Coastal Protection and Sea Level Rise

Final Report

Colophon

Publisher
Common Wadden Sea Secretariat (CWSS), Wilhelmshaven, Germany

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Cover photo
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Lay-out
CWSS

Print
Druckerei Plakativ, Kirchhatten, +49(0)4482-97440

Paper
Cyclus – 100% Recycling Paper

Number of copies
500

Published
2001

ISSN 0946-896X

This publication should be cited as:
CPSL 2001. Final Report of the Trilateral Working Group on Coastal Protection and Sea Level Rise. Wadden Sea Ecosystem No. 13. Common Wadden Sea Secretariat, Wilhelmshaven, Germany.

WADDEN SEA ECOSYSTEM No. 13

Coastal Protection and Sea Level Rise

Final Report of the Trilateral Working Group on Coastal Protection and Sea Level Rise

2001
Common Wadden Sea Secretariat

Contents

Executive Summary

At the 8th Trilateral Governmental Wadden Sea Conference (Stade, Germany), it was decided to investigate the possible effects of enhanced sea level rise and, on the basis of such an investigation, develop proposals for future integrated coastal defense and nature protection policies. In 1998 a trilateral expert group, the Coastal Protection and Sea Level Rise group (CPSL) was installed with this remit. The members of the group represent coastal protection and nature protection authorities in the three Wadden Sea countries. The results of the work of the CPSL, carried out in the period 1 January 1999 till 30 June 2001, are in this Report.

The remit of the CPSL can be divided into two main phases. In the first phase a so-called "common knowledge basis" was elaborated providing the starting point for the second phase of the project in which an analysis was carried out of expected future developments.

Common agreement about basic facts was reached regarding Wadden Sea morphology and sedimentology, effects of changes in tidal drainage area, effects of fixing parts of the islands and mainland coast, the relevance of salt marshes for coastal and nature protection and the relevance of biota for sedimentation and erosion processes.

The group acknowledged that the main elements of the Wadden sea system are the barrier islands, the tidal inlets, the ebb-tidal deltas, the tidal channels, the tidal flats and the salt marshes and that there are strong interactions between these elements. The main driving forces are the tides, the waves and the wind and the main linking factor is the sediment transport. All parts of this sediment- or sand-sharing system are coupled and can be, or strive towards, dynamic equilibrium with the hydrodynamic conditions. Changes in any part of the system will cause a sediment transport to or from other parts of the system, leading to a new dynamic equilibrium. Therefore, a moderate sea level rise in the Wadden Sea, resulting from both natural and man-induced processes, will be compensated by the import of sediment which, in the long term, derives from the tidal channels, shoreface and the beaches and dunes of the barrier islands.

In addition to these hydrodynamical and morphological processes the group underlined the importance of biotic processes for sedimentation and erosion. In this respect the relevance of seagrass and mussel beds for biodeposition and reduction of erosion and the role of vegetation in the formation of dunes were emphasized.

In the second phase of the project the CPSL made an assessment of the possible impacts of sea level rise and increase in storminess for three different scenarios, the latter based upon the latest IPCC model calculations. Scenario 1 assumes a sea level rise of 10 cm in the coming 50 years. Scenario 2, the intermediate and most realistic scenario, takes as a starting point a sea level rise of 25 cm per 50 years. Scenario 3 is the "worst-case" scenario, under which a sea level rise of 50 cm per 50 years is considered. For all three scenarios the additional impact of increase in storminess was evaluated.

For all three scenarios the impact upon selected physical, biological, and socioeconomic parameters was investigated.

It was concluded that, generally, changes caused by sea level rise will not easily be distinguishable from changes resulting from the high natural variability, which is a specific feature of the Wadden Sea system. Moreover, there will be large differences in changes occurring in the different tidal basins.

Because the Wadden Sea has a high resilience to changes it was considered plausible that the system will be able to adapt to a sea level rise up to some 25 cm per 50 years (the most realistic scenario), without substantial changes.

Beyond such levels probably a breakpoint will occur because the capacity of the system to balance the changes will become exhausted. When such a breakpoint, which will differ for different tidal basins, has been passed, substantial changes in morphological and, consequently, biological parameters are expected.

One of the major changes will be a reduction of the size of the intertidal area. The group estimates that, under the worst case scenario (50 cm/ 50 years), the size of the tidal flats could decrease by 15% (720 km^2), the tidal basins becoming more the character of tidal lagoons. An increase in storminess would further enhance this development. The reduction of tidal flats will have important consequences for biological parameters, most notably bird species depending on the intertidal for foraging. A reduction in the populations of such species can be expected, not only because the potential feeding area will be less than today but also, and probably more important, because the feeding time will be less. For the worst-case scenario, the CPSL also expects changes in other morphological and biological parameters. It concerns, amongst others, an increase of erosion on the barrier islands, a significant erosion of the salt mash cliffs, a decrease in benthic biomass, a decrease in seagrass and an increase in typical salt marsh vegetation.

The main socioeconomic consequence envisaged is an increase in costs for coastal defense. Under the most realistic scenario (25 cm per 50 years) an increase of costs for dike maintenance and strengthening of at least 5 to 15% is expected. Under the worst-case scenario costs to maintain dike safety may increase by 75% in Germany and even more in The Netherlands and Denmark. Also the costs for other coastal defense measures, such as sand nourishment and salt marsh works will increase considerably.

Another important consequence of increased sea level is that possibilities for discharging fresh water from the mainland into the sea will become less and that additional sluicing, pumping and/or fresh water storage capacity is needed.

The CPSL has, furthermore, evaluated a large number of coastal defense techniques and strategies with the aim of selecting such which may, in the long-term, help maintaining the existing safety standards and alleviate the expected impacts of sea level rise and increase in storminess and which will be beneficial or, at least not negative, for natural assets, such as natural dynamics and habitat quality.

This evaluation resulted in a list of so-called Best Environmental Practice measures. These measures should be further investigated for feasibility in terms of cost-benefit, public perception and legal aspects.

The CPSL finally formulated several recommendations for policy, management and research.

The main message regarding policies is that, as far as such is not already the case, integrated policies should be developed for coastal defense, nature protection and economic development in the coastal zone, anticipating impacts of increased sea level and storminess. Such policies should also address strategies for communication with the general public about the expected impacts and the introduction of additional and new coastal defense measures and strategies.

With regard to the knowledge basis it is recommended to start a research project in which detailed sediment budget studies for the Wadden Sea are carried out, encompassing all man-induced and natural factors, as well as, a research project in which the interactions between hydrological, geomorphological and biological changes are investigated.

1. Introduction

Climate change and, in particular, its possible effects, have become a central issue in politics and science in the 1990s. To the layman the notion climate change has almost become identical with anthropogenically induced increases in the atmospheric concentrations of the so-called greenhouse gases, most notably carbon dioxide. As a result, increasing temperatures and, consequently, increasing water levels are predicted, caused by the thermal expansion of the ocean water and the melting of glaciers and polar ice caps. Also changes in wind climate are expected or have, according to some publications, already occurred. Although climate has always changed, the new feature of the present situation is the expected speed of the change. This acceleration may induce significant changes in the Wadden Sea system.

Questions regarding the consequences of accelerated sea level rise and increasing storm levels and frequencies for the Wadden Sea ecosystem also entered the political agenda of the trilateral Wadden Sea cooperation. In 1997, at the 8th Trilateral Governmental Wadden Sea Conference (Stade, Germany), it was decided to investigate the possible effects of enhanced sea level rise and, on the basis of such an investigation, develop proposals for future integrated coastal defense and nature protection policies. In 1998 a trilateral expert group, the Coastal Protection and Sea Level Rise group (CPSL) was installed with this remit. The precise terms of reference of the CPSL are in Annex 1, the members of the group are listed in Annex 2.

In this report the results of the work of the CPSL, carried out in period January 1999 till May 2001, are presented. The report consists of two parts. In Part 1, consisting of Chapters 2 and 3, basic facts are provided. Chapter 2 addresses the national administrative structures with regard to coastal protection and nature protection. In Chapter 3 relevant facts regarding the main physical and biological aspects of the Wadden Sea ecosystem, about which a common understanding was achieved within the group, are given. In the introductory part 3.1 of this chapter the basic geomorphological principles of the Wadden Sea are described. Section 3.2 addresses effects of changes in inundation area, for example through outbanking of summer polders. In Section 3.3 the implications of fixed coastal defense constructions under different sea level rise scenarios are discussed and Section 3.4 addresses the relevance of salt marshes and summer dikes for coastal protection. In Section 3.5 the relevance of biogenic structures and biostabilisation of sediment are covered.

In Part 2, consisting of the Chapters 4, 5 and 6, an assessment is given of the possible impacts of sea level rise and an increase in storminess for three different scenarios. Scenario 1 assumes a sea level rise of 10 cm in the coming 50 years. Scenario 2, the intermediate and most realistic scenario, takes as a starting point a sea level rise of 25 cm per 50 years. Scenario 3 is the "worst-case" scenario, under which a sea level rise of 50 cm per 50 years is considered. For all three scenarios the additional impact of increase in storminess is evaluated. In Chapter 4 a description is given of changes in water level and storminess which have occurred in the past and which may occur in the future. In this chapter also the methodology applied by the CPSL to evaluate impacts of future changes is explained. In Chapter 5 the expected impacts of three sea level rise scenarios on physical, biological and socioeconomic parameters are described, under the assumption that current coastal defense practices are continued (Business as Usual, BAU). Chapter 6 describes a large number of coastal defense techniques and analyses these for the criteria suitability for coastal defense and compatibility with nature protection. On the basis of the analysis a series of so-called Best Environmental Practice measures (BEP), which may be used as an alternative or an addition to regular coastal defense practices, is identified. In Chapter 7, the main conclusions and the recommendations of the CPSL are presented. Finally, in chapter 8, a comprehensive summary is given.

The report contains five annexes. In addition to the already mentioned annexes 1 and 2, a comprehensive glossary of terms is in Annex 3. Annex 4 contains a list of relevant running projects. Annex 5 contains the cited literature.

2. National Administrative Structures

2.1 Denmark

The regulation of the coastal zone in Denmark is covered by a number of legislative instruments which place the responsibility on several authorities. For the most part the state authorities are responsible for the administration of the sea territory. The ministries with the greatest responsibility for coastal defense and nature protection are the Ministry of Transport and the Ministry of Environment and Energy respectively. The administration of the land territory is mainly carried out by the counties.

2.1.1 Coastal Defense

The national Coast Protection Act of 1988 is the main legislation regulating all coastal defense measures. This law is mainly a procedural code, stating the procedure that the relevant authorities are obliged to follow when an application or public initiative for building or altering coastal defense constructions comes up. The Danish Coastal Authority (DCA), an organization under the Ministry of Transport, and the county authorities, are responsible for legislation.

The overall principle is that the responsibility for establishing and maintaining protection measures lies with the persons who profit. On the other hand, landowners do not have an immediate right to protect property. Each new measure has to be considered appropriate by several authorities. The main considerations within the framework of the Coast Protection Act are whether a construction is necessary, can fulfil its purpose, will cause undesirable side effects or conflict with nature protection rules. The county considers project drafts and decides whether the project in question is suitable to be passed on for further consideration or can be rejected immediately. The local municipality and other relevant authorities are always asked to comment on projects considered suitable, and approval for all such projects has to be obtained from the DCA within the Ministry of Transport. In general there is no public obligation to undertake coastal defense. In particularly extreme conditions the political bodies have considered it a public duty to enforce or erect dikes at the Wadden Sea coast financed by public funds in part or in full through the issue of special construction laws.

The most significant element of the coastal defenses along the Danish Wadden Sea coast consists of the existing sea dikes made of sand and clay. These stretch along approximately 115 kilometers of coastline, protecting an area of approximately 600 square kilometers (Fig. 3.3). There are very few hard defense constructions and no land reclamation measures are carried out. Most dikes are maintained by local water boards under the supervision of the DCA and the County of Ribe or the County of Southern Jutland.

2.1.2 Nature Protection

The general laws in Denmark relating to nature conservation incorporate some regulations that directly influence the administration of the coastal zone. The National Forest and Nature Agency, under the Ministry of Environment and Energy, has overall responsibility for the protection of the International Nature Conservation Areas (Ramsar, EU Bird Directive, and EU Habitats). The counties administer most of the regulations. They carry out inspections, issue permits and refusals, carry out maintenance tasks, monitor, plan and disseminate information. Some regulatory measures worth mentioning include a ban on changes to the natural conditions in salt and freshwater marshes, bogs and other areas, a 300 meter general protection zone along the coast and conservation regulations for protected dune areas.

