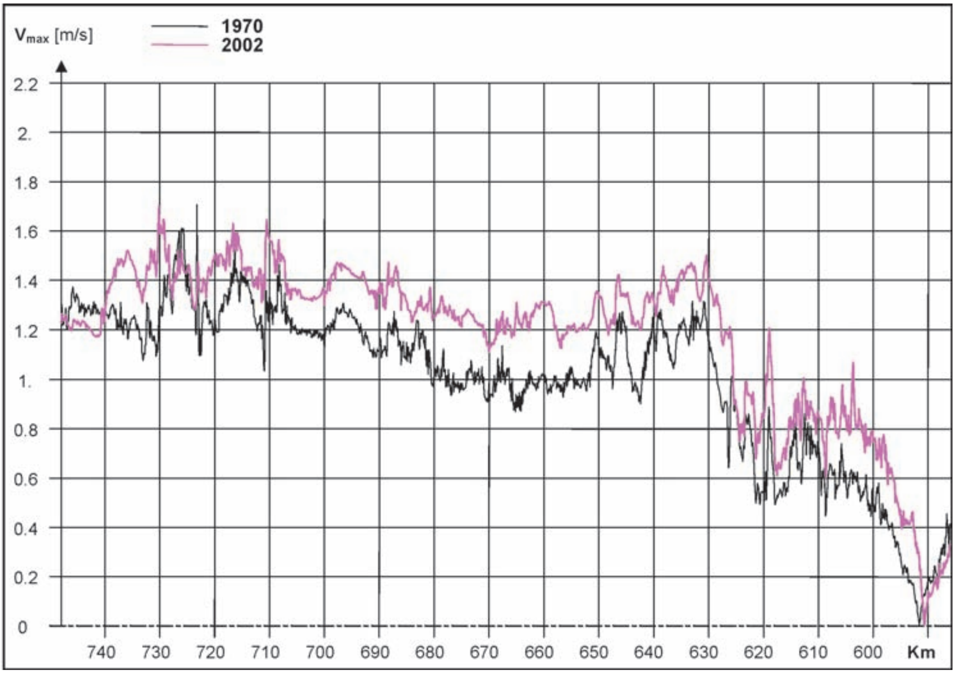


Fig. 13: Maximum current of the flood tide 1970 and 2002 in the Elbe river

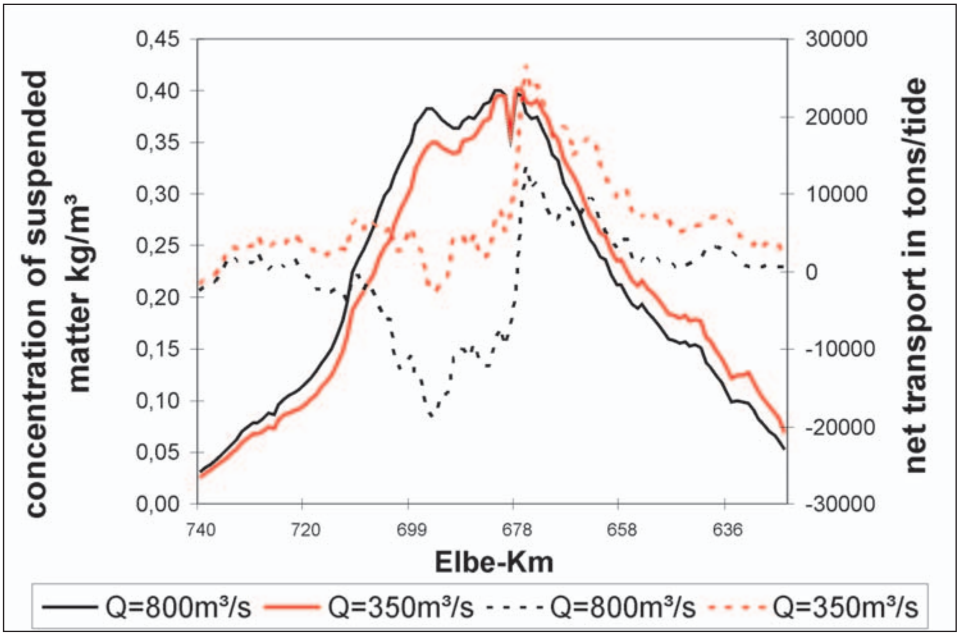


Fig. 14: Characteristics of the transport of suspended matter

The suspended load concentration varies considerably within a cross-section and during a tidal cycle. Current calculations of this concentration from the back-scatter signal by ADCP measurements (Fig. 15) give a first insight into these dynamics (MAUSHAKE and AARDOM, 2007). Near bed suspended load concentrations of an order of magnitude of O >> 1 kg/m³ occur not only in the turbidity zone, but also in the Hamburg port area.

## 4. Construction Measures in the Elbe Estuary

Since approximately the 13th century, uninterrupted dikes lined both embankments of the Tidal Elbe. Drainage of the hinterland areas lead to soil subsidence. Furthermore, sedimentation taking place during storm surges does not reach the hinterland, the elevation of which always remains below the mean water level. Today, large-scale areas are still below mean sea level (MSL).

As a result of the severe storm surges of 1962 and 1976, extensive dike realignments took place. By impoldering, additional areas were cut off from the tidal influence and storm surge events. Between 1900 and today, the foreshore areas of Schleswig-Holstein and Lower Saxony have decreased by 50 % and 74 %, respectively.

The Lower and Outer Elbe have been considerably altered by river-engineering measures. Already during the 15th century, the 'Hamburg Düpe Gentlemen' and later the 'Düpe Commission' (a committee in charge of ensuring an appropriate navigable depth towards Hamburg) had the responsibility of monitoring the fairway depth of the Lower Elbe. If somewhere within the fairway the water depth was too shallow for the ships of that

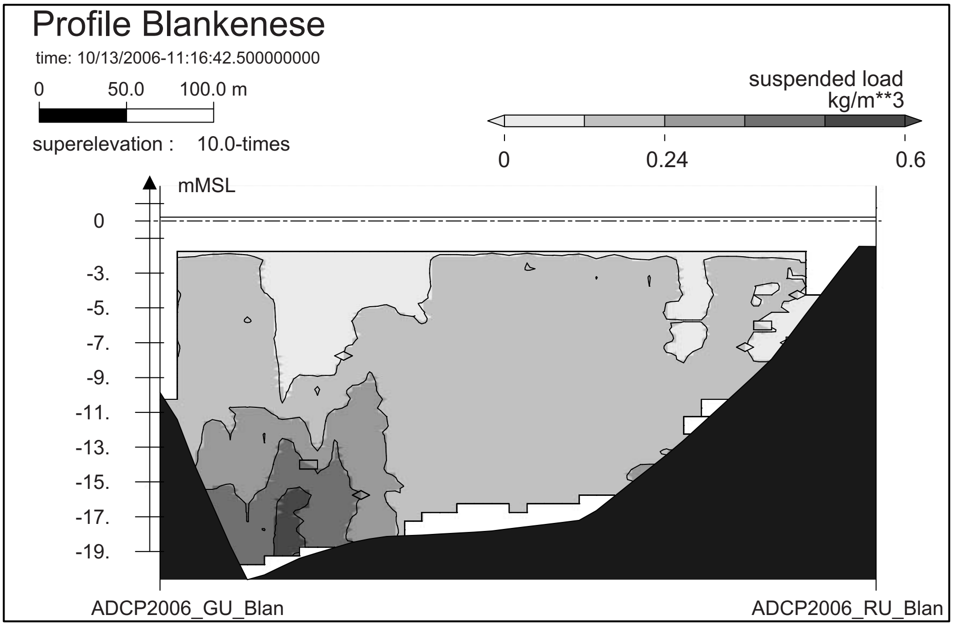


Fig. 15: Suspended matter at a cross section at Blankenese

generation, there were limited means to remove these shoals. Only since 1834, effective devices (for example steam powered excavators) were available to undertake major changes to the navigation channel. Consequently, until 1868, the channel depth of 5.30 m in the Lower Elbe could be established by only removing single sand bars and ripples. After this, several deepening campaigns were carried out to follow the rapid development of maritime traffic:

- 10.0 m depth upgrade from 1936 to 1956
- 11.0 m depth upgrade from 1957 to 1962
- 12.0 m depth upgrade from 1964 to 1969
- 13.5 m depth upgrade from 1974 to 1978
- 14.5 m depth upgrade from 1999 to 2000

The depths mentioned above refer to the chart datum which until then had been the mean low water spring tide. Fig. 16 illustrates the fact that the existing longitudinal profiles in the fairway were quite complex.

Previous upgrades of the fairway always included deepening as well as widening the navigational channel with the effect that tidal dynamics were considerably altered. Another considerable factor of influence was the change of the surface water areas. Until the middle of the 19$^{th}$ century, the Port of Hamburg was located along the northern embankment of the Elbe. Starting around 1880, construction works creating harbour basins on the south side of the Elbe were carried out. By around 1970, the water surface areas exposed to the tidal dynamics had increased by nearly 1000 ha. Between 1970 and 2005, 187 ha of these areas were converted back into land in the course of various projects.

By comparison, the construction of the storm- surge barriers at the tributaries of the Elbe, which have been carried out since 1968, as well as the dike constructions along the

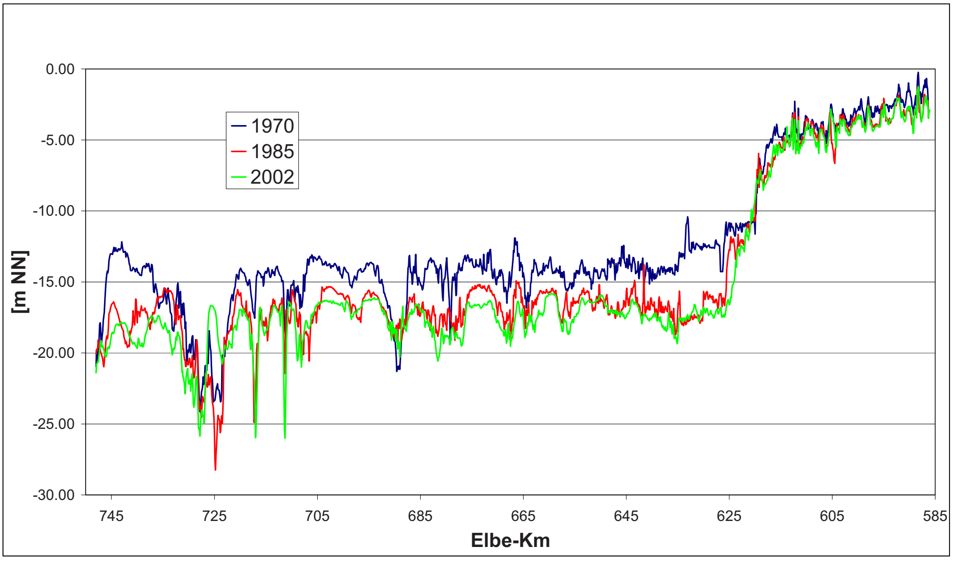


Fig. 16: Depth of the fairway of the Elbe since 1970

Lower Elbe have had only little effect on the average tidal dynamics. Their influence on storm surge elevations in the Elbe estuary, however, must be described as significant. Thus, in Lower Saxony 10,600 ha of the former 13,900 ha of foreshore areas and 14.800 ha of a total of 19,700 ha of former flood planes in Schleswig-Holstein were impoldered, which is equivalent to three thirds of the previously existing hinterland areas (Fig. 17).

Between 1840 and 1850, first considerations regarding the improvement of the fairway conditions, particularly in the stream divide area of Hamburg by systematic river training measures were taken. Initially, the dredgers deployed in the port area, ensured the necessary water depths, until larger construction and regulation projects were made possible. The Hanseatic City of Hamburg secured its right to upgrade the Norderelbe and the Köhlbrand. Additionally, a breakthrough at Kaltehofe and the construction of the training wall at Bunthäuser Spitze ensured a larger flow passage through the Northern Elbe. Further measures to regulate the Elbe from the Seeve to Brunshausen laid down the fundamentals for today's Elbe course. This marked the beginning of the human interference in the tidal regime of the Elbe. By constructing a 7.5 km long training wall between the islands of Schweinsand and Hans-Kalb-Sand, the natural cross-drift of sands into the navigation channel was prevented. Already in 1911, the dumping of sand to an elevation of the main water level at the southern side of the training wall formed the basis for the island's shape as it is today. In the course of further fairway upgrades, the island has been gradually raised up to its present elevation. On the western side of the island of Schweinsand, the new island of Nesssand emerged in 1968. In the course of the upgrade of the navigational channel in 1969, the islands of Hans-Kalb-Sand, Neßsand and Schweinsand were linked together and now form a single island between the main and the secondary channel of 'Hahnöfer Nebenelbe'.

With the same motivation of preventing uncontrolled shifting of channels, a training wall at Pagensand was built in 1922–1930. This was to prevent further shifting of the quicksand bar "Hungriger Wolf". Between 1928 and 1936, this was followed by the training wall to the

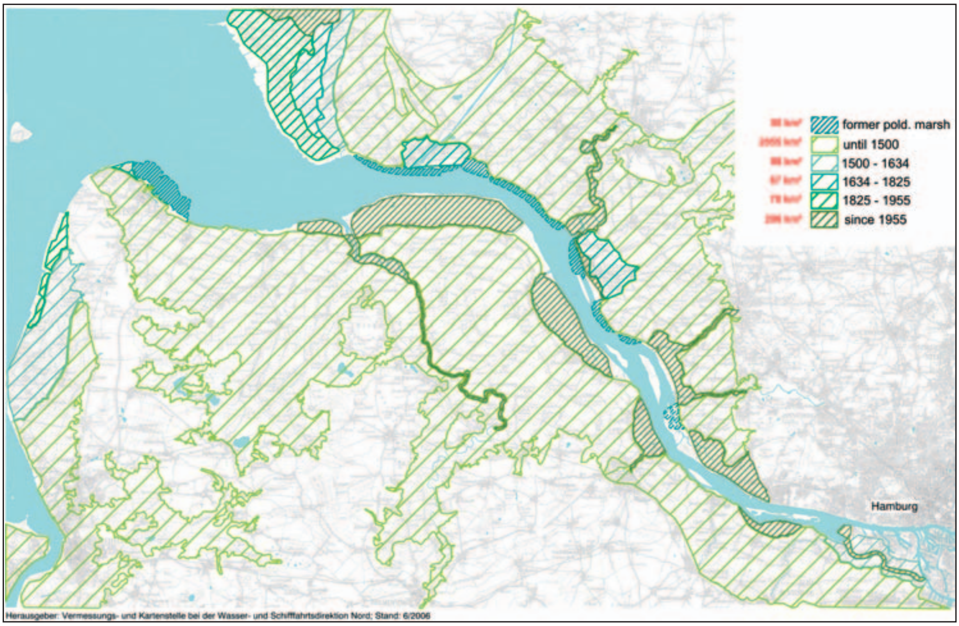


Fig. 17: Loss of flood prone areas

north of Pagensand in connection with several dredging campaign to remove sand from Schwarztonnensand. Between 1971 and 1977, substantial parts of the island of Schwarztonnensand were finally raised above MHW level. The islands of Lühesand and Rhinplatte, artificial in their present shape, serve as training walls to control and concentrate currents. The cross sections of the river should be in an equilibrium to enable the current energy to clear both channels.

Between 1922 and 1937, the building of the groynes along the Osteriff, the removal of material from the Ostebank and the construction of the training wall at Hermannshof near the mud flats at Neufeld were carried out. These measures also served to generate and maintain sufficient water depths as well as to stabilize the navigation channel. They also aimed at reducing the amount of dredged sediment at the Ostebank, a goal which has not been achieved till today. In the highly dynamic region of the mouth, a three-channel system had developed. The construction of the training wall 'Kugelbake' reduced this to two channels and stabilized its location. Construction works on the training wall were carried out in several stages between 1939 and 1962. In the beginning, the training wall was 9 km long. Between 1975 and 1977, it was extended to approx. 10 km.

The most recent river engineering measures are the under-water deposit areas at Krautsand and Twielenfleth which were constructed during the last fairway adaptation in 1999. They were meant to reduce the amount of dredging with increased current velocities keeping sediments in motion in these areas.

For the protection of river banks and in order to stabilize the course of the Elbe, extensive groyne systems were built. Some of the groynes are large enough and built with such a small slope to trigger the evolution of calm foreshores and embankments where even the growth of reeds might be possible. This could create a habitat said to have existed in earlier times.

The diversity of the morphological structure of the Elbe Estuary is significantly influenced by the tides, and its natural state is characterised by an intensive drift of solid particles, linked to a constant transformation of the river bed and foreshore. It features bifurcations, shifting, alternating widths of the water body, scours and aggradations in the form of mud flats, sands and islands, the formation of side channels and embankment collapse. In addition to the internal sediment sources, coarser sandy material is carried into the Elbe Estuary from the North Sea. In contrast, rather fine solids are carried down from the upper course of the Elbe. In spite of a qualitative improvement since the German Reunification, they are still contaminated. In the estuary, these sediments are mixed up and can settle for a short period of time or permanently. Preferred sedimentation areas are shallow water regions, such as side channels and harbour basins where weaker current conditions exist.

In order to guarantee safety and ease of navigation on the Elbe and in the Port of Hamburg all year round, maintenance dredging has to be carried out by hopper suction dredgers, bucket dredgers and water-injection devices. For economical reasons, a minimisation of the sediment volumes to be dredged is aimed at. Moreover, the impact on the benthos, the characteristics of the river bed (grain size and texture), the concentration of suspended sediments and the oxygen concentration all demand environmentally friendly dredging operations.

Dredged material is being treated in different ways according to the particular intention and the sediment quality. Either the material is extracted from the water body or it is relocated within the estuary itself. The relocation within the estuary is done by dumping the material in areas where there are sufficient depths and where it does not cause any disturbance. However, this procedure has certain limitations concerning the contamination level of the sediments. Contaminated material is removed from the water body and treated ashore. According to the degree of contamination, it can either be used for construction measures or is dumped in containment areas.

In order to maintain the required water depths in the Port of Hamburg, 3–5 million m³ of sediments are dredged, of which around 1.4 million m³ are brought ashore. Except for a smaller proportion that is used for drainage and construction purposes most of it is deposited. From September to March, the larger amount is relocated at the Isle of Neßsand at the state border. In order to avoid or minimise the effects of relocation, mandatory instructions were formulated and agreed on by the responsible ministries of the Hanseatic City of Hamburg. These involve temporal, spatial and technical mitigation measures. Another such instruction concerning the handling of contaminated dredged spoils was decided upon by the Environment Ministries of the states bordering the Elbe in 1996.

But also throughout the rest of the estuary all the way up to the mouth, there is a need for maintenance of the waterway at regular intervals. The Federal Administration for Waterways and Navigation (WSV) has to relocate up to 12 million m³/a. Around the entrance to the Kiel Canal, the regional office of WSV, WSA Brunsbüttel, commissions dredging of approx. 7 million m³/a. In the secondary channels of the Elbe and its tributaries, maintenance dredging of around 0.6 million m³ is necessary in order to maintain the navigable water depths.

To avoid or minimise any negative effects due to the maintenance measures, the Federal Ministry for Transport, Building and Urban Affairs issued the *'Instructions for Dealing with Dredged Material in inland areas'* (Handlungsanweisung für den Umgang mit Baggergut im Binnenland – HABAB-WSV) (BMVBW AND BFG, 2000). Further downstream beyond Elbe-km 683 (Freiburg Haven Creek) the *'Instructions for dealing with Dredged Material in Coastal Areas'* (Handlungsanweisung für den Umgang mit Baggergut im Küstenbereich – HABAK – WSV) (BFG, 1999) have to be applied accordingly.

## 5. On-going Monitoring and Analysis

The first regular tidal observations at the German coastal region already took place upon orders by the Hamburg Navigation and Port Deputation in 1841. For this, measurement stations were installed at Hamburg St. Pauli and Cuxhaven. Ever since, high and low tidal peaks have been registered (STEHR, 1964). Today, water levels are recorded by 29 tidal gauges in the Tidal Elbe between Geesthacht and the former lighthouse "Großer Vogelsand". Since 1997/98, current velocities have been measured at 13 stations (partly at two different water depths); some of these measuring devices are equipped with a supplementary sensor for measuring the turbidity. On five selected profiles, single point current measurements are made in cross sections. Conductivity and salinity have also been continuously measured in some parts of the Elbe since 1987.

Along with the upgrade to a 13.5 m depth, a working group on 'Preservation of evidence' consisting of members from federal and state authorities (Bund-Länder-Arbeitsgruppe 'Beweissicherung') was established. This group has submitted in a two-part final technical report data concerning the changes in water level, current velocities, salinity and bank development. Conversely, during the Planning Approval Procedure for the 14.5 m deepening, a considerably more comprehensive monitoring programme was imposed with a main focus on biotic parameters. The reports and data published so far can be loaded down from www.portal-tideeelbe.de.

## 6. Acknowledgement

The authors would like to thank Dr. Holger Weilbeer (BAW) for his contribution on suspended matter in the Elbe.

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# The Eider Estuary

By Klaus Bednarczyk, Detlef Schaller and Ulrich Vierfuss

Contents



## 1. Introduction

### 1.1 The Waters of the River Eider

The Eider rises "in the heart of Schleswig-Holstein" to the North-east of Neumünster; its former course to the North Sea covered about 190 kilometres (Fig. 1). As the Upper Eider, it first ran through the young-moraine region of Ostholstein in a northerly direction until it came close to the Baltic Sea near Kiel. Then it turned west and reached the town of Rendsburg half way across to the North Sea. Here, the river reached the lowlands, which it crossed as the Lower Eider in great meanders before the Eider estuary met the North Sea near Tönning. The corresponding catchment area was about 3,300 km² in size.

The condition of the Eider today is the result of extensive intervention measures which have drastically changed the river over the last 400 years and divided it repeatedly.

Today, after about 54 km, the Upper Eider merges with the Achterwehr shipping canal and then empties into the Kiel Canal after another three kilometres. Up to this point the catchment area amounts to around 300 km². Only rudimentary parts of the stretch towards Rendsburg have survived as the "Alte Eider" and as the "Obereidersee", a secondary channel of the Kiel Canal with the harbour "Obereiderhafen" in Rendsburg.

The Lower Eider begins as a river without a source in Rendsburg's harbour "Untereiderhafen". The section to the interim reach at Lexfähr (km 23) and on to the tidal boundary at Nordfeld tidal gate (km 78) is referred to as the "Upper" and "Lower Inner Eider". Further on, the "Tidal Eider" is separated from the subsequent channel of the "Outer Eider" by the Eider Barrier (km 110). In addition to the tidal volume, a freshwater discharge from a catchment area of around 2,100 km² flows through the mudflats into the North Sea at this point. The Eider estuary consists of the Tidal and the Outer Eider (Fig. 2):

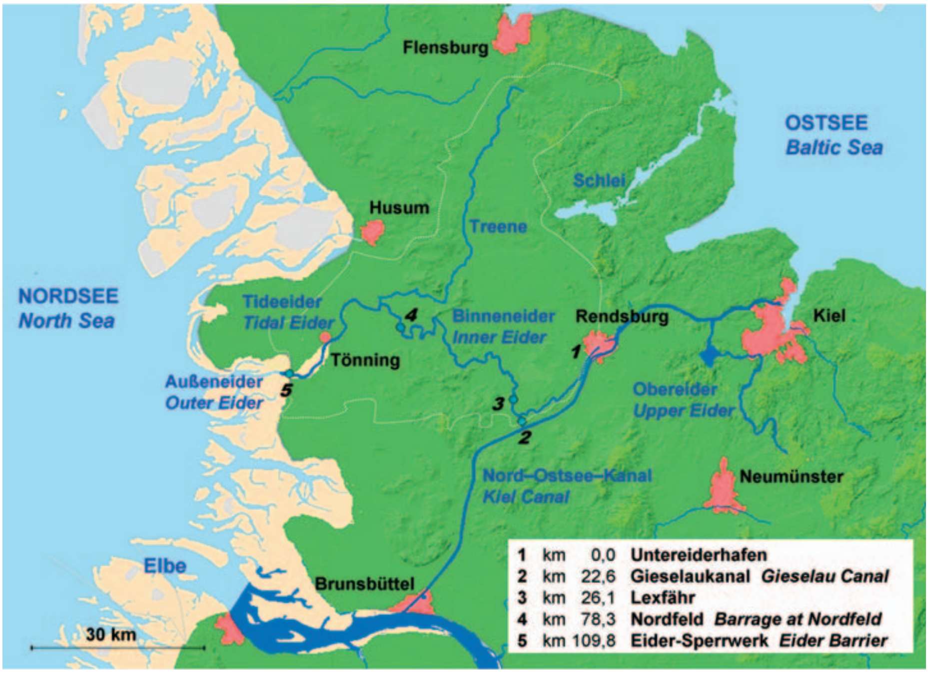


Fig. 1: Layout drawing of the Eider region

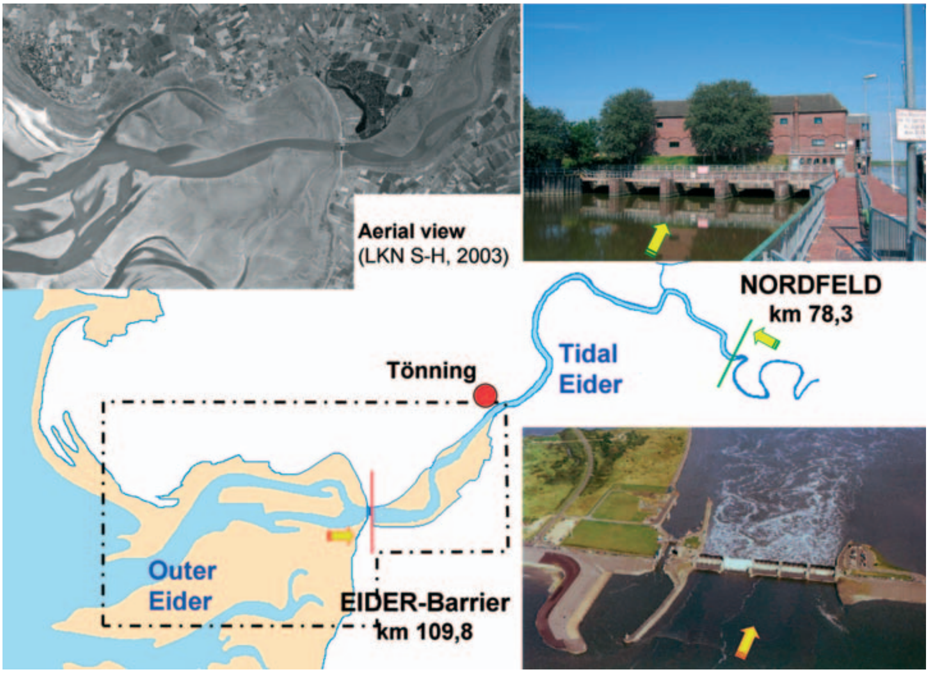


Fig. 2: Layout drawing photos of the Eider estuary (Tidal and Outer Eider)

### 1.2 Hydrological Characteristics of the Eider

Table 1: Hydrological characteristics of the Eider

| | | | |
|---|---|---|---|
| Catchment area | 2100 | $km^2$ | |
| Length of the tidal estuary | 31 | km | |
| Tidal range | 0–3.5 | m | Tide control |
| Tidal volume | 25–30 | mio $m^3$ | |
| Current velocity | 2 | m/s | $v_{max}$ Tönning |
| Current velocity | 4 | m/s | $v_{max}$ Eider Barrier |
| Salinity | 16–26 | ‰ | Eider Barrier |

### 1.3 Development of maritime traffic

The Eider already served the Vikings as a waterway from the North Sea to the Baltic region taking the route through the Eider–Treene lowlands to Haithabu on the Schlei. In those days, however, there was no through connection. The boats had to be pulled across land for several kilometres.

Under Danish rule, a continuous waterway between the North Sea and the Baltic was established with the construction of the Schleswig-Holstein Canal (Eider canal) between Kiel and Rendsburg in 1777–1784. It served also the trade between England, France, Holland and the Baltic states. Boats sailing on the Lower Eider could make use of the tidal flow, while those on the canal stretch sailed or were hauled. Compared to sailing around Skagen, the canal route only saved 1–3 days on average; but this was the safer route so that through-traffic accounted for about 45 % of shipping.

Traffic along the waterway brought economic prosperity; the Eider was theoretically affected by the Continental System (1807–1814), so that particularly intensive contraband traffic developed between Helgoland and Tönning, both occupied by Great Britain. Tönning

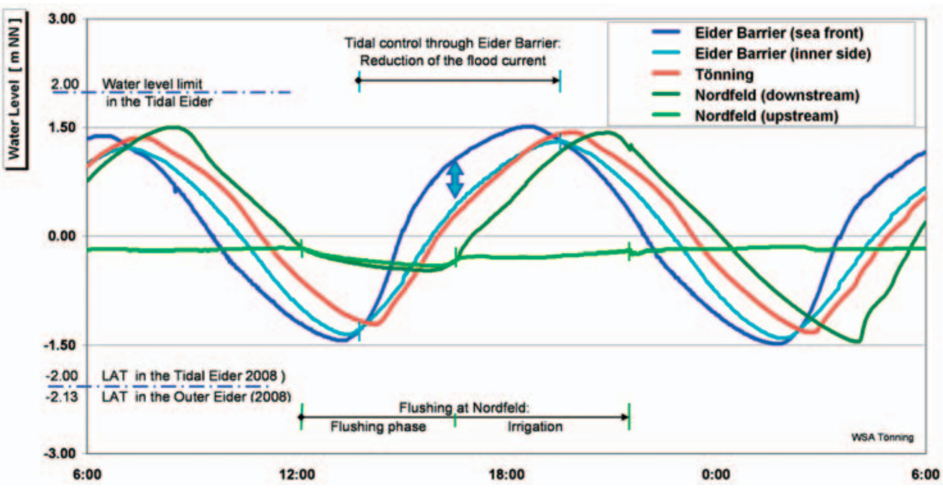


Fig. 3: Time series of tidal elevations in the Eider (August 7th and 8th, 2000)

Table 2 : Historical and current lock dimensions

| Lock dimensions Eider | | | |
|---|---|---|---|
| | **Historical Eider canal :** Lock (canal dimensions) | **Gieselau lock, Lexfähre and Nordfeld** | **Eider Barrier** |
| **Serviceable length** | 35.0 m* (28.7 m) | 70.0 m | 75.0 m |
| **Inner width** | 7.80 m (7.45 m) | 9.50 m | 14.00 m |
| **Sill depth** | 3.50 m (2.68 m) at MW | 3.50 m at MW | 4.00 m at MTlw |
| **Tol. draught** | – | 2.,80 m | – |
| * Rendsburg from 1990: 70.0 m | | | |

later became an export harbour for sheep and cattle to England. This trade abruptly succumbed to the outbreak of foot and mouth disease on the European continent in 1889.

In 1887–1895, the Eider canal was replaced by the Kaiser Wilhelm canal, today's Kiel Canal. By then, more than 284,000 ships had passed through the canal (STOLZ, 1984).

The connection between the North and the Baltic Sea along the Eider remains preserved to the present day, initially through the lock at Rendsburg between "Ober- and Untereiderhafen" which was rebuilt in 1887/95. Afterwards, from 1935/38, the waterway was substituted by the "Gieselau Canal" which is about 3 kilometres long and branches off the Lower Eider towards the Kiel Canal about 21 km downstream of Rendsburg. The route along the Eider could not compete with the Kiel Canal and rapidly lost its significance as an international trading route. Attempts around 1905 to revive ocean-going traffic in Tönning with regular services to England and Australia were short-lived.

As part of the Eider upgrade in 1935–38, dimensions for breakthroughs were defined: a maintained depth of the bottom at MW 3.30 m, the width of the bottom at 25.0 m and underwater slopes at 1:4 / 1:3.

Following the improvement of the network of highways and roads in the second half of the last century, the Eider also lost significance as a regional transport route. Hardly any commercial use can be seen today. The river has become popular for pleasure craft which sometimes take advantage of the tidal wave when passing shallow water reaches.

## 2. Geomorphology

### 2.1 History of Encroachments on the River System

In the face of recurrent storm surges, the construction of dykes along the Eider from the coast on upstream was furthered.

After damming the tributary Treene in 1570 and the Sorge in 1624, the tide progressed further inland, making more dyke construction necessary. Tidal influence was observed at the water-mill in Rendsburg for the first time in 1700. With the construction of the Eider canal at the end of the 18$^{th}$ and the Kiel Canal at the end of the 19$^{th}$ century (see section 1.3), the upper third of the discharge from the catchment area was partially and later on completely drained off into the Baltic Sea.

Following the construction of the Kiel Canal, measures for straightening of the Eider to approx. 20 km downstream of Rendsburg.

Between 1935 and 1938, extensive flood defence measures for 40,000 ha lowlands were carried out. This included the barrage with a drainage sluice at Nordfeld, the reach with a sluice at Lexfähr, the new construction of the Gieselau Canal and closure of the lock at Rendsburg, as well as the straightening of the Eider with a breakthrough at Tielenhemme.

Starting in 1950, attempts were made to solve the so-called "Eider problem", resulting from the tidal limit being pushed back to Nordfeld, by pumping stations installed along the lower Inner Eider and in the sluice at Lexfähr. The sluice at Nordfeld was used to flush the Tidal Eider, and from 1960 on approx. 100 groynes were built to reinforce the flushing effect on the section up to Tönning.

In the context of the Eider Barrier which was completed in 1973, the tidal volume of the Tidal Eider was considerably reduced by dyking the Katinger Watt. Further reductions arose by the restricted intake as normal business (lowering HW), by the introduction of the limit water level at MHW + 0.5 m and by the temporary inhibition of the flood current (only drainage) to support the drainage capacity. Normal operation also includes intermittent flushing in ebb direction to keep the tidal channel of the Outer Eider open.

In 1979, the north channel of the Outer Eider was blocked with a sandbank to support coastal protection at the peninsula of Eiderstedt.

## 2.2 Reaction of the System to the Encroachments

### 2.2.1 Construction of Dykes and Canals till 1936

With the completion of the Kiel Canal (1895) and no more freshwater discharge at Rendsburg, accumulations of silt increasingly interfered with the operation of the lock in Rendsburg. Moreover, as already observed before, the increase of the tidal range at the gauge at Rendsburg continued noticably, while the development of water levels at the gauge at Tönning close to the estuary mouth followed the trend as observed at the comparable tidal gauge at Husum. It was also ascertained that storm surges in relation to Tönning progressed further into the Eider estuary.

The main cause for this development was seen in on-going dyke construction along the Eider, while less significance was attributed to the reduced freshwater discharge and minor river improvement measures (MÜLLER and FISCHER, 1955).

### 2.2.2 Eider Barrage at Nordfeld (1936)

The barrage at Nordfeld moved the tidal boundary of the Eider around 80 km seawards. Already in the first planning stages in 1928, people were aware of possible difficulties arising from the barrage because of the expected deformation of the tidal wave and resulting silt deposition. A monthly accumulation of 2 cm of silt was expected on a section of 5 km below the dam (MÜLLER and FISCHER, 1955). The silt accumulation had been considerably underestimated. Thus, already within just a few years, the cross-sections along the 5 km stretch up to the mouth of the Treene near Friedrichstadt had sanded up and shrunk by up to 90 %. Investigations carried out after 1950 showed that the sediments came from the North Sea (WEINNOLD and BAHR, 1952). The deformation of the tidal wave with a steeper flood branch and flatter ebb branch resulted in an increase in the flood current velocity and decrease in the ebb current velocity to such an extent that sediment transported into the river by flood currents could no longer be eroded again and carried away during the ebb tide.

