3.3 Effects of fixing of parts of the islands and the mainland coast

Around 1000 AD the inhabitants of the higher dry areas in the coastal zone started to colonize the lower lying peatlands. To keep the storm tides out they started to surround part of the lands by dikes. From the 13th century on, polders were created. Windmills made it possible to change inland lakes into polders. In the last centuries also measures were taken to stabilize the sandy coast itself. In order to prevent erosion, groynes perpendicular to the coast were built. At other places the coast was embedded in stones. More recently sand nourishment was introduced as a means of combating erosion.

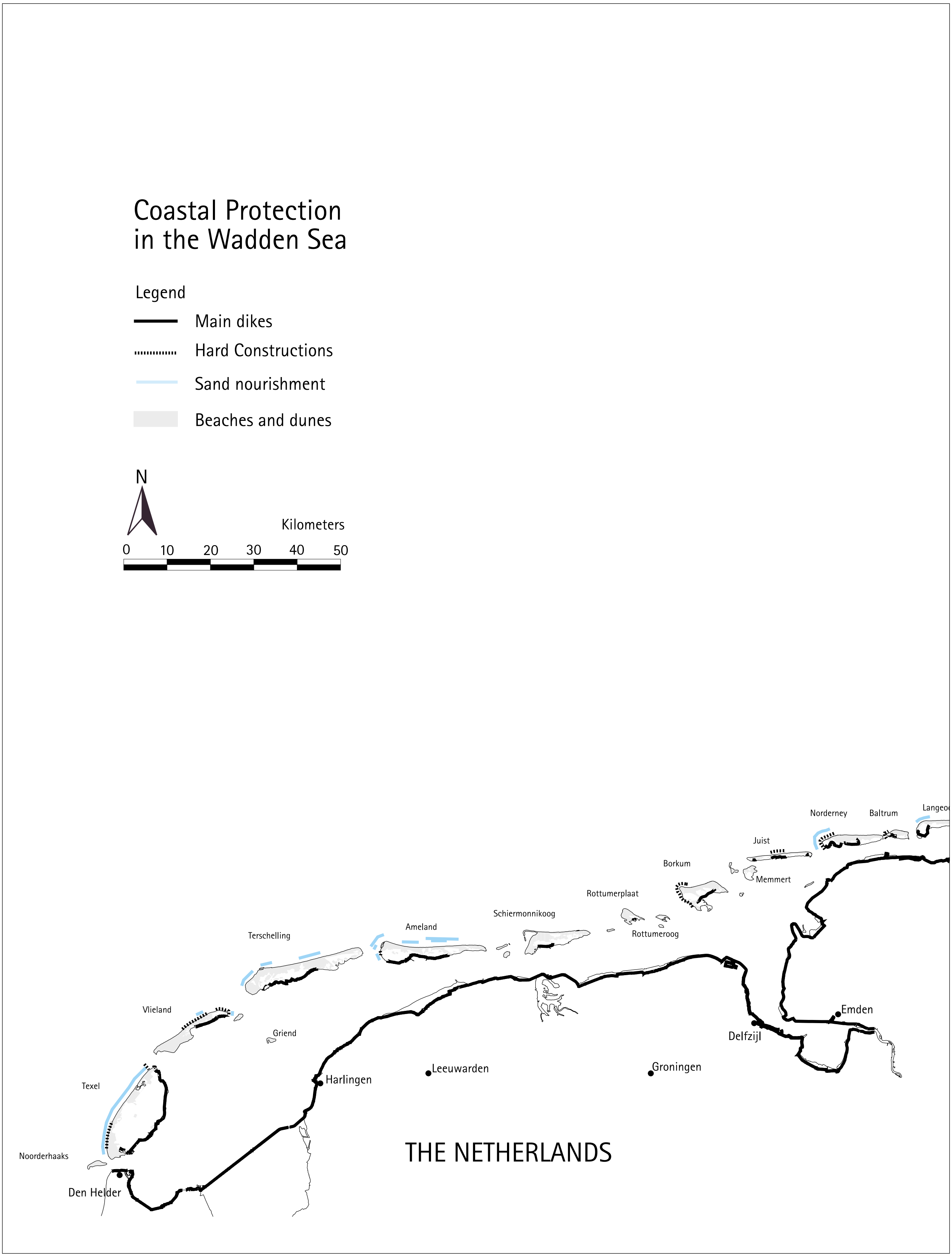
In The Netherlands coastal defense measures were also undertaken at the uninhabited parts of the islands. Starting in the 14th century sand dunes were stabilized by planting marram grass and individual dunes were connected to each other in order to get an elongated uninterrupted dune ridge all along each island. In Germany and Denmark coastal protection is mostly restricted to safeguarding the inhabited parts and infrastructure of the islands. On other parts of the islands almost no protective measures were taken. One exception is the island of Sylt where the entire 38 km long beach has been nourished at least once since 1984.

Often the introduction of hard constructions results in an accelerated erosion at the edges of the defended parts. Consequently, the defended parts need to be extended with more constructions. An example of this is given by the sea defense along the island Vlieland in the western part of the Wadden Sea (Fig. 3.3). The first groynes were built in the 19th century on the western part of this island. In the course of time next to existing groynes new groynes were built in easterly direction. Nowadays the complete North Sea coast of this island is embedded in groynes. Another example is the holiday resort Westerland at the North Sea coast of the island Sylt. Here, in the year 1907, a 70 m long wall was constructed at the upper beach to protect a hotel. As a result of intense erosion at its ends, this wall had to be lengthened to about 850 m until 1954. Strong erosion due to wave reflection at the foot of the wall was combated by revetments and, since 1960, by large tetrapods. However, the beach in front of the wall still suffers from erosion and, since 1972, regular sand nourishments are carried out to compensate for this loss. Also the island of Norderney has a long history of subsequent enforcements. These were carried out mainly on the western part.