Besides the Danish Nature Protection Law, the most significant nature protection regulation in the Wadden Sea Area is the Executive Order on Nature Conservation and a Wildlife Reserve in the Wadden Sea. This executive order covers large parts of the Danish section of the Wadden Sea Area, and is an expression of efforts to establish sustainable development for the region as a national and international nature conservation area, as well as, a way of ensuring that Denmark meets its obligations for the area including those under the EU Bird and Habitat Directives. The Executive Order contains prohibitions that regulate in detail aspects such as land and sea traffic, the collection of organisms from the sea bed, hunting, civil engineering work including coastal defense, alteration of the terrain, canals, mineral extraction and other technical installations. The Executive Order falls under the jurisdiction of the Ministry of Environment and Energy and the National Forest and Nature Agency. The provisions of this order make it possible to involve other authorities, such as the Ministry of Transport and the counties.

Finally, the Danish system of planning regulations and inter-sector spatial planning is carried out in practice with regard to the areas that border the Wadden Sea. Such planning results in the definition of a framework for future development, which is expressed in guidelines for the administrative procedures of the regional and local authorities. The general public is always involved in the planning procedure. In certain situations the planning act also dictates that larger construction projects should be subject to an EIA (environmental impact assessment).

2.1.3 Future policy principles

The agreements contained in the Wadden Sea Plan are currently being incorporated into the national and regional plans, regulations and administrative practices.

The two Wadden Sea Counties and the DCA are conducting a technical reassessment of the safety of the dikes in the Wadden Sea Area in the light of changes in sea level. This will form the basis for the various water boards to make a decision as to whether to upgrade the safety level of those dikes for which they are responsible. In practice this is mainly expected to take place through reinforcement of existing dikes.

In general there seems to be a trend towards more emphasis on the regulation of use and protection of the Danish coasts. For instance a special 3 km broad planning zone has been imposed to the land territory. A greater part of applications for defense measures to protect uninhabited areas is now rejected because it is considered important to protect the natural coastal processes. At the same time it is considered very important to maintain and if necessary improve the protection of the inhabitants in areas threatened by flooding.

The protection methods in the Danish Wadden Sea continue the tradition of using green dikes. The use of other hard constructions along the west coast is getting rare in favor of sand nourishment.

2.2 Schleswig-Holstein

2.2.1 Coastal defense

The Wadden Sea coastline of Schleswig-Holstein measures about 553 km, 297 km of which are mainland, the rest island coasts (Fig.3.3). About 425 km of the coastline are protected by State (355 km) and other dikes (70 km). In all, these sea walls protect an area of 3,472 km^2 against flooding during severe storm surges. In these coastal lowlands 253,000 people live, and economic values of about 31 billion EURO are concentrated. Further, on the islands Sylt and Föhr, sand nourishment is conducted to prevent coastal retreat. The third major coastal defense activity (apart from sea walls and nourishment) in the Wadden Sea of Schleswig-Holstein are salt marsh works, nowadays carried out mainly to protect existing salt marshes from erosion and, eventually, disintegration.

Coastal defense (coastal protection and coastal flood defense) is regulated in the Schleswig-Holstein State Water Act and the Master Plan Coastal Defense (the technical and financial concept). In principle coastal defense devolves on the persons who profit. However, flood defense that is in the interest of the public is a public obligation. Depending on the measures, the responsibility lies with state or municipal administration or with local water boards. Coastal protection that is in the interest of the public (i.e. protection of settlements against land loss) devolves on the state administration.

The Schleswig-Holstein State Ministry for the Rural Areas, Agriculture, Food and Tourism is responsible for legislation, general planning and financing. Two regional offices for the rural areas implement the state coastal defense programs. Public participation in state coastal defense is regulated in the Schleswig-Holstein State decree on the implementation of public plans. Since 1998 the integration of different uses and interests has been realized with the establishment of the "Integrated Coastal Defense Board". This advisory board is chaired by the Secretary of State for the Rural Areas and consists of representatives from all relevant public and private parties involved in the different aspects of coastal defense management.

The organization and administration of (public) coastal defense in Germany is in the responsibility of the respective states. However, as coastal defense has national consequences, capital measures are co-financed by the federal government with 70% of total eligible costs (the other 30% are matched by the states). The maintenance of existing state coastal defense structures, on the other hand, is financed 100% by the state. Municipalities and/or local water boards that are responsible for coastal defense measures in their area normally have to contribute between 5 and 20% to the costs. The rest is financed by state (and federal) government. Finally, a small but increasing financial contribution to coastal defense comes from the European Union.

In all, in Schleswig-Holstein (Wadden Sea and Baltic Sea coast) about 40 to 45 million EURO is spent on coastal defense each year.

2.2.2 Nature conservation

Nature conservation is regulated in the Schleswig-Holstein State Nature Conservation Act and the State Act for the National Park Wadden Sea of

Salt marsh works at Nordstrand (FRG). (Photo: J. Hofstede)

Schleswig-Holstein. Responsible for environmental legislation, financing and general planning in Schleswig-Holstein is the State Ministry for the Environment, Nature and Forests. Two state environmental offices, the Schleswig-Holstein State Office for Nature and the Environment and the Schleswig-Holstein State Office for the National Park Wadden Sea of Schleswig-Holstein (NPA) are responsible for research, preparation of plans, and (partly) permits. Finally, several regional environmental offices, as well as, the counties are responsible for monitoring and permits.

The Wadden Sea of Schleswig-Holstein (exclusive of the islands) is a national park, administered by the NPA. In 1999, the national park was extended with a whale protection area in the North Sea west of the island Sylt. The NPA is, amongst others, responsible for research and permits in the national park. On the Wadden Sea islands several nature reserves exist that are mainly managed by environmental NGOs.

2.2.3 Future policy principles

The old philosophy of executing coastal defense (building sea walls) in order to reclaim fertile land already ceased in the early fifties. The last sea wall aiming at this purpose was constructed in Schleswig-Holstein in 1954 (Friedrich-Wilhelm-Lübke-Koog). Afterwards, the policy for coastal defense turned into achieving the same level of security for all state dikes (i.e. each sea wall has the same probability of breaching). The sixties, seventies and early eighties were characterized by a strong belief in engineering (hard) solutions for coastal defense. However, this attitude changed into trying to use more natural techniques and material, e.g. sand nourishment, to combat coastal retreat. In 1995 a common salt marsh management plan was established by coastal defense and environmental authorities that aims at an ecologically sound protection and management of salt marshes (see also 3.4.2), salt marshes being both an important (natural) coastal defense structure and an ecologically sensitive and valuable habitat.

In future, the coastal defense policy will probably increasingly include risk analyses for single flood units (risk being defined here as the product of the probability of dike breaching and the damage potential in the flood unit). Further, more attention will be paid to public participation and the integration of other interests in coastal defense policy (integrated coastal defense management).

2.3 Niedersachsen

2.3.1 Coastal defense

The legal basis for coastal defense in Niedersachsen is the Niedersachsen Dike Act. It contains both regulations for design, maintenance, supervision and usage of dikes, forelands, dunes and other coastal defense structures and responsibilities of the authorities and the water boards. Main objective of the Dike Act is protection of man, settlements, public, industrial and infrastructure facilities, as well as agricultural areas, against flooding. The overall principle is that all persons who profit from protection are in charge of maintaining the dikes. They are organized in water boards which have to do the maintenance and construction works on the mainland dikes, except for some which are under State responsibility. The State, moreover, is responsible for all coastal protection structures on the islands and the storm surge barriers.

The Ministry of the Environment is in charge of the general guidelines and principle issues for coastal defense, as well as, the master planning. It also supervises the regional authorities, who have to fix the dimensions of the dikes in a legal act and grant permissions for extensive coastal protection measures. The local authorities work on the rural district level and are supervised by the regional authorities. They are responsible for all other supervision tasks including the water boards and permissions according to the Dike Act.

The technical planning of coastal protection measures and the maintenance of the state coastal defense structures is done by the Niedersachsen Agency for Water Management and Coastal Defense (NLWK), which is supervised by the ministry. Special aspects of planning and applied science in coastal engineering are carried out by the coastal research station of the Niedersachsen State Board of Ecology subordinated to the ministry.

The Dike Law defines the main dikes, dunes, storm surge and all constructions that enhance their stability (e.g. groynes, revetments) as elements of coastal protection. These elements have to be maintained and, if necessary, reinforced. The foreland (salt marsh in front of a dike) has to be preserved in a defined width and maintained, including all technical constructions, as a protection element for the main dike.

2.3.2 Nature conservation

The legal basis for nature conservation are the Federal and the Niedersachsen Nature Conservation Act, the State Act for the Wadden Sea National Park of Niedersachsen and the legal act for the Nature conservation area Dollart. Except for the estuaries of Ems, Jade, and Weser, the whole Niedersachsen part of the Wadden Sea has been designated as a national park in which the uninhabited parts of the East Frisian islands are included.

The general objective for the protection of the tidal flats and the adjacent sublittoral, the dunes, and the salt marshes as valuable habitats, is to preserve the species composition and natural processes, including the natural morphology and dynamics of this area.

Under the responsibility of the Ministry of the Environment, the National Park Administration, as a subdivision of the Weser-Ems district authority, develops general guidelines and executes the regulations of the National Park Act. In addition, the local authorities at the rural district level execute the regulations of nature conservation in areas above MHTL except those areas with highest protection. The other legal regulations remain in existence. Special aspects of nature conservation are assessed by the Niedersachsen State Board of Ecology.

2.3.3 Future policy principles

The future coastal defense policy will be focussed on the development of probabilistic design codes instead of the present deterministic ones. The evaluation of the feasibility of risk analyses for coastal protection structures will also be a matter of high importance.

On the islands a long term investigation program is carried out for the evaluation of sustainable future protection concepts in areas where structural erosion occurs. The future management of the foreland areas will be further harmonized by creating regional management plans that integrate demands of coastal defense and nature conservation.

2.4 The Netherlands

2.4.1. Coastal defense

The complete mainland coast of the Dutch Wadden Sea, about 200 km, is defended by dikes. Also the polders at the Wadden Sea site of the islands are protected by dikes (Fig. 3.3). The dike length on the different islands varies from a few to 30 kilometers. Dunes form the coastal protection of the 155 km of North Sea coasts of the inhabited islands. Since 1990 sand losses from the North Sea coast have been compensated for with sand nourishments and this will also be the case in the future. On Texel and Vlieland, the sandy coast receives additional protection by breakwaters made of basalt and concrete. On the tips of parts of the inhabited islands natural coastal development is allowed within certain limits. No or very limited maintenance is carried out on the uninhabited eastern part of Schiermonnikoog and the uninhabited islands Rottumerplaat en Rottumeroog.

On the national level the Ministry of Transport, Public Works and Water Management and the Ministry of Agriculture, Nature Management and Fisheries are responsible for coastal defense respectively nature protection of the Wadden area. The Ministry of Public Housing, Spatial Planning and the Environment presents the guidelines for local and regional plans in a national directive, the PKB-Waddenzee (Planological Core Decision Wadden Sea).

The protection of the North Sea coast of the islands is executed by the Directorate-General for Public Works and Water Management of the Ministry of Transport, Public Works and Water Management. The Provinces along the coast each have a Provincial Consultative Body for the Coast (POK). In this body national, provincial and municipal authorities and regional water boards discuss all issues concerning coastal defense and give recommendations to the Minister of Transport and Public works. The province Groningen has no POK. Here coastal affairs are discussed in a provincial committee on water management. Only the uninhabited barrier islands Rottumerplaat and Rottumeroog belong to this province.

The responsibilities of the different parties are divided as follows:

- the central government safeguards the position of the coastline and combats structural erosion;
- the water boards are responsible for the design and maintenance of the sea defenses, except on most of the Wadden islands, where the central government is responsible both for coastline preservation and for the sea defenses;
- the provincial authorities are responsible for the overall coordination and for the integration with other areas of policy, such as physical planning. The provincial authority also chairs the POK.

Matters which may arise in the POKs include

- the position of the coastline, to be maintained by sand nourishments;
- the annual program of nourishment works;
- plans for alternative methods of coastal protection;
- plans for developments within the coastal zone, e.g. nature development projects.

POKs increasingly pay attention to the links between coastal protection, nature development, recreation and physical planning. Therefore, in the POK for the Wadden Sea area, the central government is not only represented by the Ministry of Transport, Public Works and Water Management but also by the Ministry of Agriculture, Nature Management and Fisheries.