This aggradation considerably jeopardized the drainage of the Inner Eider as well as navigation on the Tidal Eider, because the inland water level of –1.0 m NN aimed at since 1938 could not be maintained.

After 1950, flushing operations through the sluice gate at Nordfeld, the groynes between Nordfeld and Tönning and sporadic initial dredging operations were no longer capable of reversing the aggradation. The Eider problem had not been solved satisfactorily.

### 2.2.3 Eider Barrier at Tönning (1973)

The weir structure, training walls and separating moles in connection with the lock were erected on an artificial island constructed in the protection of a ring dyke on the line "Hundeknöll-Vollerwiek" on the tidal flats.

Damming the main channel of the Eider ("Purrenstrom") initially meant that the Eider had to find a new bed around the barrage, resulting in increased aggradation in the tidal channel of the Outer Eider.

The enclosure of "Katinger Watt" by a dike and forcing the river through the barrage with a considerably reduced tidal volume completely changed the morphological processes in the Tidal Eider (Fig. 4). Already after a few years, a channel migration was established in the remaining tidal flat area which has been stable up to the present. There was a noticeable decrease in the intensity of aggradation of the Eider; in the meantime, the process seems to be limited to the relocation of sediment. This evaluation, however, does not apply to the area between +1 m NN and the limiting level of +2 m NN which has been hardly sur-

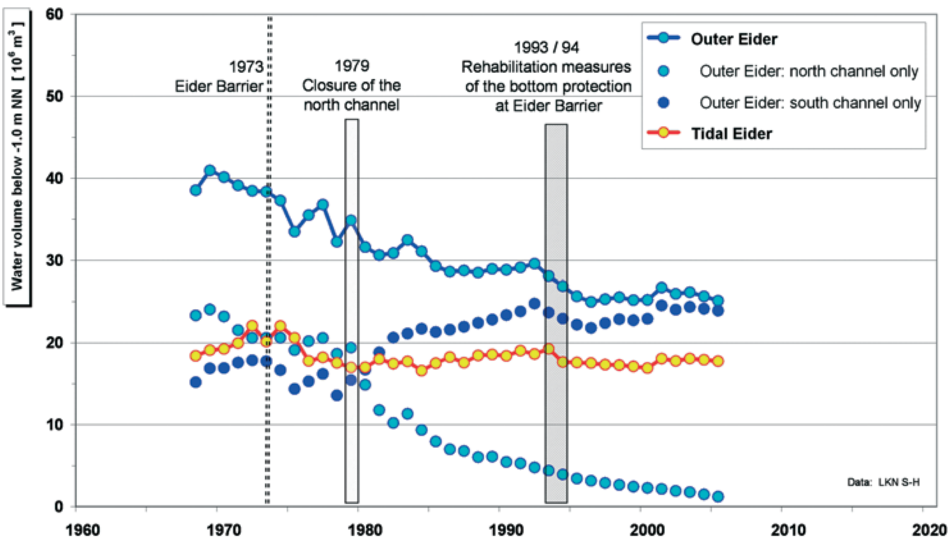


Fig. 4: Historical development of the water volumes of the Outer Eider (to 8 km from the barrage) and the Tidal Eider

veyed due to its vegetation. Given that the channel cross-sections are far narrower than in 1936 and with lowest water levels of only 0.5 to 1.0 m LAT (lowest astronomical tide), navigation is only possible depending on the tide or with tidal control through the Eider Barrier.

The migration of the channel in the Outer Eider did not take place as desired. Even after 1973, the "north channel" with a large cross-section still functioned as the main channel. By comparison, the "south channel" was only weakly developed in places. Neither initial dredging nor intensive flushing through the Eider Barrier brought any noticeable change. With the north channel moving northward towards Eiderstedt's seadike at a recent rate of about 80 m/a, it was decided in 1979 to block the channel by a sand dam which was not overtopped by HW. Since then, the north channel has been sanding up and the south channel has assumed an ebb-dominant shape over a 8–10 km long section starting from the barrage. Compared to former conditions, the channel cross-sections are far smaller, and water depths in the channel bends have been reduced. The outer banks region is located to the south of the tip of Eiderstedt. The morphologically instable region with its recurrent intensive changes from sand migration and repeated breakthroughs in the channel (delta problem) has posed a threat to navigation for more than 200 years. Correlations between the permanent transformation processes and construction measures in the Eider regime have not yet been proven.

## 3. Maintenance Measures in the Eider Estuary

### 3.1 Flushing Operations

Construction of the Eider Barrier in 1973 and damming of the "Eider North Channel" in 1979 were the last major encroachments on nature and landscape for the time being. In the interests of drainage capability and navigation, they were intended to contribute to the preservation or even improvement of the existing conditions of the Eider through special modes of operation of the flood gates in combination with flushing operations at Nordfeld. Neither did these measures result in the desirable optimum conditions of the system nor could the former status-quo be maintained.

The quality of the flushing operations can be judged as follows:

- the two systems "Tidal Eider" and "Outer Eider" have essentially reached an equilibrium with regard to volume constancy
- surveys for traffic safety reveal a trend for further growth of sandbars in the Tidal Eider
- increasing success of flushing operations can be verified in the "Outer Eider".

Up to now it has not been possible to quantitatively show an effect of tidal control on the morphodynamic processes of the Eider.

### 3.2 Dredging Needs and Technology

So far, no need for maintenance or upgrade measures for the improvement of the discharge capability could be substantiated. Neither does the above mentioned maritime traffic situation, based on the directives of the Federal Waterways Act (Bundeswasserstraßengesetz), require any action. No maintenance dredging is carried out in the fairway, although soil is relocated from "silt traps" such as outer harbours of locks or zones of minimal current action downstream of confluences.

Tidal and Outer Eider can only be travelled tide-dependent by vessels with a maximum draught of 2.0 m. Only shallow-draft special vessels are not affected by restrictions.

There is need for regular dredging in the outer harbours of the locks of the Eider Barrier where currents are small. After earlier deployment of hopper or suction dredgers, the water injection method has proved to be best for removing silty material. The water injection method is enhanced by the deep scour holes that have emerged on either side of the flood gates directly outside the harbour entrances. The centre of the inner scour hole is up to 10 m deeper than the maintained depth of the outer harbours while that of the outer scour hole is even extending to more than 25 m. Up to now, the outer harbours have been cleared once a year. Current observations indicate that the intervals will have to be shortened in the foreseeable future.

There is a need for annual dredging downstream of where the outer drains ("outer deeps") empty into the Tidal Eider, which have discharged their water on a natural gradient, so far. This also applies to Tönning harbour and a reach further upstream where, up to now, the deployment of an underwater "hydraulic plough" with air injection has proven practical for removing sediment depositions.

## 4. On-Going Monitoring and Analysis

As part of the 'preservation of evidence' (Beweissicherung) resulting from the construction of the Eider Barrier, the principal and owner of the structure, the federal state of Schleswig-Holstein, is among others responsible for a regular monitoring with

- measurements of water levels above and below the Eider Barrier
- measurements of salinity in the dammed Eider,
- surveys of the shorelines above the Eider dam and
- supplying evidence that the hydraulic storage capacity of the dammed-up Eider is sufficient.

The tasks performed by the responsible institutions are based on measurements made by the state of Schleswig-Holstein together with regular measurements by the Federal Administration of Waterways and Navigation (Wasser- und Schifffahrtsverwaltung – WSV) (water levels/surveys of the fairway). Airborne surveys complete the required surveying task of the state authority.

Within the framework of a regular monitoring of the water quality at selected locations is carried out. In parallel, the Federal Institute for Hydrology (Bundesanstalt für Gewässerkunde – BfG) has been monitoring the estuaries of the Ems, Jade/Weser, Elbe and the Tidal Eider for several years. The regional authority (Wasser- und Schifffahrtsamt – WSA) in Tönning processes water level measurements obtained from tidal gauges. Data are then analyzed with regard to their tidal parameters in the Federal Maritime Agency (Bundesamt für Seeschifffahrt und Hydrography – BSH).

## 5. Conclusions

The entire catchment area, including rivers Treene and Sorge, originally covered around 3,300 km². In a series of construction projects in the interest of coastal protection, drainage capability and navigation, one has interfered with the river regime in a substantial manner. These measures began with the construction of the dykes in the 15th century, including the reorganization of the drainage system and a repeated division of the river, completely separating the upper reaches. In 1973, measures were concluded with the construction of a storm surge barrage.

The experience gained on the Eider was of pioneering importance for other river damming measures in Germany. The concept of completely damming up tidal rivers with only a sluice structure (tidal gate) was renounced; storm surge barrages were erected instead. They prevented the penetration of only extremely high tides or were closed to protect against storm surges.

In 1964, an expert panel predicted that the solution found for the highly complex "Eider problem" would only be provisional. Meanwhile, this verdict has been corroborated by various observations. Nature always reacts to an encroachment on in the river regime. In the case of the Eider, the desired advantages were often gained at the cost of undesirable, strong side effects.

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# The Kiel Canal (Nord-Ostsee-Kanal)

By JÖRG BROCKMANN, ANNE HEELING, MARTIN POHL and KLEMENS ULICZKA

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## 1. Introduction

The Kiel Canal (in German: Nord-Ostsee-Kanal, NOK) connects the Elbe estuary at Brunsbüttel with the Kiel Bight over a length of 98.64 km (53.3 nm). Thereby, it represents a direct connection between North and Baltic Sea. Cutting across the so-called 'Cimbric Peninsula' – consisting of the Danish Jutland and the German Schleswig-Holstein – the over-water route from Brunsbüttel to Kiel as compared to the Skagerrak-passage is reduced by approx. 960 km (520 nm; Fig. 1).

The NOK is the most frequented artificial waterway of the world. In addition to its importance as an international sea route – and, therefore, as an impulse to the economic centres Brunsbüttel, Rendsburg and Kiel – the so-called 'highway of dream boats' lures scores of tourists throughout the year who are offered a multitude of recreational activities. From the point of the regional economy, the canal is the basis for direct employment of approx. 2,500 people.

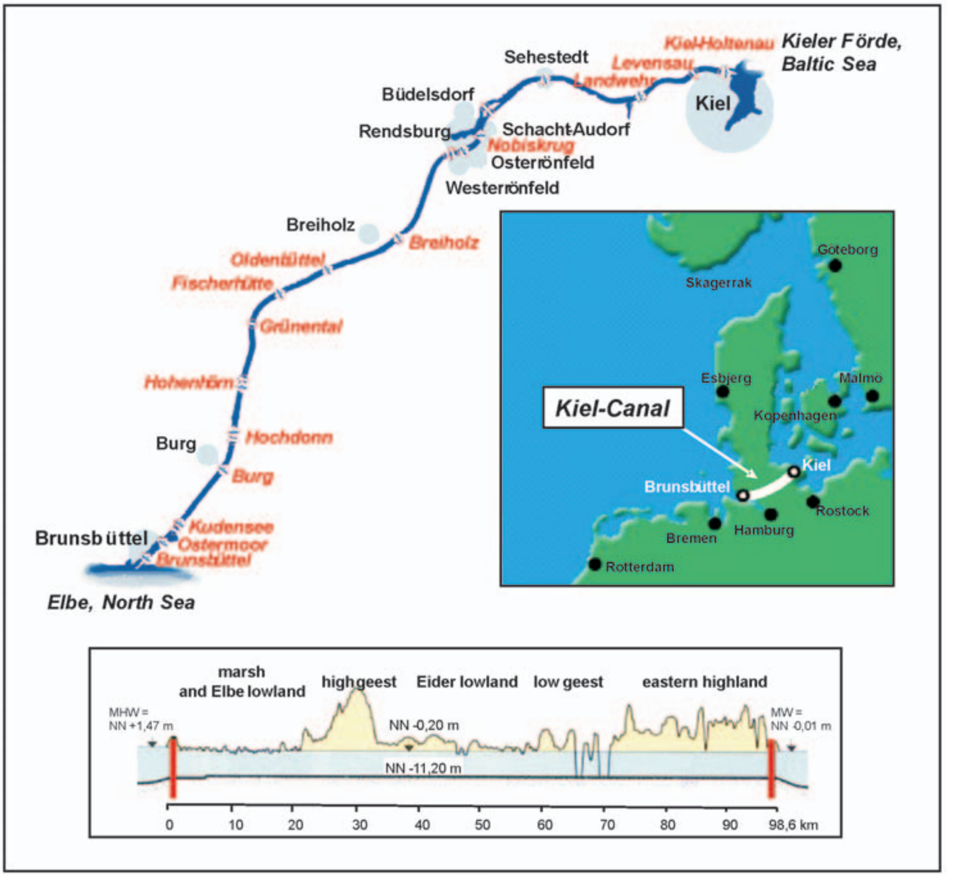



Fig. 1: The Kiel Canal (Kiel-Canal, 2008; TAG NOK, 2008; WSA Brunsbüttel, 2008a and WSA Kiel-Holtenau, 2008)

## 2. History

*„Great ventures are not the result of the moment , …. and thus, the NOK has its own history.“ („Große Unternehmungen sind nicht das Produkt des Augenblickes, und … so hat auch der Nord-Ostsee-Kanal seine Geschichte.“*; Beseke, 1893):

The motivation for building an artificial waterway between North and Baltic Sea can be found in the abridgement of the passage and the resulting time savings. Consequently, the transport of perishable goods was made possible. Nowadays, fuel savings and the reduction of ensuing $CO_2$ emissions present an equal incentive. On the other hand, in the 19$^{th}$ century the sea passage around Jutland was considered particularly prone to accidents and disasters. For example, the Jammerbucht *('Bay of Misery')* in the Northwest of Denmark owes its name to this fact. Already in the 7$^{th}$ century, the first plans were made to connect the Viking settlement of Haithabu at the Schlei fjord with the North Sea by a canal. These plans, however, were not realized.

In 1784, the Schleswig-Holstein-Canal (from 1853: "Eider Canal") was officially ope-

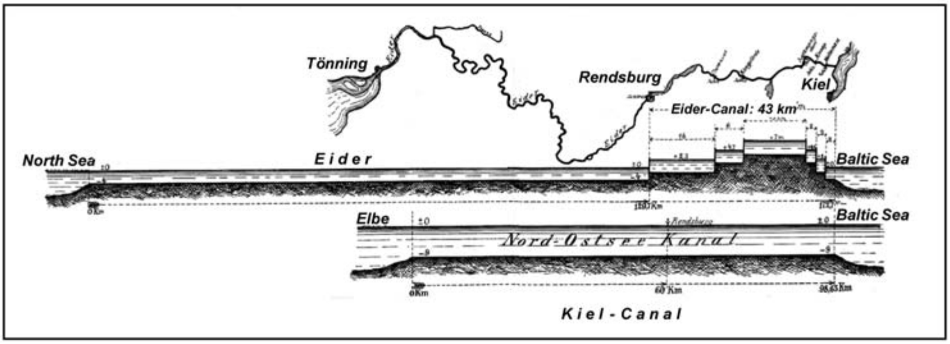



Fig. 2: Comparison Eider Canal / Kiel Canal (after BESEKE, 1893)

ned. The canal of a length of 43 km had been commissioned by the Danish King Christian VII. and joined Kiel at the Baltic Sea with the river Eider. It matches the eastern stretch of the present NOK.

Around 1850, the Eider Canal with a width of 18 m and a depth of 3.45 m could no longer satisfy the demands of a growing marine traffic. Travel times of 3 to 4 days needed for hauling the boats by horses on the trip of 180 km between Kiel (Baltic Sea) and Tönning (North Sea) became increasingly uneconomical.

More and more military aspects in connection with the canal were considered: first plans for a new canal were commissioned by Bismarck in 1864. The German fleet was to be capable to change its station from the Baltic Sea to the North Sea without *'having to pass under Danish canons'*. However, in 1873, these plans fell through due to the opposition of the generals Moltke and von Roon who preferred separate naval forces both in the North and Baltic Sea. Moreover, the question of who was absorbing the costs could not be solved.

In 1878, due to an initiative of the Hamburg shipowner Dahlström and the waterways engineer Boden investigations towards an optimized canal route were carried out. Ultimately, these investigations resulted in passing the Bismarck *'law for the construction of the canal'* in 1886.

This cleared the road towards building the NOK: on June 3, 1887, groundbreaking of the canal was carried out by Emperor Wilhelm I. in Kiel-Holtenau. Up to 8,900 workers were employed during the construction of the largest civil engineering works at the time. Floating bucket dredgers and a lorry railway system were developed especially for the canal construction in order to enable overall earth moving works of approx. 80 Mio. $m^3$.

Contrary to its predecessor, the Eider Canal, the NOK is a breakthrough waterway without level differences (Fig. 2). Hence, locks at both ends at Brunsbüttel and Kiel-Holtenau were only necessary to compensate for water level variations. The following crossings were built:

- a road and railway bridge each at Grünental and Levensau,
- two railway bridges and a road swing bridge at Rendsburg,
- a railway swing bridge at Kudensee and
- a floating pontoon bridge at Kiel-Holtenau
- as well as 16 manually operated cable ferries.

At that time, the minimum size and carrying capacity of a ferry was designed to accommodate a four-in-hand hearse and the mourners.

After a construction period of 8 years and costs of approx. 156 Mio. Goldmarks (which was within the planned investment) the canal was officially opened by Emperor Wilhelm II. on June 20, 1895. To the surprise of the invited guests, the canal was christened "Kaiser-Wilhelm-Kanal"; the originally intended German name "Nord-Ostsee-Kanal – NOK" was only adopted in 1948.

Already after the first ten years of its operation – at that time vessel dimensions were at a length of up to 135 m, a width of up to 20 m and a draft of up to 8 m – the canal proved to be too small and the passage time of 13 hours too long. After the improvements of the canal bed of 1914 and 1966 (cf. 3.1.1) the passage takes only 8 hours today.

## 3. Development of Maritime Traffic

### 3.1 Classification of Vessel Groups

The Maritime Waterways Code (Seeschifffahrtsstraßen-Ordnung – SeeSchStrO) and the concerning regular announcements of the Directorate of Waterways and Navigation (Wasser- und Schifffahrtsdirektion, WSD) North include the traffic regulations for the NOK.

In September 2006, a new computer-aided system for traffic guidance and safety (VSS-NOK) was introduced. Under a round-the-clock surveillance of the maritime traffic by an AIS (= Automatic Identification System) traffic is piloted by the nautical employees of the VSS on the basis of the sidings (lay-bys) along the canal.

Ships with a length of up to 235 m and a width of up to 32.5 m can pass the canal. For traffic regulation, they are classified and put into six groups according to their size (VG 1–VG 6; Tab. 1).

Table 1: Classification of vessel groups (VG) for NOK (WSA Brunsbüttel, 2008)

| VG | Vessel/Push tow | | | Barge train | | |
|---|---|---|---|---|---|---|
| | length up to | width up to | draught up to | length up to | width up to | draught up to |
| 1 | 45 m | 9.5 m | 3.1 m | 40 m | 10 m | 3.1 m |
| | 55 m | 8.5 m | 3.1 m | | | |
| 2 | 65 m | 13 m | 3.7 m | 60 m | 13.5 m | 3.7 m |
| | 85 m | 11 m | 3.7 m | | | |
| 3 | 120 m | 19 m | 6.1 m | 110 m | 19 m | 6.1 m |
| | 140 m | 17 m | 6.1 m | | | |
| 4 | 130 m | 23 m | 9.5 m | 130 m | 23 m | 6.1 m |
| | 160 m | 20 m | 9.5 m | | | |
| 5 | 200 m | 25 m | table | 160 m | 27 m | 9.5 m |
| | 210 m | 27 m | table | | | |
| 6 | 235 m | 32.5 m | table | approved extreme barge trains | | |

Vessels without pilot support and a speed of less than 15 km/h may pass only during the day. Pleasure craft have to find a moorage before the end of daylight operation time.

### 3.2 Traffic Statistics

The NOK is the most frequented artificial waterway of the world: Without pleasure craft and other small ships, 114 vessels/day passed the NOK in 2006.

Fig. 3 shows the total number of ships and their payload for the years between 1996 and 2006. While the number of passages is fluctuating the payload increases distinctly.

A new payload record of almost 100 Mio. tons was reached in 2007 and showed the following statistics: 99,600,730 tons were transported in transit through NOK and on partial routes. Another record was the number of passages of 43,231 vessels. This number had been reached the last time in 1995. A specially high increase of 5.7 % could be noted for the transit traffic.

Even though the classification into traffic groups was changed during 2007, a distinct increase particularly for the groups 4 to 6 of larger vessels can be seen: In the comparison between 2007 and 2006, the number of largest vessels of the group 6 rose by 7 % to 264. In the future, this positive trend will be held and increased by the scheduled widening of the eastern reach (cf. 3.1.2) which will improve the possibilities of traffic encounter on the range, reduce waiting time in the sidings and, thereby, the passage time, too (WSA Brunsbüttel, 2008).

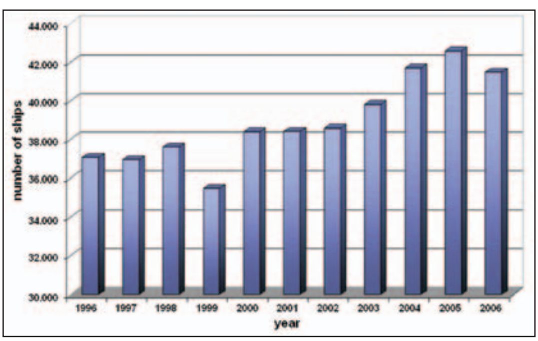
## 4. Structural Measures for Adaptation

### 4.1 Improvement of the Canal Bed

#### 4.1.1 Present Status

Responsibility for the NOK lies with the WSD North and its regional authorities (Waterways and Shipping Board, in German: Wasser- und Schifffahrtsamt, WSA) Brunsbüttel (west of km 49.46) and Kiel-Holtenau (east of km 49.46). Both regional authorities plan and carry out maintenance and improvement measures following the principle of 'ease and safety of maritime traffic'.

Between 1907 and 1914, the first deepening and widening of the original canal bed required approx. 242 Mio. Goldmarks and, thereby exceeded the cost of the original canal by far. However, this resulted in a reduction of the passage time from 13 to 10 hours.



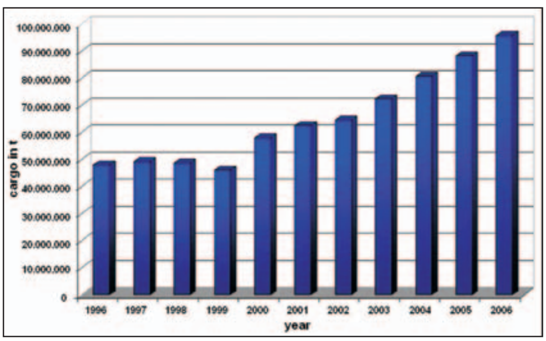




Fig. 3: Total number of ships and their payload during the years from 1996 to 2006 (Kiel Canal, 2008)

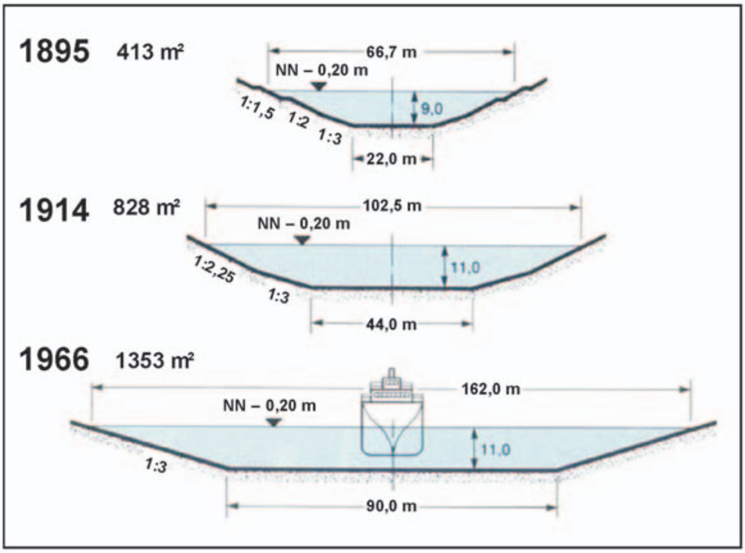



Fig. 4 Development of the cross-section of the canal (WSA BRUNSBÜTTEL, 2008)

Since 1966 the canal has been successively improved; construction measures west of km 79 are already completed.

Previous improvement works on the canal bed are carried out to:

- enhance the stability of the embankments by establishing an overall slope of 1:3 for minimization of slope erosion,
- enhance the alignment by straightening and/or increasing the radii of curves (1914: breakthrough at Rade) and, thereby guarantee the 'ease and safety of maritime traffic',
- enlarge cross-sections to permit the passage of larger vessels.

Within the framework of improvement measures, the canal was widened by almost 100 m and deepened by 2 m compared to its original dimensions. Bottom width has been more than quadrupled and, consequently, the cross-section more than tripled. Fig. 4 depicts the development of the NOK cross-section from its inauguration in 1895 to the present status as of 1966.

#### 4.1.2 Scheduled Improvement of the Eastern Range

As a consequence of the increase in shipping traffic and the modification of the fleet structure on the Kiel Canal, the narrow curves and the reduced cross-sectional width of the 1914s between Königsförde and Kiel-Holtenau in the eastern range (NOK-km 80–96) increasingly prove to be a bottleneck to the traffic flow. Detailed preliminary investigations have led to the choice of an improvement variant which shows the best possible benefit for maritime traffic together with a minimum encroachment on nature and landscape.

The adaptation works are divided into two sections (Fig. 5). In the first section (■) the curves at Landwehr and Wittenbek as well as the transition to the passing place at Schwartenbek are to be opened up. The piers of the Landwehr ferry are repositioned and renewed. The second section (■) includes the straight stretch Königsförde, the curve 'Groß-Nordsee' and the reach of the high bridges at Levensau.

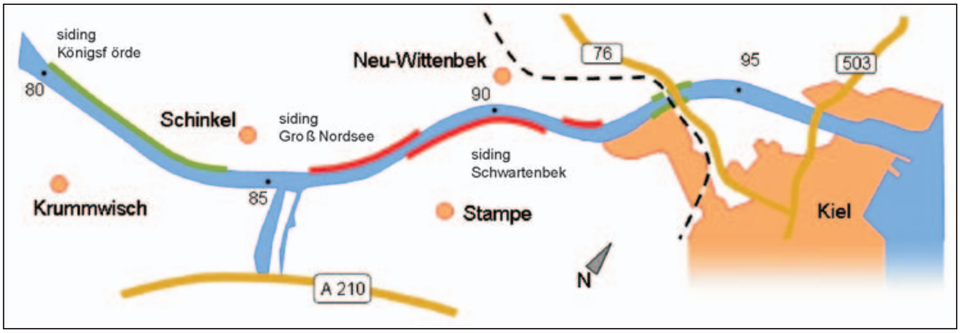



Fig. 5: Schematics of the eastern reaches to be improved (WSA KIEL-HOLTENAU, 2008)

By digging off the insides of the curves and widening the straight reach at Königsförde the bottom width is increased to 70 m with a water depth of 11 m. This new cross-section permits the passage of larger and deeper-drawing vessels. Altogether, earth movements are in the order of 8.5 Mio. $m^3$.

Presently, vessels with dimensions of (length, width, draft in [m]) 235/32.5/7.0 resp. 175/24.0/9.5 can navigate the NOK. Future dimensions will be 280/32,5/9,5. The project will be completed in 2014.

### 4.2 Structures

The locks in Brunsbüttel and Kiel-Holtenau are the access structures to the NOK. Nowadays, a road and a pedestrian tunnel (both at Rendsburg), four elevated highway and two railway bridges, two elevated combined road-rail bridges, two motorway (Autobahn) bridges as well as 13 freely operating ferries and a suspended ferry permit the crossing of the NOK. Due to a decree of the Emperor Wilhelm all crossings are free of charge.

#### 4.2.1 Locks

In 1914, during the first expansion of the NOK two 'new' large locks were constructed to the existing 'old' Wilhelminian-style locks at Brunsbüttel and Kiel-Holtenau. These access structures designed as double-locks are almost identical concerning their characteristic dimensions (Table 2).

Table 2: Characteristica of the locks (KIEL-CANAL, 2008)

| | Small (Old) Locks, 1895 | Large (New)Locks, 1914 |
|---|---|---|
| Effective length: | 125 m | 310 m |
| Effective width: | 22 m | 42 m |
| Sill elevation: | Brunsbüttel: NN –10.2 m<br>Kiel-Holtenau: NN –9.8 m | NN –14.0 m |
| Lock gates: | per chamber:<br>2 ebb- und 2 flood mitring gates | per chamber: 3 sliding gates;<br>the centre gate (doubles as a reserve gate) allows for a faster operation in a shorter chamber |
| Filling procedure: | by 2 side channels with 12 branches each | Brunsbüttel: by recirculation flow through gates<br>Kiel-Holtenau:<br>by two side channels with<br>29 branches each |
| Passage time: | 30 minutes | 45 minutes |

Based on the water level in the canal (NN –0.20 m) and the average tidal elevation of the North Sea (NN +1.47 m) or the mean water level of the Baltic Sea an average lifting range of approx. 1.7 m (Brunsbüttel) and 0.2 m (Kiel-Holtenau) results. Due to the different geological situation at both locations the foundations of the locks are designed differently (Fig. 6 and Fig. 10):

- Brunsbüttel (marsh): the Small (Old) Lock have a foundation floating in the sand-layered marsh soil. The load of the chamber walls of the Large (New) Lock, designed as gravity structures, are carried into the sustainable Pleistocene sandy subsoil by piles at about NN –20 m. The heads are built on shallow foundations on the Pleistocene sand.
- Kiel-Holtenau (eastern highlands): both lock foundations are built on a varying layering of sustainable till and sand.

The age of the Large (New) Lock at Brunsbüttel as well as disruptions of operations require a basic overhaul. A cost-benefit-analysis showed that the highest value of benefit would be obtained through an accelerated new construction of a lock on the sluice-island (‘5$^{th}$ chamber’, Fig. 7) and the consecutive overhaul of the existing lock. Presently, the new structure is being planned to avoid an interference with traffic flow by the overhaul of the Large (New) Lock.

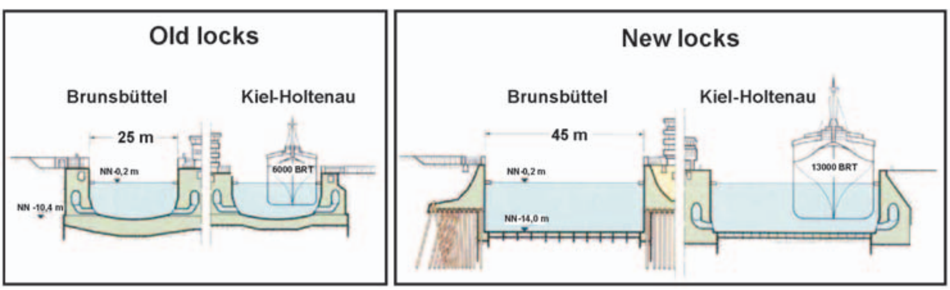



Fig. 6: Cross-section of the lock structures (WSA BRUNSBÜTTEL, 2008)

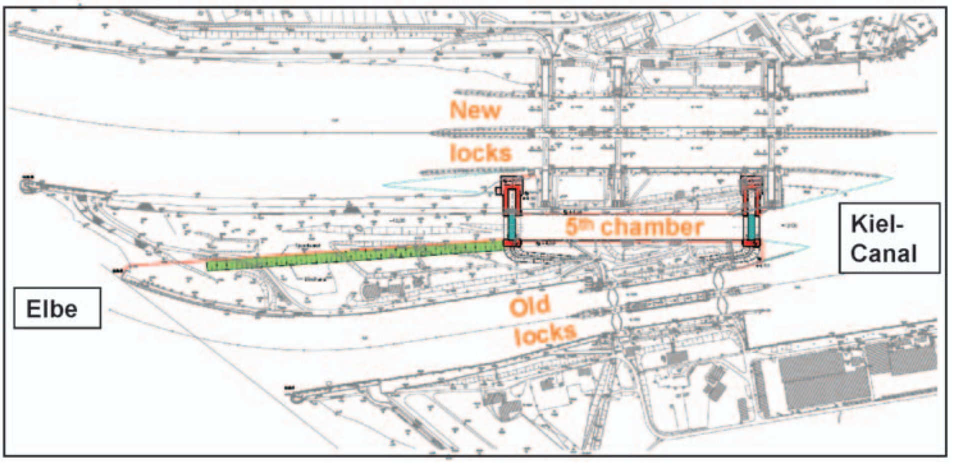



Fig. 7: Planned location for the 5th chamber (WSA BRUNSBÜTTEL, 2008)

In the projected construction area the present power supply of the locks exists. This has to be relocated before construction begins. For that purpose, a new culvert for pipes and cables, having a walkable cross-section of an inner diameter of 2.2 m, has to be driven underneath both locks at a depth of approx. NN –31 m.

### 4.2.2 Bridges

Together with the construction of the NOK two elevated compact railway and road bridges at Grünental and Levensau were built in the first instance. Today, ten solid bridges with a guaranteed clearance for vessels of 42 m span the canal. The following table compiles the technical specifications of the bridges:

Table 3: Bridges across the NOK (WSA BRUNSBÜTTEL, 2008)

| Structure | NOK-km | Length [m] | Steel used [to] | Year of construction |
|---|---|---|---|---|
| Elevated road bridge Brunsbüttel | 6.123 | 2,826 | 5,000 | 1979/83 |
| Elevated railway bridge Hochdonn | 18.778 | 2,218 | 14,900 | 1915/20 |
| Elevated motorway bridge Hohenhörn | 24.882 | 390 | 4,200 | 1985/89 |
| Elev. railway/road bridge Grünental | 31.115 | 405 | 3,600 | 1983/86 |
| Elev. railway bridge Rendsburg | 62.664 | 2,486 | 17,740 | 1911/13 |
| Elev. motorway bridge Rade | 68.114 | 1,498 | 14,020 | 1969/72 |
| 1. Elev. railway/road bridge Levensau | 93.478 | 180 | 2,600 | 1893/94 |
| 2. Elev. road bridge Levensau | 93.581 | 365 | 4,310 | 1980/83 |
| 1. Elev. road bridge Holtenau | 96.589 | 445 | 3,650 | 1992/95 |
| 2. Elev. road bridge Holtenau | 96.623 | 518 | 3,380 | 1969/72 |

Fig. 8: Elevated railway bridge (STADT RENDSBURG, 2008)

The elevated railway bridge at Rendsburg (Fig. 8), built in 1913, was the largest steel construction in Europe at that time; it replaced the original railway swing bridge. Simultaneously, the framework construction of the elevated bridge served as the carrying base for a suspended ferry, which is unique in Germany and under protection as a historical monument.

In the abutments of the first elevated bridge at Levensau (arch bridge) an overall of approx. 6,000 bats hibernate. This makes the bridge the most important wintering grounds of the noctule bat ("Großer Abendsegler") in Central Europe.

### 4.2.3 Tunnels

The increase in maritime and road traffic and the ensuing long waiting periods at the road swing bridge at Rendsburg necessitated its replacement by two tunnels:

The road tunnel Rendsburg was built between 1957 and 1961 and carries the highway B 77. With a closed tunnel reach of 640 m, its overall length is 1,278 m. In its lowest point, the upper edge of the tunnel is at NN –14.55 m, approx. 1.5 m below the canal bed.