Physically, the Wadden system forms an ensemble of islands, inlets, outer deltas and a series of adjacent tidal basins with channels, flats and salt marshes. They are interacting through the longshore transport of sediment. The Wadden system can be said to have a closed sand economy (compare 3.1.3). If part of a tidal basin in such a system becomes deeper, for instance by relative sea level rise, the system re-establishes equilibrium by importing sediment and by internal sediment redistribution (from the channels to the flats). As the ebb tidal delta is in equilibrium with the tidal volume of the tidal basin, the ebb tidal delta cannot be a net sediment source. Consequently the sediment import of the Wadden Sea will eventually lead to a net loss of sediment from the North Sea coast. In case of an accelerated sea level rise more sand will be transported from the North Sea, mainly the coastal zone, to the Wadden Sea. If the islands are fixed by hard constructions the question arises at what costs those constructions must be safeguarded.

Another, more recent, method of fixing the coast are sand nourishments. With this method natural processes along sandy coasts are taken into account and characteristic aspects of the coast are safeguarded. Compared to hard constructions it is a more flexible method because it can easily be replaced by other defense measures. In many locations sand nourishment offers a cheap and sustainable method for coastal defense. Elsewhere, for instance at places with deep tidal channels, sand is rapidly carried away. In such situations hard defense elements, possibly combined with sand nourishments, may be more suitable.

In fact, the artificial sand nourishments compensate the loss of sand from the North Sea coast to the Wadden Sea. The question is whether in the case of an accelerated rise in the sea level in the future there will be enough sand for the coast to maintain this method of coastal defense. At some places already a gradual steepening of the underwater shore can be observed. In the long run, a reduction in the amount of sand available in the underwater landward shore zone might lead to accelerated regression of the coastline.


Coastal Protection
in the Wadden Sea
Legend
Main dikes
Hard Constructions
Sand nourishment
Beaches and dunes
N
Kilometers
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50
Norderney
Baltrum
Juist
Borkum
Memmert
Rottumerplaat
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Rottumeroog
Ameland
Terschelling
Vlieland
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THE NETHERLANDS
Noorderhaaks
Den Helder

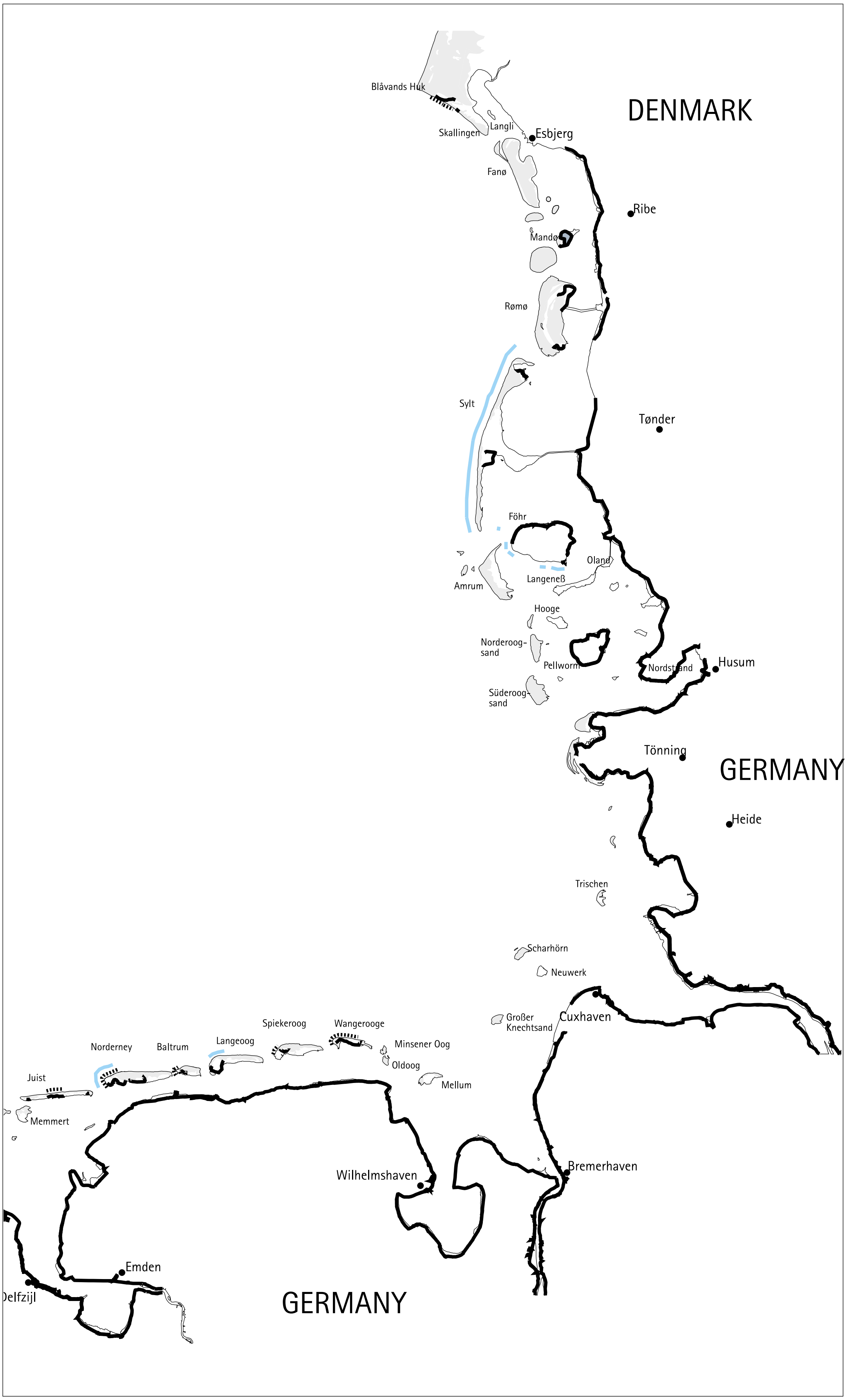


Figure 3.3: Coastal defense: Main dikes, other hard constructions and sand nourishments.