2.4.2 Nature protection

Almost the entire Dutch Wadden Sea is a nature conservation area by law. Exceptions are strips along the inner parts of the islands and the main shipping channels. The entire area, including the main parts of the islands and the coastal zone of the North Sea, is part of the core and/or nature development area in the so-called "ecological main structure". Most of the area has been designated as EU Habitats and Bird Directive area. The entire island of Schiermonnikoog has the status of "National Park".

From the central government the Ministry of Agriculture, Nature Management and Fisheries is responsible for nature conservation. Provinces and municipalities deal with nature protection in their regional and local plans. The guidelines for those plans are given in a national directive, the PKB-Waddenzee (Planological Core Decision Wadden Sea) of the Ministry of Public Housing, Spatial Planning and the Environment. Specific areas are owned and managed by nature conservation organizations.

2.4.3 Future policy principles

Coastal management is gradually changing from building sea defenses and damming off coastal inlets to dynamic preservation. Coastal management is more and more directed at working with the natural dynamics of the coast instead of trying to control it. In this way, not only safety but also ecology and human use are taken into account. Sand nourishments are considered a good method for dynamic preservation of the coast. In the back barrier area the strict divisions between dry and wet, high and low, fresh and salt are subject of discussions and projects have started aiming at restoring gradients.

For the management of the Wadden Sea itself nature conservation laws and EU-directives become more and more important leading to conflicts between nature conservation and human use.

3. Common Knowledge Basis

3.1 Wadden Sea morphology and sedimentology

3.1.1 Introduction

The objective of this chapter is to give an overview of the morphology of the Wadden Sea barrier coast. The Wadden Sea, with a tidal range from 1.4 to 3.5 m, fringes the Dutch, German and Danish coasts over a distance of nearly 500 km with a maximum width of approximately 35 km. The tidal wave in the North Sea moves from the S(W) to the N(E), that is from Den Helder in The Netherlands to Esbjerg in Denmark. Towards the North Sea the Wadden Sea is bordered by some 20 large and many small barrier islands, peninsulas and sandy shoals. Behind these islands lies the largest tidal flat area in Europe. The mainland coast consists of dikes, some salt marshes and, especially towards the northern Wadden Sea, a few Pleistocene cliffs. Especially north of the Elbe river remnants of older mainland deposits form small islands in the tidal basins, these are the so-called "Halligen".

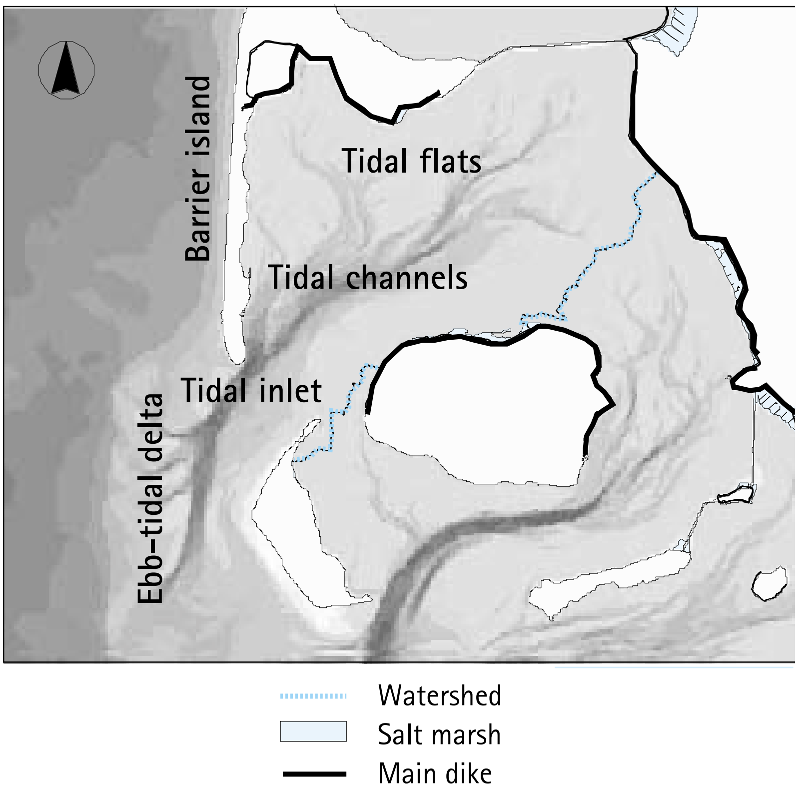


Figure 3.1: Morphological elements of the Wadden Sea system.

3.1.2 Morphological elements

The Wadden Sea is characterized by 33 adjacent tidal inlet systems, each consisting of the following morphological elements: (1) barrier island, (2) tidal inlets, (3) ebb-tidal delta and inlet, (4) tidal channels, (5) tidal flats and (6) salt marshes (Fig. 3.1).

Barrier islands

Barrier islands lie on the seaward side of the Wadden Sea. They are formed and sustained by the combined action of wind, waves and tides and represent a sediment sink. Normally a barrier island consists of a shoreface, beach, dunes and overwash areas. However, some barriers, e.g. Japsand, Norderoog- and Süderoogsand in Schleswig-Holstein lack dunes. Today, on most barriers also reclaimed salt marsh areas (polders) exist.

Tidal inlets

The barrier islands are separated from each other by tidal inlets. Tidal inlets represent the transport routes through which the tidal waters (loaded with sediment) enter and leave the tidal basins with each tidal cycle. A dynamic equilibrium exists between the tidal currents and the cross-sectional area of the inlet channel (mainly controlled by the scouring potential of the currents).

Ebb-tidal deltas

The sediment that is transported by ebb-tidal currents is deposited at the seaward outlet, caused by decreasing current velocities. In result, an ebb-tidal delta develops. However, the erosive forces of deep water waves coming in from the North Sea, limit the sediment volume of the deltas. A dynamic equilibrium exists between these erosive forces and the tidal accumulation (Oost, 1995a; Hofstede, 1999). Because the tidal channels of the inlet and the delta are strongly interrelated, they are normally treated as one element.

Tidal channels

The same accounts for the tidal channels and the sub- and intertidal flats which constitute a tidal basin. Sub- and intertidal channels function as transport routes for the tidal water masses. Hence, the same dynamic equilibrium between currents and cross-section exists as for the tidal inlet channels. Through the channels sediment is transported towards the tidal flats with the flood currents.

Tidal flats

At the tidal flats this material may become settled as a result of decreasing current velocities, i.e. the tidal flats act as a tidal sediment sink. Because the (energy-rich) waves from the North Sea are almost completely dissipated at the shoreface and ebb-tidal deltas (Niemeyer, 1986), only local (storm) waves limit the tidal accumulation on the tidal flats. Similar to the ebb-tidal delta, a dynamic equilibrium seems to exist on tidal flats between the erosive forces of storm waves and tidal accumulation (mainly controlled by the time of tidal inundation, Ch. 3.1.3).

Salt marshes

If sedimentation on the tidal flats exceeds erosion (i.e. no dynamic equilibrium), eventually a supratidal salt marsh may form. Salt marshes are inter- and supratidal areas of fine sediments stabilized by a halophytic vegetation cover. Boundary conditions for establishing and sustaining salt marshes are an adequate supply of fine sediments, a low energy environment which allows for sedimentation (see above), regular saltwater inundation and, finally, a moderate sea level rise to balance accumulation and prohibit vegetation succession. Normally (mainly controlled by the time of tidal inundation) tidal accumulation exceeds sea level rise and succession occurs. Nowadays, most of the mainland salt marshes in the Wadden Sea are artificial, i.e. developed by salt marsh accretion enhancement techniques (drained brushwood groyne fields, Hofstede, 1996).

In conclusion, the elements of the tidal systems that constitute the Wadden Sea show strong mutual interactions. All elements influence the local tidal currents and wave regime and thus the local sediment redistribution patterns. Empirical relationships document that the morphological structure of all elements strongly depends on the prevailing hydrodynamic (tidal and wave) conditions. In general, the tidal currents seem to constitute a positive (accumulative) force in most elements, whereas waves are a negative (erosive) factor. Only at the barriers waves may act as a

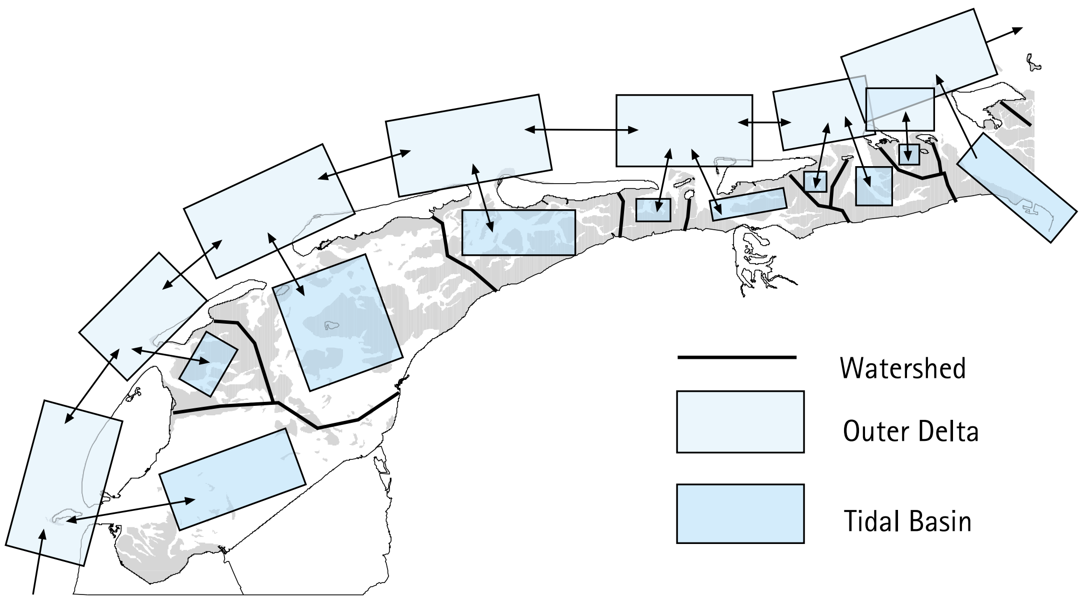


Figure 3.2: Sediment transport between Wadden Sea and North Sea and along the islands. From: Louters and Gerritsen, 1994.

positive force during fair weather conditions. The morphology and morphodynamics of the Wadden Sea are described in detail by, amongst others, Ehlers (1988) and Oost (1995a).

3.1.3 Sand-sharing system

Each tidal system can be considered to form a more or less separate (closed) sand-sharing system (Dean, 1988). However, it should be taken into consideration that adjacent tidal basins may influence each other across the tidal watersheds (Fig.3.2) (Oost & Dijkema, 1993). All parts of a sand-sharing system are coupled and can be in, or strive towards, a dynamic equilibrium with the hydrodynamic conditions. Changes in any part of the system will primarily be compensated by sediment transport to or from the other parts of the same system. When changes are temporary and limited, the old dynamic equilibrium will eventually be restored. For example, a moderate increase in sea level rise induces a stronger accumulation on tidal flats and salt marshes as a result of longer tidal inundation (i.e. the sediment having more time to settle). As a result, the elevation of the flats and salt marshes increases and the time of tidal inundation decreases again until the old dynamic equilibrium is restored. If changes are more permanent or intense, a new equilibrium will be established (e.g. reduction in the cross section of tidal channels caused by the permanent reduction in tidal prism due to land reclamation). Especially in the last situation sediment may be imported from or exported to areas outside the sand-sharing system.

To compensate for the observed secular sea level rise (Chapter 4), each year several million m^3 of material are deposited in the Wadden Sea. In this way the same altitude with regard to mean sea level is maintained or, in other words, the dynamic equilibrium between hydrography and morphology is maintained. In the long term most of this sediment is derived from the shoreface, beaches and dunes of the barriers islands, western Jutland and northern Holland. As a consequence, generally, barrier islands tend to retreat in response to sea level rise (Bruun, 1962). However, on the Wadden Sea barrier islands a number of factors (excessive sediment supply by the littoral sand transport, Pleistocene subsurface, coastal protection) may counteract this morphological response. For example, the western coasts of Fanø and Amrum seem to be rather stable, while Rømø is even expanding seaward as a result of a strong littoral sediment supply. Sylt is maintained in its position through regular sand nourishments and the western part of Norderney is kept in place by massive coastal protection measures. A further morphological result of the wave-driven littoral sand transport is the long-term eastward movement of most of the West- and East-Frisian Islands.