The pedestrian tunnel Rendsburg (Fig. 9, cf. 6.3) was built between 1962 and 1965. With an inner diameter of 4.5 m, it is 130 m long. The peak of the top edge of the structure is at NN –17.1 m. Access to the tunnel is provided by cascade-shaped caissons housing in addition to an elevator, one of the longest escalators in Europe (55.9 m).

## 5. Maintenance of the Navigation Channel

The amount of sediments entering NOK from outside through the locks at Brunsbüttel and Kiel-Holtenau or via affluents is negligibly small. Settled material comes nearly exclusively from erosion of the slopes. Because of this, the embankments of the western range, where sandy material prevails, have been regarded to a consistent slope of 1:3. Under maintenance aspects, reconstruction of the relatively stable till slopes of the eastern range could be deferred for the time being.

Noteworthy maintenance dredging works concentrate on the western access of the canal: In the outer and inner harbour basins and in the locks at Brunsbüttel between 6.0 and 7.6 Mio. m³ of a watery mud were dredged annually between 1998 and 2006.

In comparison, only between 0.008 and 0.3 Mio m³/a dredged spoils were removed from the outer harbours and the locks at Kiel as well as from the entire canal reach during the same period, predominantly from the western range.

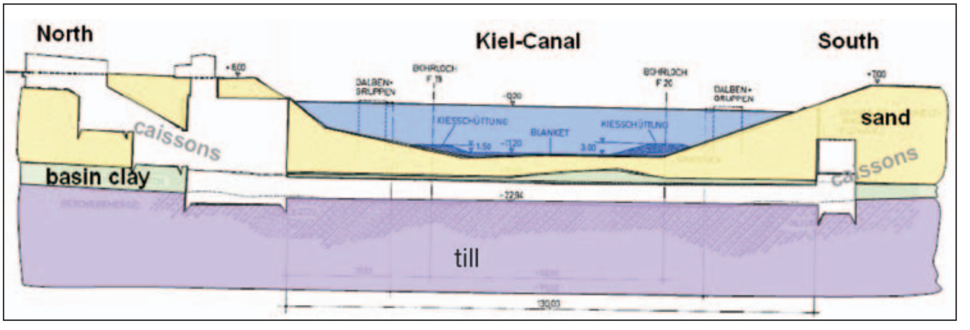



Fig. 9: Longitudinal cross-section of subsoil conditions at the Pedestrian Tunnel Rendsburg (BAW, 2007)

## 6. Monitoring and Analysis of the Canal System

### 6.1 Geotechnical Survey for the Improvement Measures

The geological structure of the upper layers along the canal is dominated by glacial and post-glacial processes (Fig. 10).

While in the West non-cohesive sediments (sand) prevail the East is characterized by cohesive material (till):

- The oldest sediments in the West – sands and till of the Saale glaciation at the high geest – were eroded by melt water and only loom like islands in the surrounding post-glacial marshes and river lowlands composed of marsh soil and sand.
- The eastern highlands consists of moraines from the Weichsel glaciation: during this latest glaciation period in Northern Germany, Scandinavian glaciers coming from Northeast advanced till east of Rendsburg, scratched out the Kiel Bight and dumped till.
- In front of this glacier barrier and because of the melt water, the lower geest and its sand and gravel developed. Locally, glacial basin sediments such as fine sand, silt and clay can be found.
- During the excavation of the canal bed, naturally occurring layers of soil were removed and used for the embankment dams.

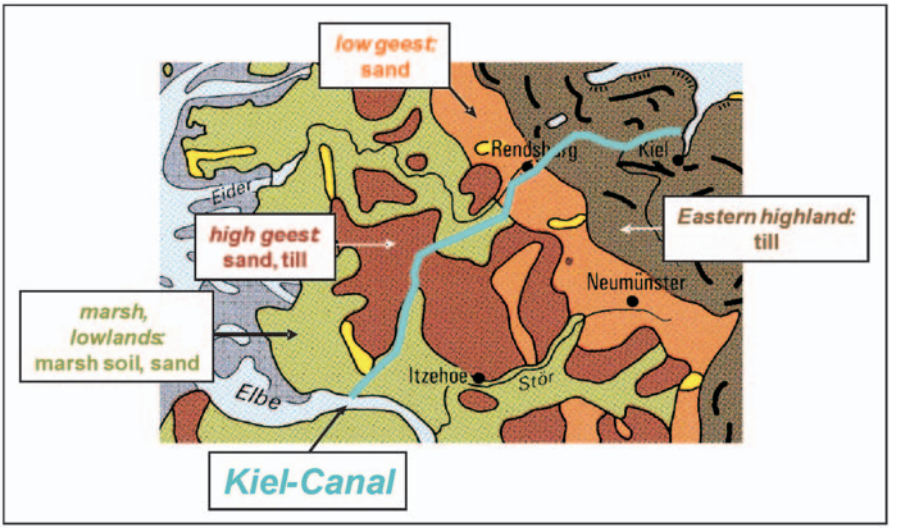



Fig. 10: Geological structure of the region around the NOK (after SCHMIDTKE, 2007)

The main intention of geological surveys lies in the specification of the generally known stratigraphic sequence and in the analysis and description of the geotechnical properties of the sediments according to the actual questions (investigation of stability of crossing structures and slopes, planning of earth moving works, preservation of evidence for project approval procedures etc.).

### 6.2 Erosion Stability in the Western Range

Natural and lock-induced currents have no detrimental effect on sediment movement. However, ship-generated waves can cause erosion on embankments, particularly in the western range with its sandy sediments. Therefore, in view of the future evolution of maritime traffic, the Federal Waterways Engineering and Research Institute (Bundesanstalt für Wasserbau, BAW) carried out hydraulic model and field investigations to determine the hydrodynamic ship-generated loads and the erosion stability of canal embankments and bed (BAW, 1998; BAW, 1999).

#### 6.2.1 Hydrodynamic Investigations

Hydraulic model investigations towards the interaction vessel-canal were carried out by BAW on the basis of Froude's model laws at a scale of 1 : 33.3, resulting in design data (drawdown, return current, squat and change of bed pore pressure). Fig. 11 shows an example of the ship-induced drawdown generated by two-way traffic.

In addition, based on a cooperation with the WSA Brunsbüttel field measurements were carried out and were compared with prognoses generated by SOCIETE GRENOBLOISE D'ETUDES ET D' APPLICATIONS HYDRAULIQUES (SOGREAH, 1966), as follows:

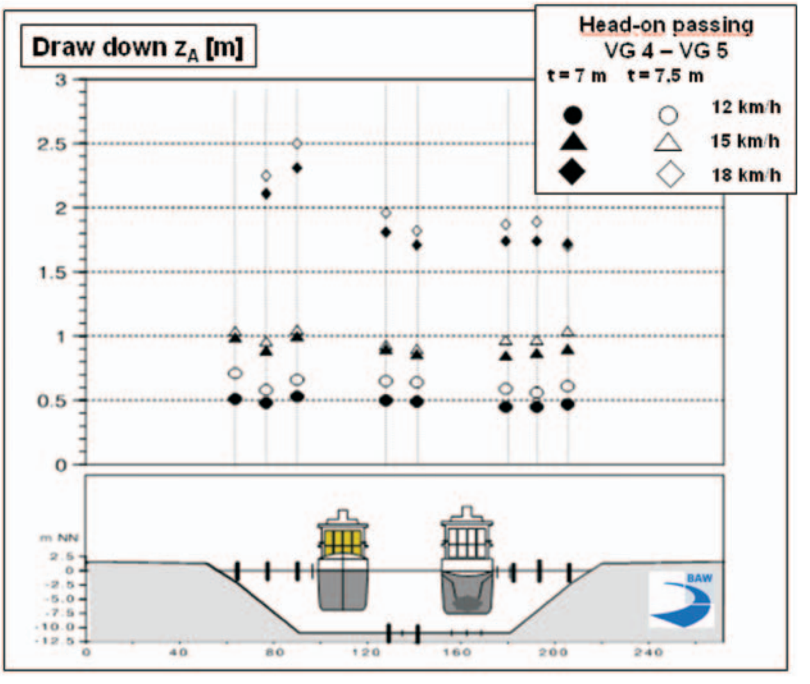



Fig. 11: Exemplary ship-induced drawdown load at two-way traffic VG 4–VG 5 in a monitored cross-section of the western range of NOK (BAW, 1998)

- Measurements of the hydrodynamic ship-induced load and of the pore pressure on the underwater embankment of a stretch at Hohenhörn which is susceptible to erosion.
- 2D-echosounding in the Hohenhörn stretch; comparison of results with the standard dimensions of the cross-section.

For 535 analyzed ship passages, drawdown events of $z_A < 0.4$ m and return currents of $v_R < 0.6$ m/s were recorded. Maximum values in the centre channel came up to $z_A = 1.66$ m and $v_R = 2.14$ m/s. There was a satisfactory agreement between field investigations and model tests.

Results also pointed at the necessity of systematic hydraulic model tests for a prognosis of ship-induced loads – even in a quasi-homogenous waterway such as the NOK.

Based on model results, the utilization of characteristic diagrams of draft- and speed-dependent ship travel for various traffic groups, travel outside the centre line, two-way, parallel and passing traffic has been supported by field measurements.

### 6.2.2 Measurements of Pore-Water Pressures

During the hydrodynamic investigations, in a stretch at Hohenhörn pore-water pressure measurements on the underwater-embankments and the canal bed were carried out.

The parameter pore-water pressure is of major importance for the stability and safety against erosion of the embankment slopes. Due to the comparatively high permeability of the local medium sand, pore-water pressure values are relatively small when measured at various elevations during the passage of a vessel. Still, for the worst case and for the duration of the drawdown, the net weight of the soil is reduced by up to 20 % due to the current load resulting from the pore-water pressures.

The determination of the pore-water pressure parameter *b* solely on the grounds of the hitherto knowledge derived from inland waterways would have resulted in an overestimation of its value. Thus, the stability of the NOK embankment slopes would have been underestimated. As a consequence, a proof of stability can presently only be produced on the basis of actually measured pore-water pressures.

Findings from these field investigations lead to the conclusion that – already nowadays – due to the increased traffic load and in passing traffic situation in stretches with weak cohesive soil the required stability during the entire event of a drawdown doesn't exists. These events can lead to grain-relocation in the slopes favouring an erosion which is already triggered by return currents during such passages.

The evaluation of the present erosion behaviour of the underwater embankments in the western range of NOK must be based – in addition to the knowledge of the present status – on the consideration of the various development stages of the unprotected underwater slopes. Since expansion activities have modified the state of the unprotected slopes and the hull shapes of ships and the ship-induced loads have changed as well during the 1960s, a calculation of erosion rates can no longer be carried out based on the erosion diagrams published by SOGREAH (1966). Thus, BAW recommended to the WSV that permanent monitoring and evaluation of the conditions of underwater slopes and canal bed under varying loads should be be carried out.

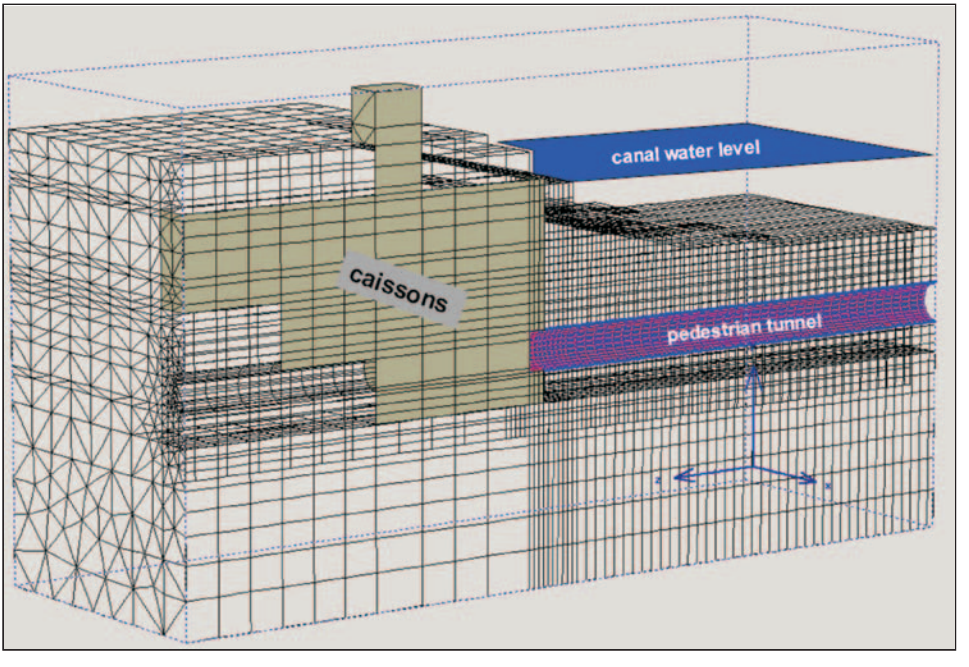



Fig. 12: Numerical quarter-model of the Rendsburg pedestrian tunnel (BAW, 2007)

### 6.3 Pedestrian Tunnel Rendsburg

After completion of the pedestrian tunnel at Rendsburg the time-settlement of the tunnel structure (cf. 3.2.3) have been measured and recorded. While the head structures, built as caissons, settle the tunnel under the canal bed heaves. The internal forces and the static exploitation of the tunnel were, therefore, investigated with a 3-D Finite Element Model (Fig. 12).

The numerical simulation was carried out for the various phases of the construction focussing on the excavation lengths, the materials used and the air pressure in the tunnel. Soil layers were reproduced by applying a constitutive law which considers volume and shear straining. Creep in the cohesive soil layers was simulated by an incremental reduction in stiffness since laboratory data of time-settlement curves of the cohesive soil layers (till and glacial basin clay) did not exist. Thus, the deformation behaviour over the past till present could be reproduced quite well.

The numerical calculations showed that the tunnel excavation governs the internal forces. The present deformations due to the tunnel's lifetime result in modified internal forces and their distribution leading to an additional stressing. This is true for the normal forces in tunnel length direction, the transverse (shear) forces in the cross-section and the bending moments due to bending around the tunnel length axis.

In-situ measurements of stresses at the cast-iron tubbings confirm the internal forces obtained through the numerical simulations. Moreover, results from both methods permit to conclude on residual stress due to the manufacturing process in the cast-iron tubbings.

More simulations with reduced stiffness serve to predict admissible deformations which would not endanger the stability and/or usability of the tunnel.

## 7. Conclusions

The Kiel Canal is the second gateway to the Baltic Sea. Being in direct competition to the Skagen route, it has served national and international navigation for more than 100 years. As part of the Trans-European traffic network it substantially helps to relieve the overland traffic that moves fast towards its capacity limits.

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# Access Routes to Baltic Sea Ports

By ANNETTE ERNST, HERWIG NÖTHEL and HOLGER RAHLF

Contents



## 1. Introduction

Due to the growing demands of maritime traffic, access channels to the German sea ports along the Baltic coast have been changing during the last centuries. A historic review particularly highlights the development of the 'Hanseatic League', a free federation of merchants dating back to the middle of the $12^{th}$ century. Members were cooperating according to self-imposed rules and privileges in foreign trade with the intention of improving safety during dangerous sea voyages using the protection convoys allowed.

Even today, natural water depths in the fjords and bays of Schleswig-Holstein are sufficient for ships calling on ports such as Kiel and to the entrance of the Kiel Canal. Access channels to Lübeck and other ports, located further east along the coasts of Mecklenburg-Vorpommern, had to be artificially deepened quite early. The existing water depths were not sufficient for modern harbour requirements. Due to the littoral drift – typical for coastlines in equilibrium – moles and breakwaters had to be constructed to protect harbour entrances and mouths of navigable rivers from the beginning, e.g. at Travemünde or Warnemünde.

Hydrodynamic processes in the access channels are governed by baroclinic processes and meteorologically induced water level variations of the Baltic Sea. Tidal influence is negligible. Thus, under normal weather conditions, water level variations along the coast are in the order of centimetres to a few decimetres. They can, however, cause compensatory currents in the access channels with a possible change of direction more than once a day. Storm surges, in the Baltic frequently called 'storm high water', are frequently connected with low water levels due to the 'seiches' (Eigenschwingungen) of the Baltic Sea.

Current velocities of more than 1 m/s in the access channels occur only with steep gradients of the water level whereas currents velocities of a few dm/s are more frequent.

Because of the low salinity of the water, a relatively small freshwater discharge and compensatory currents, no distinct brackish water zone can develop. During long calm weather periods, thermohaline stratification in the water body can persist over several days, sometimes even for weeks.

Sedimentation processes in the access channels are dominated by the littoral drift ( e.g. at Warnemünde) and partly by fluvial deposits (e.g. Trave). However, as a rule of thumb, maintenance dredging does not have to be carried out every year. In comparison to access channels in estuaries at the North Sea coast, dredged volumes are lower by an order of magnitude.

Because of the continental climate in the East, access channels at the Vorpommern coast can ice up during cold winters.

## 2. Geomorphology

An area of 415,266 km² (including Kattegat), an average depth of approx. 52 m and a volume of ca. 22,000 km³ make the Baltic Sea a small intra-continental marginal sea of the Atlantic ocean (HUPFER, HARFF, STERR and STIGGE, 2003). It is connected with the North Sea by the waterways/straits of 'Öresund', 'Great Belt' and 'Little Belt' via 'Kattegat' and 'Skagerrak' as well as through the Kiel Canal.

The German coastline in the South-west of the Baltic Sea has a length of 2,582 km, 637 km of which are part of the federal state of Schleswig-Holstein while 1,945 km belong to Mecklenburg-Vorpommern. For 1,568 km, coastal lagoons line the inner shores.

The geological and geo-morphological development of the German Baltic Sea coast has been described by KLIEWE, LEMKE, JANKE and NIEDERMEYER in KATZUNG (2004). As the result of the multiple progression and recession of the Nordic inland ice during the cold epochs of the Pleistocene, this area of the German Baltic coast is entirely covered by quaternary sediments. Only on the island of Rügen, a furrow slice of Cretaceous chipped from the pre-quaternary substrate, surfaced. Eustatically rising mean sea levels during warm periods of the Pleistocene and post-glaciation as well as epirogenetic subsidence and isostatic uplift had an influence on the course of the coastlines.

The last glaciers during the late Weichsel glaciation left a structured landscape with basins and sills, formed by till and boulder clay. During the late and post-glacial period of the transgression, first of all, the deep depressions of this till surface, such as the Mecklenburg Bay and the Arkona Basin were filled. Only with the faster water level rise during the initial Litorina-Transgression (1st main phase from 7,900 to 7,200 a B.P.) a considerable abrasion in the flooded regions occurred. This led, in connection with an increased bio-production in the water body and continually evolving hydrographical peculiarities of a thermohaline stratified marginal sea of the moderate northern latitude, to an increased sedimentation of silt. Silt was not only deposited in the deeper parts of the Mecklenburg Bay and Arkona Basin but also in the coastal lagoons. In regions of strongly structured coastlines with bays, in former near shore channels, river mouths and inlets, a fairly consolidated silt-clayey, brown to black-coloured organogenic still water sediment, rich with molluscs, was deposited (Litorina-clay/ Litorina mud).

In the shallower near shore areas, i.e. along basin banks and on the sills between the deeper basins, the sediment regime is determined by transport and erosion processes until today. Consequently, one finds boulder clay or sand, washed out from it, in the sediment surface layer. While till 2,000 B.P., during the 2nd and 3rd main phase of the Litorina transgression and intermittent phases of stagnancy and regression, the mean sea level rise in the Baltic Sea slowed down the build-up of baymouth bars and spits accelerated.

During the last two thousand years after the Litorina transgression, the processes of coastline adaptation intensified. They resulted in a permanent recession of the outer coastline by the levelling of cliffs, an increasing closure of coastal lagoon inlets by bars and spits and a parallel development of coastal dune systems. The German Baltic Sea coast is characterized by this sometimes abrupt changeover between cliffs and beaches.

Due to the westerly winds prevailing in the northern hemisphere, transport processes in the south-western Baltic Sea are shaped by currents from West to East. However, coastal recession is more distinctly induced by short-term rare meteorological/hydrological events triggering storm surges with extreme water levels and wave energy input. With regard to these dynamic geo-morphological processes, the German Baltic coast can be classified into the following regions, viewed from West to East (Fig. 1):

- Coastal fjords (Fördenküste) from Eastern Jutland to Kiel,
- large bays (Großbuchtenküste) from ‘Probstei’ (Holstein) to the tip of ‘Buk’ east of Wismar (Mecklenburg),
- the Mecklenburg ‘equilibrium coast’ to the peninsula of ‘Fischland-Darß’ with the in-between coastal fjords near Rostock,
- the equilibrium coastlines of ‘Vorpommern’ with longer spits and coastal lagoons (Bodden/Haffs) reaching to the Oder mouth.


Fig. 1: Morphological units along the German Baltic Sea Coast
(after KLIEWE and SCHWARZER, 2002)

## 3. Hydrology

The eastern basins of the intra-continental marginal sea ‘Baltic Sea’ are connected to the Kattegat in the eastern part of the North Sea by a relatively shallow passage (e.g. the Belt Sea has maximum water depths of 25 m).

Because of compensating currents between North and Baltic Sea, the permanent freshwater discharge into the Baltic and the almost total lack of tidal motion, properties and condition of the water body show a high spatial and temporal variability. This is clearly reflected in salinity, temperature and oxygen contents.

Mainly during summer and fall, baroclinic processes induce an inflow of North Sea water with a high salinity. This leads to an increasing salinity, higher temperatures and a lower oxygen content along the flow path. As a consequence of meteorologically induced high water events in the North Sea, occurring mainly in winter and spring, larger water masses infiltrate the warmer Baltic Sea water with its lower salinity. The last recorded major event of this kind was in 2003 (FEISTEL, 2007).

Salinity decreases steadily with increasing distance from the Belt Sea. Whereas in the 'Wismar Bay' long-term average salinity values of 13–14 PSU have been recorded, the 'Bay of Pommern' shows only 6–7 PSU. The Darss Sill (Darsser Schwelle) between Mecklenburg Bay and the Arkona Basin with a water depth of only 18 m separates a water body of a higher surface salinity of more than 10 PSU from the brackish waters east of Rügen with less than 9 PSU. In the inner coastal waters with bays and coastal lagoons, the salinity gradient is even more pronounced: In 'Greifswalder Bodden' approx. 7 PSU, in 'Oderhaff' only 1–2 PSU (GEWÄSSERGÜTEBERICHT MECKLENBURG-VORPOMMERN, 2000/2001/2002). The shallow inner coastal waters are usually fully mixed by wind and currents; the outer waters, on the other hand, show a vertical temperature and salinity stratification which in the deeper parts of the Kiel and Mecklenburg Bay and the Arkona Basin can cause a thermohaline discontinuity during summer.

Even though the density compensation currents decisively shape the physical and chemical composition of the water body, they hardly influence water levels along the coastline. This is also true for the tidal waves penetrating from the North Sea through Skagerrak, Kattegat and Belt Sea. The amplitude of the semi-diurnal tide in the western Baltic Sea is 0.5–3 cm; for the diurnal tide it is 0.5–15 cm.

Major water level variations in the Baltic Sea can be attributed to the dynamics of the atmosphere. The transfer of momentum from wind to water causes wind and surf set-up at the coast. Due to the physical shape of the Baltic Sea, maximum water level variations occur in its western part, in the northern Gulf of Bothnia and in the inner Gulf of Finland.

Along the German coast of the Baltic Sea storm surges are mainly triggered by winds which originate from cyclones moving from either the North Atlantic or the Mediterranean towards the Baltic. In their rear, north-easterly winds with high speeds and sufficient duration on a long fetch occur in the central Baltic Sea. In addition to the generated set-up, meteorological influences let Eigen-oscillations of the water body contribute to high water levels. An additional water level rise of an average of 20–30 cm, with a maximum of 45–50 cm, can be due to a pre-filling of the Baltic Sea (DIE KÜSTE 66, 2003).

The highest water level ever at the German Baltic coast was recorded at Travemünde, the oldest gauge in Germany, to be 3.30 m above mean water level during the storm surge of Nov. 12/13, 1872.

External loading on the coast does not only result from the height and retention period of storm surge water levels but also from the simultaneously occurring strong waves. Based on wave measurements in at least 8 m of water depth (MSL) at the Baltic coast of Schleswig-Holstein, extreme-value statistics have produced significant wave heights Hs of up to 3.8 m and a return period of 100 years (KOHLHASE et al., 2000).

At the same time, wave-induced currents are instrumental in the swirling-up and transport of sediment. For example, these processes were responsible for the coastal recession at Rosenort (Rostocker Heide) and the aggradation of 0.85 m/a at Darsser Ort (GENERALPLAN KÜSTEN UND HOCHWASSERSCHUTZ M-V, 1994).

Ice conditions along the German Baltic coast must not be neglected. During normal winters, only the shallow bays of the inner coastal waters ice up completely. Because of their secluded location, there is no significant water exchange with the warmer open sea. Minor formation of ice in the outer waters can be found along the eastern coast of Rügen and off the island of Usedom. Only during extreme winters does the surface layer of Kiel and Mecklenburg Bay cool off sufficiently to allow for ice formation on open waters (BSH, 1996).

## 4. Important Harbour Access Channels

### 4.1 Lübeck (Trave)

The River Trave empties into the Lübeck Bay at Lübeck-Travemünde. In comparison with the natural water level variations of the Baltic Sea of around ± 0.50 m (occurring approx. 95 % of the year), the freshwater discharge of the Trave is so small (riverine area of Schlei/ Trave: MQ = 7.53 $m^3/s$), that it hardly affects the current regime in the Lower Trave. Depending on the season, salinity in the Lübeck Bay around Travemünde varies between 8.2 and 18.7 PSU (time series 1997–2006). Baroclinic processes let salinity be felt at Lübeck (Trave km 5.55 with a step in the bottom from 8 m to 3 m). It is only in a few reaches, that sediment deposits as a result of the freshwater discharge of the Trave and its tributaries are noteworthy. However, more substantial sediment depositions in the river mouth stemming from littoral transport play an important role for maintenance of the depth of the navigation channel. Extreme storm high waters have moved the location of the Trave mouth several times in the past (SPETHMANN, 1953). Thus, one attempted to fix the course of the Trave channel in its river bed. Starting in 1465, training walls were built to be replaced by various mole structures later on. The present stable 'Northern' and 'Northern Channel' moles (Norder- und Norderrinnenmole) have proven their worth and have firmly established the river mouth (Fig. 2).

In the past, the Lower Trave between Lübeck and Travemünde has been adapted to the continuously increasing requirements of commercial maritime traffic (VON LILIENFELD-TOAL, 1981). An admiralty chart (map with surveyed depths) of 1811 shows water depths of only 2.20 m over a sand bar outside of Lübeck. Vessels with a draft of 2 m were only able to reach Lübeck during elevated water levels. Up to the Lübeck city ports, water depths were only between 2.50 and 4.00 m below MSL. Around 1840, steam-powered dredgers succeeded in breaking through the bar off Travemünde and established a water depth of 4.7 m in the area.

The first correction of the Trave was carried out between 1840 and 1854 (VON LILIENFELD-TOAL, 1981). Together with a straightening of the fairway at 'Herrenfähre' (km 13.7) and 'Stülper Huk' (km 21.0), a continuous depth of 4 m was established. During the 2nd correction (1878–1883), the cutoffs at 'Teerhof' (km 8.7–9.5) and at 'Schlutup' (km 16–17) were completed. During the 3rd correction of the Trave, the fairway was deepened to 7.5 m between 'Stadthafen' (km 5.9) and the roadstead off Travemünde (km 28). Now, the bottom width of the fairway ranged between 40 and 90 m.

Both world wars and the economic crisis in between let a further improvement of the Trave (4$^{th}$ correction) to a water depth of 8.5 m proceed only slowly (1908–1961). Due to the fast growth of vessels of the international commercial fleet, the 5$^{th}$ correction was carried out between 1961 and 1982. It included a depth increase to 9.5 m and further improvements of fairway and bends. Now, the width of the navigation channel from the Lübeck city ports to 'Siems' (km 15.3–the former 'Flender' shipyard) is 60 m, in the adjacent stretch to 'Stülper Huk' (km 21) 90 m and to the open sea (ca. km 29 ) it is 100 m. Presently, in the reaches from

Fig. 2: Mouth of river Trave at the Baltic Sea coast (Travemünde)

'Siechenbucht' to Travemünde (km 26.9 – 'Süderrinnenmole') the fairway has a depth of 10.0 m. From here on to the open sea a water depth of 10.5 m is being maintained.

Fairway maintenance dredging of about 22,000 m³ of sandy sediments is carried out mainly in stretches from 'Siechenbucht' (km 24) to the Trave mouth (km 27) approx. every 6 to 8 years. In a second reach between km 6.9 to 21.0, approx. 10,000 m³ of prevailingly muddy depositions have to be removed. A trailing suction hopper dredger is normally used. Within the framework of environmental monitoring, physical parameters such as oxygen content, temperature and turbidity as well as current velocities and directions are usually being recorded.

Sediment depositions, which have accumulated after the last correction of the Trave, will be removed within a maintenance dredging campaign, planned for several longer stretches for the years to come. In many reaches of the Trave, contamination of the bottom sediment, due to sewage disposal by harbour and industrial operations, has been going on for decades. Therefore, the selection of suitable dumpsites is a major difficulty. In cooperation with the Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde-BfG), conceptions for the treatment of contaminated bottom sediments are presently being developed.

In addition to the standard hydrological assignments, the Federal Waterways and Engineering Research Institute (BAW) has carried out investigations of ship-generated wave and current loads on embankments.

### 4.2 Wismar (Wismar Bay)

The Bay of Wismar is located in the southern part of Mecklenburg Bay and, being a deep indentation, extends to the Hanseatic City of Wismar. Even in medieval times, the harbour of Wismar was of major importance for trade in the Baltic region. In 1810, the territory of the present city harbour had a mean natural water depth of 2.50 m. During the following 100 years, the first dredging measures (1845, 1849–1857, 1863 and 1908) were carried out to finally result in a water depth of 6.0 m in the harbour and 5.2 m in the access area on a width of 35 m. In the years from 1947 to 1950, the access to the harbour was improved to a depth of 7.0 m with a width of 35 m. Deepening of the fairway to 9.5 m while maintaining the width followed. In 1961, the fairway has widened to 60 m at the bottom. In the 1980s, widening of the bends at 'Walfisch' and 'Hohen Wieschendorf' was executed. Within the framework of another fairway improvement in 1998, extension of both sides of the fairway by 30 m each at a depth of 6.0 m was carried out (Fig. 3). This measure established a possibility of two-way traffic for vessels with a lesser draft. Presently, planning for deepening the navigation channel towards Wismar to 11 m with a width of 100 m is underway. Supplementary measures will be the establishment of the same water depth in the harbour reaches, the turning circle and the access to the shipyard.

Because of a sufficient natural water depth, maintenance works are only necessary for parts of the navigation channel in the inner Wismar Bay. Hydrodynamic processes in the bay with only weak current velocities result in only marginal morphological changes. Maintenance dredging, therefore, is only necessary every 7–10 years with an annual volume of 12,000 $m^3/a$. Dredged spoils in the harbour consist mainly of muddy material while sandy sediments have to be removed normally with hopper dredgers in the fairway.

Parallel to the maintenance dredging works, monitoring field programmes agreed on with the environmental agencies are carried out. The water body at the dredging and dumpsite is checked for oxygen contents, water temperature, turbidity as well as current velocity and direction.

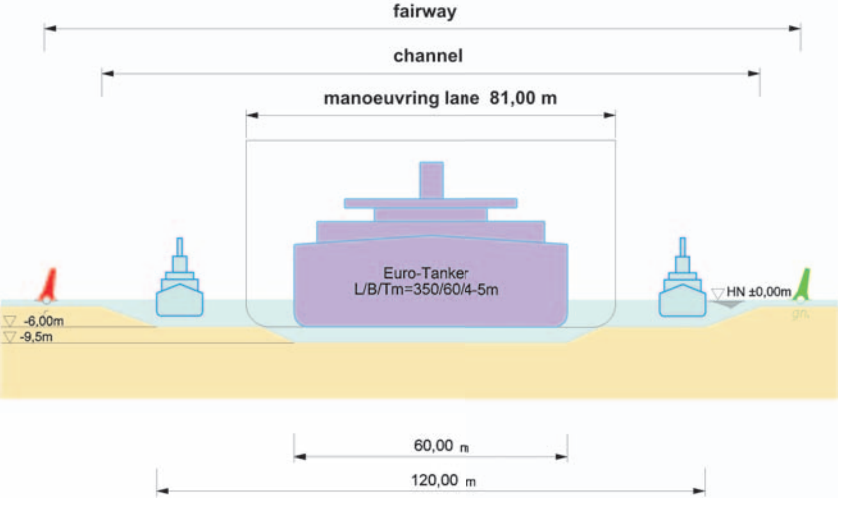


Fig. 3: Occupancy of the present cross-section of the fairway to Wismar during transfer of a new vessel

The contaminated dredged spoils are dumped on the containment area 'Fährort' on the island of Poel. In order to match its limited capacity, already dumped sediment is to be removed for an alternative utilization or recycling.

During the recent improvement measures, the entire system of the Wismar Bay, including the protected commodities according to the environmental compatibility code (UVPG), has been examined in detail. For the adaptation and improvement of the fairway, supplementary investigations are necessary. These include various field measurements, sample-taking and surveys as well as the preparation of a baroclinic hydro-numerical model for the simulation of advective salinity transport in the bay.

### 4.3 Rostock (Warnow)

Before the most recent improvement of the access to the sea port of Rostock at the end of the 1990s, a system of 4 separate moles protected the harbour entrance. The western mole (Westmole) dates back to the 16th century. Together with the eastern mole (Ostmole = presently called 'Yachthafenmole'), it sheltered the real mouth of the Warnow, called 'Alter Strom' today. Between 1901 and 1903 and for the establishment of the railway ferry terminal for the link Warnemünde – Gedser, the new channel 'Neuer Strom' was initally dredged to a depth of 5 m and then protected by a mole on its eastern shore. At the same time, the 'Westmole' was extended by 200 m to the North by building a sand spit. This was to prevent further sediment influx into the channel. By 1955, a water depth of 8 m on a width of 35 m had been established.

Together with the construction of the new seaport (Überseehafen) of the German Democratic Republic (GDR), the access channel (Seekanal) with a water depth of 10.5 m and a length of 4.5 nm was built in 1958. Sediment volume to be dredged was 5.3 million m³. The 'Ostmole' of the 'Neuer Strom' became the 'Mittelmole', and another mole was constructed at the eastern shore of the 'Seekanal'. The mole heads of 'West, Mittel and new Ostmole' were located on a straight line (SCHOCKEL, 1960). In 1963–1966 and 1972–1976, the depth of the 'Seekanal' was increased to 11.5 m and 13.0 m, respectively, with a width of 80 m.

Between 1996 and 1999, during the last upgrading of 'Seekanal', a water depth of 14.5 m with a width of 120 m was achieved in the inner part in order to enable two-way traffic. For this, the 'Westmole' had to be demolished. The 'Ostmole' became part of a new eastern mole, and the new 'Westmole' was fitted with a fork, arranged symmetrically to the new eastern mole, to reduce the energy of waves penetrating the 'Seekanal'. With an overall length of 7 nm, the 'Seekanal' widens to 220 m from the entrance to the offshore approach. Altogether, 4.5 million m³ of sand and till were dredged and dumped offshore. All engineering structures were designed such as to match another deepening to 16 m.