3.4 The relevance of salt marshes and summer dikes

3.4.1 Introduction

Salt marshes are tidal areas of fine sediments stabilized by a halophytic vegetation cover (see also 3.1.2 and 3.5.3). They are favored in sheltered (low energy) tidal environments with an adequate sediment supply and a moderate sea level rise. For coastal defense purposes salt marshes may be defined as the area between the dike-foot and the MHW-level. Summer polders are former salt marshes protected from inundation by lower storm surges through lower sea walls, the summer dikes.

Most of the salt marshes along the mainland coastline of the Wadden Sea are artificial, i.e. have been developed through management techniques. Until the mid of the 20th century the main purpose of salt marsh works was to reclaim new fertile agricultural land. Later, in the 1960s and 70s, the main argument became coastal defense (Hofstede & Schirmacher, 1996). In the mid of the 1970s nature conservation in the Wadden Sea became more important and, consequently, the nature function of salt marshes.

In this section the relevance of the salt marshes and summer dikes for coastal protection and nature conservation will be discussed on the basis of an integrated analysis of costs, benefits, risk of flooding, cultural-historic and natural values and public perception .

3.4.2 Salt marshes

Coastal protection functions

A salt marsh in front of a sea wall (also called foreland) reduces the wave energy and transfers the energy-impact of storm waves from the dikes towards the edge of the salt marshes. After dike breaching, a salt marsh prevents the establishment of a scour hole within the breach and prevents water to flow through the breach during succeeding tides. Further, the salt marsh provides material (clay and salt marsh sods) for dike reparation and maintenance. Finally, salt marshes reduce the energy input and prevent damage at the outer dike foot. Therefore, in Niedersachsen, Schleswig Holstein and Denmark higher salt marshes render the building of revetments superfluous. These arguments underline the importance of salt marshes for coastal defense. For example, in the Niedersachsen Dike Act (2.3.1) and the Schleswig-Holstein State Water Act (2.2.1) it is written that salt marsh management techniques for coastal defense purposes are a public affair.

Grazing

In Germany, grazing of salt marshes has long been regarded necessary for enhancing salt marsh stability and reducing the amounts of flotsam. This has created a controversy with nature protection aims, which were directed at achieving a natural vegetation by abandoning grazing. Several recent investigations have made clear that, even without grazing, the shear strength of the salt marshes suffices to prevent erosion of the surface (Erchinger et al., 1994). The same authors concluded that very intensive grazing may even reduce sheer strength.

With regard to reducing the amount of flotsam there is still controversy. Most investigations could not demonstrate a relationship between grazing and amounts of flotsam washed ashore (Gerlach, 1999). According to an evaluation in Niedersachsen intensive grazing might significantly reduce the amounts. Investigations in the Leybucht have shown that the amount of flotsam increased due to a reduction of grazing (Erchinger et al., 1996). It was concluded that, in general, grazing might influence the flotsam potential and that further investigations have to be carried out.

Erosion

A more pertinent threat to salt marshes is cliff erosion. Most salt marshes are nowadays situated in an exposed high-energy position as a result of the former practice of artificial salt marsh creation and subsequent reclamation. Without protective measures a large part of these salt marshes would probably erode and in the end disintegrate. This problem will intensify if the input of energy by waves and tides into the Wadden Sea increases. If the height of the tidal flats does not increase enough to balance the expected sea level rise, water depths in front of the salt marshes will increase. This, in combination with an increasing storminess, might enable higher waves to reach the salt marshes and induce cliff erosion.

Intensive investigations into the stability of artificially created salt marshes under an increasing sea level rise have been carried out in the Netherlands (Dijkema et al., 1990; Dijkema, 1992). The results indicate that vertical accretion at the lower mainland salt marshes is high enough to compensate for a sea level rise of about 1 to 2 cm per year. Although at this moment the higher mainland salt marshes could not balance such a sea level rise, it is expected that the higher flooding frequency will induce a stronger accumulation (see 3.1.3). The critical zone will be the higher mud flats in front of the salt marshes. Here, no significant accumulation could be observed during the

Salt marsh cliff, Norddeich (FRG). (Photo: J. Hofstede)

last decade, nor can a significant increase in sedimentation be expected as a result of higher water levels. As a consequence, the gradient between the salt marshes and the mud flats might increase. This, in combination with an increasing wave attack, could lead to cliff formation and a horizontal erosion of existing salt marshes. Dijkema et al. (1990) concluded that future management techniques to stabilize existing salt marshes should pay most attention to the fronting mud flats.

Wave climate

Results of model investigations have shown that the effect of salt marshes on wave damping mainly depends on the water depth and the wave characteristics. The waves are breaking the first time on the salt marsh and the wave energy is reduced before the waves reach the dike. Generally, this effect is getting smaller with increasing water level (Niemeyer & Kaiser, 1999; Zimmermann et al., 1999). If local water depths exceed 2.5 m, results of model investigations indicate no significant effect of salt marshes on waves and wave run-up at the outer dike slopes (Zimmermann et al., 1999). Hence, in the case of a design storm surge, no direct positive effects of salt marshes on the reduction of wave impact at the outer dike slope may be expected. In the Danish part of the Wadden Sea there are dikes with security levels of 30-50 years. Secondly, the tidal range is smaller than in Germany and The Netherlands. This means that the design water level for these dikes is lower than in Germany and The Netherlands. As a consequence, the water depth under design storm in Denmark is lower, so the salt marsh has an influence on the proceeding design waves.