3.2 Effects of changes in tidal drainage area

Sea level rise, as well as, human interventions may lead to a change in tidal drainage area. From human interventions it is known that changes in drainage area of a tidal inlet system may affect dimensions and orientation of the various parts of the system, as well as, sedimentary characteristics.

3.2.1 Dimensions and orientation of the various parts of the system

If changes in tidal drainage area result in changes in tidal volume, the dimensions and orientation of various parts of the system may also be influenced. A decrease in size of a tidal drainage area will generally result in a decrease in tidal volume. This decrease in tidal volume will result in a decrease of the channel dimensions and the ebb-tidal delta sand volume. An enlargement of a tidal drainage area will lead to a larger tidal volume and consequently bigger channel dimensions and ebb-tidal delta sand volume.

An Example of a Change in Tidal Volume

In 1969 the Lauwerszee, an embayment of the Wadden Sea, was diked and the tidal prism of the tidal inlet Zoutkamperlaag decreased from 305 million m^3 to 200 million m^3. Before the closure of the Lauwerszee, a dynamical equilibrium was maintained in the ebb-tidal delta and the backbarrier area of the Zoutkamperlaag Inlet. The reduction of the tidal prism led to the development towards new equilibrium dimensions. In the period 1970-1987 26 million m^3 of sand was transferred from the ebb-tidal delta. Also sedimentation in the inlet and erosion of the ebb-tidal delta occurred as a result of reduced tidal currents. In the backbarrier area the main backbarrier channel was partially filled and the eastern watershed shifted as the channel east of it filled up. The changes in the Zoutkamperlaag inlet system thus also influence the adjacent, downdrift inlet system. In the period 1987-1993 the inlet itself became reoriented into a more downdrift orientation, as might be expected for a decrease in tidal prism.

Under equilibrium conditions, the net amounts of sediment which are trapped or eroded are normally small. Gradual changes in, for instance, sea level rise or bottom subsidence, cause a slight distraction of the dynamic equilibrium between hydraulics and morphology. As a reaction more sediment will be trapped or eroded in order to restore the dynamic equilibrium situation.

After sudden changes in the size of tidal basins, for instance by embankments, sediment deficits or surpluses may become so large that it takes decades to reach new hydraulic and morphologic equilibria. Those bigger changes in one basin may also affect neighboring basins. Examples of such sudden changes are the closures of Zuiderzee en Lauwerszee which took respectively 60 and 25 years erosion and sedimentation before more or less new dynamic equilibrium states were reached (see Box).

3.2.2 Sedimentary characteristics of the system

As a result of the sorting processes, caused by decreasing dynamics with increasing distance from the inlet, the grain size of the sediments decreases in this direction. The finer sediments will also settle in the more sheltered embayments. The embankment of mainland areas in the past and resulting decrease of tidal basin dimensions has led to a decrease of the surface of those muddier environments. As a result, muddy environments are rare nowadays. Flemming and others showed for the Spiekeroog backbarrier area that, due to the embankments, the hydrodynamic energy in the remaining area increased, resulting in a decrease of the mud content in front of the dike through time.

In the Netherlands dikes around some summer polders have been opened to establish new tidal marshes. Because those polders are situated just above MHW-level, sedimentation of mud during storm set-up is expected. Due to their relatively small sizes and height above MHW level, the opening of the summer polders has no effect on tidal volume, height of storm-surge levels or sediment budget.

Changes in grain size may have a profound influence on the species composition of the sediment (compare also 3.5) and, consequently, foraging animals.

Beach wall in Westerland, Sylt (FRG). (Photo: J. Hofstede)

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.

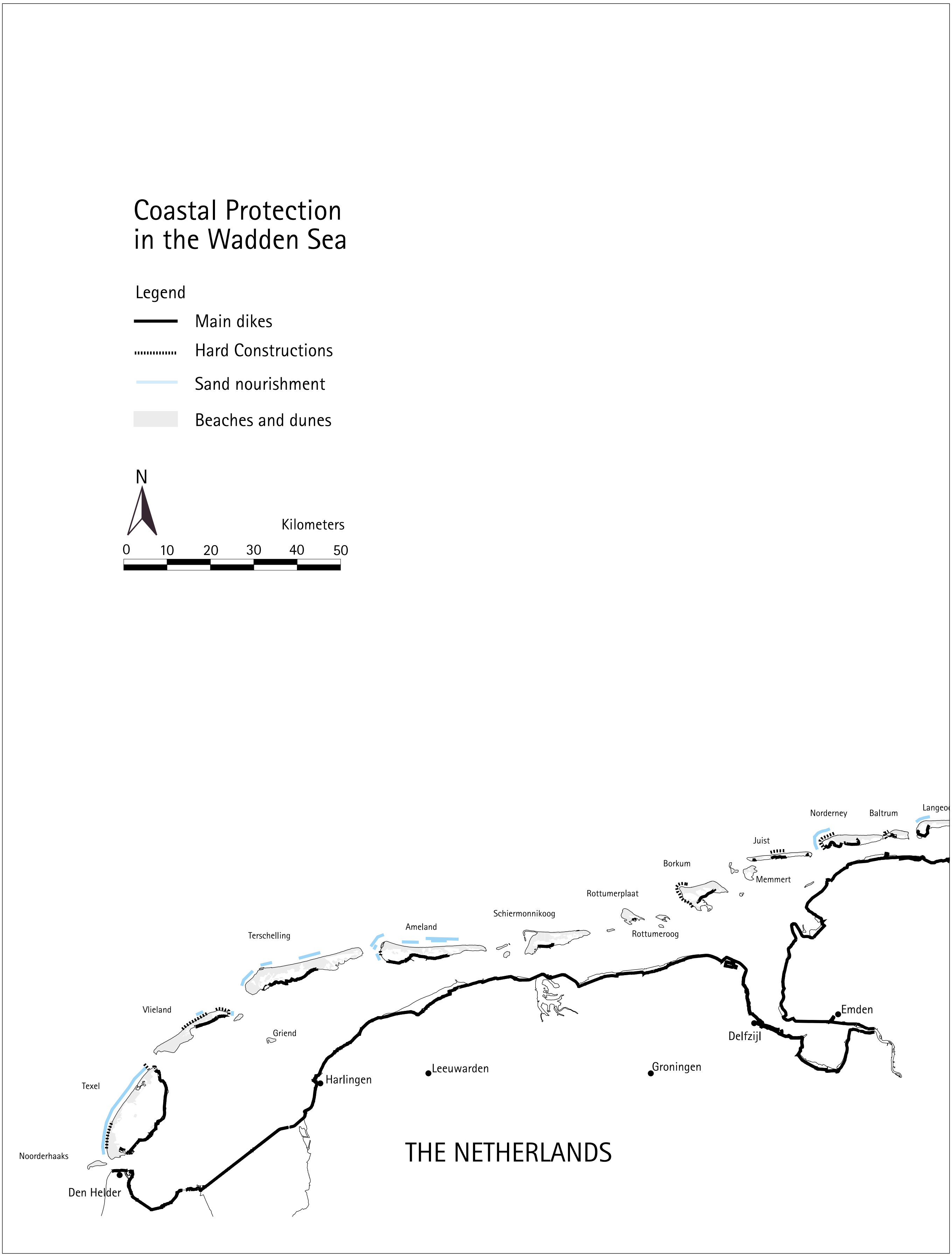
In The Netherlands coastal defense measures were also undertaken at the uninhabited parts of the islands. Starting in the 14th century sand dunes were stabilized by planting marram grass and individual dunes were connected to each other in order to get an elongated uninterrupted dune ridge all along 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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Terschelling
Vlieland
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Den Helder
THE NETHERLANDS

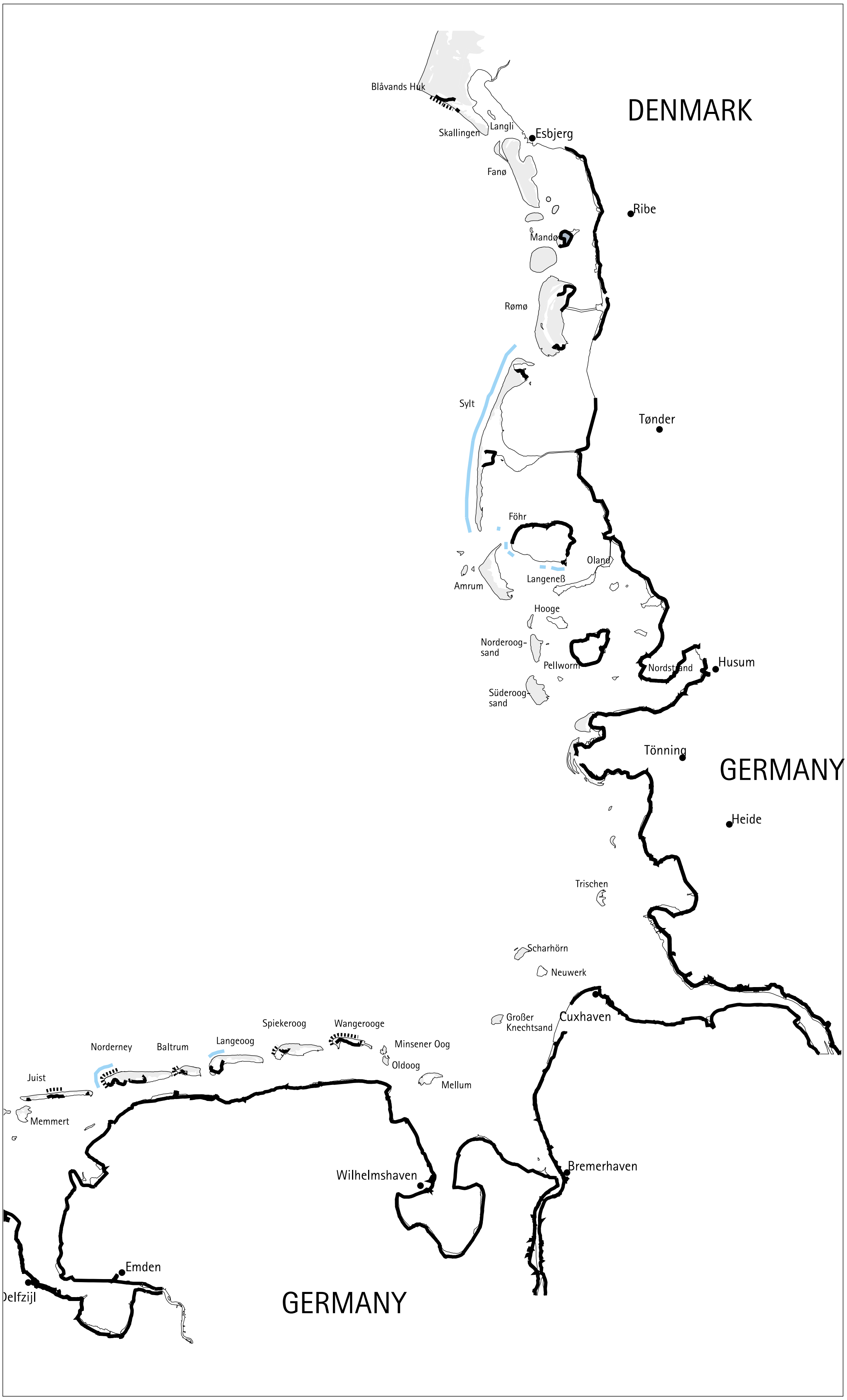


Figure 3.3: Coastal defense: Main dikes, other hard constructions and sand nourishments.

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.

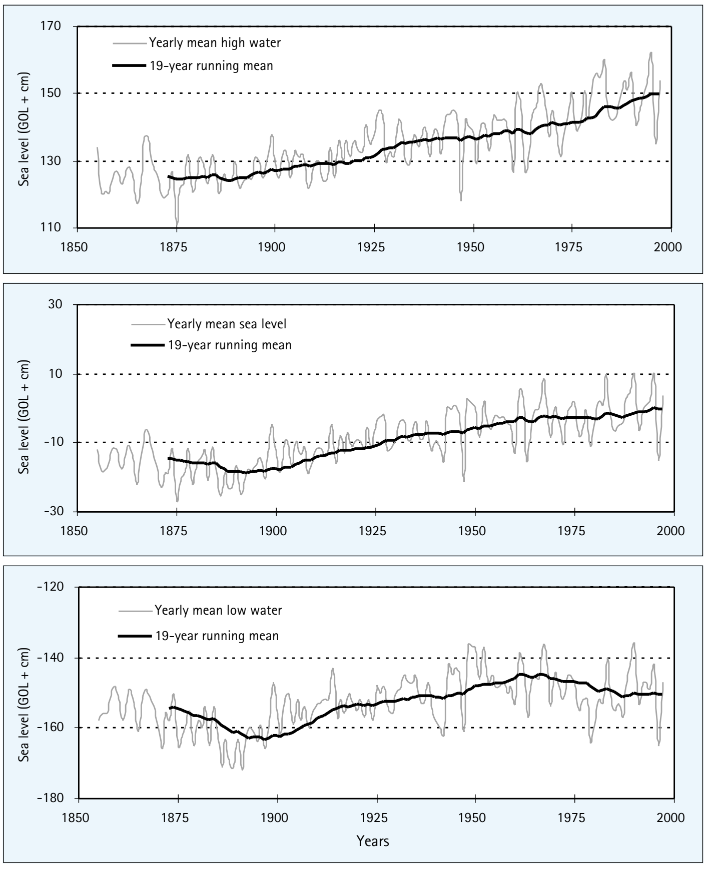


Figure 4.1: Mean MHW, MSL and MLW at gauge Cuxhaven.