When maintaining the depth of the 'Seekanal', one has to differentiate between sedimentation immediately in front of the 'Westmole', which is due to littoral drift, and silting-up of suspended matter with a high content of autochthonal organic substance in the inner 'Seekanal'.

To prevent sedimentation at the western edge of the channel between the moles, up to 34,000 m³ of sand were removed in front of 'Westmole' in bi-annual precautionary dredging operations and dumped east of the channel. In 2001, a sand trap of 200 x 60 x 16 m dimensions was created and has to be cleared only every 7 years. The excavated sand will be dumped on a site 6 nm offshore.

After the last deepening of the 'Seekanal' was completed in 1999, the navigation channel in its inner reach has to be dredged for the first time in 2008. Dredged spoils are to go to the containment area 'Markgrafenheide'. Offshore of the entrance, hopper dredgers are operating exclusively while in the inner 'Seekanal' mainly bucket dredgers, dipper dredges and cable dredgers are being deployed.

In the beginning of the 1990s, BAW issued a number of prognoses on the impact of the last upgrade. Because of the existence of baroclinic processes, the impact on the hydrodynamic conditons in the 'Seekanal' were investigated using a 3D-model with a high spatial and temporal resolution. Physical model investigations were carried out for the forecast of wind and ship-wave induced loads and became part of an extensive preservation-of-evidence programme (Fig. 4).

More recent model investigations were conducted in the context of construction measures in the Navy Arsenal, e.g. to predict the effect of a new ammunition pier on circulation processes in the ‚Breitling' coastal lagoon.

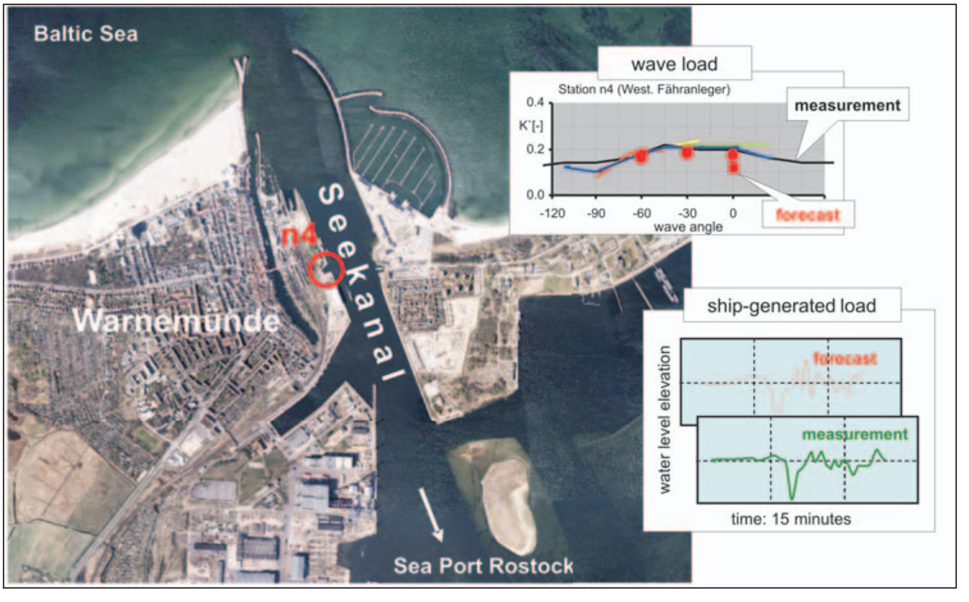


Fig. 4: System of moles at Warnemünde – predicted and measured wind and ship-generated wave loads at the ferry dock

### 4.4 Stralsund (Strelasund)

Stralsund, located on the 'Strelasund' has an access to the sea both from the North past the island of Hiddensee (Northern approach-'Nordansteuerung') and from the East via the coastal lagoon of 'Greifswalder Bodden' = eastern approach-'Ostansteuerung'). The evolution of the waterways is described in KÖHLER (2005).

First mention of navigation problems due to insufficient water depths in the northern approach go back as early as the 17$^{th}$ century, when water depths were probably around 2.50 to 3.0 m. Since the 18$^{th}$ century, major efforts to improve channel depths were undertaken, initially by manual excavation. In 1890, the fairway was upgraded by deepening to 3.5 m and a breakthrough at 'Vierendehlgrund'. In the years 1910, 1938 and 1944, the upgrade was continued to depths of 4.0, 4.5 and 5.0 m, respectively, at a bottom width of 40 m. The deepened navigation channel acted as a sand trap accumulating the west-east oriented littoral drift. Sand deposits had to be removed continuously.

Dredged sand from deepening and maintenance had been pumped ashore to build up to an elevation above high water and crop the neighbouring 'Bock', a wind-influenced wadden area (Windwatt). Thus, the considerable constriction of the flow passage between the new island 'Bock' and the island of Hiddensee and resulting intensification of currents were expected to lead to an increased clearance of the navigation channel. This measure, however, was only partially successful since meandering tendencies of the channel necessitated a frequent adaptation of the light line marking the location of the channel. During those years, approx. 100,000 $m^3/a$ had to be removed from the navigation channel annually. In 1985, the light lines were abandoned and the fairway, maintained to a depth of 4.5 m and marked by light buoys, has been following the morphological development of the natural channel. Consequently, dredged volumes dropped to 70,000 $m^3/a$. In 1986, dumping of material on 'Bock' was completely stopped. Ever since, spoils from the annual maintenance dredging works have been used for coastal protection measures (e.g. dike construction 'Ostzingst'), or the material has been dumped offshore north of 'Hiddensee'. Dredging is mainly done by hopper dredgers, seldom by bucket dredgers.

Since 1857, because of a considerably smaller maintenance effort in the eastern approach, the fairway has been upgraded in steps from 5.2 m (until 1943), via 6.0 m (1945–1954; 1961–1965) and 6.9 m (1997–2000) to 7.5 m (2006). Thereby, it has developed into the more important route to Stralsund. Construction measures mainly concentrated on a straight-line connection between two shallow water regions: the 'Ziegelgraben' close to Stralsund and the 'Palmer-Ort' channel where the 'Strelasund' merges into 'GreifswalderBodden'. Outside of this area, the fairway follows the naturally stable flow trench of the Strelasund. As a consequence of each upgrade, however, the reaches to be improved get longer: while during the 6.9 m-deepening approx. 1 million $m^3$ of Litorina-mud had to be dredged on a length of 15 km, establishing the 7.5 m depth along 23 km required dredging of 2 million $m^3$.

Maintenance of the eastern approach concentrates on the 'Palmer Ort' and 'Ziegelgraben' channels. In addition to the running of mud from the underwater slopes into the 4–5 m deep channels, sand, eroded along the northern shores of Strelasund and driven by the oblique current, deposits in the 'Palmer-Ort' channel.

Towards the end of the 1980s, dumping of dredged spoils had to be stopped because of environmental concerns. Thus, the material, rich in organic components, as well as dredged sediment from the last two upgrading measures (6.90 and 7.50 m depths) had to be dumped on the land-based containment area 'Drigge'.

For the maintenance of the eastern approach, an average of 65,000 $m^3$ has to be removed annually, varying between 20,000 and 100,000 $m^3$. For this, mainly bucket dredgers, dipper dredges or cable dredgers are deployed. They cut into the bed material with an optimum cutting depth and guarantee to produce an accurate transect of the channel with a minimum of sediment and almost no water removed.

In order to solve the continuous sedimentation problems in the northern approach, numerous investigations have been carried out by scientific institutes. During the 1950s, physical models have been run at 'Forschungsanstalt für Schiffahrt, Wasser- und Grundbau' (FAS) to look into the usefulness of river training methods for reducing sediment depositions. Extensive investigations with numerical simulation models on the morphodynamics of wind affected wadden areas (Windwatten) were carried out in the GCERC (KFKI) project MORWIN (BARTHEL and LEHFELDT, 2000).

Based on a literature search and data measured in the field, the effect of the last two upgrades of the channel on abiotic system parameters have been predicted using empirical methods. Results have been confirmed by runs of a 2D hydro-numerical model (Fig. 5).

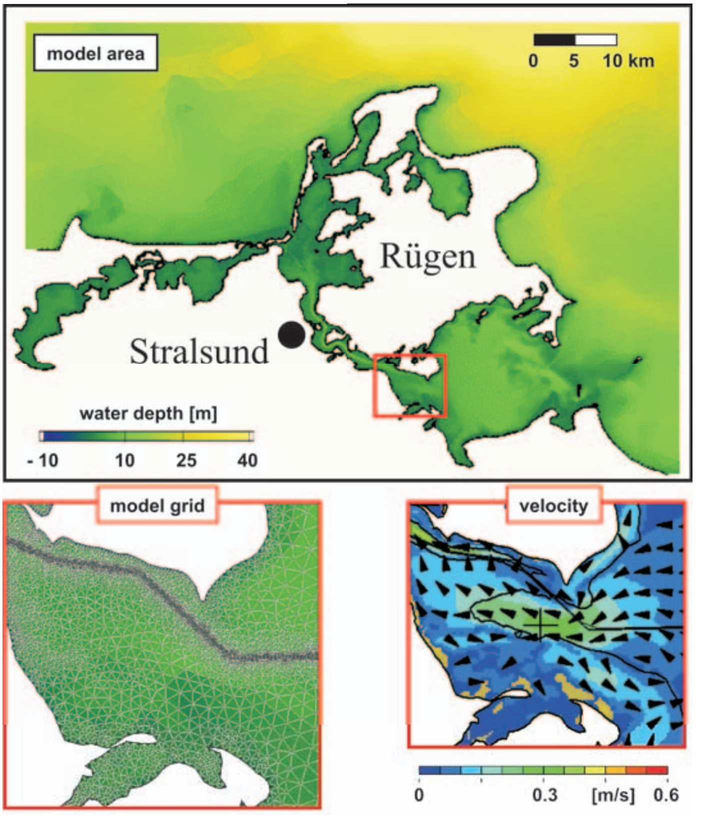


Fig. 5: Overview of 2D HN-model area, section of model grid and calculated velocity values

### 4.5 Wolgast (Northern Peenestrom)

Wolgast, located at the western shore of the 'Peenestrom' can be accessed from offshore via 'Osttief' or via 'Landtief' and 'Greifswalder Bodden'. The northern part of the 'Peenestrom' has been used as an approach to the Hanseatic City of Wolgast from time out of mind. At the beginning of the 20$^{th}$ century, one finds mention of the maintenance by dredging of the access channel with a width of 40 m and a minimum depth of 5.0 m (KRES, 1911). Only with the establishment of a naval base at Peenemünde towards the end of the 1950s, the fairway was improved in steps to a width of 70 m and a water depth of 6.0 m between Peenemünde and 'Osttief'. The stretch between Peenemünde and Wolgast received a water depth

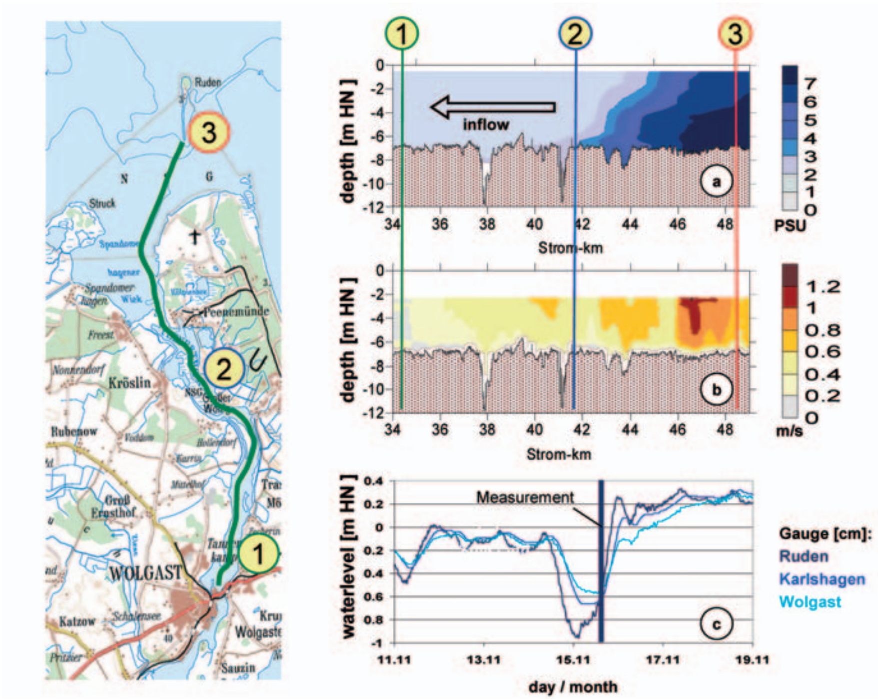


Fig. 6: Salinity values and current velocities during a period of water inflow, measured in the field on a longitudinal section in the northern 'Peenestrom' (WSA STRALSUND, 2007)

of 5.5 m in 1979/1980. In 1996/1997 it was deepened between Wolgast and 'Osttief-Ost' to be 6.5 m and the width was increased to 60 m from Peenemünde to Wolgast. The latest upgrade of the northern 'Peenestrom', with an adaptation of the bend as a reaction to increased length of vessels delivered by the shipyard, was carried out in 2007. In addition to dredging in 7 curves, a partial relocation of the fairway using naturally available water depths was done. In 2008/2009, the northern 'Peenestrom' will be deepened to 7.5 m till Wolgast.

Maintenance works on the navigation channel to Wolgast have to be carried out every 5 years on average. Approx. 150,000 m³ of dredged spoils are mainly dumped on sites off the island of Usedom. Smaller contingents are placed on a containment area at the 'Peenestrom'. Dredging works are done by hopper and bucket dredgers as well as dipper dredges.

In addition to dredging measures in the eastern approach to Stralsund and the access to Wolgast, some dredging is necessary in both connections of 'Greifswalder Bodden' to the Bay of Pomerania (Pommersche Bucht), namely the 'Osttief' and 'Landtief'. Dating back to documents of 1254, 'Osttief', cutting through the coastal lagoon sill between the islands of Ruden and Usedom, is mentioned to be a navigation channel which, at the beginning of the 19th century, was less than 4 m deep. During the course of the upgrade of the 'Peenestrom' its depth was increased from 6.0 to 6.5 m. 'Landtief', crossing the sill between Ruden and Usedom, was travelled after the removal of large boulders and the first dredging works at the end of the 18th century. The channel had a water depth of only 3.3 m in 1834 (DWARS, 1958). As an after-effect of WW II, the fairway, which in the meantime showed a depth of 4 m and a width of 60 m, had to be shut down for navigation in 1945. After cancellation of the

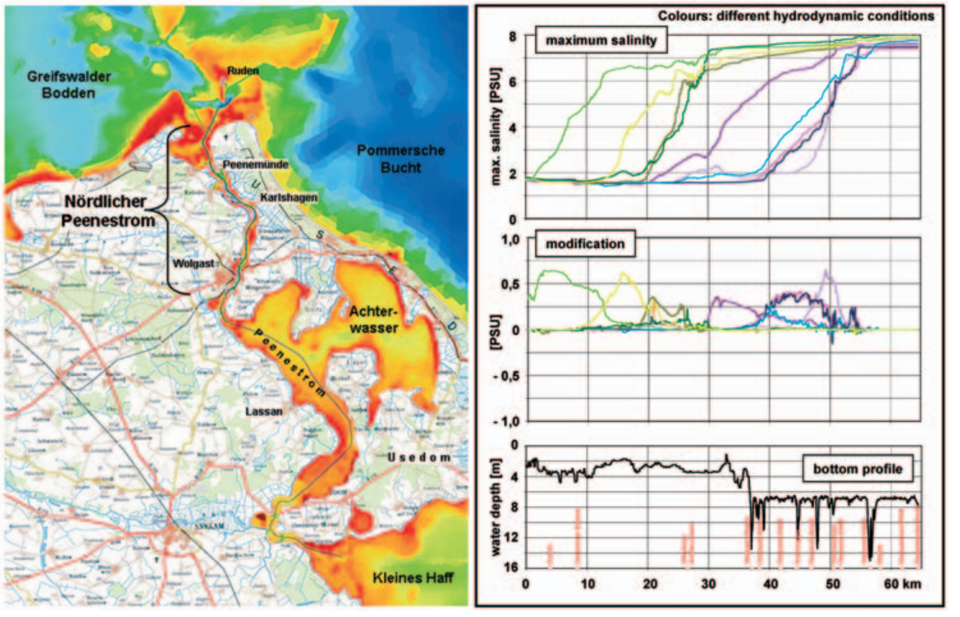


Fig. 7: Section of the model topography (left side) to give an overview of the northern 'Peenestrom'; modifications of maximum calculated salinity values due to construction measures (right side) (BAW, 2007)

blockade, the 'Landtief' was improved to have a water depth of 8.0 m with a width of 60 m in 1966/1967. Together with the upgrade of the eastern approach to Stralsund, it was widened to 90 m at a water depth of 7.5 m.

In the course of the environmental impact assessment for the two latest improvement plans, especially the baroclinic processes have been investigated in hydro-numerical simulation models. For the present planning process, a 3D-model of the southern Baltic Sea and coastal waters around Rügen was applied by BAW. Calibration of the model was based on extensive field investigations, documented in a technical report on the hydrodynamic conditions (WSA Stralsund, 2007) (Fig. 6). Model results concerning the baroclinic processes show that, with the realization of the presently planned construction measures, the maximum salinity in particular will increase due to an upstream shift of the mixing zone. The upgrade will boost the hydraulic capacity of the 'Peenestrom'. As a result, salinity-rich water volumes will be increasingly transported upstream (Fig. 7). Outside the mixing zone, no significant modification of salinity conditions will occur as a consequence of the construction.

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# Ports in Lower Saxony

By HANS-JOACHIM UHLENDORF and DÖRTE SCHMITZ

Contents



## 1. Introduction

One of the most frequented sea traffic routes in the world is located in the southern part of the German Bight along the Lower Saxony coast of the North Sea. The North Sea itself is an important trade route and serves as Europe's access to the globalized markets.

The Lower Saxony seaports of Brake, Cuxhaven, Emden, Stade-Bützfleth and Wilhelmshaven have free accessibility to the interregional sea traffic routes and the open sea via the estuaries of Weser, Elbe, Ems and Jade.

Hinterland connections are well established through an efficient network of roads, railways and inland waterways.

The seaports of Lower Saxony make an essential contribution to the supply of goods and commodities for the Federal Republic of Germany. With an overall cargo handling of 63.7 million t (SEAPORTS OF NIEDERSACHSEN, 2006), they secure the export capacity of the German economy. Furthermore, the sea and inland ports of Lower Saxony ensure a clear employment effect: 74,000 employees – around 2.1 % of all people employed in Lower


Fig 1: Locations of Niedersachsen Ports GmbH

Saxony – directly or indirectly work at the ports in Lower Saxony. (Source: Niedersächsisches Hafenkonzept, Lower Saxon Port Concept).

In addition to the large German container ports in Hamburg and Bremen, the seaports of Lower Saxony maintain an important position in the handling of bulk and general cargo, in special bulk carriers (oil, coal) and of raw materials such as resins and basic chemicals, general cargo and special cargo such as e.g. motor vehicles, forestry products and project cargo (parts of or entire industrial and power plants). A large part of this load is handled within the port system of Niedersachsen Ports GmbH & Co. KG (Niedersachsen Ports).

Niedersachsen Ports, a state-owned private company, is responsible for the construction, the maintenance and the operation of the state-owned seaports in Lower Saxony. Moreover, an important area of activity is the management of the extensive port areas and real estate. The federal state of Lower Saxony has transferred responsibility of 13 state-owned ports to the company. These include Brake, Cuxhaven, Emden, Stade-Bützfleth and Wilhelmshaven, seven island supply ports as well as one regional port.

By the year 2012, the state of Lower Saxony will have invested more than 200 million Euros into the construction and maintenance of the infrastructure in the seaports of Niedersachsen Ports.

Further seaport locations in Lower Saxony are the private port Nordenham as well as the communal ports in Papenburg, Leer and Oldenburg.

## 2. Locations of Niedersachsen Ports GmbH & Co. KG

### 2.1 Brake

The seaport Brake is located at the western bank of the Weser estuary 26 km upstream of Bremerhaven. Depths in the navigational channel are sufficient for sea-going vessels. The port has a quay length of 1,700 m, and the port area includes 195 acres of land and 50 acres water surface. Today, ships with a draft of up to 11.9 m (planned development depth: 12.8 m) and a length of 275 m can call at the port of Brake. Pilot-aided passage through the Outer Weser generally takes about 5 hours.

The southern port area serves for the handling of animal feed and grains, the northern port area for the handling of forestry products, iron, steel, machines and sulfur. At the inland port, which can be reached through a lock with a chamber length of 95 m, coasters and seagoing barges servicing the European logistics traffic can be processed. Brake is connected to the European inland waterway network through the Lower and Middle Weser as well as through the Hunte and the Coastal Canal (Küstenkanal). Thereby, inland vessels can reach the port of Brake from all European inland waterways.

Since the port turnover reaches its capacity limit in the existing port area, Niedersachsen Ports is realizing the investment measure "Port Expansion North" with a volume of 37.5 million Euros. By 2009, the construction project will establish an expansion of the port area of approx. 75 acres with a 270 m quay. This offers additional berthing space for one large and one inland vessel together with the necessary connections to the existing traffic infrastructure. Due to an expected high utilization of the port facility Niedersachsen Ports is considering the immediate construction of a second berth which will enable a simultaneous processing of two large ships.

Fig. 2: Brake (53° 20' N, 8° 29' E)

### 2.2 Cuxhaven

Being located at the junction of the maritime traffic lanes from the North and Baltic Sea, Cuxhaven has good transport connections. Moreover, its location approximately 104 km downstream of Hamburg at the mouth of the Elbe, the busiest maritime route in the world, makes the seaport the starting point for sea-bound traffic to Great Britain, Scandinavia and the Baltic Sea region. At the Elbe estuary with a navigational channel, which is deep enough for deep-drawing ships, an access to the port with a maximum allowable draft of 14.5 m is guaranteed.

The port is connected through an access road to the autobahn roundabout with branches of the autobahn A 27 and the highway B 73 both going towards Hamburg. A two-track railway line to a major junction at Hamburg/Maschen is the most important connection for cargo trains. The Elbe waterway provides access to the inland canal system towards the hinterland.

The overall surface area of the universal port is 788 acres, 571 acres of which are on land and 217 acres are expanses of water. As an important turnover port for Roll-on/Roll-off traffic (Ro-Ro) and for the turnover of general cargo, steel products, project cargo and cars, Cuxhaven has become an important logistics hub at the North Sea coast.

In the eastern part of the 'Amerikahafen' with a total quay length of 840 m, a multipurpose handling facility with a total of four berths is located. Handling and equipment quays for general cargo and small bulk carriers as well as for large cruise ships complete the picture of a versatile America port.

Another part of the port accommodates a handling and equipment quay for fishing boats (Alter Fischereihafen/Old Fishery Port), some other equipment quais for fishing boats

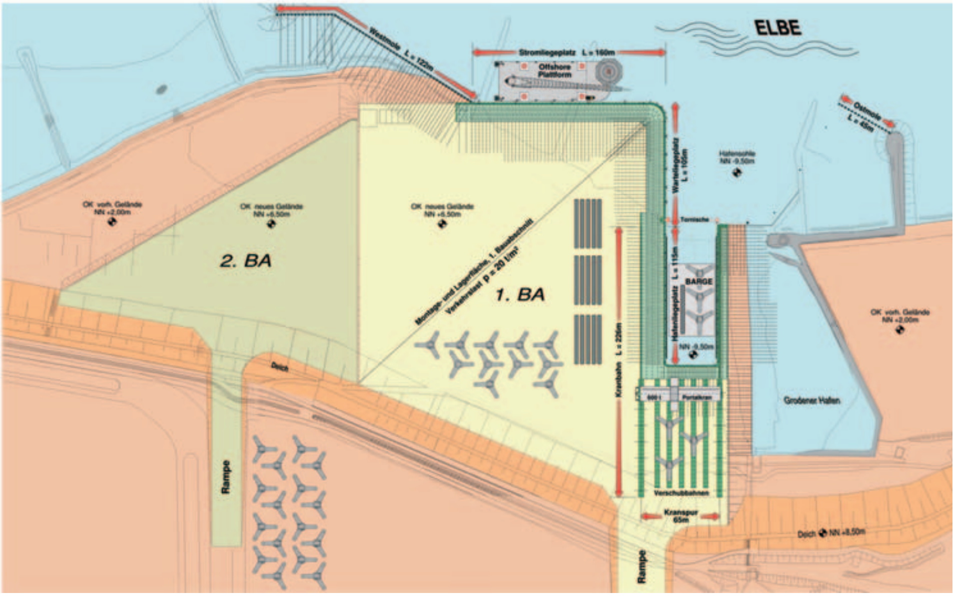


Fig. 3: Cuxhaven (53° 52' N, 8° 42' E)

(Neuer Fischereihafen/New Fishery Port) as well as the Old Port and the 'Ritzenbütteler' Lock Gully serving as a multi-purpose harbour for shipyards and smaller passenger vessels servicing the islands (MINIST. F. WIRTSCHAFT, ARBEIT U. VERKEHR DES LANDES NIEDERS., 2007).

In addition to the increasing Ro-Ro traffic, Cuxhaven has a long tradition as a fishing harbour and cruise ship centre. Moreover, the port will secure a future market segment with processing and servicing offshore windpower installations. As an example, the heavy-duty platform recently built by Niedersachsen Ports will be the basis for loading wind power generator units fully assembled with a weight of up to 2000 tons. The 1,580 m² assembly hall is planned to be operational in spring of 2009 (Verlag Kommunikation u. Wirtschaft, 2007), a production facility for foundation elements for offshore wind power generators in the direct vicinity is under construction.

In order to meet the urgent need of additional port capacity, Niedersachsen Ports is planning on building another berth with a length of 240 m and 21 acres port operation area towards the East of the new heavy-duty platform.

## 2.3 Stade-Bützfleth

The port of Stade-Bützfleth is directly located at the Elbe between Hamburg and Cuxhaven. The access route from the open sea to the port via the Elbe has a length of around 60 nm.

The port includes the 345 m long North Pier, at which on the river side ships with a length of up to 270 m long and a draft of up to 14.5 m can berth. On the land side of the pier (North Port), the maintained depth is 7 m.

Fig. 4: Stade-Bützfleth (53° 39' N, 9 ° 31' E)

Together with a berth for ships on stand-by, the South Pier is 380 m long. On the river side, sea-going vessels with a length of up to 270 m can be serviced; on the land side, ships with a length of up to 155 m and a width of up to 28 m can berth. Navigable depth in the South Port is 10 m. There, two quay facilities for ships with a length of up to 200 m and 33 m width are located.

The Nordwest Kai/Northwest Quay is currently being expanded from 90 m to 315 m length by Niedersachsen Ports. This will add 9 acres of port space near the quay.

The port of Stade-Bützfleth offers handling and storage of bulk and general cargo on a fortified and flood-protected area with tide-independent access of sea-going vessels. The port is closely integrated into the regional industrial structure and possesses a particular competence and experience in the area of hazardous materials and the handling of solid and liquid bulk materials. Therefore, the Stade location is highly recommended and accepted by authorities, private industry and people.

### 2.4 Emden

The state-owned seaport in Emden is the most western harbour in Germany. It is located approx. 38 nm south-east from the open sea at the Ems estuary. The port consists of two parts: the outer port under tidal influence as well as the tide-free inland port which is accessible through two sea locks.

The handling facility in the outer port has a total quay length of 1,715 m (outer port

1,190 m, Ems quay 275 m, Ems pier 250 m). The water depth in the outer port and at the Ems quay is 8.5 m, at the Ems pier 9.5 m below mean sea level. The quay storage space adds up to a total of more than 90,000 m²; in addition, there is a spacious retral warehouse and storage space available (Source: Niedersächsisches Hafenkonzept).

Depending on the tide, access for vessels with a draft of 10.67 m is possible.

The port facilities are capable of handling heavy loads and are connected to both the railway network of Deutsche Bahn and the German and Dutch road network by autobahn A 31. Canals towards the hinterland provide the connection to the German as well as to the Dutch waterway and canal network.

New cars directly from the factory and destined for export constitute an important part of the cargo handled in Emden. Hence, the area of logistics services for the automobile industry has developed in an important manner.

In addition, the port is an important transshipment place for goods and products of a wide variety such as forestry products of all types, liquid chalk/Kaolin, components for offshore wind power plants, minerals, magnesium chloride and liquid fertilizers as well as project cargo. Port facilities include 12 Ro-Ro berths, a floating Ro-Ro ramp (100 t) for versatile deployment at various quays, a container terminal and a high capacity handling bridge (SEAPORTS OF NIEDERSACHSEN).

The relatively new classification of the sea port has its origins in the structural change of the past 25 years. Emden has developed to become a universal port with an emphasis on general cargo whose share has substantially increased. Port areas freed up by the re-structuring process have been allocated for the settlement of new companies and for expansion.

Fig. 5: Emden (53° 21' N, 7° 12' E)

Fig. 6: Wilhelmshaven (53° 31‘ N, 8° 08‘ E)

Emden aims at playing an important role on the emerging market of regenerative energies, in particular wind energy. To the North of the Island of Borkum, the establishment of the first 80 offshore wind power generators will be realized. For this project and further wind parks in the German Bight, Emden will serve as a basis for pre-assembly, transport and maintenance of the facilities.

Emden's potential lies both in the diversity, which is available through the competency and technical equipment on site and on an enormous potential in expansion areas important for future development of the port at the Ems estuary.

### 2.5 Wilhelmshaven

Wilhelmshaven is Germany's only deep water port, located between the Ems and the Weser on the western side of the Jade estuary. The nautically unproblematic, very short access channel with a length of – depending on the docking point in the port – between 23 and 32 nm – is maintained through regular dredging to guarantee a depth of more than 18.1 m below mean sea level. Depending on the tide, ships can enter with a draft of up to 20 m (outgoing 19 m).

The port consists of two parts: the outer deep water port 'Jade channel' and the tide-free inner port behind a double-chamber sea lock.

The inner port with its characteristic handling bridges is equipped with modern quay facilities for the handling of bulk cargo, containers, refrigerated cargo, food stuffs, general and project cargo (SEAPORTS OF NIEDERSACHSEN).

The port of Wilhelmshaven as a central handling location for fossil fuels is continuously expanded by improving the state-owned handling facility for coal and LNG as well as the preparation of an area set aside for the construction and operation of a coal-fired power plant and the connected coal storage. Thereby, port greatly contributes to the energy supply in Germany.

A good traffic infrastructure between all port areas and to the outside and the hinterland is based on access to interregional road network through the autobahn A 29. The railway network also extends into all port areas.

The advantages of the present port location led to the decision to build the Jade Weser Port, Germany's future deep water terminal for large container vessels of the coming generations. More detailed information can be found in section 5.3 in this issue.

## 2.6 Norden

A branch of Niedersachsen Ports in Norden manages the island supply ports of Norddeich (starting point of the ferry lines to Norderney and Juist), Bensersiel (starting port of the ferry line to Langeoog) and the island ports of Norderney, Baltrum, Langeoog, Spiekeroog and Wangerooge. This includes the maintenance dredging in the access channel of the community-owned port Juist as well as the operation and maintenance of various port navigation lights.

Fig. 7: Norddeich (53° 36' N, 7° 9' E)

With around 1.5 million tons being handled, more than 10 million passenger transfers and around 80,000 ship movements, the average annual balance of the 14 coastal and island ports between Greetsiel and Harlesiel and Borkum and Wangerooge, respectively, is an essential economic factor in the East Frisian region. Ferry traffic and island supply, fishing boats and pleasure craft reach the capacity limits, especially during the summer months. Based on its individual characteristics, each port is a center of attraction for tourists and a starting point for the passenger ferry and/or island supply traffic to the East Frisian islands. Thus, these ports provide an essential contribution to securing and strengthening the economy of the Lower Saxony coastal region.

The accessibility of the coastal and island ports depends on the natural conditions in and around the tidal flats and the state of maintenance dredging in the access channels. Most ports can only be reached under certain tidal conditions (Tab. 1).

Table 1: Island supply ports in Lower Saxony

| **From mainland port to island** | | **reachability** |
|---|---|---|
| Emden | Borkum | independent of tide |
| Norddeich | Juist | depending on tide |
| Norddeich | Norderney | independent of tide |
| Neßmersiel | Baltrum | depending on tide |
| Bensersiel | Langeoog | independent of tide |
| Neuharlingersiel | Spiekeroog | depending on tide |
| Harlesiel | Wangerooge | depending on tide |
| Cuxhaven | Helgoland | independent of tide |
| Cuxhaven | Neuwerk | depending on tide |

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# Bremen and Bremerhaven

By STEFAN WOLTERING and IVEN KRÄMER

*Upon explicit request of the authors this article has not been peer reviewed*

Contents



## 1. Introduction

Bremen/Bremerhaven, Germany's number two seaport with an annual throughput of about 70 million tons of cargo (2007) has, like many other seaports, undergone a phase of substantial growth and change. The booming container traffic sector (4.9 million TEU in 2007) and Bremen's role as the main hub for European automobile distribution have been principal drivers of the local port business and, in anticipation of a further duplication of cargo handling volumes, the largest investment scheme in Bremen's port history is already well under way.

The current number four container terminal on the European continent is to be enlarged by 1700 metres of new quay wall and about 90 hectares of new reclaimed land. A new sea lock to strengthen the position of the automobile logistics centre is under construction and dredging work to adapt the River Weser as the main navigational channel to future ship sizes will be carried out in 2008/2009. Furthermore, new logistics facilities for Europe-wide distribution centres are expanding in and around the ports, so that Bremen and Bremerhaven are well prepared for the next few decades.

## 2. Historical Development of Bremen's Ports

The Free Hanseatic City of Bremen consists of the cities of Bremen and Bremerhaven. The two-city state has a surface area of about 400 m² and a population of about 680,000, making it Germany's smallest Federal Land. Bremen is mentioned for the first time in a historical document which dates back to 782 AD. Its citizens were busy traders who used the River Weser to take their goods to market.

In the 13th century, Bremen joined the powerful city alliance of the Hanseatic League. In 1410 Bremen received the privilege to set beacons and buoys on the Weser in order to direct maritime traffic and in 1541 Bremen was granted "*stacking rights*" by Emperor Charles V. This privilege, which meant that all goods passing through a trading place had to be unloaded and offered to the local merchants for a certain time, boosted trade so that Bremen became increasingly significant as a city republic and a trading metropolis with highly influential merchants and traders.

A major milestone in Bremen's port history was the year 1827. After the end of the Napoleonic Wars, when Bremen became a French department for some time, the Bremen Senate along with Mayor Johann Smidt faced the problem of ongoing siltation of the River Weser. They devised a plan to build a new port for Bremen closer to the North Sea and persuaded the Kingdom of Hanover to sell them 89 hectares of land, where the river Geeste joined the Weser. This project was intended to make the city more independent of the problems of shipping on the Weser at that time and also as a precaution against Hanover's ambitions in the shipping trade. And so the construction of the new port was simultaneously the origin of the city of Bremerhaven. In 1830 the American "*Draper*" was the first ship to call at the new port which, in response to growing business, was substantially enlarged in 1847 with the construction of the New Harbour.

Another fundamental decision was taken in 1859, when Bremen and Hanover agreed on the construction of the Geeste line to connect the port of Bremerhaven to the emergent continental rail network. This development opened up a much wider hinterland for the ports, as goods could now be transferred from ship to rail and transported to destinations throughout the whole country.