In Germany also the perception that local inhabitants have of salt marshes as an essential factor in flood protection must be taken into account. For them, any reduction in salt marsh maintenance is a defeat in the continuous battle against the sea and, consequently, a reduction in safety.

Nature protection

During the last decades a growing environmental concern has led to a new appreciation of the Wadden Sea salt marshes as areas of very high ecological value.

The main aim of the German National Parks is that salt marsh flora and fauna be governed by the geomorphological structure of the habitat and that natural processes can take place (Stock, 1997; Bunje, 1997). For coastal defense this would imply the abandonment of (most) management techniques. For example, for reasons of nature protection, generally, clay may only be taken from salt marshes in case of emergency. In Schleswig-Holstein the following compromise between the coastal defense and environmental demands was realized (Hofstede & Schirmacher, 1996): The common goal of both coastal defense and environmental authorities is to preserve existing salt marshes. Where no salt marshes exist in front of sea walls, they should be created. The techniques used to reach this goal depend upon local circumstances and must be carried out as ecologically sound as possible. If local circumstances allow such, technical measures are abandoned.

In Schleswig-Holstein the area with intensive grazing of sheep has decreased from 95% in 1989 to 45 % in 1995. (Stock et al., 1996). Also artificial drainage has decreased. In accordance with the Schleswig-Holstein salt marsh management plan (Hofstede & Schirmacher, 1996) artificial drainage in ungrazed salt marshes within the Schleswig-Holstein National Park has been stopped.

Also in the Niedersachsen National Park there has been a progressive reduction of grazing. Presently 60% of the salt marshes are unused, 24% are extensively used and 16% are heavily grazed. Also artificial drainage has been reduced considerably. With the aim of integrating coastal protection and nature protection interest an ad-hoc Project Group was established in 1997. With regard to the management of the foreland this group, which has in the meantime finalized its work, recommended that only in specific cases grazing and mowing would be possible with the aim of reducing flotsam (Striegnitz, 1999).

Most salt marshes in The Netherlands have a nature protection "function". On the minority (mainly privately owned) salt marsh areas agriculture is the main use. The policy for the salt marshes is to establish a differentiated pattern of grazing (no grazing to intermediate grazing pressure) and to stop heavy grazing with the aim of enhancing the diversity of flora and fauna. To this end also drainage has been reduced considerably: The amount of clay from digging activities in the Dutch mainland salt marshes has decreased from 500,000 m^3 to 150,000 m^3 in the past ten years. This reduction is mainly due to the reduction of the size of ditches and of the maintenance frequency. The reduction of artificial drainage will be further continued, both by the cessation of drainage and the introduction of better techniques, such as the reduction of the number of ditches. Reduction of drainage could lead to less sedimentation. Therefore, artificial drainage is reduced to such an extent that no unacceptable erosion occurs.

In the Danish Wadden Sea there is, so far, no explicit nature protection policy for the salt marches which has been implemented in a management plan.

The policies laid down in the Stade Declaration are considered as management guidelines. The Wadden Sea Nature Conservation and Wildlife Reserve Executive Order aims to promote sustainable management, as far as the natural dynamics in the evolution of the landscape is not influenced unnecessarily. This can be regarded as an implementation of the Stade Declaration.

Furthermore, the Danish Nature Protection Act prohibits changes in the state of salt marsh areas. This prohibition includes changes in present use (amongst which agricultural use), which leads to any change in the condition/state of the area. The regulation preserves the present situation with a differentiated pattern of extensive and ungrazed areas. Only few areas are grazed intensively. The legislation and the limited actual demands keep artificial drainage and maintenance activities to practically zero. In general the morphological situation in the zone between existing foreland and mudflat is in equilibrium and, consequently, coastal protection activities are presently at a low level. It is practice (as a public task carried out by the Ministry of Food, Agriculture and Fishery) to maintain existing salt marshes in front of dikes as a couple of hundred meters broad foreland. This is done mainly with brushwood groynes.

3.4.3 Summer Dikes

Coastal protection

Summer dikes only exist in the Dutch and Niedersachsen parts of the Wadden Sea. In The Netherlands they have no coastal protection function.

The present summer dikes in Niedersachsen have a function in the collection of flotsam. They also avoid penetration of water in the dike foot up to medium storm surges and decrease the wave energy input on the main dike. Up to medium storm surges flotsam accumulates at the summer dike and is collected here. Should summer dikes be removed, a berm and a road would have to be constructed at the foot of the main dike for the same purpose. Moreover, the construction of the outer slope of the main dike in Niedersachsen differs from the situation in The Netherlands. In The Netherlands the outer slope and the foot of the main dike are well protected with a hard construction whereas in Niedersachsen there is only a clay layer. Also here adaptations would be necessary in case summer dikes are removed.

In Denmark there is no hard construction on the outer slope or the foot of the main dike and there are no summer dikes. Instead, the salt marsh/foreland is maintained in areas where erosion is observed.

Wave climate

In The Netherlands summer dikes are not regarded relevant for the design of the main dike. Summer dikes in Niedersachsen are part of the foreland which is mentioned in the dike law. There is, however, discussion about the possible safety function of summer dikes and its relevance for the design of the main dike. This discussion is relevant for the option of opening or removing summer dikes for nature conservation purposes (see further below). On the basis of model calculations and hydraulic model tests Niemeyer and Kaiser (1999) concluded that, at design water level, summer dikes have only a small wave damping effect. Mai et al. (1998) found in physical and numerical model tests a reduction in wave of more than 20% in case the water depth over the crest of the summer dike was lower than the relative wave height. These authors concluded that, due to the reduction of wave height and, to some extent on the wave period, the wave load on the main dike is significantly reduced. For very high water levels (water level above crest more than 2.4 times wave height) the influence of summer dikes is negligible.