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).

5. Impacts of Changes

Impacts of Changes in Sea Level and Storminess

5.1 Introduction

In this chapter, the possible changes in morphology, biology, and coastal defense efforts for the hydrological scenarios under the assumption "Business As Usual - BAU" are described. To this end, appropriate parameters that characterize morphology, biology and coastal defense in the Wadden Sea were selected. The results represent the expert opinion of the working group members. For most of the parameters almost no quantitative data and/or scientific outcomes exist, either because there is no monitoring of appropriate parameters or monitoring has only started recently. Hence, it was only possible to achieve qualitative estimates based on the present state of knowledge and (practical) experience. Consequently in Table 5.1 no absolute figures but percentage ranges or, for biologic parameters and storminess, signs (positive, neutral or negative) indicate the expected relative changes for each scenario. The present situation has been set at 100%. Under the 10 cm scenario no or only minor changes are expected, as this scenario represents the continuation of present sea level rise.

In sections 5.2 and 5.3 the expected changes in physical and biologic parameters under the three hydrological scenarios are presented. The consequences for safety, fresh water run-off and harbor/shipping and salinity for each hydrological scenario are described in Section 5.4.

All results have been summarized in the overview Table 5.1.

5.2 Physical consequences

To characterize the possible physical consequences for the Wadden Sea under the three hydrological scenarios, six parameters have been selected by the working group:

- flooding time intertidal flats (the period with salt water cover);
- spatial extent intertidal flats (surface area between mean low and mean high water level);
- tidal channel cross-section;
- salt marsh accretion (changes in height of the salt marshes);
- salt marsh cliff erosion (horizontal development of seaward salt marsh edge);
- barrier retreat (migration of barriers).

5.2.1 Flooding time intertidal

The flooding time of the intertidal flats is expected to increase by 2.5 to 7.5% under the 25 cm scenario, and between 5 and 15% under the 50 cm scenario. This increase will be further aggravated if storminess increases as well. However, the working group stresses that the changes will strongly differ from one tidal basin to another (Fig. 5.1), depending on the amount of sediment available to balance sea level rise. Some tidal basins already seem to suffer from a sediment deficit. Hence, the flooding time in these tidal basins will probably be much more affected than suggested by the mean values mentioned in the table.

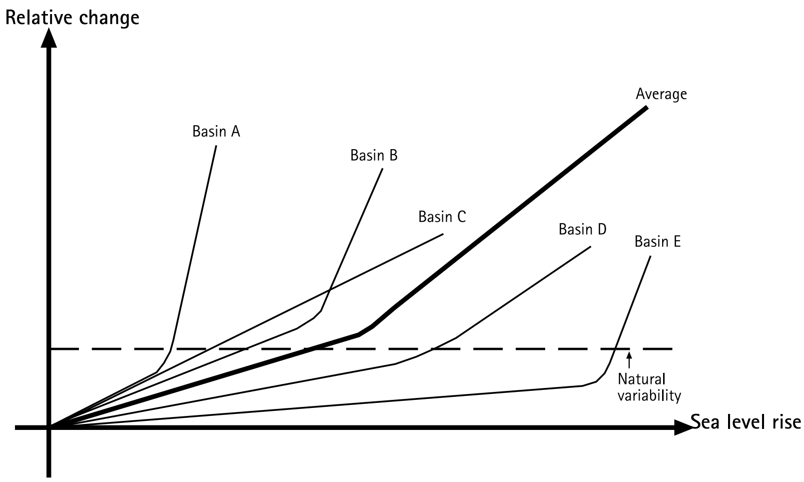


Figure 5.1: Possible changes in geomorphological and biological parameters for individual tidal basins under sea level rise. Up to a certain „break point" parameters react slowly and within the range of natural variability. After the break point, which differs for different tidal basins, reaction to SLR is evident but again different for the individual tidal basins.

5.2.2 Surface area intertidal

The effects of rising sea levels on the surface area of the intertidal flats are expected to be the same as for the flooding time. Hence, the spatial extent might, under the 50 cm scenario, diminish by up to 15% or 720 km^2 compared to the present situation (4,800 km^2). This will, obviously, significantly influence the biological parameters (Ch. 5.3). Under the "worst case" scenario the Wadden Sea might start to evolve from an ecosystem characterized by large intertidal areas, towards a more open water, lagoon-like environment.

5.2.3 Tidal channel cross-section

A well-known parameter to characterize tidal channels is the tidal channel cross-section (Fig. 5.2). In general it is expected that a rise in sea level will result in a (relatively small) increase in the cross-sectional areas of the tidal channels. An increase in storminess might, on the other hand,

Table 5.1: Overview of expected changes in physical, biological and socio-economic parameters under three hydrological scenarios under Business as Usual (BAU) policies.

*1) The change is given as either absolute, relative (Situation in 2000 = 100%), qualitative (+,-, 0) or descriptive. The range given is an average (compare figure 5.1).

*2) Qualitative indication of additional effect increase (frequency/intensity).

*3) Generally sea level rise will increase erosion. A sea level rise of 25 cm to 50 cm will cause an additional retreat of ca. 1.50 m per year or more. Along the western shores of Amrum, Eiderstedt barriers and Dithmarschen retreat is balanced by a strong sediment input from the longshore drift. Rise in sea level will not have a large affect on the accretion at the west coast of Rømø and Fanø, with a sea level rise of 50 cm a decrease of accretion, or even erosion, can be expected.

*4) For each country the relative share of expenditure for each of these categories is given in Table 5.2.

	Present situation	Change 2050 compared to present situation *1)			Storms *2)	Remarks
		10 cm/50yr scenario	25cm/50yr scenario	50 cm/50yr scenario		
I. PHYSICAL ASPECTS						
Flooding time intertidal area		0	+2.5 to +7.5%	+5 to +15%	+	Assuming sedimentation. Large differences between tidal basins (0 to +25%).
Surface area intertidal flats	NL 1,300 km^2 Nds+HH 1,500 km^2 SH 1,300 km^2 DK 700 km^2	0	-2.5 to -7.5%	-5 to -15%	-	Lister Dyb tidal basin -30% (under 50cm/50yr scenario).
Channel cross-section			0 to +5%	Up to +10%	0 to +	
Salt marsh accretion (in height)	SH +0.5 to +2.5 cm/yr	+0.5 to +2.5 cm/yr	0 to +2.5 cm/yr	-0.5 to +0.5 cm/yr	-	In worst-case scenario less accretion and some drowning.
Salt marsh cliff erosion		0 to 2 m/yr	0 to 2 m/yr	0 to 4 m/yr	+	Very large local differences.
Barrier Retreat		*3)	*3)	*3)		
II. BIOLOGICAL ASPECTS						
Benthic biomass		0	0 to -	-	-	Depends strongly on sediment composition (and, consequently, dynamics).
Birds (selected species) population size		0	-	-	-	Depends on frequency of high floods (breeding birds) and benthic biomass
Fish nursery		0	-	-	-	Temperature, change of habitat and turbulence important factors
Seal population size		0	0	0 to -	-	
Seagrass area		0	-	-	-	Related to decrease intertidal
Dune vegetation		0	0	0 to -	-	
Salt marsh vegetation diversity		0 to +	+	+		
III. SOCIOECONOMIC ASPECTS						
Efforts to maintain present safety standards						
Dikes	100% *4)	0	5 to 15%	15 to 75%	15%	Depends to an important degree on whether strengthening has been carried out recently
Other hard constructions	100% *4)	0	10 to 40%	40 to 140%	15%	
Sand suppletion (incl. Dunes)	100% *4)	0	50 to 100%	100 to 300%	10%	
Salt marsh works	100% *4)	0	5 to 10%	10 to 25%	30%	
Efforts to maintain discharge capacity	100%	0	20 to 50%	50 to 200%	+	
Salinity ground water		0	0 to +	+		
Dredging effort	100%	0	-5 to 0%	-10 to -5%	0 to +	

induce a (insignificant) reduction of the cross-sectional area due to silting up of the channels. However, the changes will probably remain within the natural variability of the system.

5.2.4 Salt marsh accretion

Present day accretion rates on the salt marshes may vary from about 0.5 cm/yr on the barrier salt marshes to more than 2.5 cm/yr on some mainland salt marshes. With increasing sea level the time of tidal inundation and, subsequently, accumulation will increase. Hence, up to a certain limit (vertical) salt marsh accretion will be able to balance a stronger sea level rise. It is expected that under the highest sea level rise scenario (50 cm in 50 years) the salt marshes with low accretion rates will start to drown. An increase in storminess and, consequently, increased amounts of suspended material may cause a stronger sediment transport towards the salt marshes. A stronger accretion (counteracting the drowning tendencies) might be the result. Depending on which process dominates, the salt marshes will drown or balance sea level rise.

5.2.5 Salt marsh cliff erosion

Although salt marshes with a perennial halophytic vegetation cover are rather robust to hydrological changes (they even depend on a rising sea level, see 3.1.2, 3.5.3), the fronting pioneer zones are much more sensitive, especially to changes in storminess. An increase in wave-impact during storms will, under natural conditions, result in (an intensifying) salt marsh cliff erosion at the seaward edge of the salt marshes. If this process continues, the salt marshes might be eroded by (locally) up to 4 m/y until they finally disappear. However, as with flooding time and surface area of the intertidal flats, the working group stresses that large regional differences may prevail depending on the exposition of the salt marshes to incoming (storm) waves. In the Dutch and German sectors of the Wadden Sea cliff erosion is prevented or hindered by the construction of salt marsh works that dissipate the incoming wave (and current) energy (Table 5.1, Ch. 3.4).

5.2.6 Barrier retreat

A final parameter to characterize possible morphological consequences of hydrological changes along the outer North Sea coast is barrier retreat (i.e., the coastal strip from the dune crest to the foreshore). Under present conditions, a large range of morphological reactions to present sea level rise (from retreating to prograding) exists, depending on the sediment availability or, rather, the longshore drift. In general, barriers retreat in response to sea level rise. Thus, an increase in sea level rise and/or storminess will accelerate this trend. However, a number of barriers like Fanø, Rømø and Amrum, are rather stable or even prograde in a seaward direction. This is the result of a strong sediment input towards the beaches from the longshore drift. The working group estimates that under the "worst case" scenario the accretion

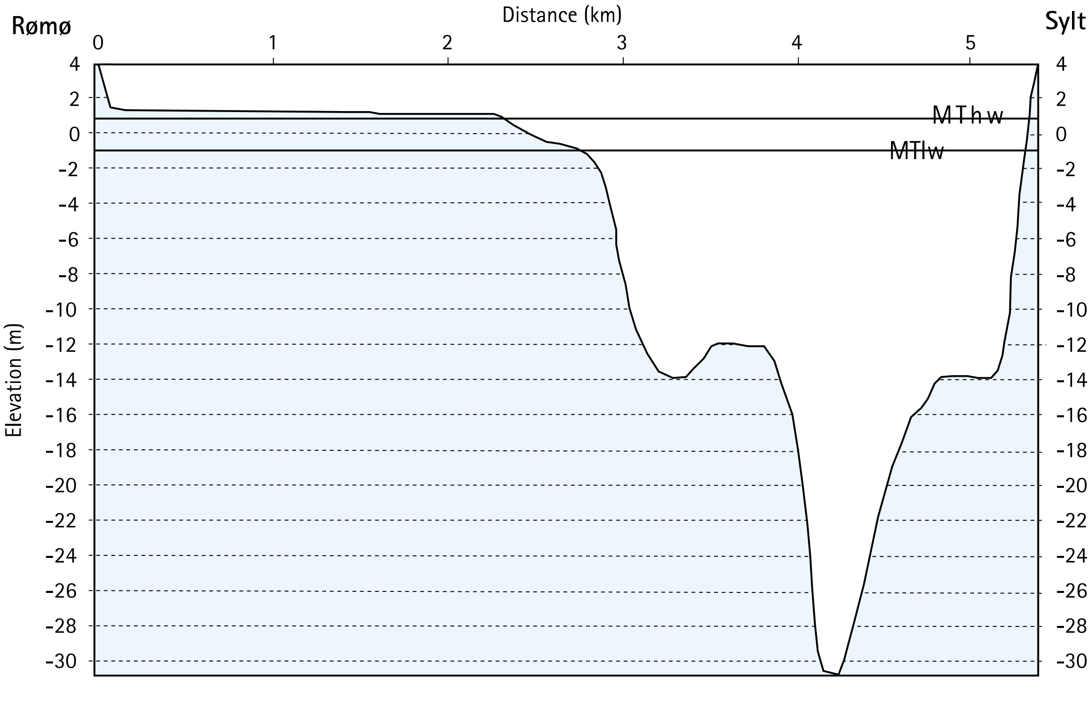


Figure 5.2. Cross-sectional diagram of "Lister Tief" tidal inlet.

might turn into erosion. In the Dutch and the German sector of the Wadden Sea, barrier retreat is mostly balanced by sand suppletion (Table 5.1, Ch. 3.1.3).