Besides the ongoing success of Bremerhaven, the late 19$^{th}$ century was also marked by new developments in Bremen itself. New port facilities with state-of-the-art rail-mounted cranes were constructed and management of the port was transferred to the newly founded Bremer Lagerhaus Gesellschaft (now BLG Logistics Group). But for the time being, one problem remained unsolved: the Weser fairway, which was no more than two metres deep. Almost every winter, a thick, unyielding layer of ice covered the Weser between Vegesack and Brake, bringing maritime traffic to a standstill and threatening to cut Bremen off from the trading routes. The Royal Prussian Academy of Construction consequently accepted a proposal submitted by Ludwig Franzius, Bremen's chief civil engineer, to counteract silting of the Weser. Franzius' ingenious idea was to design the Lower Weser without barriers or narrows, to remove islets and sandbanks, and to shape it like a funnel, so that the incoming tide could reach Bremen unobstructed. The higher speed of the ebb tide meant that the Weser would clear the silt from the riverbed itself. The anticipated costs of the project amounted to 30 million marks, which in those days was an incredible sum, equivalent to 500 million euros by today's standards, so that the city was allowed to levy a tax of one mark for each ton of cargo from all ocean-going ships. In 1887 work began to ensure that ships could make their way unobstructed from the city of Bremen to the North Sea, and a number of new large harbour basins were also built.

The early 20$^{th}$ century was marked by another package of construction measures involving two new sea locks, an increasing number of harbour basins in Bremerhaven and a completely new 300-hectare industrial harbour in Bremen. Furthermore, Bremen's ports continued to specialise, with the development of grain, banana and passenger facilities.

During World War II, there was extensive destruction of the ports between 1940 and 1945. Cargo volumes recovered only slowly and did not reach the status of 1938 again until the early 1950s. New projects, such as a ro-ro terminal in Bremerhaven and an additional harbour basin in Bremen, were then undertaken to enhance the port capacities.

May 1966 saw the start of a new era when the first container was discharged at the Überseehafen in Bremen. From then on, local port development was dominated by the continuous enlargement of the container facilities, with at least one new terminal per decade. The second mainstay of the ports, the automobile business, began in the 1970s when German car producers started to sell their products overseas. Only a little later, they were joined by Japanese and later Korean cars as they conquered the European roads.

Looking back on this colourful history with centuries of expertise in handling cargoes ranging from cotton, coffee, cocoa, tobacco, beer, wine and linen to today's containers, automobiles, fruit and break-bulk, it is the courage to tackle new trends and the determination to shape new developments that have made Bremen and Bremerhaven what they are today: one of the largest seaport complexes on the European coast.

## 3. Status Quo

Over the years, a pronounced division of labour has evolved at the twin ports. While Bremerhaven specialises in handling containers, vehicles and fruit, the terminals in Bremen city, 60 km upriver to the south, concentrate on bulk goods (e.g. ore, coal and grain) together with conventional general cargo (including project cargo, steel and steel products as well as forest products). Total cargo throughput at Bremen's ports in 2007 amounted to almost 70 million tons, an increase of 7 per cent year on year. The terminals in Bremerhaven handled roughly three quarters of the total amount (including 4.9 million TEU and more than two million automobiles) and were thus able to increase their share of cargo throughput.

Fig. 1: Aerial view of the overseas port of Bremerhaven

More than 100 scheduled services regularly call at the terminals in the two-city state, linking Bremen and Bremerhaven with all major transhipment locations throughout the world. Every year, some 10,000 ocean-going vessels tie up at the quaysides in the twin ports, and roughly half of them are fully containerised ships. Liner customers include such familiar names as Maersk Line, MSC, China Shipping, Cosco, Deutsche Afrika Linien, Evergreen, Hamburg-Süd, Hanjin, Hapag Lloyd, Hyundai, K-Line, Mitsui OSK Lines, NYK, OOCL, Yang Ming and Zim. The port is also regularly called at by numerous feeder vessels which link Bremerhaven Container Terminal with ports, for example, in the upcoming Baltic region (Baltic Container Lines, Samskip, Team Lines and Unifeeder etc.).

Fig. 2: Aerial view of the ports of Bremen City

Bremerhaven is the largest European hub for the overseas automobile import and export trade. In 2007, more than two million vehicles were transhipped on the banks of the River Weser. The storage space is sufficient for 120,000 vehicles at the same time and almost 1500 car carriers are handled at the overseas terminal every year. Automobile manufacturers such as Daimler, BMW, Ford, VW, Audi and Porsche all have their products shipped via the automobile terminals at the mouth of the Weser. Most of the vehicles produced in Europe are headed for the USA, East Asia and the Middle East, while the imported vehicles come mainly from Asia and the United States. Well known automobile shipping companies – including Wallenius Wilhelmsen, NYK, Hual and Eukor – all call at Bremerhaven. The facilities at Columbus Cruise Centre Bremerhaven are used by about 100,000 passengers annually and belong to the most modern cruise terminals anywhere in Europe.

Sea freight transhipment in the city of Bremen is divided between several different sites: Neustädter Hafen on the left bank of the Weser, the industrial port (Industriehafen) on the right, behind Oslebshausen lock, Mittelsbürener Hafen, and Holz- und Fabrikenhafen. Hemelinger Hafen handles mainly inland waterway traffic. In contrast to Bremerhaven, the majority of these port areas and also the infrastructure are owned by private terminal operators, which focus mainly on conventional general cargo. The goods include steel products, scrap metal, machinery and entire factory plants, pipes, paper, timber and pulp.

The Neustädter port area on the left bank of the Weser, with its 2340-metre long quay and water depth of up to 11.30 metres, annually handles more than three million tons of general and project cargo, whereas the Mittelsbürener port area focuses mainly on iron ore and coal distribution to the nearby steel plant. The companies within the industrial port together handle more than 6 million tons per annum.

## 4. Current Construction Projects

To respond to these diverse challenges and to shape the future at the beginning of the new century, Bremen has launched a massive 800 million euro port investment programme, involving primarily the enlargement of the container facilities and the construction of a new sea lock. The Container Terminal 4 project has already been completed and will come into full operation in the course of 2008. Construction work on the new sea lock "Kaiserschleuse" began in autumn 2007 and is scheduled for completion in spring 2010.

### 4.1 Container Terminal Enlargement

The Container Terminal 4 project involved extending the existing 3237-metre long quay wall on the banks of the River Weser by a further 1681 m towards the north. The new quay follows the course of the navigation channel, turning off towards the north-west at an angle of 10 degrees after around 540 m. The calculated depth for the quay is 19.50 m below mean sea level, which means that on completion it will be able to handle vessels with draughts of 16 metres.


Fig. 3: Development stages of Container Terminal Bremerhaven

The existing container terminal and CT IIIa, the previous construction phase which went into operation in autumn 2003, largely determined the overall concept for CT 4 as a non-independent terminal. The plans had to take into account general construction conditions resulting from aspects such as shipping traffic, the existing infrastructure and the nearby residential districts. It was not possible to provide a separate traffic connection owing to the given geographical situation. All additional infra- and superstructure required for terminal operations will therefore be provided exclusively through the terminal which is already in operation. The CT 4 construction project consequently cannot be regarded as an independent terminal. The construction work itself began on June 16th 2004, just one day after planning approval was received from the Federal Waterways Directorate, a branch of the German Federal Transport Ministry.

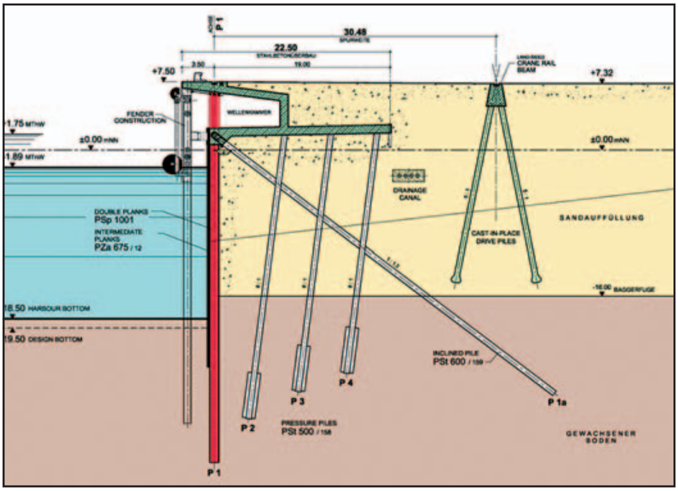


Fig. 4: Cross-section of CT 4 quay wall

As in the case of terminal section CT IIIa, the new quay construction consists of a load-retaining slab on deep foundations with an integrated wave absorber and heavy-duty sheet piling on the waterside. The piling is a combined structure of 39.00 to 41.00 m long Peine double piles, PSp 1001 and PSp 1013, with PZa 675/12 used as filler piles. The sheet piling is anchored with up to 47.00 m long PSt 600 S batter piles. The poor quality of the subsoil around the site of the quay meant that the layers of unstable marsh soil had to be replaced by sand up to depths of 16.00 m below mean sea level.

Wherever possible, the foundation elements were vibrated in order to keep noise to a minimum. Only the piling along the last five metres had to be driven into place to guarantee sufficient load-bearing capacity. The load-retaining slab (total width: 16.00 m) has deep foundations consisting of three rows of PSt 500/158 steel piles. The wave absorber, already a familiar element from former construction projects, is integrated at the head of the quay. The concrete structural elements have a standard thickness of 90 cm and a reinforcement component of approx. 160 kg/m³. The concrete superstructure was produced as a monolithic element over the entire length of 1681 m.

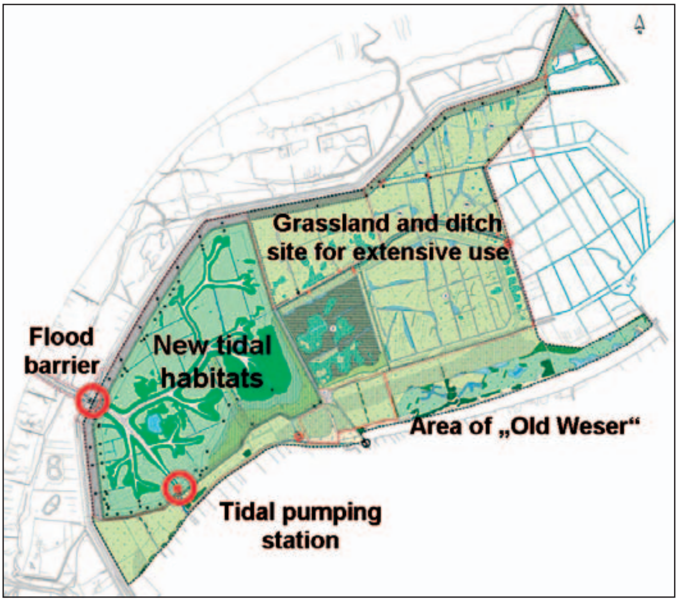


Fig. 5: Environmental compensation scheme on Luneplate

The hinterland of CT 4 covers an area of around 900,000 m². A total of roughly 10 million m³ of sand was needed to raise the level of the entire area. The material itself was obtained by hopper dredgers during maintenance work on the fairways of the Outer Weser and the River Jade. As another part of the overall project, the "Weddewarder Tief", a watercourse that drains the marshy areas to the north of Bremerhaven, had to be rerouted and given a new tidal outlet, so that it now flows into the River Weser to the north of the new terminal site.

To improve hinterland connectivity, the new facilities will also be linked up to a direct rail connection in the course of 2008, with six loading sidings on the eastern boundary. The storage and shunting tracks will also be enlarged in order to cope with the additional traffic volume.

The new terminal facility touches the boundary between Bremen and Lower Saxony. To the north of the site lies the Lower Saxony Wadden Sea National Park. CT 4 was consequently built on an area which consisted largely of protected natural habitats, such as tidal mud flats, brackish reed beds and estuarine salt meadows. These important habitats for flora and fauna were replaced by approx. 110 hectares of land areas for the new terminal and approx. 40 hectares of usable water site. A massive compensation scheme therefore had to go hand in hand with the terminal construction.

The central substitute site for CT 4 is currently under development on Luneplate to the south of Bremerhaven. It involves a tidal habitat with an area of 215 hectares, created by means of a new flood barrier installed in the dyke. A system of artificial tidal channels connected to the Weser will later run through this barrier, enabling the tide to flow in and out here unhampered up to a height of + 2.50 m above mean sea level. Brackish mudflats, brackish reed beds and brackish marshland reed beds will be able to develop here, as well as saltwater ponds and ditches.

The plans envisage a 240-hectare extensively used grassland and ditch site for the east of this tidal polder. This will further improve the area's function as a breeding and resting habitat for migrating birds. Arable land will be converted into grassland for this purpose.

A second compensation measure is under development in the north of Bremerhaven, on the Wursten coastline, where the summer dykes have been opened along a width of 20 to 50 m at 10 different points. This enables high tides from the North Sea to flood the area in front of the main dyke and consequently enhance the ecological quality of the Lower Saxony Wadden Sea National Park.

Container Terminal 4 marks the end of the enlargement process of the container facilities in Bremerhaven for the time being, so that the capacity of the overall terminal complex now ranges – depending on the operational terminal system – from 7 to 9 million TEU annually.

### 4.2 Enlargement of Vessel Turning Zone

While work on the new quay wall was already under way, another important project was initiated to cope with the sharp increase in shipping traffic in front of the container terminals, with container vessels arriving, departing, shifting and turning, and more and more ships passing en route to and from the other terminals in the port cluster of Bremen, Bremerhaven, Brake and Nordenham, as well as the rapid increase in the size of the vessels. This critical combination forced bremenports to enlarge the vessel turning zone in front of the container terminal to facilitate and guarantee safe ship traffic in the future.


Fig. 6: EMMA MAERSK at her maiden call in September 2006 in Bremerhaven

Compared with the usual planning periods required in Germany, the approval process for the project took the spectacularly short period of less than one year and dredging work began for the removal of nearly 2.3 million cubic metres of sand and silt. This created a turning zone which enables two very large container vessels to turn in front of the terminal simultaneously. The new turning zone integrates the old basin, once planned by the Federal Waterways and Shipping Authority for a 300-metre class ship, and gives the new basin a total length of 2600 metres and a width of 600 metres. Following this enlargement of the vessel turning zone to accommodate the new 400-metre class ships, Bremerhaven is now the only German seaport with scheduled calls from the world's largest container vessels.

Dredging works to deepen the River Weser by roughly one metre will be carried out in 2008/2009, aimed at further improving seaward access. This will enable mega-container vessels with a draught of 13.80 metres to access Bremerhaven independent of the tide.

### 4.3 New Building of Sea Lock "*Kaiserschleuse*"

In addition to the container terminal enlargement, the new construction of the 110-year-old "*Kaiserschleuse*" sea lock is another milestone in current developments at Bremen's ports. The old lock, originally inaugurated in 1897 by the German emperor Kaiser Wilhelm, was one of the largest sea locks in the world at that time. However, its dimensions of 185 metres in length, 25 metres in width and 8.5 metres maximum draught do not allow the passage of 32-metre wide vessels, which is the typical size of today's deep-sea car carriers. The increasing


Fig. 7: The new sea lock

maintenance and repair costs and especially the dependency on just one suitable seaward access gateway to the automobile terminals, the northern lock, were the main reasons for the decision made by the Senate of Bremen in 2005 to build the new lock.

The 230 million euro project began with the driving in of the first pile in autumn 2007 and is scheduled for completion in spring 2010. The new lock will be 305 metres long and 55 metres wide, guaranteeing that the car carriers of the future, even assuming the forecast new Panamax dimensions, will be able to serve the automobile logistics centre of Bremerhaven.

### 4.4 Creation of New Berths for Automobile Handling

Construction of the new lock is just one part of a master plan aimed at ensuring the long-term competitiveness and future viability of automobile handling in Bremerhaven, and further measures have recently been implemented. One of them was the creation of new berths with a new quay wall of 550 metres in length, another the provision of additional storage and operating space for the more than two million vehicles which pass the quays in Bremerhaven every year. Both infrastructure measures could be finalised in 2007. They are accompanied by technical improvements to the superstructure which is the responsibility of the operating companies. These companies are planning to invest an additional 170 million euros in the automobile logistics centre by the year 2010.

The master plan was published in 2003 and immediately afterwards the Senate of the Free Hanseatic City of Bremen decided to realise the first project – restructuring the Osthafen area. For this project, bremenports implemented an innovative concept by using cohesive mud from the harbour bed as filling material. The decision was taken because the material would otherwise have had to be brought in from bremenports integrated dredged material management site in Bremen at much higher costs. The project target could finally be achieved even though progress was a bit slower than originally planned. The new flexible berths for use by deep-sea car carriers as well as short-sea car carriers were handed over to the terminal operators in May 2007.

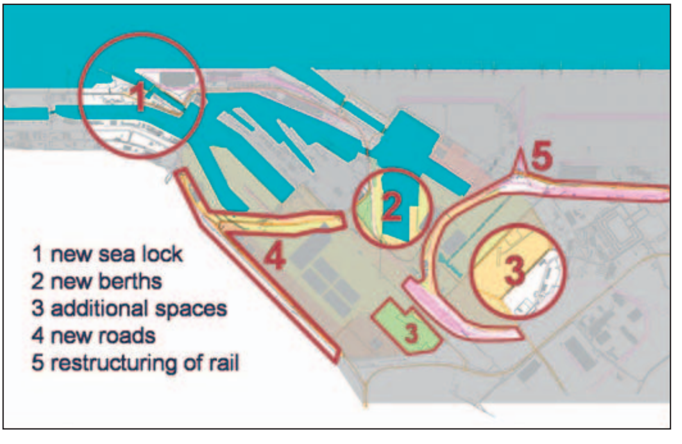


Fig. 8: Master plan for the optimisation of the automobile logistics centre of Bremerhaven

### 4.5 Jade-Weser-Port – Construction of a New German Deep-Water Container Port

As mentioned above, the Container Terminal 4 project marks the end of the enlargement process in Bremerhaven for the time being. Because the terminal has reached its geographical limits, Bremen decided to join forces with the neighbouring Federal Land of Lower Saxony to develop additional terminal capacities 40 kilometres west of Bremerhaven as a joint project. After some initial ideas about setting up a large port in Wilhelmshaven in the 1960s, the vision for a new German deep-water container terminal began to take shape in the mid-1990s. Feasibility studies and preliminary construction plans were drawn up and the administration of Lower Saxony, with backing from Bremen and Hamburg, made the general decision to


Fig. 9: Joint project Jade-Weser-Port

build a new third container port for Germany. The decision for Wilhelmshaven, rather than the city of Cuxhaven on the mouth of the Elbe estuary which had also competed as a location, was taken because Wilhelmshaven offers more expansion opportunities in the long run.

In the first stage, the new container terminal will have a quay length of 1725 metres and will thus be able to berth four giant container vessels at the same time. The anticipated capacity is 2.7 million TEU. Compared to the other German port facilities, the Jade-Weser-Port will offer improved nautical accessibility due to the greater water depth. Important milestones could be reached in 2007, when planning approval was issued by the Federal Waterways

Directorate and the operating concession was awarded to Eurogate, the leading European container terminal operator. Construction is scheduled to begin in spring 2008 and the whole terminal will become operational at the beginning of the next decade.

## 5. Upcoming Projects

On realisation of the above projects, the port facilities in the Federal Land of Bremen will be well prepared for the future, although there is still a great deal to be done in terms of upgrading the hinterland infrastructure transportation system for all modes of transport.

It is vital for the rail terminals in Bremen and Bremerhaven that diverse projects are implemented as soon as possible. This applies above all to upgrading the Bremen rail node – a measure which will eliminate time-consuming bottlenecks in the city. The road connections to the twin ports also have to be improved, with priority going to completion of the A 281 orbital motorway around Bremen, and expanding the A 1 motorway to six lanes. Increasing attention must also be given to planning the A 22 coastal motorway, which will provide a better link between the Weser ports and the economic regions of the Baltic within the next decade. The inland waterway connection will be improved by deepening the Middle Weser, where two locks also have to be upgraded to cope with high-powered barge transports. This will generate new impetus for Bremen as an inland shipping location.

In addition to the growing cargo handling activities, industrial enterprises will in future also boost the development of Bremen's ports. Plans are currently being drawn up to build a huge new dry dock for shipbuilding and repairs. The construction of new coal and gas power stations is under discussion and new production facilities for offshore windmills are being built. The upcoming completion of these projects will tremendously improve the competitive position of local companies and will round off the product and service portfolio at the ports.

As the largest investment project in Bremen's port history is currently in progress, no further spectacular port development measures can be anticipated in the near future, although it is quite likely that this situation will be reconsidered when the current measures start to bear fruit. In this age of continuous growth, this could well be far earlier than we currently believe.

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# The Port of Hamburg

By MICHAEL BÖLTING et al.

Contents



## 1. Location

The geographical position of the Port of Hamburg deep inland is a valuable natural location advantage. It allows seaborne traffic to travel approx. 130 km into the hinterland via the river Elbe without needing expensive overland transport, thus protecting the environ-


Fig. 1: The location of the Port of Hamburg

ment. The fact that railway transport covers more than 70 % of transport services to further hinterland destinations (> 150 km) shows just how environmentally-friendly it is to route cargo via Hamburg. Moreover, the port is closely linked via the River Elbe and the Kiel Canal to the expanding markets around the Baltic Sea, including Russia.

## 2. Key Data

### 2.1 Cargo Handling

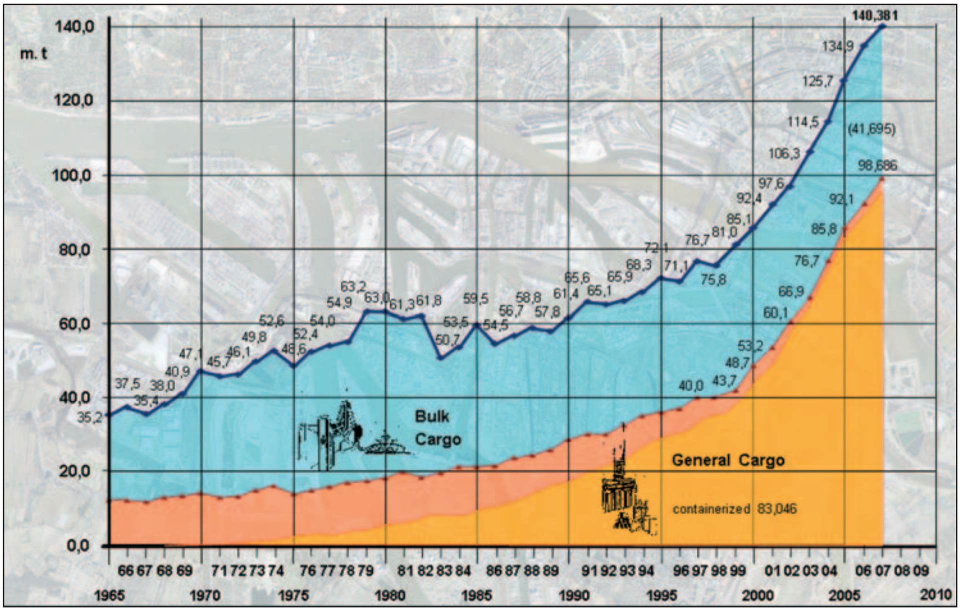


Fig. 2: Total cargo turnover 1965–2007

### 2.2 Hinterland Traffic

Table 1: Inland waterway traffic[1]

| | 1980 | 1990 | 2000 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|---|
| Total cargo (in million tons) | 11.1 | 9.0 | 9.8 | 9.0 | 11.2 | 10.5 | 12.0 |
| No. of ships (x 1,000) | 19.0 | 12.9 | 11.1 | 9.7 | 11.2 | 10.2 | 11.2 |
| Tonnage (in million tons) | 13.8 | 11.4 | 11.4 | 10.6 | 12.2 | 11.3 | 13.8 |

[1] Source: Statistik Nord

Table 2: Port railway

| | 1980 | 1990 | 2000 | 2006 | 2007 |
|---|---|---|---|---|---|
| Volume of traffic (in million tons) | 24.1 | 21.9 | 24.2 | 38.9 | 39.7 |
| Containers (TEU x 1,000) | n. s. | 512.2 | 780.0 | 1587.8 | 1801.6 |
| Incoming and outgoing wagons (x 1,000) | 1498.3 | 1198.3 | 1003.0 | 1543.9 | 1585.2 |

## 2.3 Port area

| | |
|---|---|
| Total port area | 7,236 ha |
| a) land area | 4,249 ha |
| b) water area | 2,987 ha |
| | |
| Utilised port area | 6,403 ha |
| a) land area | 3,416 ha |
| b) water area | 2,987 ha |
| Available port area | 1,634 ha |
| Port extension area | 833 ha |

## 2.4 Water Levels and Fairway Depths

| | |
|---|---|
| Tidal elevation at the tidal gauge Hamburg-St. Pauli | |
| (Mean values for 2001 to 2005) | |
| Mean high water | M.S.L. + 2.10 m |
| Mean low water | M.S.L. – 1.53 m |
| Mean tidal range | 3.63 m |
| | |
| Max permissible draught[2] | |
| Incoming vessels using high tide | 15.10 m |
| Outgoing vessels riding on the tidal wave | 13.80 m |
| Independent of tide, incoming/outgoing | 12.80 m |
| | |
| Bottom of deepest berth | M.S.L. – 17.00 m |

# 3. The Port's Contribution to the City's Economy

The port has always made a very important contribution to employment and the creation of value in Hamburg and the surrounding region. The number of jobs which depend directly and indirectly on the port rose between 2001 and 2006 by around 18,000 to 163,000.

[2] Data for freshwater

The port's contribution to the City of Hamburg's gross domestic product (GDP) has risen to € 12.4 billion, which is equivalent to 14.4 % of the total GDP. The income tax and corporate tax that the port generates for the city has risen from approx. € 586 million (2001) to € 883 million (2006). In 2006, 12.7 % of Hamburg's total tax revenue was generated by the port.

It is anticipated that the port will continue to drive employment and create more jobs. By 2012, the companies that operate in the seaport intend to return around 2,900 long-term unemployed persons back to the labour market. The expansion of facilities at the two largest container terminals will create around 1,800 additional jobs. By 2015, up to 14,000 new jobs will be created in Hamburg's logistics sector. This kind of employment boom would be impossible without the seaport and globalisation. Port-related tax revenue will continue to rise and could reach € 1,089 million by the year 2015.

## 4. The Port's Spatial Structure Development

The modern Port's History started in 1866 when operations at the first modern facility, the Sandtorkai, began. On a length of almost 700 metres, the new Sandtorkai featured quay sheds, 14 metres in width, open on the water side and equipped with ramps. In line with the most advanced technological standard of the era, the quay area was equipped with 16 rotating, steam-powered cranes on rails. The use of this quay as a transhipment point was a revolutionary departure from the traditional method of unloading and loading freighters at moorings in the middle of a harbour. The new facility combined all forms of land and water transport at one site and enabled immediate transhipment and fast sorting of cargo for forwarding. The resulting time savings were enormous. Rail tracks and an access road on the quay ensured a direct link to the land transport.

The Sandtorhafen model would be used as a basis for designing and equipping subsequent harbour basins. After the possibilities for expansion along the right bank of the Elbe adjacent to the city had been exhausted, the systematic construction of the port complex on the left bank of the Elbe began in 1888. The expansion was quickly followed with tremendous "technical energy" by the transformation of the natural landscape into a port complex. The structural element of the Hamburg pier, an innovation that had been tried and tested, was adopted and perfected in terms of its dimensions, equipment and connections. The typical Hamburg port structure was characterized by narrow piers laid out like the fingers of a hand and protruding out towards the Elbe fairway. Following the increase in container transport volumes in the early 70s, the original land structures were no longer capable of meeting the requirements of modern maritime transhipment. While utilisation of hitherto unused areas to the West of the Köhlbrand enabled container traffic to grow dynamically, in 1974 the first restructuring project in the eastern part of the harbour introduced the concept for sustainable land development by filling in entire harbour basins. Since then, there has been a fundamental structural change in the port area. During the last 30 years, the layout of the port has been changed completely from East to West in order to maximize production levels in the existing port. Exploiting the potential of land already in use has provided an ideal infrastructural basis for development. As a result, the port enterprises have been able to use state-of-the-art equipment to obtain high productivity gains at the terminals. In fact, their efforts have made the Port of Hamburg one of the world's top 10 container ports. This consistent reuse of industrial port areas is, in terms of its scope and commercial success, an unrivalled example of


Fig. 3: Restructured areas 1962–2005

sustainable land management. The ongoing project "Restructuring of the central freeport area" is a consequent continuation of Hamburg's successful strategy of "Inward harbour expansion".

## 5. Future Developments

### 5.1 Forecasts

Container traffic through Germany's largest seaport more than doubled in the period between 2000 and 2007 to around 10 million TEU. The cargo handling forecast update for the Port of Hamburg by ISL/Global Insight shows that the volume of cargo handled in containers will increase to 18 million TEU by 2015. The total volume of cargo will increase to 221 million tons (2007: 140 million tons), and around 76 % of all cargo will be packed in containers.

In the 2025 forecast for maritime transport as part of the federal transport route planning, Planco Consulting predicts that the total volume of goods handled in Hamburg in 2025 will be 337 million tons. Container traffic will increase to 235 million tons (not including tare weight), which is equivalent to 27.8 million TEU, putting Hamburg ahead of Rotterdam in terms of container volumes handled.

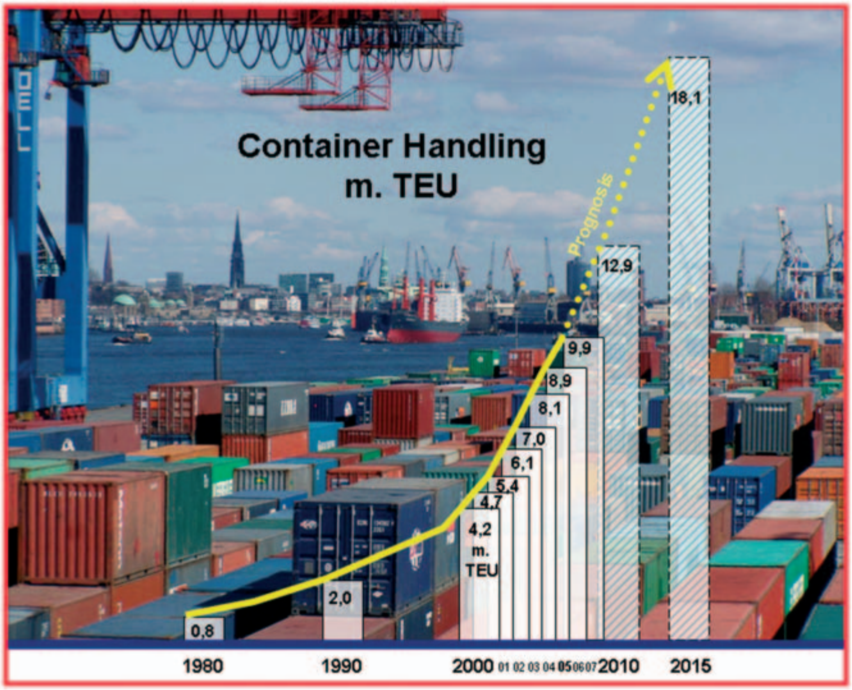


Fig. 4: Container handling prognosis

An investment volume of € 3 billion has been budgeted for the port expansion project, which will run until 2015; this extension and enhancement programme will enable the port to fully exploit all the opportunities presented by the growth in cargo traffic. A central sub-project in the programme is the adaptation of the fairway of the Lower and Outer Elbe.

### 5.2 Increasing Infrastructure and Suprastructure Capacity

The predicted growth in the volume of cargo handled in the Port of Hamburg presents a major challenge for the port's development. The objective of all plans is to provide the necessary handling and transport capacities in a timely, synchronised manner. The strategy which is being used to achieve this goal comprises three coordinated components: increasing efficiency – upgrading existing sites – expansion. The Port of Hamburg's strategy has received international acclaim for its resource-saving redensification approach.

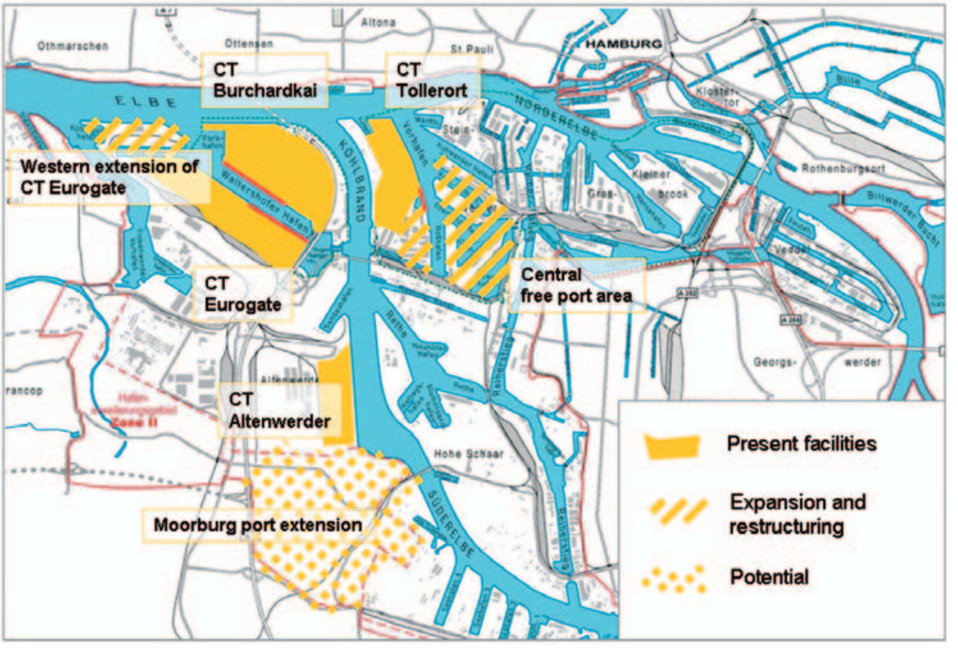


Fig: 5: Overview of the expansion projects

### 5.2.1 Container terminals

The expansion of the existing terminals will include the following measures:

- the capacity of Container Terminal Altenwerder (CTA) will be gradually increased to 3.0 million TEU by 2008 with the final extension target of 4.1 Mio. TEU,
- the handling capacity at Container Terminal Burchardkai (CTB) is to be doubled to 5.2 million TEU by 2012,
- in a two-phase project, the capacity of the EUROGATE Container Terminal Hamburg (CTH) will initially be raised to 4.0 million TEU by 2009,
- the western extension of CTH will increase the capacity by a further 2.0 million TEU to a total of 6.0 million TEU by 2014 and
- a variety of measures at the Container Terminal Tollerort (CTT) will increase the terminal's handling capacity to 2.1 million TEU by 2010. Further options for the extension of CTT will allow to create additional capacity.

#### HHLA CTA

At Container Terminal Altenwerder (CTA) a variety of additional internal improvement measures, site expansions and the optimisation of internal landside processes will increase the capacity from the current level of 3.0 million TEU to 4.0 million TEU. In order to achieve the necessary productivity targets for vessel handling, an optimised horizontal transport (AGV) system must be used to operate all gantry cranes. To optimise the AGV rail system, the Bullerrinne tidal gate at the northern perimeter will be overbuilt in order to create an extension site of approx. 1 ha in the northern section of the quayline. The terminal's expanded container capacity will also lead to an increase in the volumes of project and mixed cargo consignments handled here. Additional sites totalling 2.3 ha will be created to handle these types of consignments in the area directly adjacent to the North of Korbmachersand.