Nature protection

It is the Dutch policy to outbank summer polders by opening summer dikes so as to increase the total salt mars area. The background is that in the past large areas of salt marsh have been embanked for agricultural purposes. It is not intended to remove the whole summer dike. Only several openings are made.

In Niedersachsen the option of outbanking summer polders was discussed in the framework of compensatory measures for the construction of the Europipe. The discussion mainly focussed on the role of summer dikes for coastal and flood defense (see above) and has, as yet, not been finalized.

3.4.4 Conclusions

From the above it is concluded that existing salt marshes have important functions in coastal protection and that maintaining existing salt marshes has several advantages compared to dikes without salt marshes. Salt marshes have a significant effect on wave damping up to medium storm surge levels but their effect at high storm surges is limited. In the public opinion, however, salt marshes are still considered an important safety element.

Also from the nature protection point of view maintaining salt marshes is the preferred option. There have, however, been differing positions as regards salt marsh maintenance, i.e. the intensity of grazing and drainage. With regard to grazing, there is broad consensus about the fact that this is not necessary for the stability of salt marshes.

There is still discussion about the relevance of grazing for reducing the amounts of flotsam. Investigations have shown that either there are no causal links between grazing and amounts of flotsam or that only intensive grazing would have a significant effect on flotsam amounts.

Summer dikes, which only exist in Niedersachsen and The Netherlands, have a coastal protection function in Niedersachsen. Their removal would imply adaptations to the foot of the main dike, i.e. the construction of a berm and a road for removal of flotsam and strengthening of the outer slope.

Summer dikes have only a limited function in flood defense, although there is still controversy about the question to what extent summer dikes are relevant for the design of the main dike. In this discussion also the perception of the local inhabitants plays an important role.

3.5 The relevance of biota for sedimentation- and erosion processes

3.5.1 Introduction

The influence of biota on marine sedimentation and erosion processes is usually ignored. This is certainly not justified for the Wadden Sea where innumerable individuals of plants and animals influence the muddy and sandy intertidal flats. Depending on abundance and species composition this biota influences transport, sedimentation and erosion of the sediments. Moreover, the vegetation in salt marshes and dunes is the most important factor for the retention of mud respectively the formation of dunes and their protection against wind erosion.

3.5.2 Intertidal area

Biogenic sedimentation

Changes in the sedimentation and erosion processes and in the sediment composition caused either by biological activities or biogenic structures are defined as biogenic sedimentation. Depending on the local conditions biogenic sedimentation can prevail physical sedimentation as reported from the tidal basin of List (Sylt) (Bayerl et al., 1998) or the Meldorfer Bucht (Gast et al.,1984) and can contribute to the raising of tidal flats (Thiel et al.,1984).

Wadden Sea organisms living on or in the sediment actively contribute to sedimentation by deposition (biodeposition) or by stabilization (biostabilisation) of the sediment. More passive epibenthic biogenic structures, such as mussel beds, affect the local hydrodynamic conditions, enhance sedimentation or prevent erosion. On the other hand biota is also able to increase the erodibility of the sediment or to destruct the surface by bioturbation, burrowing activities and resuspension of particles.

Biodeposition

Biodeposites are fecal pellets (feces and pseudofeces) being deposited at the sea floor (Haven & Morales-Alamo, 1972). Biodeposition influences the sediment composition and, subsequently, the habitat and community structure of the intertidal ecosystem. Austen (1997) found that up to 80% of the sediment volume of mudflats of the Königshafen (Sylt) was formed by fecal pellet.; On flats with mixed sediment the rate was 1 – 50% and on sand flats 1 – 13%. Biodeposites change the sediment composition by agglomerating fine particles (e.g. clay, silt, organic debris) to pellets with the size of sand grains. Because these pellets show the same sedimentation behavior as sand, fine material is deposited at locations where, under normal physical conditions, only sand may be expected. The fine material can be worked into the sediment by bioturbation. Biodeposites, moreover, do not take part in the current induced transport processes of their original particle size (Thiel et al., 1984). Pellets can mainly be found in the sediment layers near the surface, whereas in deeper layers they are normally converted into homogeneous mud (Bayerl et al., 1998; Austen, 1997). Maximum deposit rates of 10.5 mm/month were calculated for cockles, 0.1 mm/month for the Baltic tellin and 0.04 mm/month for the soft clam (Thiel et al., 1984).

Very high biodeposition rates are common in mussel beds. For the period 1975 to 1978, when mussel beds covered about 41.5 km^2 of the Dutch Wadden Sea, Oost (1995b) calculated an amount of 7.7 million tons of sediment bound in the eulittoral mussel beds and 9.8 million tons in sublittoral beds. To a certain degree biodeposites will be exported from mussel beds so that mixed sediment can be found in the vicinity (Oost, 1995b). The substantial loss of mussel beds in the Dutch and Lower Saxonian Wadden Sea during the 1980s and 1990s caused a decrease of areas with mixed sediment (Obert, 1995; Oost, 1995b). It is concluded that mussel beds have an important influence on the amount of fine material and the sediment balance of the Wadden Sea.