5.3 Biological consequences

A central factor in the assessment of the consequences for biological parameters are the foreseen morphological changes. As mentioned in 5.2, these will be only minor up to a 10 cm sub-scenario. With higher values for sea level rise and, consequently, morphological changes, most biological parameters are expected to respond, and often the response will be abrupt, indicating a break-down of interrelations formerly in a buffered balance. These "break points" will be reached at different sea rise levels in the different tidal basins (see Figure 5.1).

Another central factor is the sediment composition. It is generally assumed that sea level rise alone has no major influence on the sediment composition. Increase in storminess, however, will generally result in coarser sediments and increased turbidity. Because coarser sediment has, generally, a lower productivity, an increase in area with coarser sediment will lead to a general decrease in biomass input to the entire biological system. Mussel beds will be reduced with more storms. The decrease in biomass will become visible in a decrease in the number of migrating and breeding birds. Storms in (late) spring will have severe consequences for breeding birds.

Sea level rise and increased storminess are expected to have a clear effect on the following biological indicators:

- Benthic biomass;
- Birds;
- Fish;
- Seals;
- Salt marsh vegetation.

Other parameters will also be affected, but the CPSL working group does not have sufficient indications to allow a prediction.

5.3.1 Benthic biomass

Benthic biomass is expected to decrease slightly with a sea level rise up to 25 cm. Under the 50 cm scenario some decrease in total benthic biomass is foreseen, but not in a scale that could be termed "catastrophic". The interspecific distribution could well be affected, resulting in effects on the stocks of birds and fish feeding on special food sources.

Increased storminess will reduce mussel beds, including the quite rich benthic fauna associated with these beds. Also the possibilities for restoring mussel beds will be reduced as a result of increasing storminess.

5.3.2 Birds

Feeding possibilities are central for the birds in the Wadden Sea. Possibilities are regulated by water depth and bottom substrate. Most bird species are specialized to a limited range in these two parameters and prefer to feed on emerged flats, where they select their specialty from the benthos. A shift in flooding time will affect the time available for feeding and a change of sediment composition affects the composition of food items available.

Birds, mainly waders, will also be affected at the lowest sub-scenario. But up to some 25 cm of sea level rise the effect will be difficult to isolate from general stock fluctuations, perhaps with the exception of small waders, which will have markedly less feeding time. Ducks and geese will not be affected to a measurable extent. With higher sea level, the number of waders will decrease, mainly due to increase in flooding time. An exception is the greenshank (and perhaps also the redshank), which may benefit from the expected increase in channel width, resulting in a larger area of channel slopes where the greenshank feeds.

A sea level rise of 50 cm in 50 years will result in a marked decrease in all waders, owing to an expected increase in flooding time, leaving less time for the birds to feed on the intertidal flats. Duck and geese stocks will also go down because salt marshes will be flooded more frequently, leaving less time for feeding.

Increased storminess will have an effect mainly on breeding birds. Oystercatchers and other bird species feeding on blue mussel will be affected, also when migrating. Birds breeding on low lying areas will be at higher risk (e.g. avocet, little tern), where a sequence of late spring floods can eradicate a whole colony and, in worst cases, the whole Wadden Sea breeding population.

5.3.3 Fish

Fish stocks in the Wadden Sea are not expected to be affected by sea level rises below 25 cm. Above this, the increase in flooding time could affect living conditions for flatfish hatchlings negatively, e.g. by reducing tidal pools and the surface relief. Fish migration could be impaired under the 50 cm sea level rise scenario, because the sluice opening periods will be shorter. But the anticipated increase in sluice capacity will (probably) balance the negative effects. Increased storminess could lead to increased loss of fish eggs and thereby affect breeding fish stocks.

5.3.4 Seals

Seals are not expected to respond to sea level rise in general. A decrease in fish stocks at higher sea levels due to a lack of suitable habitats for juvenile flatfish may affect seal population size. This effect could be (partially) compensated by the seals finding new foraging areas. At the highest sea level rise scenario also a shortage of haul-outs may affect the populations.

An increase in storminess will have a negative effect on the grey seal (breeds early, pups vulnerable to spring storms), whereas no effect is expected on the common seal.

5.3.5 Seagrass

The seagrass area will decrease with increased storminess because higher water turbidity leads to a decrease in light influx to the bottom. No effect is expected from sea level rise itself. It should be noted that the seagrass area has fluctuated strongly over the last century.

5.3.6 Salt marsh vegetation

Salt marsh plants are adapted to a harsh climate. The lack of shade requires resistance to extreme temperatures and they must tolerate high salt concentrations in the soil. Artificial drainage has changed the natural habitat of most salt marshes. Natural processes will eventually lead to less salty environments at some places, but not to the extent seen today.

The salt marsh vegetation will become more "typical" with a sea level rise above the 25 cm scenario and also with increased storminess. Both factors lead to more frequent and longer-lasting inundations with salt water, favoring the specialized, typical salt marsh plants. Moreover, the typical morphology of the salt marsh with meandering creeks and salt pans will be promoted, leading to increased variation in habitats within the salt marsh.

5.4 Socioeconomic consequences

5.4.1 Safety

Under the category safety the existing strategies to maintain present safety standards in coastal defense are categorized as follows:

- dikes;
- other hard constructions (revetment, groynes, stone walls);
- sand suppletion incl. complementary biotechnical measures in dunes, such as planting marram grass and installing brushwood fences;
- salt marsh works.

A comparison of the current relative expenditure for each of the four coastal defense categories is in Table 5.2. For all four strategies, the increase in intensity is expected to be insignificant for the lowest sea level scenario (10 cm in 50 years). Further, the expected changes do not increase linearly with sea level rise. It is suggested that, somewhere between 25 and 50 cm of sea level rise in the next 50 years, the costs to maintain present safety standards with traditional measures may start to rise more than proportionally.

For dikes (maintenance and strengthening) the expected increase in costs for the most realistic sea level scenario (25 cm in 50 years) is expected to be in the order of 5 to 15 % for the German Wadden Sea. In the Dutch and the Danish Wadden Sea the relative increase is estimated to be much higher. The main reason is that at present dikes are only maintained in these two countries, not strengthened as in Schleswig-Holstein and Niedersachsen. For the high sea level scenario (50 cm in 50 years) the costs to maintain present dike safety in the year 2050 may rise by up to 75 % (Germany) and even more in The Netherlands and Denmark. As an example, the present yearly ex-

	Dikes	Other hard constructions	Sand nourishment	Salt marsh works
The Netherlands	35	10	50	5
Niedersachsen	80	10	5	5
Schleswig-Holstein	50	10	15	25
Denmark	90	5	0	5

Table 5.2: Current national relative expenditure (%) for four categories of coastal defense measures in the Wadden Sea.

penditures on dikes in Schleswig-Holstein of about 24,0 million EURO may maximally increase to about 42,0 million EURO in the year 2050. This figure may still be about 15 % higher (i.e. 48.3 million EURO for Schleswig-Holstein) if storminess increases as well. Under this "worst-case" scenario the necessary costs to keep the present dike safety could double!

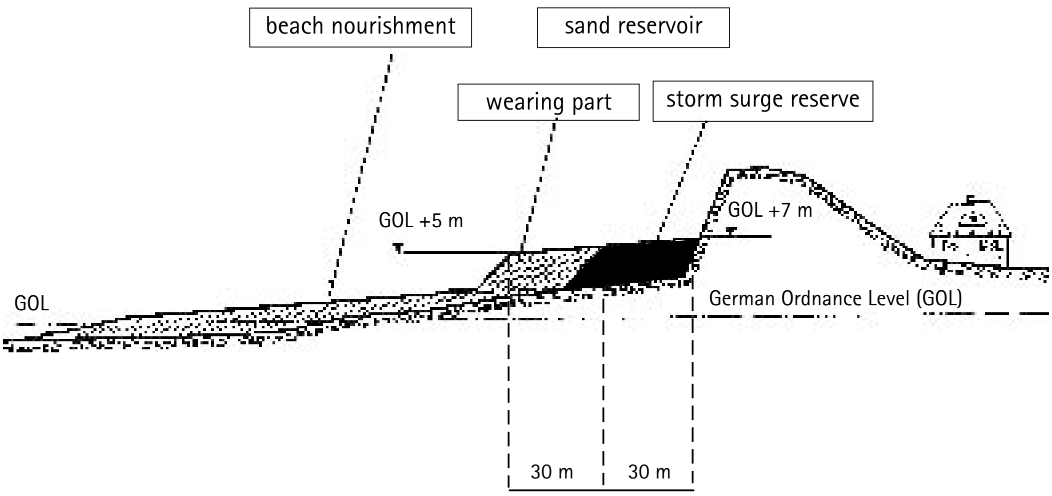
Under "other hard constructions" several measures like revetments, groynes and stone walls are combined. The crests of these constructions are situated near or only a few meters above present sea level. With rising sea level they will increasingly be exposed to tides and waves. Therefore, it is suggested that the costs may (relatively) increase more than the expenditures on dikes. As the present expenditures on these measures are normally much lower than on dikes, the absolute increase in costs will not be so high. However, under the BAU-scenario it may become necessary to build new or to strengthen existing hard constructions, which could raise the costs significantly.

One of the main measures to keep the coastline in its present position is the suppletion of sand on the beach or in the nearshore (Figure 5.3). According to present knowledge (the so-called Bruun rule) the upper nearshore and beach will increasingly erode with increasing sea level and, consequently, the coastline will retreat faster. Therefore, more sand is needed to maintain the coastline. At present, about 6 million m^3 of sand is suppleted each year along the total Dutch coastline (incl. the provinces of Holland and Zeeland). The volume of sand needed to stabilize the Dutch coastlines in the year 2050 might increase to more than 10 million m^3 for the "worst-case" scenario (50 cm of sea level rise in 50 years, combined with increasing storminess). For the most realistic sea level scenario (25 cm in 50 years) the estimated amount of sand needed would increase to about 8 million m^3.

Under the strategy "salt marsh works" the techniques to stabilize (and in some places create) salt marshes in the Wadden Sea are combined (Figure 5.4). One of the basic requirements for salt marshes to persist is a moderate sea level rise. Without sea level rise a vegetation succession towards fresh water biotopes would prevail. Hence, the expected increase in the intensity of salt marsh works under the different sea level scenarios is rather modest compared to the other strategies. One of the most destabilizing factors for salt marshes is wave attack along the outer edges (Ch. 3.4). As a result, cliffs may develop and the salt marsh may be eroded from its seaward side. An increase in storminess and, correspondingly, wave attack will thus result in much higher efforts to protect salt marshes. In Schleswig-Holstein the costs could rise from about 12 to 20 million EURO. For the most realistic sea level scenario on the other hand, the yearly costs in Schleswig-Holstein would rise by about 1 million EURO.

Some larger harbors, especially in the estuaries (e.g. Hamburg, Bremerhaven), have extensive out-of-dike areas. The efforts to maintain these areas will certainly increase with rising sea level. However, considering the huge investments in these areas, the working group expects that the

Figure 5.3: Schematic presentation of sand nourishment on the isle of Sylt.