### HHLA CTB

In the first extension project, a new berth for large container vessels will be built directly to the West of the present Berth 1. The new berth will also integrate a berth for feeder ships. The total length of the new extension will be 435 metres plus a 60 metre wing wall. In a subsequent extension project, the wing wall can be upgraded to form a complete quay wall. In the next phase, another new berth for large container vessels will be built to the West of the present Berth 2. A new yard design, based on the system in use at CTA but with an optimised stacking block system, has been gradually phased in at CTB since 2007. There will be 29 blocks, each with three automatic stacking cranes on separate tracks, capable of passing over each other.

### EUROGATE CTH and the western extension

After the new Berth 2 at the Predöhlkai has been completed and starts operating, a further berth for large container vessels will be built in the third project phase. The total length of this new extension will be 330 metres. The extension of the Predöhlkai and the Bubendeyufer will create around 1,000 metres of new and highly efficient quay line for handling large container vessels. The new stretch of quay line created by the western extension joins the existing berths at the Predöhlkai and extends north for approx. 600 metres down to the Elbe. There it turns to the West and extends for approx. 400 metres parallel to Bubendeyufer. The seaward access to the new berths is to be deepened, and the turning circle in the Elbe in front of the new quay line will also be enlarged to a diameter of 600 metres. By filling in the old Petroleumhafen and including the sites located to the North of the harbour basin, 40 ha of additional terminal sites and storage area will be created.

### HHLA CTT and restructuring the central freeport

The gap between the Europakai and the Hachmannkai is to be bridged by building a new stretch of quay line with the same draught conditions for the new generation of very large container vessels. Similar to that at Waltershof; the new quay line is designed to be optionally extendible to the South to keep pace with future growth. Demolition of the old structures and filling in the old basins will be carefully planned to ensure that the work takes place in as short a time as possible and that all mass balances are maintained. Operations will gradually extend towards the filled-in basins of the old Vulkanhafen and Kohlenschiffhafen. The access to the central freeport will be enlarged to accommodate vessels up to 400 metres in length. This will be achieved by demolishing sections of the Toller Ort headland. The measure will also serve to create an access channel to the future Container Terminal Steinwerder. Work on this new terminal, which will be created by completely restructuring the eastern part of the central freeport, is to start in 2011. By 2016, the cargo handling capacity of the central freeport will increase to between 7 and 8 million TEU.

As of 2016, all Hamburg's container terminals will have a combined cargo handling capacity of around 23 million TEU. This target will be achieved by upgrading existing facilities, boosting efficiency and implementing expansion measures within the present port area.

Development of the Altenwerder West logistics site

After the last remaining empty sites in the Dradenau industrial area and the Altenwerder industry and logistics centre have been developed there will be no further sites available for major development projects. At some point in the future, the port could potentially be unable to meet the demand for new sites. To avoid this happening and to ensure that the port remains in a position to offer companies suitable sites, approx. 40 ha in the Zone II port expansion area to the South of the present Altenwerder West logistics centre will be developed and will become part of the utilised port area.

### 5.2.2 Traffic Infrastructure

Rail

Rail transport is set to play an even more important role in transport services to the hinterland in the future. With trains accounting for 25 % of seaborne traffic and with moderate growth in bulk commodity traffic, the volume of goods transported by rail will double by 2015. The number of trains will increase from the present 200 to 400 trains a day via Hamburg. The Hamburg Port Authority (HPA) responded to this anticipated growth by preparing a "Port Railway Hamburg 2015" master plan in close cooperation with the German national railway company, Deutsche Bahn (DB) Netz AG, and all other parties involved. The master plan was passed by the senate and local government of Hamburg. The development concept includes the following objectives:

- priority is to be given to upgrading rail infrastructure in the Port Railway facilities, the terminals and cargo handling companies,
- efficiency is to be increased by optimising and enhancing the coordination of processes and interfaces between all parties involved, including all IT systems and
- the infrastructure of DB Netz AG is to be upgraded.

Based on the results of the maritime traffic forecasts of the Federal Ministry of Transport, Building and Urban Affairs' (BMVBS) and the Port of Hamburg's updated cargo handling predictions, a new master plan will be prepared for the period up to 2025.

Inland waterways

Inland shipping is the most eco-friendly method of shipping cargo from the seaport to the hinterland. The Mid and Upper Elbe represents an environmentally compatible and cost-effective transport route for cargo going to and from the growth regions of south east Europe. The target is to provide a minimum depth of 1.60 metres on 345 days a year as soon as possible and well in advance of the 2010 deadline being discussed by the federal government. These conditions are required to maintain regular transport services between Hamburg and river ports on the Mid and Upper Elbe, right down to the Czech Republic. Improving the navigability of the network of canals in northern Germany, including the Kiel Canal, also plays an important role in ensuring that the transportation of cargo from Hamburg to the hinterland is as clean and environmentally friendly as possible.

Road network

As part of the "Port Road Network 2015" master plan, a traffic concept is presently being prepared to identify all construction measures that will be required. Additionally, the traffic concept examines the impact of operational and organisational measures.

Key construction projects include the following:

- The A 252 cross-port motorway link, which will serve the purpose of keeping the main route through the port clear of non-port traffic and which gives the container terminals in the central freeport a direct link to the motorway.
- Improving traffic flow in the Süderelbe area by building a new bridge to reduce traffic on the old Kattwyk bridge, which is too narrow to cope with present traffic volumes.
- Better road links to the existing terminals and the construction of landside access to the new terminals.

Freeport boundaries will be shifted back from the main roads, which will help to ensure that traffic flows smoothly through the port area. The urgently required extension work on the A 1 and A 7 motorways and the completion of the A 26 and link to the A7 motorway must be expedited to ensure that hinterland traffic from the port can run smoothly.

The "Port Road Network 2015" master plan will also include an in-depth analysis of the potential for an effective traffic management system for the port's road network, an integrated traffic control scheme for the trucks entering the port and an action plan to implement these recommendations.

### 5.3 Deepening the Fairway in the Lower and Outer Elbe

The Lower Elbe, a federal waterway, is the seaward access to the Port of Hamburg. It is one of the most important and busiest waterways in Europe and is also the lifeline of the entire region. Under the plans for the fairway adaptation, the Lower and Outer Elbe would be made navigable for large vessels with draughts of up to 14.50 m. Recent years have seen a steep increase in the number of very large container vessels with draughts of 14.50 m. These vessels are expected to become the typical workhorses in the booming international cargo transport industry.

Presently, the Lower Elbe can only be navigated by departing vessels with a maximum draught of 12.50 metres independent of the tide and 13.50 metres at high tide. This means that restrictions will apply if the new super vessels wish to dock in Hamburg, which they can presently only do when not fully laden. Adapting access conditions is urgently required if the Port of Hamburg intends to continue playing a leading role in global container traffic. Container handling will continue to be increasingly important for the city and the port.

The section of the fairway which must be adapted is around 130 km long and stretches from the Port of Hamburg to the Großer Vogelsand in the Outer Elbe. The implementation of this project will require that around 38.5 million $m^3$ of sediment – mainly sand, but also till deposited in the ice ages – be dredged in the fairway. The major portion of the dredged material will be used for an integrated river construction project at the mouth of the Elbe. As part of this project, submerged banks will be built to minimise the hydrological impact of the fairway deepening. The river construction plan also helps to ensure that the fairway adaptation project is environmentally compatible and has no impact on high tide levels. The impact of the fairway project on the environment will be minimal.

The fairway adaptation will commence as soon as the planning approval procedure has been completed. The approval is expected in mid-2009. The realization of this important project will make a substantial contribution to the port's economic viability and ability to compete globally, and will help to boost economic growth in the whole of northern Germany.

For further port development information concerning e. g. 'City and Port' or 'Environmental protection' see the port development plan "Focus of dynamic growth markets – Prospects and development potential for the Port of Hamburg". It is available at Hamburg Port Authority, telephone: 040/42847-2311 & 040/42847-2301. Internet: www.hamburg-port-authority.de.

Die Küste, 74 ICCE (2008), 1-417

# The Ports of Schleswig-Holstein

## Hubs of maritime economy between North and Baltic Sea and Continental Europe

By GESAMTVERBAND SCHLESWIG-HOLSTEINISCHER HÄFEN

Contents



## 1. Introduction

The range of Schleswig-Holstein ports is manifold: High performance installations for handling large numbers of passengers, bulk and mixed cargo, as well as of Ro-Ro freight are available in the major sea ports. A consolidated network of regular ferry and freight lines provide continuous service to the Northern European States, as well as to Russia and the Baltic States. Destination and source areas of the products handled in these ports extend from the German industrial centres far into mid-, western- and southern European Sates. Numerous regionally important harbours open the waterways for Schleswig-Holstein's trades and industry, afford unobstructed traffic to the islands and create an essential basis for local fisheries. Schleswig-Holstein's ports along the Lower Elbe between Hamburg and the North Sea are partly located on junctions of the Elbe and the Kiel Canal. Due to their location, the ports of Brunsbüttel, Glückstadt and Wedel, are ideal partners for Metropolitan Hamburg in managing its streams of goods and traffic by water, rail and road. These Lower Elbe ports are poised to relieve the strain on Hamburg's traffic arteries.

Schleswig-Holstein also has, by nature of its location as a "Country between the Seas", a traditionally strong maritime imprint in the tourist trade. With its 1,190 km of coastline, 250 lakes, the Kiel Canal and a multitude of rivers and creeks, Schleswig-Holstein possesses ideal conditions and development potential for aquatic tourism. Roughly 30,000 pleasure craft are home-ported here, and their skippers find attractive services for boating.

All told, roughly 47,000 persons are employed in Schleswig-Holstein's maritime industry. In connection, the ports provide important transit functions for the handling of traffic via environmentally compatible sea routes and create the prerequisites for multifaceted revenue and employment in maritime industry branches, as well as in tourism.

## 2. Selected Ports as Examples for the Current Situation and Development

Approximately 86 % of the entire cargo turnover of Schleswig-Holstein are accrued by the ports of **Lübeck, Brunsbüttel, Puttgarden, Rendsburg, Flensburg** und **Kiel**. Of this total, 72 % consist of trade with other Baltic States, primarily Sweden, Russia, Denmark and Finland.

### 2.1 Lübeck – Germany's largest Baltic Port

The port of Lübeck is the southernmost trans-shipment centre on the Baltic Sea and has become the central hub for traffic between the traditional Western- and Central-European industrial centres and the rapidly developing Baltic Economic Area. Almost 33 million tons of goods were turned over in 2007, the Lübeck Port Corporation (LHG) amassing a 90 % share in these transactions.

One of the most important factors in the success of this by far largest German Baltic port with a market share of over 40 %, is the extremely high departure schedule of the regular shipping lines. The ports of Lübeck offer over 150 departures per week connecting to 25 partner ports along the entire Baltic Sea and, thus, afford the highest ability to deliver, as well as to safeguard the European cargo flow. The services to each destination are largely matched, so that the freight capacities of both the ferries, as well as the hinterland transports are always fully utilised. Thus, compared to alternative transportation routes, substantial financial advantages for transport companies can be expected.

Additionally, the Port of Lübeck extends the advantages of a logistics centre, commanding a high degree of quality and know-how. This goes especially for forestry products such as paper and pulp. Lübeck is the largest turnover and distribution centre for the Swedish and Finnish paper industry in Europe. Over 4 million tons of paper were shipped via Lübeck in 2007.

Lübeck's strength lies in RoRo transport, i.e. expedited cargo, which rolls on- and off-board on trucks, undercarriage units, owned by the shipping company, or railway cars. Individually tailored logistics systems provide the customer with the guarantee of optimum service, 365 days per year. Approximately 850.000 trailers and trucks, as well as 200.000 new vehicles are shipped annually via Lübeck. Handling of more than 200,000 standard containers (TEU) makes Lübeck the largest German container port on the Baltic. In addition, 700,000 passengers embarked or disembarked in the port of Lübeck in 2007.

The location of the Port of Lübeck offers an exceptional transportation network to the hinterland. The three-lane autobahn A1, via Hamburg, ties Lübeck to the major economical centres of Europe. The railway network is marked by its high efficiency in 'Dedicated and Combined Cargo Service'. Each week, approx. 150 block and dedicated trains depart for the major European industrial centres. The Elbe-Lübeck-Canal supports this connectivity by giving access to the European inland waterway system.

Over the preceding years, the number of employees in the port has risen steadily. At present, the LHG holds 1,050 workers in direct employment. In total, 7,000 jobs are directly dependent on the harbour. This makes the port of Lübeck a major contributor to the current revenue and economic stability of the region.

The LHG operates five port sections with a total area of over 170 hectares and 26 berths.

**Skandinavienkai Terminal:** Europe's biggest ferry port in Lübeck-Travemünde offers over 80 departures per week at 9 piers, of which two are equipped with railway access. In 2007, 22 million tons of cargo were turned over. Emphasis lies on handling all types of rolling goods such as trucks, trailers, new-production vehicles, railway cars, chassis, containers and passenger cars. The handling of mixed cargo is also possible. A railway terminal for 'combined freight transport' (KV) was opened in May of 2003 and handles about 100,000 units annually. In the previous years, the Skandinavienkai terminal has been substantially improved, expanding the area, creating new berths, a new access tract, areas for harbour-related industry, as well as a spacious administration building.

**Nordlandkai Terminal:** In 2007, the Finland-Centre of the Port of Lübeck showed a turnover of 3.9 million tons. Including five berths and a warehouse capacity of 130.000 square meters, the Nordlandkai is the primary distribution centre of the Finnish paper industry for all of Europe. Further goods being handled here consist of trucks and trailers, new-production vehicles, containers and all types of heavy lift and mixed cargo. Expansion areas, which would enable a substantial increase in the terminal's capacity, are currently being planned. In early 2007, a new concept based on specialised containers for paper freight handling was implemented on the Nordlandkai, involving new ships and handling installations.

**Schlutup Terminal:** Completed in 1994, the terminal is the leading European distribution centre for the Swedish paper industry with a volume of 1.8 million tons in 2007. The warehouse capacity amounts to 64,000 m².

**Seelandkai Terminal:** The new container and RoRo-terminal has been operational since the late summer of 2006. On just under 20 hectares, trailers, new vehicles and containers are dispatched. Containers can be loaded either by the RoRo-system or by container bridges. In its first year of operation, 1.4 million tons were turned over.

Fig. 1: Aerial photo of the Skandinavienkai Terminal in Lübeck-Travemünde.
Photo: LHG/Vögele

**Konstinkai Terminal:** The multi-functional RoRo-terminal for forestry products, trucks, trailer, new vehicles and heavy lift cargo and bulk material offers 24,500 m² of warehouse capacity. Following a restructuring in 2007, the Konstinkai Terminal is now the location of a new ferry connection to St. Petersburg, as well as of an additional handling centre for paper products from Finland.

### 2.2 Port Operating Company Brunsbüttel / Harbour Group Brunsbüttel and Glückstadt

The former federal state-owned ports of Brunsbüttel, *Elbehafen*, *Ölhafen* and *Hafen Ostermoor*, have been privately owned since 1999 and are operated and maintained by the Port Brunsbüttel Ltd. They continue to be "public ports", servicing the industrial area of the Lower Elbe around Brunsbüttel, but also carrying out a supra-regional transhipment functions. The Port Association Brunsbüttel Ltd. is part of the privately held Schramm Group with headquarters in Brunsbüttel.

The Elbehafen Brunsbüttel, built in 1968, plays a decisive role for metropolitan Hamburg. It is located at the Elbe estuary downstream of Hamburg, at the junction of the Elbe and the Kiel Canal near the open sea. Thus, it is an ideal location joining water, rail and road transport. The Elbehafen specialises primarily in the handling of dry and liquid bulk cargo. In addition, a concentration on the up-and-coming bulk goods sector is complemented by a strong commitment to project logistics and to the container business. Ocean-going vessels profit from the easy access to the *Elbehafen*.

A little further upstream, the harbour of Glückstadt is located directly on the Lower Elbe as part of a chain of harbours along the Elbe estuary between Hamburg and Brunsbüttel. The harbour is federal state property and is operated by the Harbour Operating Company Glückstadt Ltd., under the auspices of the Port Operating Company Brunsbüttel within the Schramm Group.

With an emphasis on the Elbehafen, the Port Operating Company Brunsbüttel ranks sixth in volume among German seaports. The Elbehafen alone handles approx. 6 million tons of goods annually, among them hazardous materials. Thus, the port is subject to stringent safety standards. For 2007, the cargo volume of the Elbehafen can be broken up as follows: about 40 % fluid goods such as oil and gas, about 55 % bulk goods such as ore, fertilizer and coal, etc. and roughly 5 % heavy lift cargo and containers.

Enough flexible berths along the 1,100 meters of quay, handling equipment, stationary and mobile cranes are available to ensure short cycle times. Storage installations for bulk goods (250,000 m²), warehouses (in addition to the new copper ore storage for Norddeutsche Affinerie for 120,000 tons, ca. 12,000 m²), as well as storage areas for containers are available in abundance and can be easily expanded at short notice. On shore, high-performance conveyor belts are readily available and are constantly being upgraded. Several siding tracks connect to the main network. The entire site is closed off and barred to the public. The Operating Company has been ISO 9002- and SCC-certified since 1999.

The volume of goods turned over in Brunsbüttel has enjoyed a very positive development in comparison to previous years, showing a 50 % increase from 2006 to 2007. Thus, the Brunsbüttel Elbehafen ranks first among German seaports in percentage progression. The years since privatisation of the port in 1999 have been shaped by continuous growth and canvassing of clients, diversification of product types being handled, ranging from coal to fertilizer and lumber unto wind power plants. A container terminal for combined cargo

Fig. 2: Elbehafen Brunsbüttel, aerial view

traffic was built, alongside the continuous expansion and enhancement of storage space, warehouses and handling equipment.

One of the highlights of this development was the acquisition of the handling of raw materials (copper ore) for Norddeutsche Affinerie of Hamburg in 2007, with an investment volume of 38 million Euros in storage facilities, quay equipment and operating facilities. This was tantamount to a quantum leap for the Port Operating Company Brunsbüttel and proved their consistent long-term investment policies in securing the location and workforce. As a result, new employment opportunities at the company and within the Schramm Group were continually being created. The Norddeutsche Affinerie Project alone accounted for 40 new jobs. Currently, the Port Operating Company Brunsbüttel has a workforce of nearly 100.

Additional growth potential for the Elbehafen arises from the handling of coal and by-products for the newly planned coal-fired power plants in Brunsbüttel. To meet the potential requirements, the Port Operating Company is considering a possible extension of its capacities, in particular the lengthening of the quay by roughly 360 meters. The company is well aware of the port's central role for the Brunsbüttel industrial region and is willing to meet the challenges within the framework of economically responsible investment planning, coupled with support by investors and the federal state.

### 2.3 Rendsburg District Harbour

The Rendsburg District Harbour has been in existence since the opening of the Kiel Canal in 1895. The port has a traditionally high agricultural orientation. Two large animal feed plants are located here, which are supplied with raw materials from South America and

Africa via the port. The export of grain is of considerable importance to Rendsburg, with Northern Africa being the major destination. Further bulk goods being handled in large quantities particularly include building materials and mineral oil.

The District Harbour Rendsburg-Eckernförde counts among the most environmentallyfriendly in Schleswig-Holstein. It possesses a complex system for the treatment of surface water, as well as an encapsulated handling plant for fertilizer, unique to Northern Germany. In regards to port safety, Rendsburg meets the highest requirements.

Due to its central location in Schleswig-Holstein, the Rendsburg District Harbour offers ideal conditions for the onward transport of all kinds of imported goods to the interior. This applies equally to the storage and transhipment of export goods such as grain, lumber or bulk material. The port's connection to the railway system is currently shut down, but can be reactivated at short notice, when required.

The Rendsburg District Harbour is operated by the Business Development Association of the County of Rendsburg-Eckernförde, which – in cooperation with the municipality of Osterrönfeld on the opposite side of the Kiel Canal – will shortly begin construction of a new port with specialisation in heavy lift cargo and containers. Completion is scheduled for the fall of 2009. The new port will have a direct access to the A7 autobahn, and its main emphasis will be in handling of wind-power generators for off-shore operation.

### 2.4 Flensburg

The Port of Flensburg offers 800 meters of quays for ocean-going vessels with a length of up to 220 meters and a draft of up to 8,50 m, as well as inland vessels with approved seaworthiness. Separate sectors of the Flensburg Port are dedicated to loading and unloading of miscellaneous types of bulk and mixed cargo.

A direct link to the road network and the advantageous proximity to the Scandinavian and Baltic neighbours make the port of Flensburg an attractive transhipment location.

Passenger traffic has enjoyed a renewed growth over the last few years. In this respect, the Flensburg port profits from an attractive downtown core and the plentiful tourist attractions in the surrounding area. This has also been recognised by several cruise lines, making Flensburg a regular port of call for cruise ships in addition to the existing regular service ferries on the bay.

Core of the transhipment operations via the Port of Flensburg is the handling of bulk goods. For this year, the port counts on a volume of 550,000 to 600,000 tons. Last year's volume of 550,000 t was tackled with 5 cranes with a lift capacity of 5–40 t, a continuous conveyor system for bulk, a pneumatic suction device and two loading conduits. Warehouse and storage areas of 3,500 $m^2$ and 12,000 $m^2$, respectively, emphasize the transhipment capabilities of the Port of Flensburg. Further storage facilities are privately owned and can be made available upon request.

In the new year, the first of two mobile high-performance cranes was handed over to the Flensburg Port Ltd.. With the support of its "big brother", it will tremendously increase turnover speed.

This shows that the Port of Flensburg is preparing for future challenges. After several difficult years for the port economy, it is now easily recognisable that the producing industry of the region, as well as the federal state government, have renewed their confidence in the port and its future potential. This can be rightfully claimed due to the port's ideal location.

Fig. 3: New harbour crane in Flensburg

Situated close to the border the Port of Flensburg is, furthermore, an integral part of the European domestic and foreign trade. The changing political climate and growing international trade support the increasing importance of the port, which takes on an additional role, while other, often larger ports reach the limits of their capacities in the way of ferry operations and container handling. Independent of that, industrial enterprises such as the shipyard of the Flensburger Schiffbau Gesellschaft Ltd. – a market leader in RoRo- and RoPax-shipbuilding – have taken good advantage of the unimpeded access to the open sea from their production facilities. Thereby, large vessel sections and engines can be delivered on the waterway.

Over the last 100 years, Flensburg, a port city with a 700-year old tradition, has proven that it will always meet new challenges and adapt to them. With an investment into new quays, piers and handling capacities, the local and regional economy has been given an attractive opportunity to use the sea as an increasingly advantageous transport route. This background assures the Port of Flensburg an ever growing significance.

### 2.5 Seaport Kiel – Logistics Hub and Germany's most important Cruise Terminal

The **Seaport Kiel**, with its many different harbour sections around the Bay (Kieler Förde), offers more than 5,000 meters of quays and piers for ocean-going and inland vessels of almost every size. Its ideal geographic location, continually navigable waters and direct access to the railway and road network, its direct connection with the busiest waterway in the world, the Kiel Canal, as well as with the European inland waterway system, make the

Fig. 4: Seaport Kiel

port equally attractive for transhipment and passenger service. Ferry operations make up about 2/3 of the total volume of over 5 Mio. tons, handled in 2007, and form the economic backbone of Kiel's port. The passenger volume of over 1.6 million travellers emphasizes the attractiveness and potential of Kiel for tourism.

The major proportion of harbour activities consists of transit cargo. Kiel's trading sphere stretches from Scandinavia over Finland and Eastern Europe down to Southern and Southwestern Europe. Combining high-performance installations, an advantageous geographical location and an extensive schedule of ferry and regular-route departures, the Port of Kiel has become a central gateway and logistics hub for domestic and foreign trade within the European traffic system. Thus, it is an important part of the European infrastructure.

Kiel has taken on this role despite its relatively brief history in comparison to other ports, owing much of its development to the emerging RoRo-traffic of the 1960's and the connected structural change in Baltic Sea shipping. Kiel availed itself of these opportunities through a constructive and progressive harbour and investment policy.

The 1961 construction of the former 'Oslokai' (now 'Ostseekai'), an installation for the handling of ferries with passengers and rolling cargo, laid the cornerstone for Kiel's reputation as 'Gateway to the North'. The following decades saw extensive port reconstruction measures, which shaped the appearance and broad range of services of today's port: the 'Schwedenkai', another terminal for combined ferry service, was constructed in 1982. The 'Ostuferhafen' – former shipyards taken over in 1985 – has been converted into a functional, high-capacity transhipment centre with financial support by the federal state, the federal government and the EU. It now includes 10 berths, 7 of them RoRo-docks, approx. 30 hectares of terminal area and 2.5 hectares warehouse space, as well as a handling facility for 'combined freight traffic' (KV). Along a total of 1,700 m of quays, with a water depth of up to 11.5 m, the Ostuferhafen handles roughly half of the total volume of cargo in the seaport, especially for the Eastern European sector.

The former Oslokai could no longer handle increasing ship sizes and cargo volumes on the Norwegian ferry routes. In the mid-90's, this led to the construction of the 'Norwegenkai' with 2 docks for modern Combi-ferries, 400 m of quays with a water depth of 10 m, a multi-level terminal building for passengers and the clearance of rolling cargo, as well as handling, storage and traffic areas.

Together with the traditional ferry and cargo traffic, the cruise ship business has been gaining an ever larger market share in Kiel. Within one decade, the number of departures has tripled, the number of passengers even increased eight-fold. With 114 departures, Kiel was Germany's most popular port of call in 2007 with the number of passengers rising to 173,000 (+ 12 %). 127 departures are already registered for the 2008 season; 190,000 travellers are expected. With financial support from the federal state of Schleswig-Holstein and the German federal government, the Ostseekai (the former Oslokai) was converted into a cruise terminal in 2006/2007 to accommodate the increased volume. With two berths with lengths of 360 m and 285 m, a guaranteed water depth of 10 m and an attractive, glass-front terminal building with two levels, which offers direct access to the ships via mobile gangway bridges, the old Oslokai was converted into one of the most capable installations of its kind in all of Northern Europe. With a total area of 40,000 m², the terminal is ideally suited to serving large cruise ships and offers generous facilities for 3,000 passengers, as well as excellent accessibility by rail, bus and car.

The mean annual growth rate of 5 %, shown by external prognoses for the future development of the Seaport Kiel, is considered positive. Moreover, the RoRo- and container trade, particularly with Eastern European destinations, is allotted an especially positive growth potential. Even the cruise sector, according to industry prognoses, can look forward to a sustainable growth.

With this background, the conceptual planning for a powerful development of capacities for future transport requirements is currently being devised: the expansion of the Ostuferhafen, as well as of the Norwegenkai by a total of 5 hectares is already in the planning stages. Plans for the Schwedenkai call for the renewal of the terminal building with a significant increase of service area and handling capacities in light of the expanding cruise ship sector. Furthermore, numerous capital investments aim to strengthen the supra-structure and improve the quay equipment.

### 2.6 Puttgarden

Presently, the ferry port of Puttgarden is Germany's biggest passenger port and one of the most important transit passages for freight between Continental Europe, Denmark and Sweden. In 2007, the Scandlines Shipping Line carried roughly 7 million passengers, almost 1.8 million passenger cars, 388,000 trucks, 32,500 busses and 8,600 railway passenger cars on the Puttgarden-Rødby route.

The Port of Puttgarden is located on the northern tip of the island of Fehmarn, at the end of the E47 highway connecting to the A1 autobahn, and covers a total area of ca. 36,000 m². Enclosed by two moles the harbour has a guaranteed depth of 8.50 m. A considerable percentage of the entire surface area of the port is staging area for outbound vehicles (cars, trucks, motor homes, busses, etc.). It also includes service areas for catering and maintenance of the vessels of the Scandlines Shipping Line, as well as their technical installations.

Fig. 5: Puttgarden Ferryport (Source: Scandlines GmbH)

Of the existing four ferry docks, two are in continuous operation for 24 hours a day. The four double-ended Scandlines ferries – commissioned between 1997 and 1998 are the – “Deutschland”; “Schleswig-Holstein”, “Prinsesse Benedikte” and “Prins Richard” – operate around the clock at 30-minute intervals. One of the piers allows the embarkation of the Danish IC 3 train set as well as of the German ICE-TD onto one of the double-ended ferries. As of December 9, 2007, the Puttgarden-Rødby ferry is part of the new ICE connection Berlin-Copenhagen. Another dock is used for the transport of hazardous goods on the FS “Holger Danske”.

In 2001, sheet piling was put up in the western part of the port, and a total area of 10.000 m² was reclaimed. As of late 2001, the “Portcenter” has found its new ‘berth’ here. It is home to Scandlines’ “Bordershop”, with a sales area of 6,000 m² on 4 floors.

The history of the Puttgarden Ferryport goes back to the year 1958, when the German and Danish governments signed an agreement on the extension of the “Vogelfluglinie” project, the most direct connection between the two countries. In the following construction phase, two moles of 630 m and 820 m were erected in Puttgarden, and 850,000 m³ of sand were dredged in the harbour basin. With the completion of the ‘Fehmarn Sound Bridge’ and the two ferry ports, the ‘Vogelfluglinie’ Puttgarden–Rødby was officially opened by the Danish king Frederik IX. and the German Federal President Dr. Heinrich Lübke on May 14, 1963. The ferry service, originally operated by the German Federal Railways and the Danish State Railway, has now been taken over by Scandlines Ltd.

From 1996 to 1998, Scandlines invested approximately 270 million Euros in a sophisticated, future-oriented ferry concept and innovative port logistics. With the introduction of four modern double-ended ferries, the transit time has been reduced from 60 to 45 minutes.

The 'Vogelfluglinie' has been a success from the beginning: in the first year of its existence, 2 million passengers used this shortest ferry connection between Germany and Scandinavia. In 2002, their number had risen to 6.6 million.

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# Ports in Mecklenburg-Vorpommern

By Ulrich Bauermeister

Contents



## 1. Introduction

In the heyday of the Hanseatic League, virtually all of the ports active in Mecklenburg-Vorpommern today were important trading centres on the "Mare Balticum" and their long-distance merchants were members of the Hanseatic merchant guild.

In former East Germany, the locations for cargo handling between Wismar and Ueckermünde played their role as centres of sea-bound foreign trade until 1989. It was not the market that decided the path of the goods, but rather political demands. In 1990 a process of fundamental restructuring began for the ports in Mecklenburg-Vorpommern. The top priority was to establish a competitive maritime transport industry: to catch up on productivity lags, to rearrange the cost-intensive and largely worn-out port infra- and superstructure and to adapt the traffic connections by sea and to the hinterland to the new requirements.

With the arrival of the new millennium this restructuring process has been mostly completed. Sea access routes to Wismar, Rostock, Stralsund and Wolgast have been deepened and widened. Today Mecklenburg-Vorpommern has modern, efficient ports with excellent transport connections by sea and land.

The construction of modern terminals for handling environmentally and weather-sensitive bulk cargo as well as facilities for handling and manufacture of wood in Wismar, the upgrading of berths for super tankers in Rostock, the construction of new, efficient ferry facilities for the transport of standard-gauge railway wagons and for road haulage and passenger traffic at the ferry ports of Sassnitz and Rostock as well as the newly built or reconditioned berths in Stralsund and Wolgast describe this development process, which has led to a highly efficient port industry.

The federal trunk road network has also been reconditioned and extended. The most important road project is the A 20 motorway which connected all seaports directly to the western European trunk road network since 2005.

The completion of the A 20 has provided major stimuli for traffic via the ports of Mecklenburg-Vorpommern. The good railway connections in the north-south direction are being complemented by the traffic project No. 1 instituted after German reunification, the refurbished railway line Lübeck – Hagenow Land – Stralsund which provides the link in the eastwest direction. On this basis the ports of Mecklenburg-Vorpommern face the competition as major logistics sites at the Southern Baltic Sea Coast.

The ports' position in the market is reflected in their confident slogan "When you say Baltic Sea, you mean us". The impressive achievements of the last 18 years are a clear indication of this. The fact that smaller ports such as Wolgast, Greifswald, Ueckermünde or the cargo and fishing port of Rostock have taken up commercial seaport cargo handling and increasingly contribute to growing handling volumes is particularly noteworthy.

The spread of efficient ports along the relatively long coastline allows for excellent radial development of the immediate and the wider hinterland which is of particular interest for implementing the "from road to sea" concept.

The economic region around the Baltic Sea, which is the key operating area of the ports in Mecklenburg-Vorpommern, has around 100 million inhabitants spread over an area of 2.4 million square kilometres and is one of the strongest growth regions in the European Union (EU). This will result in an even greater increase in the exchange of goods, which is forecast to have an annual growth rate of three to four percent in terms of tonnage loaded. The basis for this positive trend is provided by the enlargement East of the EU. This must now be the focal point for the planning and implementation of trans-european transport networks.

Ferry and ro-ro operations form the transport technology on the Baltic Sea. Ferry traffic in particular is determined by the increase in the speed of transport sequences. Increasingly the location in terms of traffic geography is becoming a prime criterion for assessment and decision-making when it comes to choosing the routes and the cargo flows in ferry transport, and this is what makes the ports of Mecklenburg-Vorpommern transport hubs in the southern Baltic Sea today. Moreover, the ports in Mecklenburg-Vorpommern are the best locations to avoid the bottelnecks on road and rail at the North Sea ports.

## 2. Seaport of Rostock

With the enlargement of the EU the Port of Rostock has gained yet more importance as a traffic hub. The settlement of the industrial enterprise Liebherr has also put the port on the map as a major industrial estate of the Hanseatic City of Rostock. Currently there are more than 150 companies in and around the port of Rostock who handle, store, produce or offer services to shipping, transportation, handling, storage and treatment of goods. Around 9,000 people are directly and indirectly employed at the port.

The port of Rostock looks back on 800 years of history. From the 14th to the 17th century Rostock was a major site of the Hanseatic League. In subsequent centuries there were many ups and downs. With the opening of a new seaport on river Warnow in 1960 the former East Germany made Rostock its "gateway to the world". In the following years the so-called overseas port was expanded into an efficient universal port. After German reunification the port began its transformation into a Baltic Sea port with a thoroughly altered appearance and range of services. With a modern oil port, facilities for grain, coal, fertilizer and cement handling and with the terminals for general cargo export it continues to be a universal centre of transshipment. No other German port on the Baltic coast offers such a wide range of services as Rostock seaport.

But, thanks to the very good road and rail connections, its heart became the ferry port with its adjoining terminals for intermodal transport, for paper and ro-ro traffic.

Ferry traffic, in particular, is seeing rapid growth. Modern ferries of the shipping companies Scandlines, Tallink Silja, TT-Line and Finnlines connect Rostock with Denmark, Sweden, Finland, Estonia and Latvia. More than two million passengers use the most important German passenger ferry port every year. Rostock has the largest number of liner connections to and from Germany. With more than 100 arrivals of about 30 cruise ships and approximately 170,000 passengers Rostock also underscores its significance as one of Germany's most important cruise ship ports. The new Warnemünde Cruise Centre offers ideal conditions for cruises to the North Sea and the Baltic Sea.

Fig. 1: Seaport Rostock (54° 09' N, 12° 06' E)

Rostock seaport is one of the most important centres for tri-modal traffic on the Baltic Sea. With the Baltic Sea motorway A 20 between Lübeck in the west and Stettin (Szczecin) in the east and with the north-south motorway A 19 between Rostock and Berlin the road connections are outstanding. In a few years, when the motorway A 14 between Wismar and Magdeburg will be finished, the road-connections will be much better. Combined with direct trains as part of intermodal traffic from and to Basel, Verona, Duisburg and Wels the Port of Rostock forms an important and high capacity junction between Scandinavia and Central Europe.