Biostabilisation

Biostabilisation is defined as the stabilization of sediment by organisms (Thiel et al., 1984) e.g. the mucous coating of upper sediment layers by benthic diatoms, filamentous networks of blue-green algae or microbial mats. The mucous excretions of these organisms have a cohesive effect on the sediment particles and decease the roughness of the sediment surface (Asmus et al., 1994; Paterson et al., 1994) which results in an increased critical velocity for erosion processes. Field experiments in an intertidal area of the Oosterschelde (SW Netherlands) have shown that in higher energy parts of the intertidal flats strong erosion may occur in places where the algae cover is chemically destroyed (De Boer, 1981). Laboratory experiments have revealed that a diatom population that was allowed to re-establish itself for 24 hours after stirring, increased the critical velocity by several tens of percents, as compared to freshly stirred and redeposited sand. Stabilization by diatoms can therefore be an important factor in the stability of sediment in intertidal and shallow subtidal areas. In addition the cellular network of filamentous blue-green algae causes a mechanical consolidation of the sediment (Stal, 1994). Anoxic sediment surfaces like the black spots in the Niedersachsen Wadden Sea, which have very low abundance of microphytobenthos, show a decrease of the critical threshold velocity and can easier be eroded (Austen & Witte, 1997).

Biogenic structures

Biogenic structures also have effects on the sedimentation processes. By decreasing current velocities or water turbulence these structures act as sediment traps for fine grained material. Mussel colonies form a semi-rigid framework which tends to bind the sediment, thereby protecting it from erosion. In seagrass meadows the proportion of fine particles is higher than in the surrounding flats and the meadows are slightly elevated (Asmus & Asmus, 1998). The loss of sublittoral seagrass in the 1930s increased the erosion in the areas where the losses occurred (Reise, 1998). A high abundance of tube building polychaete worms can change the small scale topography of the flats by forming a layer of mud on the former sandy sediment surface or by developing a distinct structure of consolidated embossed patterns and erosive troughs (Heuers et al., 1998).

Bioturbation

One effect of bioturbation is the transport of fine-grained material, e.g. biodeposits, from the surface into deeper, less erodable sediment layers. But bioturbation can also enhance the erodibility: (1) by increasing the bottom roughness; (2) by actively bringing grains in suspension; (3) by sorting of sediment. The increase in erodibility enhances the sediment transport. Some forms of bioturbation tend to destroy small-scale structures on the surface. Intensive bioturbation can obliterate ripples formed during one tide.

On the higher parts of the tidal flats organisms have sufficient time to completely modify the original depositional structures. One of the most important bioturbators in the Wadden Sea is the lugworm. The animal lives in a U-shaped burrow at depths of 15 to 20 cm, almost continuously ingesting sand. From time to time the animal excretes the ingested sand at the surface. It has been calculated that the top 30 cm of the tidal flat sediments can be reworked completely by lugworms each year (Cadée, 1976). The grains that are too large to be swallowed are concentrated at the deepest point of the U-burrow. In this way extensive layers of shells, especially of mud snails, are formed.

3.5.3 Salt marshes

In the pioneer zone (the transition between tidal flats and salt marshes) and in salt marshes, plants adapted to the extreme environmental conditions are the principal biotic component influencing sedimentation. Where a tidal flat is elevated to some decimeters below the mean high water level, the pioneer plants glasswort and common cord-grass settle, followed with increasing elevation by the sea aster and the annual sea-blite (Dijkema et al., 1990). Glasswort does not significantly influence sedimentation, but enables other plants to settle, while the common cord-grass is known to enhance sedimentation. When the elevation of the pioneer zone increases, the vegetation cover of pioneers becomes denser and other plants start to settle.

The border between the pioneer zone and the lower marsh, i.e. the area around or above the mean high-water level is characterized by the appearance of marsh grasses. By decelerating the flow of the current during flooding, the vegetation of halotolerant plants enhances sedimentation rates to maximum values (Dijkema et al., 1990). In this way large amounts of sediment are retained and stabilized by the root systems of the marsh plants; the marsh accretes vertically. In addition, erosion is strongly reduced. When the marsh becomes even higher, sedimentation rates decrease due to the decreasing number of floodings and also due to the lower sediment supply of individual floodings. As a result of sedimentation the lower marsh zone evolves into a middle marsh zone with a characteristic plant community. Above this zone the upper marsh commences with normal grassland plants.

Besides the deposition of fine silt and clay in the middle and higher marshes during (very) high water, beds of sand and shells may be deposited during storms over kilometer wide areas. More substantial shell hash deposits, situated further inland, are the result of activities of birds such as eiderducks, oystercatchers, gulls and crows.

3.5.4 Dunes

Along the Wadden Sea coast dune formation, stabilization and protection against erosion, is closely connected to plants which are able to settle in such a barren sandy environment. Dunes without vegetation are unstable, for example small barkhans (Sicheldünen) on the beaches or very large, moving "transversal ridges" (Wanderdünen) at the inner borders of the dune areas on some islands, which occur when the vegetation cannot cope with the moving sand or after destruction of fixed dune systems (Doing, 1983; Ellenberg, 1982). The establishment of more permanent dunes starts when, under "favorable" conditions, e.g. sufficient rainfall and presence of some organic matter, pioneer plants settle on sand which is piled up by the wind in the lee of shells, plants or flotsam. Sand couch grass and lime grass are the halotolerant pioneers which are able to start dune succession on the beaches, accumulating sand to primary dunes with maximum heights of about 2 m. The second step of dune development, the white dunes, which can be piled up to ridges of up to 10 m, is a result of the growth of sea marram which is the most effective dune forming plant. The plants are able to fix the sand with their strong vertical straws and long horizontal root systems and are able to grow through the sand when they are covered during storms. Layer by layer they climb up with the sand which is deposited due to the drop of the wind speed in their presence (Ellenberg, 1982). More landward, where the moving sand calms down and the accumulation of humus, decalcification, leaching of nutrients and acidification starts soil development, gray and brown dunes, densely covered with characteristic plant societies, form the next stages of dune succession (Neuhaus & Petersen, 1999). Here, vegetation mainly prevents wind erosion. In all successional stages and in all dune areas where wind, waves, rainwater, animals or man damage the vegetation, sand drifts may occur.