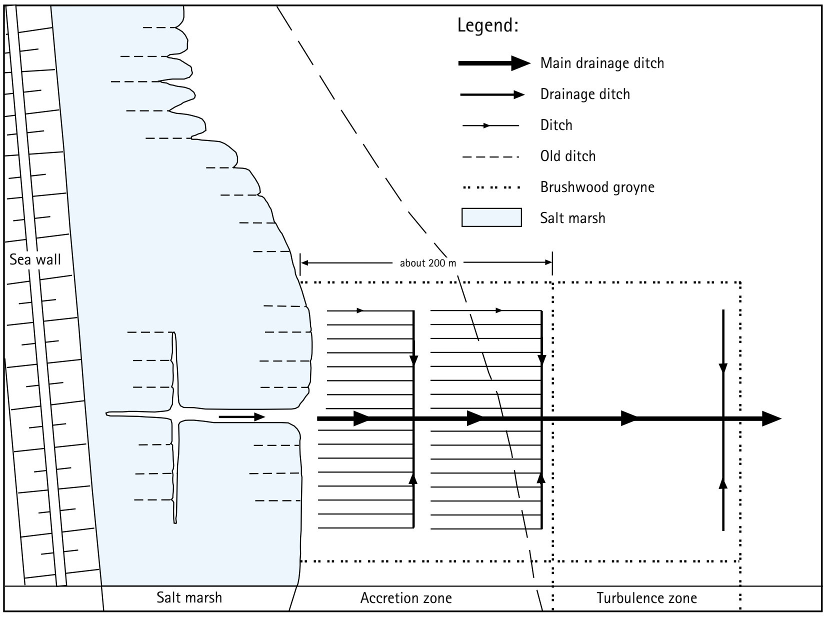


Figure 5.4: Schematic presentation of salt marsh works in Schleswig-Holstein.

relative increase in costs will remain low. Furthermore, it is assumed that an increase in sea level rise is already anticipated in the planning schemes for these areas.

5.4.2 Fresh water run-off, harbors/ shipping, tourism, agriculture and salinity.

Although the working group concentrated on the effects of changes in sea level rise and storminess on coastal defense, it was decided to consider some other relevant aspects as well. Efforts to secure fresh water run-off from the hinterland and the functionality of harbors and shipping routes are often closely connected to coastal defense measures. Further, as stated in the terms of reference of the working group, tourism and agriculture are two significant uses in the Wadden Sea with direct interrelations with coastal defense and nature conservation.

To secure fresh water run-off into the North Sea or, rather, to prevent the coastal lowlands from drowning by rainwater (e.g. during storm floods) the following combination of measures is used:

(1) water storage basins behind the dikes;

(2) gates/sluices in the dikes;

(3) discharge channels through the salt marshes and tidal flats towards the tidal gullies.

Normally, the sluices are opened during ebb (tidal low water) and the fresh water, stored in the basins during flood, runs off through the channels towards the tidal gullies. However, at some places pumping stations already have to pump the water into the channels. With increasing sea level, the tidal low water level will probably rise as well. As a consequence, the water stored in the basins during flood may not be able to flow out naturally during ebb any longer. Moreover, the time during which discharge can take place will become shorter. Extra pumping stations, as well as, more and larger storage basins (and eventually dikes along the lower courses of some Danish rivers) may become necessary. In consequence, the efforts to secure fresh water run-off are estimated to increase by 50 to 200% for the highest sea level scenario (see box text on Lake IJssel in Chapter 6). An increase in storminess will probably result in more storm rainfall and, therewith, higher peak water discharges. Further, a more intense silting up of the discharge channels is expected under an increasing storminess. The efforts to secure fresh water run-off will increase correspondingly.

One further problem that is closely linked to fresh water run-off and sea level rise is increased salinity behind the dikes. Available data do not give indications about significant changes in salinity.

The navigability of the main shipping routes in the Wadden Sea is mainly secured by dredging. This artificial deepening of gullies has direct implications for the hydrology and morphology of the Wadden Sea. Vice versa, changes in the hydrology will influence tidal gullies morphometry and, therewith, dredging activities. It is expected that an increase in sea level rise will generally result in deeper channels and, consequently, in a (small) reduction of dredging efforts. In contrast, an increase in storminess may induce a stronger sedimentation in the channels and harbors. The efforts to maintain shipping channels and harbor access would increase correspondingly. Which of the two effects (deepening or sedimentation) would prevail under the "worst case" scenario cannot be predicted with present knowledge. The situation is even more complex in the estuaries. For example, salt and fresh water meet and mix here which strongly influences local sedimentation patterns. A shift in the position of this mixture zone resulting from sea level rise may have unknown implications for the navigability of the estuaries.

Two important uses/interests in the coastal zone that affect coastal defense and nature protection are tourism and agriculture. Tourism has become the most important source of income in many parts of the Wadden Sea region. The reaction of the public to sea level rise and increase in storminess is expected to be rather complex or even divergent. For example, an increase in storminess may result in an emotional negative attitude towards the Wadden Sea as an unsafe holiday region. Another example is mud flat walking that might be negatively affected if flooding time of the tidal flats increases. At the same time, however, increasing storminess may induce a new kind of active tourism during winter (watching and experiencing storm surges). Agriculture may, on a small scale, be influenced by an increase in sea level and/or storminess. If the present fresh water run-off is to be secured, extra arable land needs to be set aside for fresh water storage basins. Further, an increase in storminess (during summer) might result in more damages to the crops. In general, it is expected that, for the hydrologic scenarios, the effects on tourism and agriculture may be neglected. Other factors like atmospheric conditions (e.g. precipitation, hours of sunshine) or EU-policy will dominate the future development.

Flatwalking in the Wadden Sea. (Photo: H. Marencic)

Best Environmental Practice (BEP) Options

6.1 Introduction

In the previous chapter 5 an analysis was made of, amongst others, the consequences of increasing sea level and storminess for present coastal defense practice, taking as a starting point that today's safety level would be maintained.

In this chapter several technical measures and practices are being evaluated with a view to their possible application in future coastal defense strategies. It concerns not only the „classical" measures covered in chapter 5, but also a large number of alternative measures, most of which are not being applied yet. The assessment was carried out by the working group with a view to having a broader array of measures and practices available for future choices, especially in the light of increasing sea level and storminess.

The measures and practices have been evaluated on the basis of two main criteria, namely their contribution to maintain safety and their impact on the environment. These criteria are called „Best Environmental Practice" (BEP) criteria.

The following BEP criteria were applied in the evaluation:

- safety: the contribution to coastal defense;
- Impact on habitats;
- Impact on natural dynamics.

All measures with a positive scoring for these criteria have been selected as Best Environmental Practice measures (BEPs). In some cases also a slightly negative scoring for the criteria impacts on natural dynamics and habitats was considered acceptable.

It is stressed that the selection of BEP measures has not taken into account aspects which are relevant for their feasibility. Because feasibility aspects will, in general, play a dominant role in the decision whether or not to apply the measure, the working group has also made a scoring for the following feasibility criteria:

- Technical: Technical possibility to carry out the measure, also considering the time it will take for the measure to become effective;
- Financial: Indication of costs;
- Legal: Agreement with current laws and rules;
- Public opinion: Acceptance by the public.
- Spatial: Applicability on a local or wider scale.

An evaluation of all individual measures, according to running number, is given in 6.2. A brief description of the measures is given in the box on the following page. The measures have been structured according to Sandy barrier coast (6.2.1), Tidal basins (6.2.2), Salt marshes (6.2.3) and Mainland (6.2.4). Brief descriptions of all measures are in the Box. An overview of the scoring of all measures is in Table 6.1.

In 6.3 the main conclusions of the evaluation and the selected Best Environmental Practice options are presented.

Sandy barrier coast

1. Artificial reefs: Reefs of hard constructions in the foreshore in order to reduce wave impact on the shore.
2. Beach drainage: Draining the beach by tubes and pumps in order to stimulate sedimentation of the beach.
3. Enhance dunes creation: The stimulation of sedimentation by marram grass and sand-trapping fences and thus accumulation of sand transported by the wind.
4. Dunes relocation: The building up of new dunes landward of the eroding old ones. In practice this will mean a gradual retreat of the dune front.
5. Natural dune dynamics: The transport of sand from the North Sea shore to the inner part of the barrier island where accumulation causes a gradual landward shift of part of the barrier island with rising sea level.
6. Overwash creation: Allowing water and sand transport across unprotected parts of barrier islands through wash-over channels. As with natural dune dynamics the transport of sand from the North Sea shore to the inner part of the barrier island and accumulation there causes a gradual landward shift of part of the barrier island with rising sea level.
7. Revetment building: Protecting the dunes against erosion by hard constructions.
8. Groynes: Constructions perpendicular to the coast into the foreshore. Comparable to revetment building.
9. Sand nourishment: Taking sand from outside the sand sharing system deeper water and pumping it on the beach or on the foreshore with the aim of stabilizing the beach.
10. Spatial planning: Spatial planning aiming, in the long term, at creating and maintaining buffer zones between land and sea where safety is not guaranteed under all circumstances.

Tidal basins

11. Dam building: Building dams between the mainland and the islands in order to stabilize tidal basins.
12. Dredging reduction: Reducing the dredging of shipping lanes.
13. Gullies damming: Diversion of tidal gully by 1) closing off the old gully with a sand dam and 2) dredging a new gully on another location in order to obviate hazardous gully meandering (e.g. gully approaching a dike foot).
14. Mussel bed reinstallation: Promoting the settling of mussels in order to stimulate accumulation of mud including protection of existing beds or potential locations for these beds:
15. Sea-grass bed reinstallation: Creating seagrass meadows in places with low hydrodynamics in order to try to stimulate sedimentation.

Salt marshes

16. Revetments: Hard constructions protecting the salt marsh edges in order to prevent cliff erosion.
17. Creation marshes from dredged material: Deposition of dredged material on intertidal areas along the mainland or Wadden-sea side of the barrier island.
18. Outbanking of summer polders: Opening summer dikes in order to get a more frequent flooding of the area and higher sedimentation rates.
19. Groyne fields: Areas, sheltered by groynes, with reduced waves and in which accumulation of fine sediments is stimulated.
20. Artificial drainage: Digging ditches in the salt marsh in order to stimulate water run-off after the area has been flooded and vegetation growth in the lower parts of the salt marsh.
21. Grazing: Grazing by sheep and cattle with the aim of keeping a short vegetation and reducing the amount of flotsam.

Dikes

22. Revetments: Using hard material at the dike surface to protect the slope against damage by wave impact and currents.
23. Enforcement: Heightening and/or strengthening the dikes in order to maintain safety standards.
24. Second dike line: A dike, situated behind a primary sea wall, that serves to limit the area flooded after the primary sea wall breached.
25. Relocation of first dike line: Building a new dike landward of the old one.
26. Spatial planning: See running number 10.

Mainland

27. Pumping stations: Pumps for active discharge of fresh water from the inland to the to the sea.
28. Sluices: Constructions allowing passive discharge of fresh waters from the inland to the sea.
29. Storage basins: Inland basins for storing fresh water in periods when sea level is too high for the passive discharging the fresh water.

6.2 Evaluation

6.2.1 Sandy barrier coast

Artificial Reefs (1). Artificial reefs may be an option to reduce wave impact on the shore. Their contribution to safety is estimated as medium. Reefs form substrate and shelter for flora and fauna but they interfere with natural dynamics. The construction of artificial reefs is technically unproblematic and can be done at medium costs. They will be only locally applicable, and no substantial legal problems or public resistance are expected.

Beach drainage (2). Beach drainage is expected to have a medium contribution to safety and some impact on both the habitat (impact on the interstitial fauna) and natural dynamics. It is only locally applicable and considered very expensive. No substantial legal problems or public resistance are expected.

Enhance dune creation (3). Very locally it is possible to create new dune areas by catching wind driven sand. More often stimulation of dune growth will take place in the vicinity of existing eroding dunes. From the past there is already a lot of technical experience. On strong eroding beaches accumulated wind driven sand will be eroded by waves and currents. Dune creation will interfere with natural dynamics and existing habitats will be replaced by others. The public opinion is expected to react positively on the enlargement of dune areas.

Dunes relocation (4). This forms a cheap and technically practical way of sea defense but is only applicable if human interests in the dune area or the area behind it are low (no buildings, no infrastructure etc.).

Natural dune dynamics (5). By allowing natural dynamics, sandy areas lost by erosion will be replaced by sandy areas somewhere else. It is only applicable in uninhabited areas where safety is not at stake, but even then public resistance can be expected. On the long term natural dune dynamics contributes to the shifting of islands with rising sea level.