### 2.1 Hafen-Entwicklungsgesellschaft Rostock mbH

The federal state of Mecklenburg-Vorpommern and the Hanseatic City of Rostock are the owners of the port of Rostock. Their interests are represented by the Hafen-Entwicklungsgesellschaft Rostock. The name of the company reflects the will of the city and the state to develop the largest port in the state in such a way that it meets the continuously rising demands of forwarders and tourism.

Hafen-Entwicklungsgesellschaft Rostock focuses its work on a forward-looking upgrading and expansion of the infrastructure and on its maintenance. As the owner of the land, the quay facilities and the aquatory the company ensures in close cooperation with the shipping industry and the port companies working on site that Rostock has all prerequisites in order to continually improve its competitive position. On behalf of its owners the company pursues an active policy of canvassing new companies to settle at the port. In the leasing of land and the renting of buildings it follows the principle of opening up new fields of business by encouraging competition at the port, winning over new customers and canvassing goods.

Hafen-Entwicklungsgesellschaft Rostock, which is certified to DIN EN ISO 9001:2000, is the sole operator of the ferry and cruise port. It is also a shareholder of the operating company at the multimodal transport terminal.

It is also the task of the company to perform and market further services which serve to improve the competitive position of the company or the location. To this end it may establish and acquire companies, participate in them or use other companies; it may establish, acquire and lease ancillary companies and branch offices and open subsidiaries. As far as these concern cargo handling services or activities in the field of storage and treatment of goods the company may however neither perform these itself nor through a company in which it holds a majority stake.

It is the cleared aim of the Hafen-Entwicklungsgesellschaft to further consolidate the market position of the port as a modern, competitive logistics centre under the umbrella brand “Rostock Port”. Much has already been done towards this in the past. Hundreds of millions of Euro have been invested in improving the port infrastructure since 1991.

By attracting large manufacturing companies who produce, among other things, mobile cranes or large pipes, rapeseed oil or biodiesel the port managed to improve its competitive position. The establishment of further cargo handling, distribution and industrial businesses will continue to add to the profile of the location in years to come.

### 2.2 Freight and Fishing Port of Rostock

Rostocker Fracht- und Fischereihafen GmbH, a company certified to DIN EN ISO 9001:2000 and GMP, is the sensible logistical alternative in Baltic Sea traffic: its excellent location in the south-western bend of the lower Warnow river with good railway and road links to the A 19 and A 20 motorways allows for a fast transportation of goods to and from Scandinavia, Eastern Europe and the Baltic states.

The port is a flexible company which continues to successfully expand its range of services. Its specialisation favours the handling and storage of bulk goods, general cargo and project cargo. It has the particular advantage of providing a refurbished cold storage unit certified to EU standards for refrigerated and frozen products which is situated right by the pier.

With the well developed infrastructure and the change in its profile the entire port territory upgraded into a modern industrial estate and offers the best prerequisites for the establishment of companies.

Modern cargo handling facilities, an own port railway, best storage conditions and an experienced port crew allow for an all-round port operation and assure professional handling of bulk and general cargo. The 10 km of railway tracks as well as mobile cranes guarantee quick discharging and loading operations.

Storage, securing of cargo and other services will be performed reliably, quickly and correctly upon request by customers. All points of transshipment and facilities have a rail and road connection and allow for an efficient transport chain within the European logistics network.

Fig. 2: Rostock freight- and fishing port (54° 07' N, 12° 05' E)

## 3. Ferryport of Sassnitz

The ferry port of Sassnitz/Mukran, situated on the north-easternmost tip of the island of Rügen, has been modernised for around Euro 81 million since 1998 and is the German port with the shortest geographical and nautical distance to Scandinavia, Finland, Russia and the Baltic states.

It offers regular, high-frequency ferry connections to Trelleborg (Sweden), Rönne (Denmark), Klaipeda (Lithuania), Baltijsk and St. Petersburg (Russia). Additional ferry routes to other destinations are in the pipeline which will increasingly make the location a major transport hub in the enlarged European Union.

Already the easy navigational accessibility without compulsory pilotage from the waters of the Baltic Sea with a depth suitable for sea-going vessels creates cost advantages for shipowners and clients. A navigable depth of 10.5 metres and modern quay facilities make the port accessible for nearly all classes of ships operating in the Baltic Sea region. It also provides optimum conditions for cruise vessels calling at the port. A comprehensive service offer is available for their passengers.

The ferry port of Sassnitz/Mukran is the only German port with around 40 kilometres of Russian wide-gauge railway tracks which are used both for changing the axle gauge of railway wagons and for transshipment between trucks, standard-gauge railway wagons and Russian widegauge wagons. With the start of operation of the Scandinavia terminal in 1998 it has become Germany‘s largest place of transshipment for railway ferry transport.

Speed, modern and mobile port facilities and industrial trucks, but most of all its experienced and well-trained staff guarantee a wide range of services. Together with forwarders, agencies and brokers it provides complete solutions and handling alternatives which make it easy to opt in favour of the ferry port of Sassnitz/Mukran.

Fig. 3: Ferryport Sassnitz (54° 28,66’ N, 13° 35,44’ E)

Sassnitz is one of the few ports in the Baltic Sea region fortunate enough to still have 150 hectares and thus ample space available for the settlement of port-related industries and commercial enterprises. Logistics service providers like Sea Terminal Sassnitz GmbH & Co. KG (STS), a company of the BUSS Group of Hamburg, operate the port handling of containers, general and bulk cargo.

The road link has clearly improved with the construction of the A 20, the feeder road from the A 20 to Rügen via Stralsund and the four-lane bypass road around Stralsund. Road blocks caused by the opening of the bascule bridge at the old Rügendamm and impediments caused by traffic lights are a thing of the past now with the new bridge to Rügen so that the flow of traffic to and from the ferry port has improved considerably.

## 4. Seaport of Wismar

Wismar seaport is a modern port logistics company: Since 1990, decision-maker have pushed ahead its dynamic development and orientation in the market with comprehensive new building, refurbishments and investment activities.

As the greatest southernmost Baltic Sea port in Germany, Wismar seaport is the ideal import and export hub for many goods flows. North-South traffic flows between Central Europe and Scandinavia, the Baltic states and Russia are bundled and distributed in Wismar.

Next to the geographical location of a port, its economic accessibility and thus its attractiveness for potential forwarding customers does, however, depend first and foremost on the quality of its connections with the hinterland. With the extension of the A 14 motorway (Wismar to Schwerin) and the connection with that motorway, the coastal motorway A 20 (Lübeck to Szczecin) and the newly electrified railway link the port provides excellent transport links.

The interaction of modern, efficient handling equipment, highly motivated and qualified staff and an excellent location in terms of transport geography assures a fast loading and unloading of sea-going vessels in good quality and expertly performed port services around the cargo.

Handling focuses on environmentally and weather-sensitive bulk goods, liquid and solid chemical products as well as general bulk cargo such as logs, forestry and agricultural products, iron, steel and building materials.

Staff of Wismar seaport will provide advice to solve all logistical tasks and help its clients to tread new paths. Customer-oriented and flexible service for all demanding cargo handling and transport tasks make Wismar seaport a logistics alternative at the Baltic Sea. The quality management of Seehafen Wismar GmbH is certified to DIN EN ISO 9001:2000.

Fig. 4: Seaport Wismar (53° 54' N, 11° 28' E)

## 5. Seaport of Stralsund

Universality combined with high standards of quality, flexibility and years of experience in stevedoring and storage operation – those are the trademarks of this Hanseatic port location at the straits between the mainland of Western Pomerania and Germany's largest island of Rügen. The manageable, well-structured size of the port with the facilities of the city harbour and the north port situated to the north of the new Rügen bridge and the most recently added areas of the south and Franken ports, situated south of Germany's largest bridge structure provide forwarders with excellent conditions for the handling of conventional dry bulk and general cargo.

Fig. 5: Seaport Stralsund (54° 18' N, 13° 06' E)

As a reliable partner in the transport chain, Stralsund seaport is today a provider of logistical services to eastern German power stations, the building trade and the import and export of agricultural products. Together with companies established at the site it has a leading role in the handling and processing of metals to be supplied to European shipbuilding operations. In this it cooperates with major steel producers from Germany and abroad and with suppliers to the maritime industry.

The importance of this port location in hinterland transport to and from seaports by rail continues to grow, once again underscoring the historical role of Stralsund as an intersection of railway transport to and from the conurbations in north-eastern Germany between Berlin and the Baltic Sea coast. The universal character of the port is amended by the fact that Stralsund is the only seaport in Mecklenburg-Vorpommern with access to the European network of inland waterways. Via the bypass road of the Hanseatic City of Stralsund ending at the port, the coastal motorway A 20 can be reached in no time, smoothly, without traffic jams and time lost for forwarders.

Thanks to the unique location and vicinity of the berths in the city harbour to the historic city centre of Stralsund, which was listed as UNESCO world heritage in 2002, cruise tourism is becoming an important field of business. A unique highlight has been created in the shape of the OCEANEUM on the northern harbour island which is expected to spark off international cruise tourism in Stralsund. The only newly built museum in recent German history, it is also considered a masterpiece of contemporary architecture and draws numerous visitors from near and far each year.

## 6. Port of Wolgast

The town of Wolgast is the centre of the region around the mouth of river Peene with approx. 60,000 inhabitants and a port location with a long tradition. Commercially it is characterised by the Peenewerft shipyard as well as by trade and services.

Its optimum infrastructure and superstructure are of great importance to the port of Wolgast, the easternmost German seaport. Via the Peenestrom channel and the river Oder it has a direct waterway connection with Poland and the German capital, Berlin, which provides access to the network of inland waterways of Central and Western Europe. The connection with the efficient railway network of Deutsche Bahn AG, federal trunk roads to Berlin and the nearby coastal motorway A 20 provide ideal conditions for solving logistical tasks.

Fig. 6: Port Wolgast (54° 02,3’ N, 13° 46,0’ E)

With a navigable depth of 6.5 metres (from 2009: 7.5 metres) the port is suitable for ships up to 150 metres length and 5.7 metres draught (from 2009: 6.5 metres).

Together the Südhafen (south port) and the Stadthafen (city harbour) have more than 1,250 metres of quays, 15,000 square metres of open-air storage and 2,000 square metres of covered storage. The annual cargo handling of around 500,000 tonnes consists mostly of imported building materials and fertilizer as well as grain export.

The south port industrial estate offers considerable areas of developed land for the establishment of port-related operations.

## 7. Port of Greifswald-Ladebow

The port of Greifswald-Ladebow is managed by Greifswalder Hafengesellschaft mbH, a fully-owned subsidiary of the Hegemann group. It has 290 metres of quays, 25,000 square metres of open-air storage and 1,000 square metres of roofed sheds. These areas are very well suited for the location of companies. The navigable depth is 6.9 metres. The close proximity of the A 20 motorway provides flexible conditions for preliminary and subsequent transport of the goods handled at the port.

For the handling of ships the port of Greifswald offers a continuous performance with optimum equipment. This includes a gantry crane with a jib length of 30 metres and 16 tonnes hoisting capacity. This crane also allows for handling from board to board. The grab capacity is 6.5 cubic metres. The discharge performance of this crane is between 250 and 300 tonnes per hour depending on the type of cargo. Furthermore a hydraulic excavator with 14 metres jib length and 200 tonnes discharge rate per hour is available.

Fig 7: Port Greifswald-Ladebow (54° 06,4’ N, 13° 26,5’ E)

The port is accessible to shipping day and night without impediments by bridges. Modern management systems according to DIN EN ISO 9000 et seq. and ISO 14001 create all conditions for the work of Greifswalder Hafengesellschaft so that it can meet present market demands.

## 8. Industrial Port of Lubmin

The industrial port of Lubmin is situated in the district of Ostvorpommern in the south of Greifswald lagoon between Greifswald and Wolgast. The operating licence for the industrial port was granted to the special purpose association "EFT" as the operator of the port facility on 27/01/2006. Since then the port is developing into an internationally recognised place of transshipment.

The industrial port of Lubmin has a south quay 740 metres in length with five berths and an east quay 135 metres in length with one berth. With a navigable depth of seven metres ships with a maximum draught of 6.1 metres may enter the port.

The network of inland waterways is also within easy reach from here. The hinterland connection with the A 20 motorway, the link with the public road system and the direct connection with the railway network of Deutsche Bahn AG via the industrial railway of EWN GmbH provide optimum conditions for solving logistical transport tasks.

The port basin has an overall length of 890 metres and is 94 metres wide. The port turning basin is 175 metres wide. The quay facility consists of a sheet-pile wall with concrete capping and has a height of 3 metres above mean sea level. There is a heavy-duty area (100 x 30 metres), a paved storage area (135 x 30 metres) and approximately 12,000 square metres of

Fig. 8: Industrial port Lubmin (54° 09,24' N, 13° 38,38' E)

open space in the port area. Right at the port border an area of 120 hectares is available for the establishment of industrial and commercial enterprises.

## 9. Industrial Port of Ueckermünde

The industrial harbour of Ueckermünde in its present shape was created in 1993. Today the harbour is a modern place of transshipment for seagoing and inland waterways vessels and enjoys favourable infrastructure connections.

Fig. 9: Industrial port Ueckermünde (53° 44' N, 14° 05,9' E)

Via rivers Oder and Peene it is directly connected to the German system of inland waterways. By way of the Piastowski channel (Kaiserkanal) and the Bay of Szczecin there is access to the Baltic Sea free of bridges. The A 20 motorway comes close to the economic area of Ueckermünde. These reasons also spoke in favour of establishing the Umschlaggesellschaft Industriehafen Ueckermünde mbH and the company Nordholz GmbH at the site.

The port basin is 135 metres long and 40 metres wide and open in a north-south direction. The usable length of both quays is 125 metres each. West of the port basin is berth No. 3 which is 140 metres long. It is mostly used for timber handling. The turning basin is situated east of the port.

Thanks to its equipment the port meets the requirements for a modern place of transshipment. Around 10,000 square metres are available for storage. The main goods handled are pig iron, fertilizer, limestone and paving stones as well as industrial timber.

## 10. Port of Vierow

The port of Vierow is located on the southern rim of Greifswald lagoon. It specialises in the handling and storage of grain. oilseeds, animal feeds and other foodstuffs.

In the past years the port of Vierow has grown into the second largest place of transshipment for grain and animal feeds in Mecklenburg-Vorpommern. Ships are handled in a continuous shift system. For this service the port is certified to GMP+ B2.

At their location in Vierow, Hafen Vierow GmbH and VIELA Export GmbH have a grain storage capacity of more than 60,000 tonnes at their disposal. There is also a direct link to a semi-mobile conveyor belt for direct loading of sea-going and inland waterway vessels.

Further areas are available for building to investors at the "Industriegebiet Hafen Vierow". The handling performance in grain loading via the conveyor belt facility is 300 tonnes per hour, while the discharge rate of the excavator used for handling is 250 tonnes per hour.

The port is accessible for shipping at all times without temporary limitations or impediments by bridges.

Fig. 10: Port Vierow (54° 08,1' N, 13° 34,5' E)

## 11. Inland port of Anklam

The inland port of Anklam is the biggest of its kind in Mecklenburg-Vorpommern today. It is managed by the municipal Binnenhafen Anklam GmbH. The goods handled here are predominantly fertilizer, scrap, building materials, grain, rapeseed and timber.

It is especially its favourable geographical location which makes the inland port of Anklam attractive for goods handling. The town on river Peene is intersected by the federal roads B 109, B 110 and B 197. The coastal motorway A 20 passes around 25 kilometres to the south. Via a railway siding there is a connection to the main railway line between Stralsund and Berlin.

Binnenhafen Anklam GmbH also manages the ports in Jarmen and Demmin. The port of Jarmen is situated very close to the federal roads B 96 and B 11 0 and to the motorway A 20. The commercial port of Demmin is situated right at the B 110 and has a good connection with the B 194.

Fig. 11: Inland port Anklam (53° 51,7' N, 13° 41,7' E)

Die Küste, 74 ICCE (2008), 1-417

# Marinas in German Coastal Areas

By Peter Fröhle

Contents



## 1. Introduction

Pleasure boat navigation is one important part of maritime tourism which is, with a main focus on the coastal areas, very important for the tourism and vacation industry in Germany as well as world-wide. The demand for pleasure boat berths for motor boats and yachts is increasing in many areas. This demand comes from permanent owners, boat charterers and – especially in the Baltic Sea region of Germany – from yachtsmen on vacation needing guest berths.

The strongly increasing demand of pleasure boat berths in Germany after re-unification in 1990 has caused an exceptional development of pleasure boat navigation and of marinas at the Baltic Sea Coast of Mecklenburg-Vorpommern. This also applies to other parts of the German Baltic and North Sea Coast. In many regions along the coast, a wide variety of efforts are taking place to develop existing potentials in maritime tourism.

The success of a marina is depending on the level of fulfillment of the needs and requirements of the users of a marina. These requirements can be very specific for the different users and regions. At the German North Sea coast and particularly at the German Baltic Sea coast maritime tourism is characterized by day sailing trips and marina hopping.

Trends in the development of the marina business in Germany are focussed on increasing marina size and quality of berthing facilities; the demand for luxury five star marinas is another factor to be considered.

## 2. Characteristics of German Marinas

Fig. 1 gives a brief overview on important pleasure boat areas in the northern part of Germany. The most important and most frequently used areas are located directly at the sea shores and around the islands (area I: North Sea; area II: Baltic Sea) or in the tidal estuaries; here, the Lower Elbe from Cuxhaven to Hamburg is very much in demand.

In 2008, more than 44,000 berths in more than 360 marinas were available at the German coastal areas of the North Sea and the Baltic Sea. The majority of marinas and berths can be found in the Baltic Sea, i.e. approx. 30,000 berths in 250 marinas and pleasure boat berthing areas. The average number of berths per marina is slightly higher in the Baltic than in the North Sea.


Fig. 1: Important pleasure boat areas in northern Germany (I: North Sea, II: Baltic Sea, 1: Elbe, 2: Alster, 3: Lake Ratzeburg, 4: Lake Schwerin, 5: Mecklenburger Lakes), after DWIF (2005)

A detailed compilation of marinas and number of berths for the various coastal areas in Germany is given in Tab. 1. It shows, that the vast majority of marinas and berths can be found in the Baltic Sea.

On an average each marina has approx. 120 berths, which is comparatively small in the international context. Approx. 50 % of the marinas have between 60 and 500 berths for permanently docked boats and guests. 50 % of all berths in the North and Baltic Sea can be found in marinas with more than 200 berths, and 80 % of all berths are in marinas with more than 85 berths. The largest marinas are the Marina 'Hamburger Yachthafen' and the 'Ancora Marina' in Neustadt. The 'Hamburger Yachthafen' features approx. 2,000, the 'Ancora Marina' approx. 1,400 berths.

Table 1: Compilation of berthing capacity of marinas and pleasure boat harbours in Germany (data source: http://wtg.vivawasser.de/)

| North Sea Area | Berths | Baltic Sea Area | Berth |
|---|---:|---|---:|
| Ems/Dollart | 273 | Flensburger Förde | 2,237 |
| Ostfriesische Inseln – Ems | 2,160 | Schlei/Eckernförde | 4,017 |
| Weser und Jade | 3,295 | Kieler Förde | 4,721 |
| Elbmündung | 1,321 | Fehmarn-Sund | 2,809 |
| Elbe – Glückstadt | 3,334 | Lübecker Bucht | 5,702 |
| Elbe – Hamburg | 1,906 | Wismar-Bucht/Poel/Rerik | 1,016 |
| Außenalster | 382 | Warnemünde/Rostock | 2,436 |
| Helgoland | 800 | Fischland/Darß | 1,474 |
| Nordfriesische Inseln | 816 | Rügen | 2,823 |
| | | Greifswald/Usedom/Haff | 2,715 |

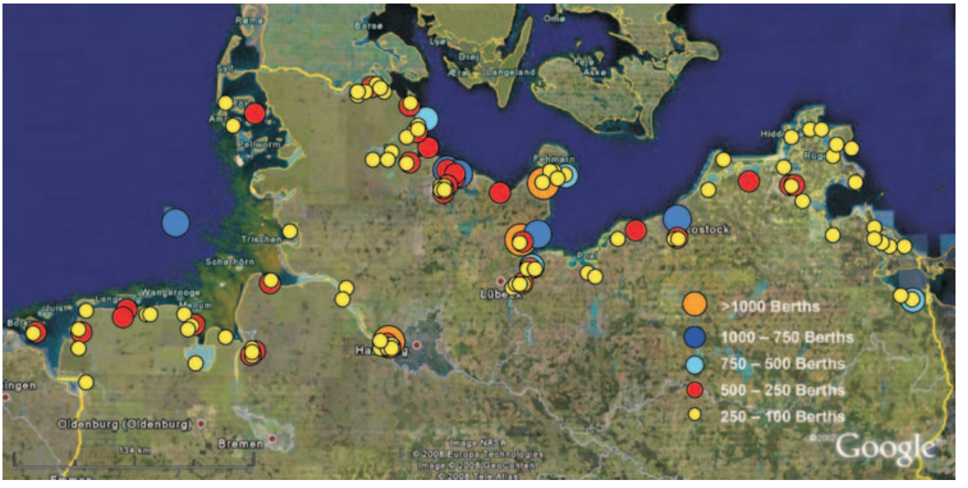


Fig. 2: German marinas with more than 100 berths

The main international sailing events and regattas are held in Kiel (Kieler Woche) and in Warnemünde (Hanse Sail), where the infrastructure for this kind of events is available.

An overview on the geographical distribution of large marinas and berthing facilities with more than 100 berths is given in Fig. 2.

According to the operators, marinas in Germany can be separated into three classes:

- municipally operated marinas (permanent rental and guests berths)
- club marinas (club members and a few guest berths)
- privately operated marinas

A comprehensive survey on the structure of all marinas in Germany is not available. Based on investigations for Schleswig-Holstein (dwif 2005), one can assume that approx. 40 % of the marinas are operated privately, approx. 40 % are club marinas and approx. 20 % are operated by municipal authorities.

An aerial view of a typical marina at the coast is given in Fig. 3.

## 3. User Requirements

The acceptance of a marina, and, hence, its commercial success is strongly dependant on the compliance with user's needs. These requirements are differing widely, depending on the area and its potentials and on the special interests of the yachtsmen. For further clarification, the University of Rostock (WEICHBRODT, 2002) has carried out an investigation to define the special needs and requirements of yachtsmen with a focus on marinas in the North and Baltic Sea. For this investigation, a questionnaire was developed and distributed through a publication in the German sailing journal "Yacht". It includes the following topics:

- Location of the marina:
  - position of the marina within the harbour network of the region
  - compatibility with different harbour usages
  - attractiveness, environmental conditions

Fig. 3: Aerial view of the marina Kühlungsborn, Baltic Sea Coast of Mecklenburg-Vorpommern (approx. 400 berths)

- Technical requirements:
  - simplicity and safety of approach
  - acceptable wave height inside of the harbour (comfort and safety)
  - maneuvering space, water depths
  - freeboard of footbridges/pontoons, dimensions of berths etc.
  - mooring systems
- Infrastructural requirements:
  - accessibility of the marina by yacht and by car
  - equipment of the berths (water, electricity, telephone/internet access)
  - service and supply facilities

Based on the evaluation of the returned questionnaires it was shown that many of the results – especially with respect to equipment and requested facilities – generally match other international studies on user requirements (e.g. PIANC, 1991). Trend-setting results have been mainly obtained for the marina location and for the requested technical requirements and infrastructure.

As one example for special requirements, the preferred sailing distance between two marinas is shown in Fig. 4. Approx. 80 % of all yacht owners prefer that sailing distance to be less than 20. This result indicates clearly that it is necessary to establish a narrow network of marinas in order to meet the needs of and attract yacht owners.

Another interesting result of this survey is shown in Fig. 5. Despite the fact that many boat owners are presently using berths in comparatively big marinas, it seems that a majority would prefer a comparatively small marina if they had the choice (WEICHBRODT, 2008). This indicates a possible trend to small, natural marinas with a familial touch. This trend can also be derived from other results of the survey.

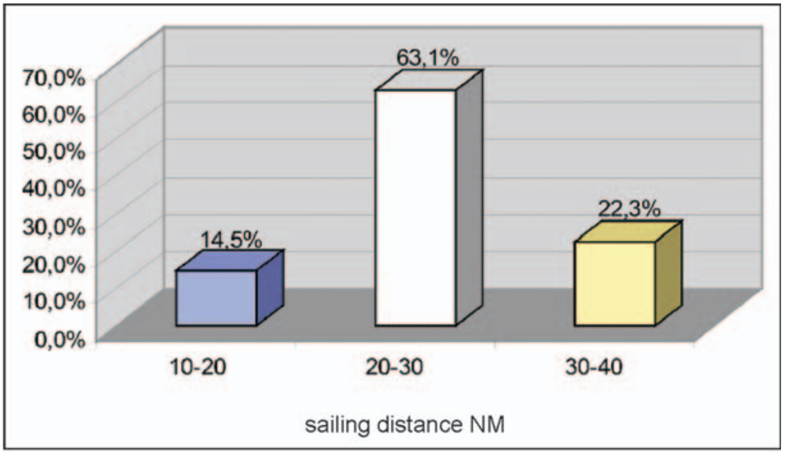


Fig. 4: Preferred sailing distance between marinas (WEICHBRODT, 2002)

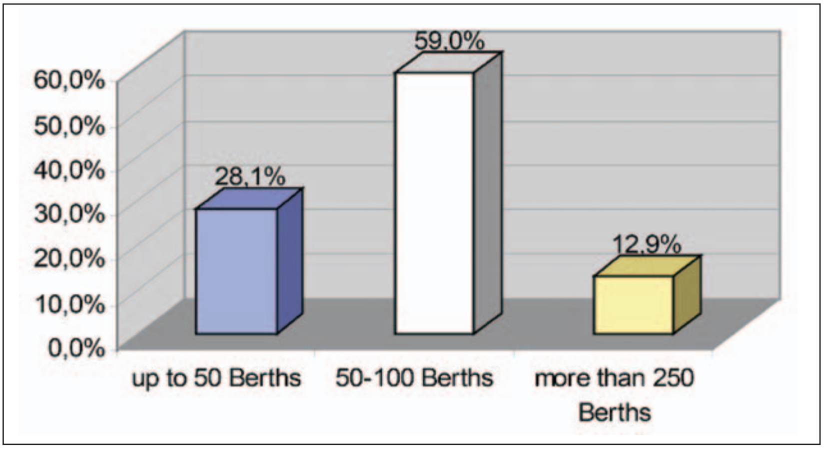


Fig. 5: Preferred number of berths in a marina (WEICHBRODT, 2002)

## 4. Actual Trends and Future Developments

Actual trends in the development of existing marinas and their maritime infrastructure are mainly connected to the improvement of technical facilities and of the infrastructure (FRÖHLE, 2005). The trend to more comfortable sailing and motor yachts with increasing boat sizes (length and especially width) is obvious also in Germany (e.g. DWIF, 2005; PLANCO, 1997). As an example, results of an actual survey on the average length over width ratio of modern sailing yachts and motor boats are depicted in Fig. 6.

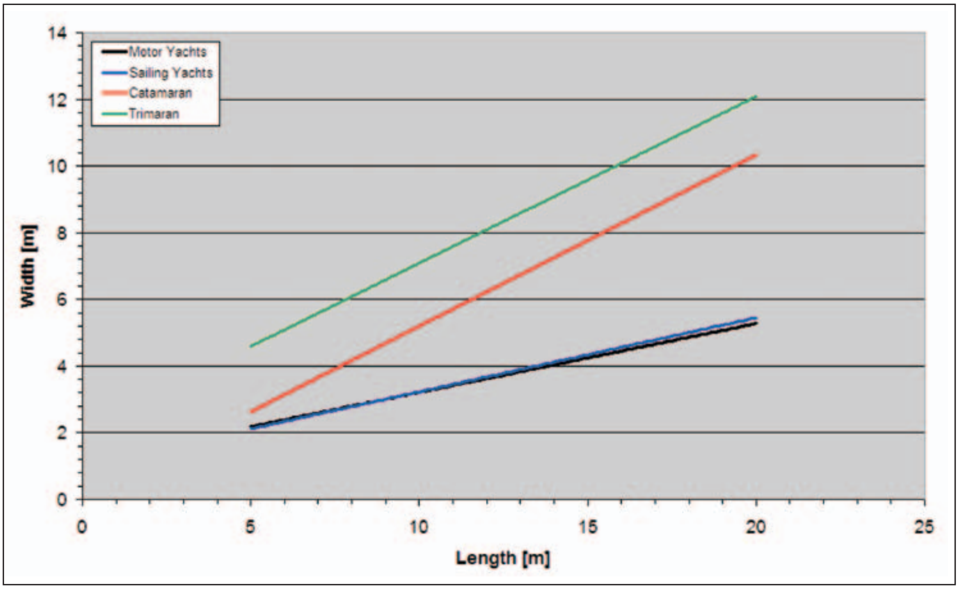


Fig. 6: Average width over length ratio of modern sailing and motor yachts

Presently, the main focus for planning and design of new marina facilities is on the improvement of the marina network, especially in the German Baltic Sea, since the requirements of the yachtsmen clearly indicate that it is – at least in Germany – necessary to create a comparatively narrow network of marinas at the coasts and tidal estuaries to strengthen water sports and in particular yacht sport. An isolated marina does not seem to be too attractive for yacht tourism. Travelling from one to the next and the next is more interesting and attractive. A detailed survey of possible new marina sites in Mecklenburg-Vorpommern has been performed by PLANCO (2004). A suggestion for new sites can be seen in Fig. 7.

Major issue in connection with the extension of the marina network is the possible encroachment of marinas as well as pleasure boat traffic on the environment, in particular on nature protection areas and animal sanctuaries. Possible adverse effects on the natural development of the mainly sandy coastlines and on coastal and flood protection in the adjacent areas are another concern.

Comfort and infrastructure of a marina as well as its technical equipment are described using the MQM (Maritime Quality Management) classification, which has been developed by IMCI (International Marina Certification Institute). Classification of quality levels is characterized using 1 to 5 blue stars. Main criteria for the assessment of marinas are related to the sectors: formalities and communication, safety, sanitary facilities, service, food & recreation, management, environment and waste management, dry-storage & winter-storage.

Another focus, related to the planning of new marinas, is the possible construction of so-called Mega Marinas for Mega Yachts. An example is the Marina Baltic Bay, intended to be built in Kiel as the first harbour for mega yachts at the Baltic Sea. Whether there is a strong demand for Mega Yacht Marinas in Germany as assumed by the planners seems not to be clear at the moment. It is obvious that so far the longest sailing and motor yachts which are plying German coastal waters are significantly less than 20 m long.

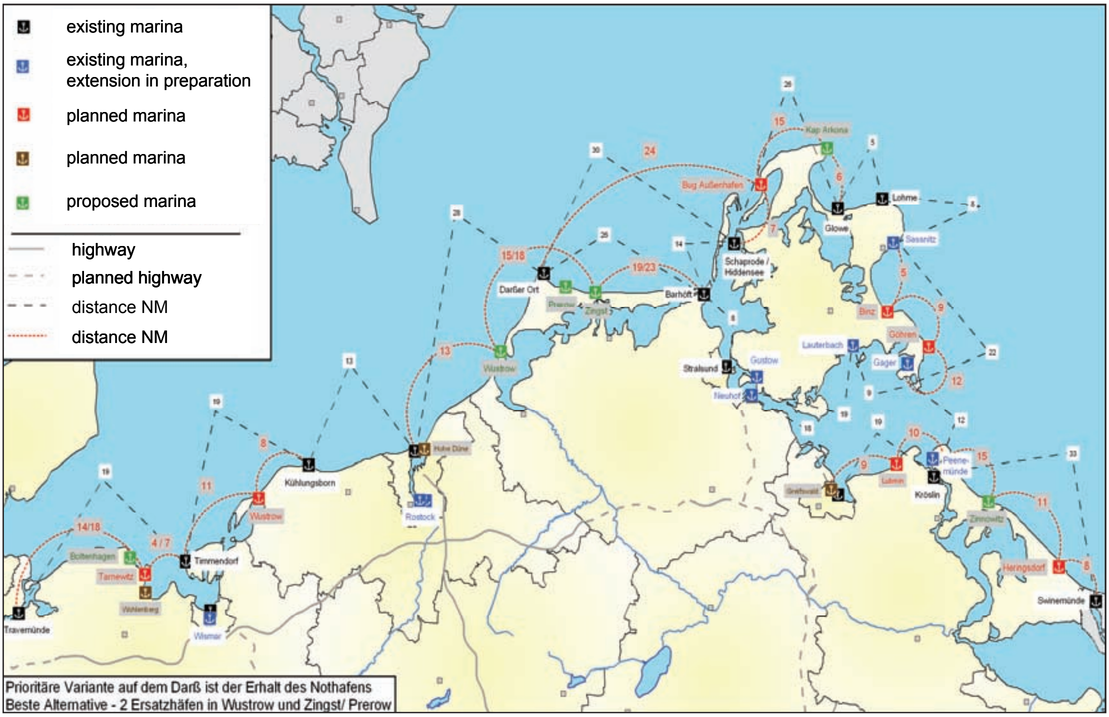


Fig. 7: Existing and recommended marinas in the marina network at the Baltic Sea Coast of Mecklenburg-Vorpommern (PLANCO, 2005)

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Die Küste, 74 ICCE (2008), 1-417

# The Construction of JadeWeserPort
# A Deepwater Container Terminal in Wilhelmshaven

By JadeWeserPort Realisierungsgesellschaft

Contents



## 1. A Terminal for Next Generation Container Ships

The JadeWeserPort deepwater container terminal is to be constructed on the west bank of the Inner Jade – part of the Jade estuary of the North Sea – approx. 9 km northeast of centre of Wilhelmshaven. Its location east of Voslapper Groden, between the "Niedersachsenbrücke" (coal terminal) in the South and the WRG Pier facility to the North will make it an integral part of the port facilities of Wilhelmshaven. The average distance to the WRG Pier and jetties to the North is around 2,200 m.

The ideal location of the port was confirmed by nautical simulations. With a short approach channel of a length of 23 nm, the next generation of super-large vessels of well above 8,000 TEU with dimensions of up to 430 m in length, 58 m width and drafts of up to 16.5 m will be able to call at the port with a tide-independent access. A planned quay length of 1,725 m guarantees that 4 large container vessels together with feeder ships will be simultaneously served by way of 16 container bridges. The project timing is considered critical: international trade is growing rapidly and container traffic is booming. Experts agree that this growth rate will persist for many years ahead.

After completion, JadeWeserPort will be the most easterly deepwater port of the European North Range between Le Havre and Hamburg. Its annual turnover is predicted to be approximately 2.7 million TEU. It is anticipated that around 60 per cent of the overseas container turnover via the Wilhelmshaven main hub will comprise sea transit shipments within European distribution traffic to Scandinavian, EU Baltic state and Russian seaports. JadeWeserPort will be an essential key component of the trans-European "Motorways of the Seas".

The terminal area of 120 ha is complemented by another 170 ha for logistics and port-oriented services, with a freight village also in the planning. Both, road and rail networks will offer a high capacity access; for road traffic, the German A29 motorway ends at the port gates. The overall investment volume amounts to Euro 950 million. The EUROGATE group as port operator will invest Euro 350 million into the port superstructure.