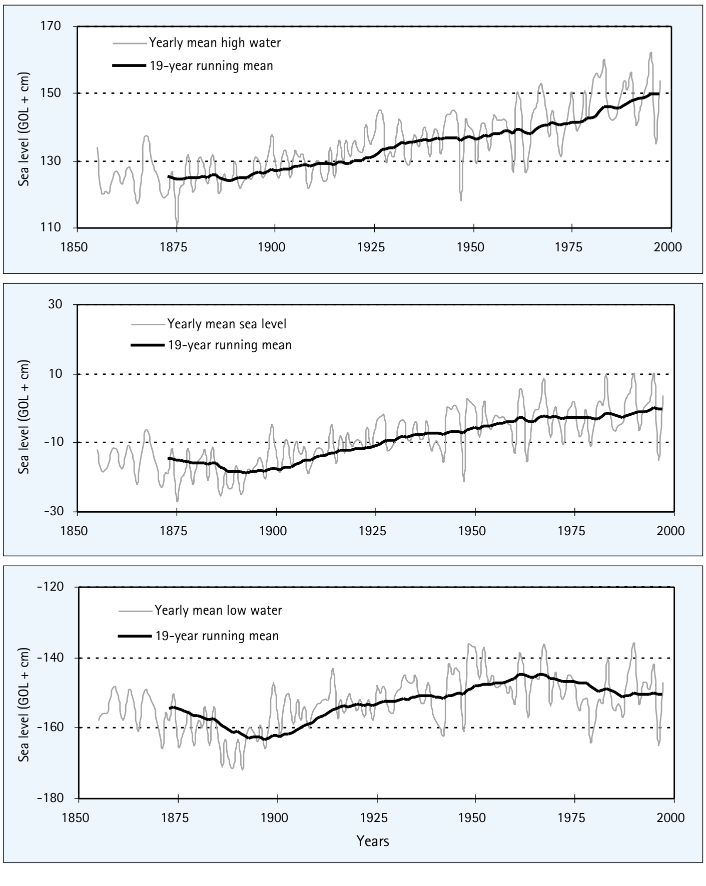
4. Analysis of Changes

Analysis of Changes: Basic Assumptions and Methodology

4.1 Introduction

In the foregoing chapters an overview has been presented of current Wadden Sea nature protection and coastal defense polices and the common knowledge basis regarding geomorphology and related biological processes and coastal defense techniques in the Wadden Sea. In this chapter an overview will be given of changes in water levels and storminess which have occurred in the past (section 4.2) and which are expected to occur in the future (section 4.3). For the latter the scenarios as elaborated by the Intergovernmental Panel on Climate Change (IPCC) will be used. In the final section 4.4 a description is given of the methodology applied by the CPSL for the evaluation of possible consequences of changes in sea level and storminess.

Figure 4.1:
Mean MHW, MSL and MLW at gauge Cuxhaven.



4.2 Past

About 18,000 years ago, during the maximum of the last glacial period, global sea level stood somewhere between 120 m and 175 m lower than the present (Jelgersma & Tooley, 1993). Huge volumes of water were bound on land in icecaps. With increasing temperatures, these icecaps started to melt. As a consequence of this melting, but partly also by subsidence of the North Sea basin, sea level rose by as much as 21 mm/yr (2.1 m per century!) over the time period 8,600 to 7,100 BP (Streif, 1989). After about 6,000 BP bottom subsidence (at a rate of 1 to 1.5 mm/yr) began to dominate, eustatic sea level (the change in sea level without considering changes in bottom level) now rising at a rate of only 0 to 1 mm/yr.

Over the last about 100 years numerous gauges have registered tidal water levels in the Wadden Sea. Long-term analyses of changes in tidal water levels show a high spatial and temporal variability. Some of the gauges, especially those in the inner parts of the estuaries, are influenced by human activities like dredging. For these gauges anthropogenic effects may outweigh the natural long-term changes in tidal water levels. However, mean trends in yearly mean high water (MHW), yearly mean low water (MLW) and yearly mean tidal range (MTR) in the Wadden Sea become obvious. Over the last about 100 years a mean MHW-rise of about 0.2 to 0.25 mm/yr, an insignificant mean MLW-rise, and a mean MTR-rise of about 0.2 to 0.25 mm/yr is given by most authors (e.g. Jensen et al., 1990, 1993; Töppe, 1993). On the basis of time series for the period 1890 - 1989, Jensen et al. (1990) observed a strong increase in the mean MHW-rise for 12 German gauges over the last decades. A linear regression through the yearly MHW-values for the time period 1890 - 1989 resulted in a mean MHW-rise of 2.5 mm/yr, for the period 1971 - 1989 this value amounted to 6.7 mm/yr. This acceleration is probably the result of long-term cyclic fluctuations and human activities (see above), rather than a consequence of an (anthropogenic) climate change (Töppe, 1993). From 1990 to 1997 the MHW level did not change significantly at most German gauges. As an example MHW, MSL and MLW at gauge Cuxhaven are given in Figure 4.1.

Long-term changes in wind (and storm) climate, wave climate and storm surges have been investigated by different authors. Based on a 1907-1980 time series of wind data from five lightships, Hoozemans (1989) established an increase of mean wind speeds of about 1 to 2 m/s per century along the Dutch coasts. Using long-term observational records of sea level, wave height and wind, Bijl (1996) could not find a sign for a significant increase in storminess over north-west Europe (German Bight and south-western North Sea) over the past 100 years. However, on smaller time-scales there is considerable natural variability. Schmidt (1997) investigated the geostrophic wind speeds in the German Bight (1876 - 1992) to arrive at possible trends in storminess. He could find no long-term trend either. Using the same data (geostrophic wind speeds), von Storch et al. (1993) calculated monthly mean wave heights in the northern North Sea. Again, no trends but high values in the beginning and the end of this century were established. Finally, Siefert (1984) and Führböter and Dette (1992) investigated the development of storm surges in the German Wadden Sea after 1900. They observed a clear increase in storm surge activity since about 1959/60 in this area.

