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

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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

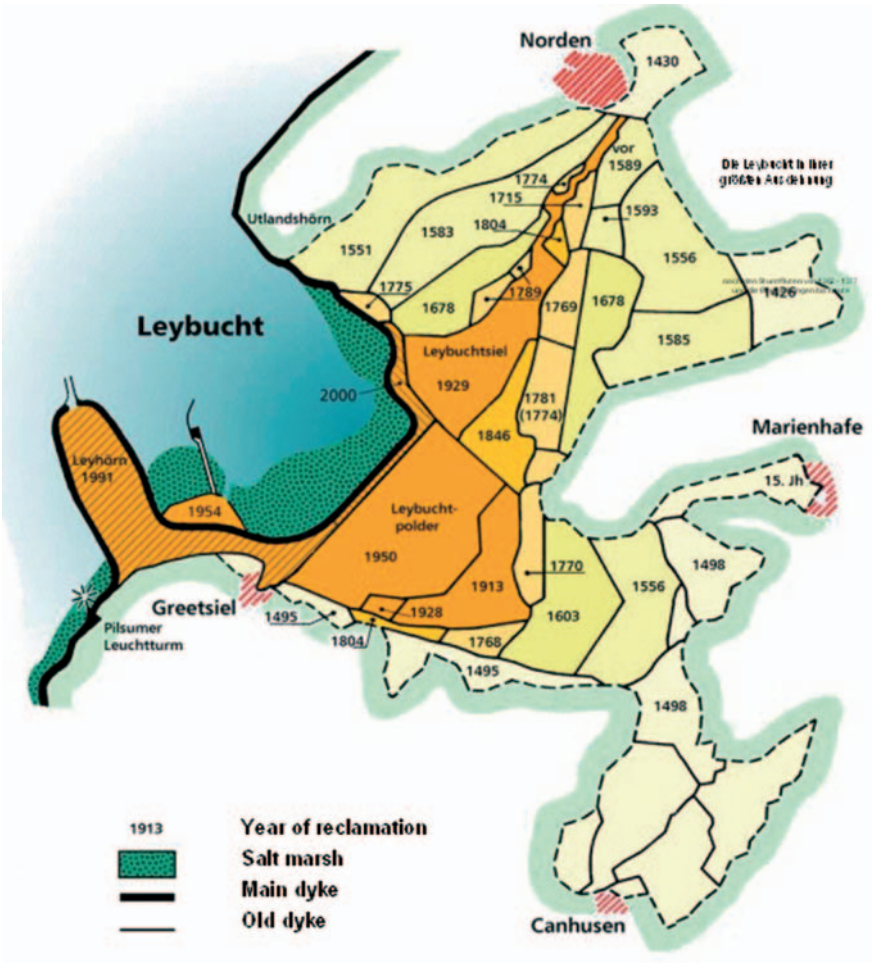

Fig. 1: Ley-Bight – History of reclamation

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

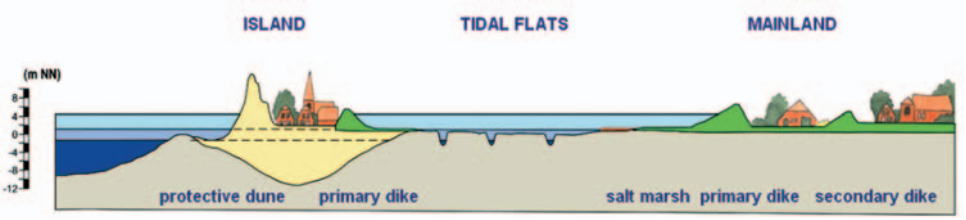

Fig. 4: Coastal flood defence system in Niedersachsen

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 19th century, many

Fig. 6: Ems storm surge barrier

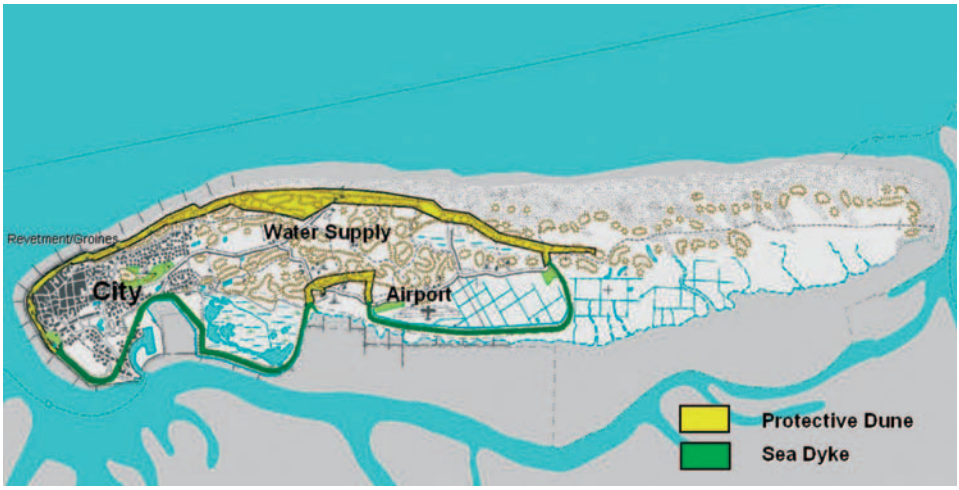

Fig. 7: Flood defence system for the island of Norderney

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 19th 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 m^3 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 m^3 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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