Fig. 1: Aerial view with the proposed new port area

## 2. Current Planning Status

The realisation of the JadeWeserPort project has involved planning approval procedures in accordance with the German Waterway Act (WaStrG) and the German Mining Act (BBergG). Final approval was granted in accordance with the German Mining Act in September 2006 with immediate execution granted, effective November 2007. The plan approval order in accordance with the German Waterway Act was pronounced with immediate execution rights in March 2007. Six objections against this planning approval order were submitted to the Higher Administrative Court in Lüneburg. Two of these were expedited appeals to suspend the immediate execution of the plan approval order. Both of these claims were dismissed in March 2008.

The JadeWeserPort construction project as applied for in accordance with the German Waterway Act includes the following measures:

- Creation of a new terminal area:
  - land reclamation with embankments
  - construct quay, return and embankment walls
- Quayside transport connection
  - realign the Jade channel
  - construct terminal access channels
  - relocation of a leading light
- Landside transport connection
  - construct road access
  - construct rail access
- securing the “Niedersachsenbrücke”

Tenders for the construction works for the terminal land areas including the quay and embankment walls were invited according to a European pre-qualification procedure in early January 2006.

Bids received from approved bidding consortia were opened on 4 May 2006. The five approved consortia submitted not only their principle proposals but offered also 400 specific proposals.

## 3. Construction of new Terminal Area

The central component of the proposed project is the establishment of a new port area extending into the Jade. The required land area of 360 ha for the port overall is subdivided into the following sections designed for various utilization, as shown in Fig. 2:

- Terminal area with quay,
- Hafengroden (logistics zone),
- Traffic areas for road and rail,
- River embankments.

## 4. Terminal Area and Quay

The terminal area will have a quay length of 1,725 m and an overall width of 650 m. These dimensions represent the surface area required to accommodate the predicted container volumes with consideration of expected changes in ship size and capacity.

The fundamental quay design is to be safe at high water with a ground level of 7.50 m above mean sea level. With the harbour seabed specified at – 20.10 m below mean sea level,


Fig. 2: Layout plan with subdivisions

the quay covers a height difference between harbour seabed and surface of at least 27.60 m. Adding on a safety margin for excavation tolerance and possible erosion of 3 m determines the maximum pile length for the proposed combined sheet pile walls to be around 43 m. The quay walls will ultimately be of a height almost without parallel in the world. The new port area including embankments is to be constructed by sand fill creating an overall surface area of approx. 360 ha. The landfill will require approx. 43 million m³ of sand.

Required sand quantities will be obtained from dredging works connected with the new fairway and access areas including moorings, as well as from 2 sand extractions pits located north and south of the future port area. Excavation will extend down to 35 m below mean sea level. The approval for sand removal (general operating plan) from the two sand pits was granted consequent to the planning approval procedures in accordance with the German Mining Act (BBergG).

The approx. 170 ha area located to the west of the terminal area, known as Hafengroden will be used for port-related industries and services. The area will be enclosed to the north, east and south by traffic areas. To the west the terminal area is bordered by the new Voslapper sea dyke.

The embankments planned around the new land areas will offer protection against wave action and erosion, also during the landfill phase. The extension of these dykes will involve laying between 500,000 to 600,000 tonnes of water building blocks – representing an extreme challenge to both engineering and logistics. Last but not least, the embankments also provide protection against high water levels and flooding for the terminal and the logistics areas. To the east the port is bordered by the quay structure. Preparatory calculations, taking storm water levels and tidal actions into account, have confirmed that a quay height of + 7.50 m above sea level is adequate to provide the necessary high water protection.

The northern embankment is approx. 1,950 m long; the heavy bank protection of the seaside slope will be compliant with standard dyke construction rules and regulations. A height of + 8.50 m above sea level is planned here to cope with North Sea waves.

The "Niedersachsenbrücke" will be integrated in the approx. 1,100 m long southern embankment. The lower slope directly south of the "Niedersachsenbrücke" (access road) will have a concrete cover. The upper slopes will be covered in their lower sections with Lauenburg clay topped with bran. The surface height here is specified at + 7.50 m above sea level reflecting its protected location behind the JadeWeserPort.

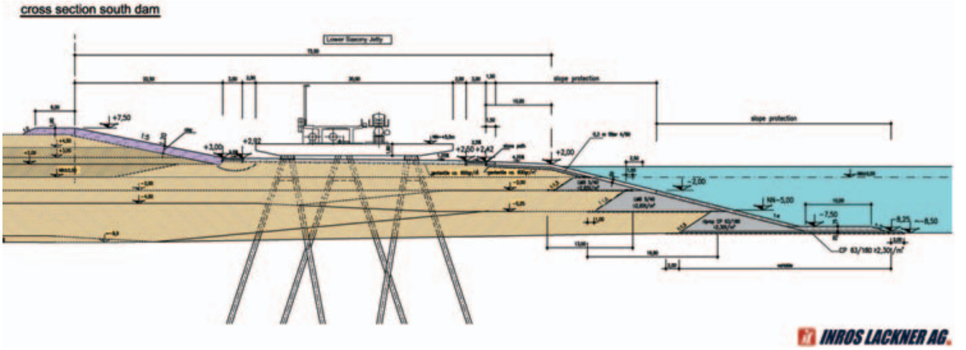


Fig. 3: Cross-section of the southern dam

## 5. Quayside Transport Connection

The Jade estuary is a federal waterway. The fairway width is 300 m. The Jade range is suitable for ships with drafts of up to 16.5 m irrespective of the stage of tide. Ships with drafts of between 16.5 m and 20.0 m may use the Jade approach under suitable tidal conditions.

One aspect of the project is the relocation of the Jade channel up to the new quay. This is necessary for nautical and hydrographical reasons between km 7 and km 15.

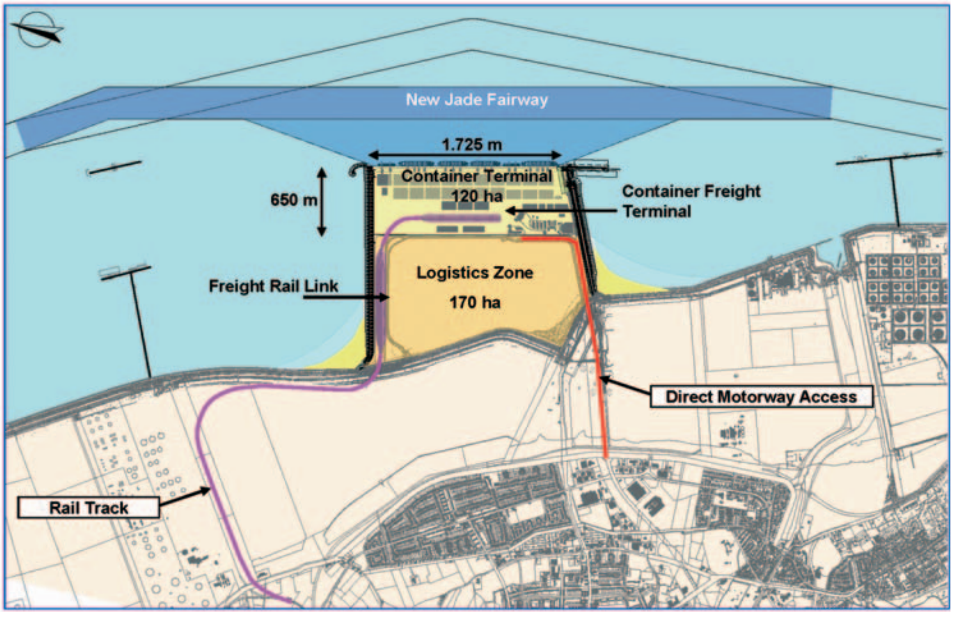


Fig. 4: The port and its modified access channel

## 6. Landside Transport Connection

### 6.1 Road Traffic

JadeWeserPort will be linked to Germany's arterial road network via the Lower Saxony embankment and a direct extension of the German motorway A29. The main arterial route for traffic to and from the port is the A29, ensuring that the city of Wilhelmshaven will not be impacted by additional road traffic.

In 2000 the traffic volume map issued by the Lower Saxony state office for road works and transport with respect to the A29 motorway indicates a capacity usage of around 43 % in the vicinity of the Wilhelmshaven intersection. Some 25,500 cars were counted there on a daily basis. The road cross-section has an existing capacity of 60–65,000 cars per day without risk of traffic jam. Port road traffic will then split at the Ostkreuz Oldenburg intersection between the A29 towards the southwest and the A28 towards the northeast, the capacity utilisation is currently approx. 61 %.

In order to optimise the road connections of the Hafengroden area and the container terminal itself, the Oldenburg branch of the Lower Saxony state office for road works and transport, is planning to extend the A29 motorway by approx. 1.8 kilometres and add two additional lanes. The motorway will then expire, approx. 1,200 m from the terminal gates, in a roundabout providing direct access to JadeWeserPort. These building measures are all scheduled for completion prior the commissioning of JadeWeserPort.

Consequent to the completion of the Wesertunnel south of Bremerhaven in January 2004, the B437 federal road took on a new role as link road between the A29 and A27 motorways. This connection is a high capacity alternative west-east connection to the A1. Due to a road traffic survey undertaken during 2000, an average daily traffic load of approx. 6700 cars per day was indicated. The degree of efficiency of the B437 is currently at approx. 34 %.

The completion of the A31 motorway in December 2004 provided an additional and noticeable improvement to road connections in the region, in particular with North Rhine-Westphalia. The A31 is reached from JadeWeserPort via the A29 and A28, such the port has an excellent high capacity road link to the Ruhr area of Germany and the Benelux countries, which is independent of the A1 motorway.

The current federal and country road network in northwest Lower Saxony has sufficient capacity to safely and adequately take up the anticipated traffic generated by JadeWeserPort. The overall road access of JadeWeserPort will be further optimised in 2008 by the completion of the stretch between the A28 motorway and the A1 in the area of the Delmenhorster intersection.

Another major transportation project in northwest Germany is the planning and construction of the A22 coastal motorway. Being part of Germany's federal road plan 2003, it is a priority project. Initial investigations have indicated that the construction of the A22 would divert approx. 16,000 trucks from the A1. When the A22 project comes to fruition, it will create a new east-west connection in the northwest, independent of the A1 motorway. It would reduce the distance from JadeWeserPort to the Ruhrgebiet/Benelux areas. Similarly the distances between the south-west and the area of greater Hamburg, Schleswig-Holstein, Denmark, Sweden and Norway would be shortened as well. The eastern regions of the Netherlands would have quicker access to the JadeWeserPort than they have to Rotterdam.

In October 2007, the governmental substitution Lüneburg commenced with a corresponding regional planning procedure. The schedule for the project until road opening is as follows:

| | |
|---|---|
| October 2007–August 2008 | Area planning procedure and alignment determination |
| September 2008–October 2010 | Drafting of technical proposals |
| November 2010–October 2013 | Planning approval procedure |
| Followed by | Commencement of construction |
| From 2017 | Available for use |

### 6.2 Railway traffic

JadeWeserPort rail connections can be divided into four sections:

1. JadeWeserPort trackages:
   - 4 km access line between DB track section 1552 – north industry branch – and the new Voslapper sea dyke

- Marshalling yard, consisting of up to 16 tracks
- bimodal traffic handling installation (suprastructure)[1]

2. DB track section 1552 – northern industry branch
3. DB track section 1540 – between Sande and Esens
4. DB track section 1522 – between Wilhelmshaven and Oldenburg

The JadeWeserPort sidings will connect to the single-track non-electrified northern industry branch line via an approx. 4 km long line. This approximate 10 kilometre long track section will be for goods traffic only, and will be upgraded by Deutsche Bahn until the start of the port commissioning, to create a high capacity rail link for the JadeWeserPort.

The development concept includes upgrading the industry track using modern control, safety and signal technologies. The ultimate capacity would be for 100 railway slots per day (24 hour period) while current usage comprises a mere eight slots on average per day for trains to the Wilhelmshaven oil refinery. The industry track will ultimately be connected via a branch line to the Sande–Esens line. This line section terminates at Sande station where it connects to Deutsche Bahn track section 1522 (Wilhelmshaven–Oldenburg). The Wilhelmshaven–Oldenburg line is a for the most part two-track non-electrified main line. This track section is used to provide regional public transport at an hourly frequency between Wilhelmshaven and Oldenburg as well as local goods traffic. During a 20-hour day, this line currently handles approx. 43 passengers and an average of 8 goods trains per day.

The track sections between Varel, Jaderberg, Hahn and Rastede also include two single-track sections of seven and five kilometres in length, respectively. The upgrading to a full two-track status – for which approvals already exist – and the electrification of this main line are also a new project classified as high priority in the German transport plan 2003. Deutsche Bahn (German Rail) has agreed to complete the engineering work necessary for twin tracks and electrification in a timely fashion prior to the start of operations at JadeWeserPort.

Trains coming from JadeWeserPort are redirected at the Oldenburg junction, travelling on to either Bremen, Lehr/Rheine or the Osnabrück/Ruhr area.

## 7. Execution of construction works

The actual construction work on the terminal will commence immediately after the higher administrative court in Lüneburg has ruled on the expedited appeals.

The order to build the terminal area and construct the quays (construction phase 1) was granted to a consortium under the management of the Bunte Group, based in Papenburg in Emsland, on 26 September 2007.

Final plans prior to construction are currently being concluded. Works on creating port transport infrastructure connections will start shortly.

The actual construction work for phase 1 is presently scheduled to start in mid 2008. The first areas of the terminal will be ready for hand-over to EUROGATE, the terminal operator, after an approx 18 month construction period such that it can commence with the installation of all necessary suprastructure, such as land surfacing, container bridges, a gatehouse, workshop area and cargo handling equipment for road and rail transports. Container operations are scheduled to commence in 2011 on the southern quay section, planned for completion by that time.

[1] Plans are based on a combined traffic transhipment facility comprising six parallel tracks of suitable length

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# Errata

Corrigenda "Die Küste" 74
Fehlerberichtigung „Die Küste" 74
ICCE 2008 Edition - Synoptic Overview of the German Coastal Zone

Please note the following revisions:
Bitte beachten Sie folgende Korrekturen:

Page 31:
The correct list of authors includes Alexander Bartholomä as third author.
Die korrekte Autorenliste enthält Alexander Bartholomä als dritten Autor.

Manfred Zeiler, Klaus Schwarzer, Alexander Bartholomä and Klaus Ricklefs
Seabed Morphology and Sediment Dynamics

Page 64:
The colour code is missing in Figure 4.
In Abbildung 4 fehlt die Farbskala.

Fig. 4: Seasonal North Sea circulation pattern, BSHcmod model data, 4-year average based on daily residual currents. The colours give the persistence in percent

Page 104:
The lower table is incorrect and is replaced by the table Warnemünde.
Die untere Tabelle ist falsch und wird durch die Tabelle Warnemünde ersetzt.

Fig. 5: Time series of mean water and high water levels at the Travemünde and Warnemünde gauge stations

Page 144:
The gauge Helgoland is missing in Figure 1.
In der Abbildung 1 fehlt der Pegel Helgoland.

Fig. 1: The island of Helgoland and Düne ('dune') (aerical Photograph © AWI, 2003)

Page 148:
The quality of Figure 4 has been improved.
Die Qualität von Abbildung 4 wurde verbessert.

Fig. 4: Development of Helgoland (main island) since 1890 (after Krumbein, 1975)

Die Küste, 74 ICCE (2008), 1-417



# Seabed Morphology and Sediment Dynamics

By MANFRED ZEILER, KLAUS SCHWARZER, ALEXANDER BARTHOLOMÄ and KLAUS RICKLEFS

Contents



## 1. Introduction

The German coasts extend along two different seas, the tide-dominated North Sea and the intra-continental non-tidal Baltic Sea. While the North Sea has an open transition to the Atlantic Ocean, the Baltic Sea has its only connection to the world's oceans through the North Sea and the shallow and narrow Danish straits and sounds (Fig. 1). Both shelf seas are not only different in their hydrographic characteristics, but also in their geological development (SCHWARZER et al., 2008, this volume), their sediment conditions and their geo-morphological features.

Although the seafloor in the German sectors of North and Baltic Sea is built up mainly of loose Quarternary deposits, the driving forces leading to environmental changes are quite different. While in the North Sea the sedimentological and geomorphological development (morphodynamics) is ruled by tides and waves, waves and wind driven currents are relevant for the seafloor conditions and sediment dynamics in the Baltic Sea. In both seas, however, phases of storm-induced high water levels often lead to severe changes of the coastal geomorphological environment. For the German North Sea coast this holds especially for storms from (north-)westerly directions, which can induce water levels of up to five meters above mean sea level usually for the duration of one or two tidal cyles. For the western Baltic Sea coast, storms from north-easterly directions have the strongest influence on coastal changes. Here, high water levels and therefore hydrodynamic extremes can last for days (SCHWARZER, 2003).

## 2. North Sea

The German Bight is a meso-tidal to low macro-tidal environment with a tidal range between two and four meters. According to geo-morphological features and sedimentological environments, the German sector of the North Sea can be divided into the three zones: the offshore waters, the tidal flats of the Wadden Sea and the funnel-shaped estuarine river mouths (Fig. 2). In the meso-tidal environment, the barrier island chain of the East Frisian as

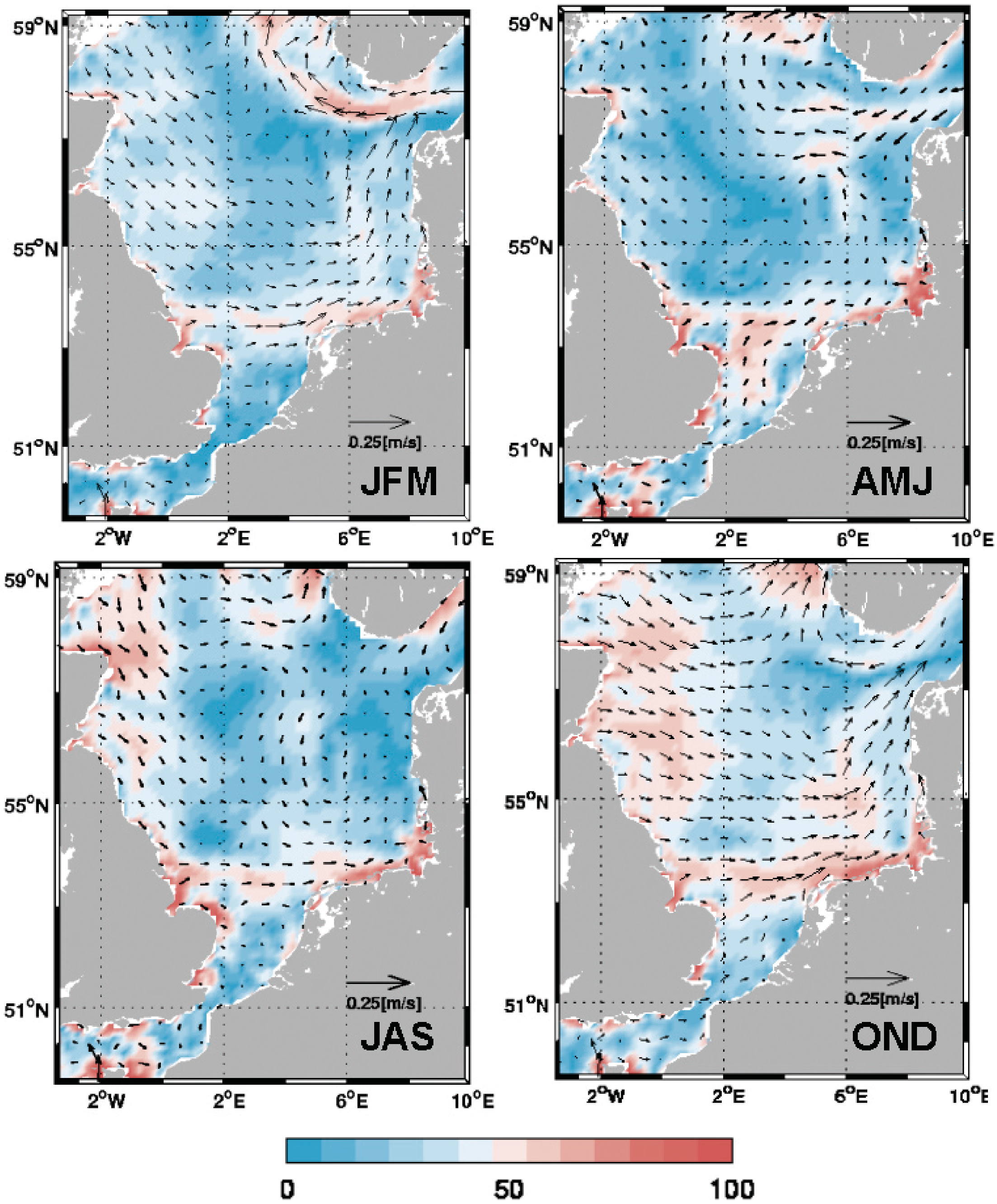
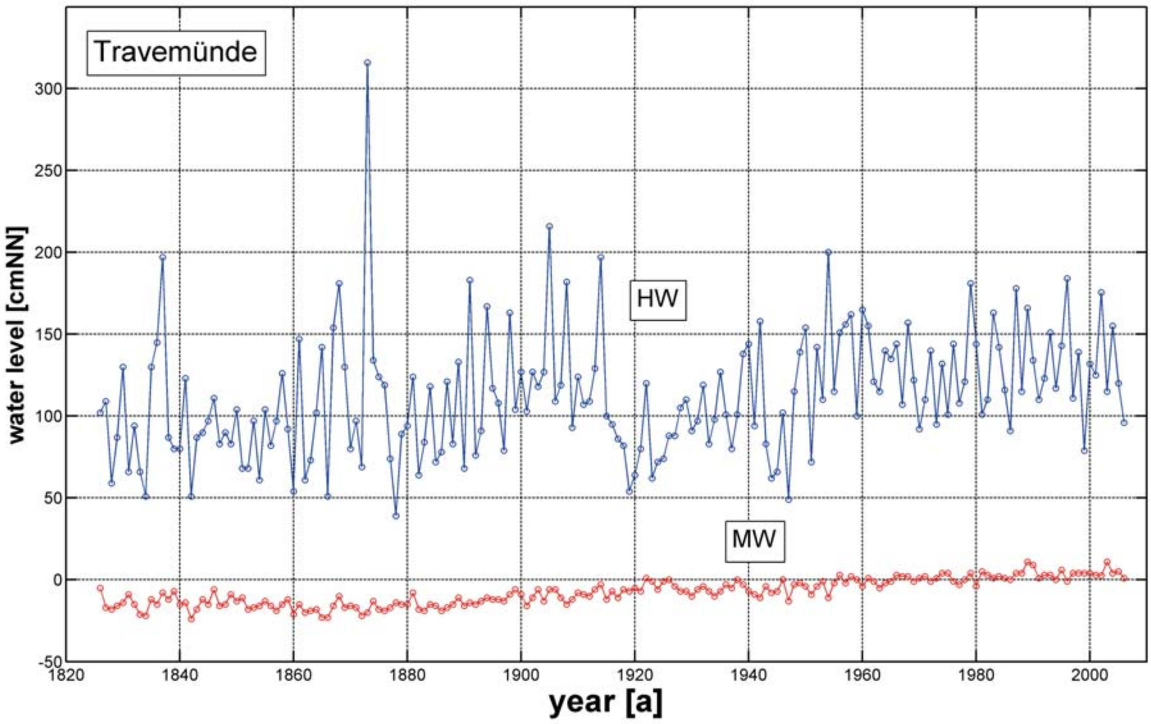



Fig. 4: Seasonal North Sea circulation pattern, BSHcmod model data, 4-year average based on daily residual currents. The colour gives the persistence in percent

In the long-term mean (1950–1986) the highest wind speeds in the German Bight occur in November (9 m/s) and decrease until February to 7 m/s. During March there is a local maximum of 8 m/s, then the values decrease rapidly to a value of about 6 m/s between May and August. Then the values increase again until they reach their maximum at the end of autumn (BSH, 1994). This seasonal cycle based on monthly means is conferrable to the sea state. At the light vessel 'German Bight' the percentage frequency distribution of both wave and wind direction shows a maximum for winds and waves from the West-south-west and a second maximum for East-south-east (LÖWE et al., 2003).



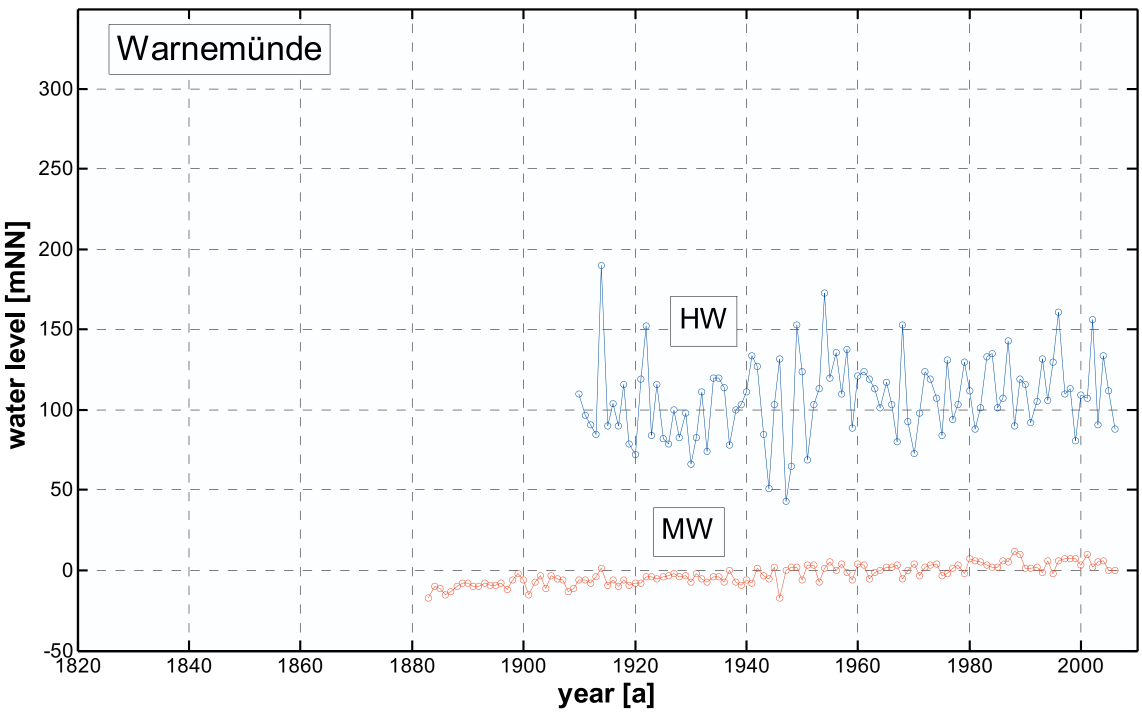




Fig. 5: Time series of mean water and high water levels at the Travemünde and Warnemünde gauge stations

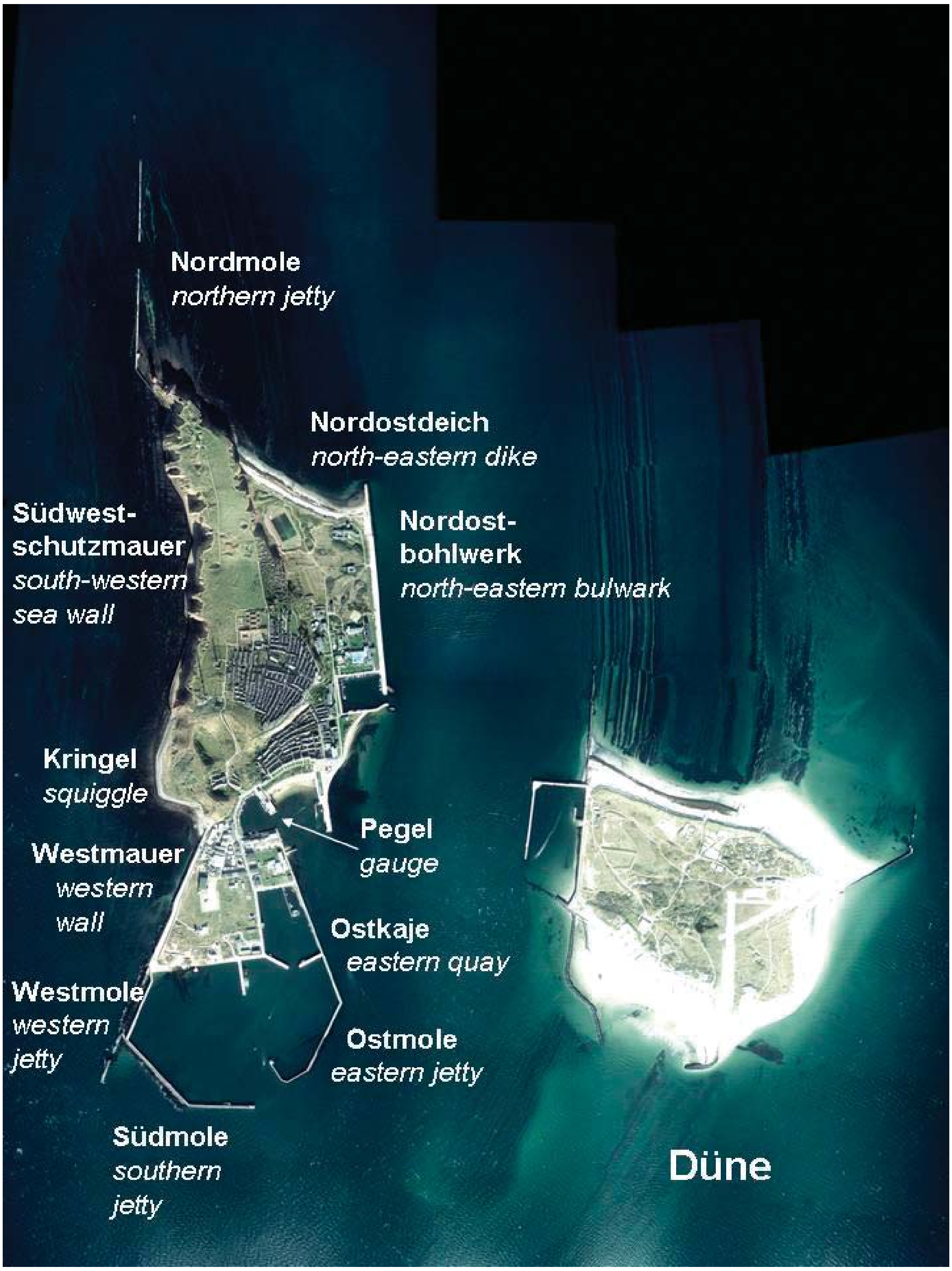



Fig. 1: The island of Helgoland and Düne ('dune') (aerial photograph © AWI, 2003)

## 2. Geology

The geological history of Helgoland starts in the Upper Permian (Zechstein) approx. 255 Mio. years ago. In an arid climate, enormous salt deposits were generated by repeated evaporation over a shallow inland lake. At that time, the present Northern Germany was located close to the equator and – as a consequence of the continental drift – migrated towards its present position only during the further course of history.

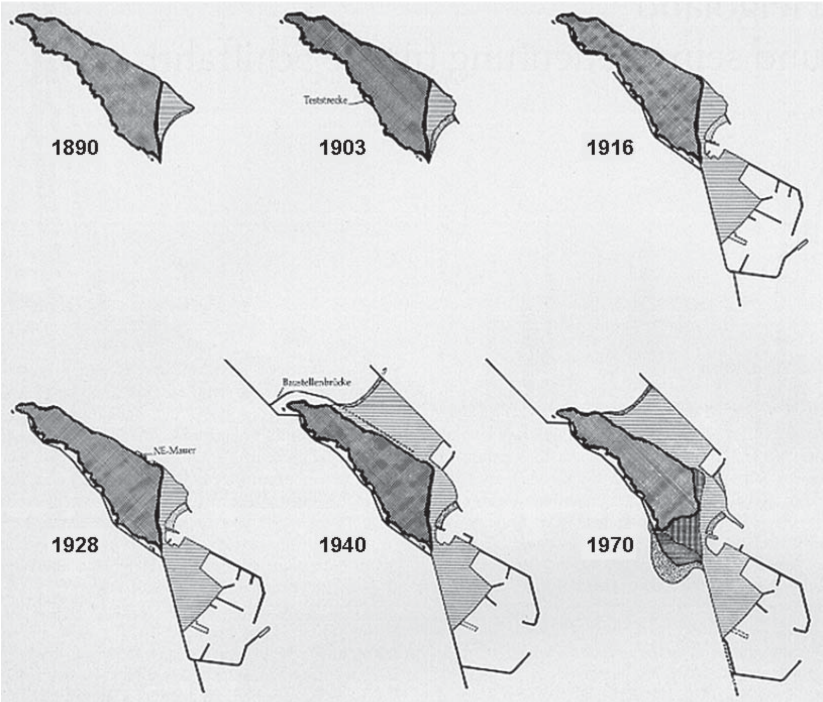



Fig. 4: Development of Helgoland (main island) since 1890 (after KRUMBEIN, 1975)

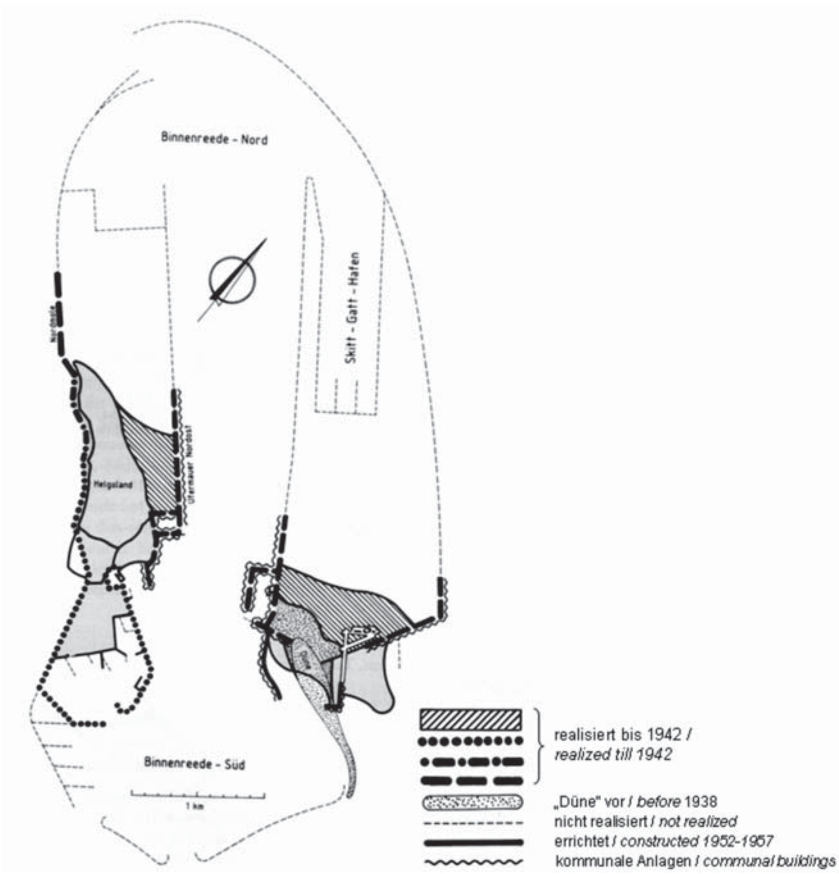



Fig. 5: Design of the mega-port 'Lobster Claw (Hummerschere)' and the realized structures (SCHINDLER and LINDEMANN, 1990)