In summary, although a clear increase in storm parameters between about 1960 and 1990 was established by most authors, no long-term trends seem to exist if we consider the last 100 years.

4.3 Future

Based upon different socioeconomic scenarios the IPCC (1995) calculated global water levels for the next century. The best estimate gives an increase in global eustatic MSL of about 0.5 m until 2100. This rise results mainly from the melting of glaciers and thermal expansion of the upper layers of the ocean. The lowest emission scenario (IS92c) gives a projected eustatic sea level rise of about 0.15 m, the highest emission scenario (IS92e) of 0.95 m until 2100. Based on numerical model investigations, Stengel and Zielke (1994) suggested that the MTR in the Wadden Sea might increase by about 30% of MSL-rise. This might result in the following (plausible) hydrographic scenario 2100:

MHW	+0.6 m
MLW	+0.4 m
MTR	+0.2 m

For the scenario 2xCO_2, von Storch (1997) calculated possible changes in storm surge heights along the North Sea coastlines. For the Wadden Sea he came up with a small increase in the order of about 0.1 to 0.2 m, i.e., well within the natural climatic variability. Zielke et al. (1997) predicted a small increase in maximal wind speeds (storminess) in the Wadden Sea for the 2xCO_2 scenario. Bijl (1997) investigated the possible effects on the storm surge heights in the southern part of the North Sea of two wind climate scenarios: (1) northward shift of the wind climate system and (2) increase in the intensity of storms. Scenario 1 only has a small impact on the storm surge heights in the area. Scenario 2, on the other hand, suggests a high sensitivity of storm surge heights on changes in the intensity of storms. Finally, regarding future storminess on a regional scale, the IPCC (1995) states: "In the few analyses available, there is little agreement between models on changes in storminess that might occur in a warmer world. Conclusions regarding extreme storm events are obviously even more uncertain".

In January 2001 the Intergovernmental Panel on Climate Change presented new figures for climate change and sea level rise. According to these new data the global average surface temperature in the 20th century has increased with 0.6 ± 0.2°C. The increase in temperature in the 20th century is likely to have been the largest of any century during the past 1000 years. Globally it is very likely that the 1990s was the warmest decade and 1998 the warmest year in the instrumental record since 1861. It is also very likely that precipitation has increased by 0.5 to 1% per decade in the 20th century over most mid and high latitudes of the northern hemisphere continents and that there has been a 2-4% increase in the frequency of heavy precipitation events over the latter half of this century.

Tide-gauge data show that global average sea level rose between 0.1 and 0.2 meters during the 20th century. Global ocean heat content has increased since the late 1950s, the period for which observations are available.

There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities. Furthermore, it is very likely that the 20th century warming has contributed significantly to the observed sea level rise, through thermal expansion of sea water and widespread loss of land ice. Within present uncertainties, observations and models are both consistent with a lack of significant acceleration of sea level rise during the 20th century.

Human influences will continue to change atmospheric composition, temperature and sea level throughout the 21st century. Based on a number of climate models the globally averaged surface temperature is projected to increase by 1.4 to 5.8°C. This is much larger than the observed changes during the 20th century. Also global average water vapor concentration and precipitation are projected to increase over northern mid- to high-latitudes and Antarctica.

Global mean sea level is projected to rise by 0.09 to 0.88 meters between 1990 and 2100 for the full range of scenarios. This is due primarily to thermal expansion and loss of mass from glaciers and ice caps. The mean values of all used climate models for all socioeconomic scenarios vary among 0.3 and 0.4 m until 2100. These may be seen as, at present, the most realistic outcomes.

Global mean surface temperature increases and rising sea level from thermal expansion of the ocean are projected to continue for hundreds of years after stabilization of greenhouse gas concentrations, owing to the long time-scales on which the deep ocean adjusts to climate change. Also ice sheets will continue to react to climate warming and contribute to sea level rise for thousands of years after climate has been stabilized.

4.4 Methodology

The IPCC scenarios are the basis for the methodology applied in the evaluation of the possible impacts of sea level rise and changes in storminess. This evaluation is presented in chapters 5 and 6.

As time horizon for the evaluation the year 2050 was chosen. On the basis of the IPCC scenarios the Working Group expects average sea level to increase between 4.5 and 44 cm within this period. In addition to the absolute sea level rise, bottom subsidence causes an increase of the water level. Therefore a range of 10 to 50 cm was taken as the expected increase until 2050. Within this range three scenarios were distinguished by the CPSL. In Scenario 1 a sea level rise of 10 cm/50 years is assumed, reflecting the current situation (compare 4.2). Scenario 2, the intermediate and most realistic scenario, assumes a sea level rise of 25 cm/50 years and under scenario 3, the worst-case scenario, a sea level rise of 50 cm until 2050 is expected. The possible impact of increase in storminess will be evaluated in addition to the impact of rising water levels.

In Chapter 5 the possible impacts of changes in sea level rise and storminess are evaluated for all three scenarios under the assumption that today's safety level is maintained. This approach has been termed "Business As Usual (BAU)". Under the BAU approach three categories of parameters have been evaluated, namely physical, biological and socioeconomic.

In chapter 6 several management practices and technical measures are evaluated. In order to make it possible to make choices on future management strategies for the Wadden Sea region these have been assessed for their contribution to maintain safety and their impact on the environment, expressed as effects on habitats and interference with natural dynamics. Also an indication of the feasibility of the different options from the technical, financial, legal, public opinion and spatial point of view is given. The options that are positive from a coastal defense point of view and which have a positive or only slightly negative impact on nature, have been selected as Best Environmental Practices (BEPs).