Overwash creation (6). This measure is locally applicable in uninhabited areas and provides, in the long run, a positive contribution to keeping areas above normal high water levels. It is also positive from a viewpoint of natural dynamics and may, on the long term, be beneficial because it stimulates island growth on the Wadden Sea side. Public resistance is expected if areas with vegetation are replaced by sandy areas.

Revetment building (7). This is an existing method of stopping retreat of the coast and guaranteeing safety. It is technically well feasible, accepted by the public but very unnatural. Erosion at the edges of the constructions make it necessary to extend the measures at those edges. Rising sea level will lead to an increase of finances needed.

Groynes (8). This method is comparable to revetment building.

Sand nourishment (9). Sand nourishment is, in general, a technically and financially feasible measure for coastal defense which has only slightly negative impacts on nature. It can be applied on a large scale.

Spatial planning (10). This is considered a good political instrument for a no regret policy. It is a useful tool by creating buffer zones where no building or rebuilding is allowed. This can work positively both from a financial point of view, as well as, for natural dynamics. The fear of loss of safety and the limitation of uses in buffer zones will lead to difficulties in public acceptance.

6.2.2 Tidal basins

Dam building (11). Although technically good applicable and positive for safety, this practice is considered negative for the environment, especially in a nature conservation area. From the public resistance is expected.

Dredging reduction (12). In estuaries the reduction of dredging in the channels will result in lower high water levels in the upstream parts. Reduction of dredging will also lead to a more natural development of the estuarine morphology. From legal and public opinion points of view this option is not regarded feasible.

Gullies damming (13). Very locally damming off gullies can prevent constructions or salt marshes to become unstable by gully erosion. It interferes however with natural dynamics. From Schleswig Holstein one example is known.

Mussel bed reinstallation (14). In general active reinstallation of biota is seen as gardening in a nature conservation area and therefore interfering with natural dynamics. Because these beds stimulate sedimentation and stabilization of the sediment they may diminish wave attack at the mainland shore. However during storm surges this effect is reduced to zero because of the large water depth. Favorable conditions for recovery of mussel beds can be achieved by limiting human exploitation of the area.

Sea grass bed reinstallation (15). Comparable to mussel bed reinstallation.

6.2.3 Salt marshes

Salt marshes can have both a nature protection and a coastal protection function (compare 3.4.2). The main functions in coastal defense are the reduction of wave energy input at the dike and the prevention of a scour hole and water flowing through the dike after a dike breach. Preservation of existing salt marshes can therefore be relevant from both perspectives.

Revetments (16). If there are big height differences between tidal area and salt marshes, the surface area of salt marshes can efficiently be protected by revetments. By preventing cliff erosion of the smaller salt marshes also the mainland shore behind them is safeguarded. Preventing erosion interferes with natural dynamics. In some countries there will be legal problems.

Creation of marshes from dredged material (17). Creation of new marsh lands may be positive from a safety point of view because an extra buffer is created between sea and land. Using dredged mud can make this option financially attractive. However, it interferes with natural dynamics and may only be applicable on a local scale.

Outbanking of summer polders (18). Outbanking of summer polders can compensate for the loss of salt marsh areas through cliff erosion or drowning caused by accelerating sea level rise and is therefore interesting from the point of view of nature protection. In the working group opinions differed strongly about the technical feasibility of this measure, ranging from very negative to very positive. In Germany the generally small summer polders have a function in sea defense. Outbanking would lead to higher expenses for guaranteeing safety. Here the feasibility is thought to be low. Public resistance may be expected if summer polders are private property. In these cases finances are needed for acquisition. Outbanking of summer polders in the inner parts of the estuaries may reduce storm surge levels because the storage capacity is augmented. However, in order to be effective, the surface area of the outbankment should be substantial compared to the total surface area of the inner estuary.

Groyne fields (19). The construction of groyne fields is an accepted, already existing measure, which is technically very good applicable. At the moment brushwood is frequently used to build the groynes. In future, with a rising sea level, hard material may become necessary. Up to a certain level of sea level rise the extra sedimentation will prevent salt marshes from drowning. Although the measure is positive for maintaining and extending the habitat salt marsh, it interferes with natural dynamics.

Artificial drainage (20) Artificial drainage of salt marshes may be positive for soil stabilization and resistance against erosion and, by this, enhances the vertical accretion of the salt marsh. It is technically good applicable. It interferes with natural dynamics.

Grazing (21). The opinions about the effectiveness of grazing in reducing the amount of flotsam and, therefore, the costs of coastal defense, differ (compare 3.4.2). Grazing with low to medium intensity causes diversification in vegetation which is interesting for biodiversity but may be regarded as undesirable from the point of view of interference with nature.

Spatial planning in Schleswig-Holstein

In the new master plan "Coastal Defense in Schleswig-Holstein" of 2001, ten strategic goals are formulated. Goal number three states: "Relocation or abandonment of sea walls is only possible as an exception". Considering the protection of human lives, houses, economic assets and inhabited land against storm floods as the primary goals, the relocation or abandonment of primary sea walls may only be an alternative if,

- the existing safety standard is maintained, including (if present) a second dike line (see option 24; [Definition of a second dike (Schleswig-Holstein State Water Act): A dike, situated behind a primary sea wall, that serves to limit the area flooded after the primary sea wall has breached]).
- the people directly affected (i.e., the inhabitants of the protected lowland) agree, and
- coastal defense administration is kept free of extra costs.

Secondary sea walls that do not protect human lives have a lower safety standard. For these sea walls, relocation or abandonment may be appropriate if socio-economic arguments, especially the cost-benefit relation, supports this.

For some lowlands along the Baltic Sea coast of Schleswig-Holstein the relocation of sea walls is or was planned. However, the right of every individual on its property and on economic development (as defined under the German Basic Law), combined with the unwillingness of the affected people to move, has, until today, prevented such a measure

6.2.4 Dikes

Revetments (22). Revetments are a classical and technically feasible method of preventing erosion of constructions. In areas with strong hydrodynamics revetments are necessary for the protection of the dikes. Revetments interfere with natural dynamics.

Enforcement (23). Dike enforcement is a classical technical solution, accepted by the public and applicable on a broad scale. It forms the guarantee for safety in future if alternatives are insufficient or not accepted. The costs for maintaining safety in this way will grow with a rising sea level. The separation between land and water will get stronger.

Second dike line (24). In the long run it may become cheaper to maintain the same safety standard by constructing a second dike line. A precondition is that there is no expensive infrastructure, either existing or planned, in the potential buffer zone between the two dike lines. Such a buffer zone with a low level of human exploitation may be positive from the nature protection point of view.

Relocation of first dike line (25). With rising sea level relocation of the dike may become cheaper compared to maintenance and enforcement of the dike. Legally this is not considered feasible. Also the public will be strongly against it. From a nature point of view it is a positive option because it means an extension of the Wadden Sea area.

Spatial planning (26). As in 10.

6.2.5 Mainland

Pumping stations (27). The use of pumps for the discharge of fresh water is regarded positive from both safety, technical feasibility and public opinion points of view. If high capacity has to be installed for incidental peak discharges this option becomes more expensive. Pumping stations accentuate the separation between the mainland and the sea. Fish traps should guarantee the migration of fish between fresh and salt water.

Sluices (28). Sluices are positive for safety, technically good applicable and accepted by the public. With rising sea level the sluice capacity has to be enlarged in order to maintain the same discharge capacity. As with pumping stations technical measures should guarantee the migration of fish between fresh and salt water.

Storage basins (29). By applying this option investments for pumping stations and sluices can be reduced because of lower necessary peak discharge capacities. It guarantees the storage of fresh water after high precipitation. Depending on the design of the basins, they can have positive functions for nature.

Enclosure Dike

In 1932 the Enclosure dike was built, separating the "Zuiderzee" from the Wadden Sea. Since then fresh water from the newly formed Lake IJssel had to be discharged into the Wadden Sea through sluices in the Enclosure Dike. 70% of the water in Lake IJssel comes from the river Rhine. Because of bottom subsidence the expected accelerating sea level rise and growing river discharges, the discharge capacity for water through sluices in the Enclosure Dike has to be doubled from 5500 m^3/s to 11000 m^3/s. Already in the last 25 years it became more and more problematic to keep the water level of the Lake IJssel at the normal level. In 1998 the water level of Lake IJssel rose up to 1 meter above the normal level. The possibility of combining the extension of discharge capacity with a more gradual transition from fresh to salt water by creating a brackish water zone, is included in the research program investigating options for the doubling of the discharge capacity.

Table 6.1:
Relative scoring of coastal defense practices for feasibility and Best Environmental Practice (BEP) criteria.

Environment	Measure	Feasibility					BEP Aspects		
		Tech nical	Finan cial	Legal	Public opinion	Spatial	Impact on Habitat	Impact on natural dynamics	Safety
Sandy barrier coasts									
1	Artificial reefs	4	3	3	3	1	2	2	3
2	Beach drainage	4	1	3	3	1	2	3	3
3	Dunes creation	4	4	3	4	2	3 Replace one habitat by another	2	4
4	Dunes relocation	4	4	3	2	2	3	3	4 Relocation=retreat
5	Allowing wind driven sand transport	4	5	3	2	2	4	5	2 Possibly positive on a long time scale and strongly dependent on locality
6	Overwash creation	4	4	2	2	2	4 Loss of fresh water species	4	2 On a very long run
7	Revetment building	4	3	2	3	3	2	2	4
8	Groynes	4	3	3	3	3	3	2	3
9	Sand nourishments	4	4	4	3	4	3	2	4 Extraction from outside the sandsharing system
10	Spatial planning (create buffer zones)	4	3	3	2	4	3	4	4
Tidal basins									
11	Dam building	4	2	2	2	3	2	2	4
12	Dredging reduction	4	4	1	1	1	4	4	3 In estuaries
13	Gullies damming	3	3	2	3	1	3	3	3 One positive example from SH
14	Reinstallation and protection of mussel beds	4	3	3	3	3	4	2 Reinstall 4 Protect	2 In the long run
15	Sea-grass beds reinstallation	3	2	3	3	2	4	3	2 In the long run
Salt marshes									
16	Revetments	4	3	2	3	2	3	2	4
17	Creation from dredged materials	3	3	3	3	2	3	2	4
18	Outbanking of summer polders	4	2	3	2	2	5	4	1 Site specific in estuaries
19	(Brushwood) groynes	4	3	4	4	4	3	2	3
20	Artificial drainage	4	3	3	3	4	3	2	3
21	Grazing	4	4	3	3	4	3	2	3 Reducing flotsam
Dikes									
22	Revetments	4	3	4	4	4	2	2	4
23	Enforcement	4	2	4	4	4	3	3	5
24	Second dike line	4	2	3	3	4	4	3	5
25	Relocation of first dike line	4	1	1	1	2	4	4	2
26	Spatial planning	4	4	3	2	4	3	4	4 In the long run
Mainland									
27	Pumping stations	4	2	3	4	3	3	3	4
28	Sluices	4	2	3	4	3	3	3	4
29	Storage basins	4	3	3	3	2	3	3	4

Legend

Technical:	1 (almost impossible)	5 (very practical)
Financial:	1 (very expensive)	5 (very cheap)
Legal:	1 (very problematic)	5 (unproblematic)
Public opinion:	1 (very negative)	5 (very positive)
Spatial:	1 (site specific)	5 (everywhere)
Impact on habitat:	1 (large scale destruction of typical Wadden Sea habitats)	5 (large scale creation of typical Wadden Sea habitats)
Impact on natural dynamics:	1 (large scale reduction of natural dynamics)	5 (large scale increase of natural dynamics)
Safety:	1 (low contribution)	5 (substantial contribution)

6.3 Conclusions

6.3.1 Sandy Barrier Coast

Sand nourishment (9) is in general a good practice for coastal defense with slightly negative impacts on nature. It can be applied on a large scale. In addition to the classical methods of coastal defense many of the other suggested practices for the sandy barrier coast may prevent erosion, stimulate accumulation of sand or enhance safety on a local scale. This holds for artificial reefs (1), beach drainage (2), overwash creation (6) and dune creation (3) or dune relocation (4). In general, these measures are more or less neutral for nature. Allowing natural dune dynamics (5) and overwash creation (6) on the uninhabited parts of the islands is positive from a viewpoint of natural dynamics and may be beneficial on the long term because island growth at the Wadden Sea side is stimulated. In this way disappearing ecotypes at the North Sea side of the islands are recreated at the Wadden Sea side.

Spatial planning (10) is a useful tool through which buffer zones are created in which no building or rebuilding is allowed. In these areas safety must no longer be guaranteed. This can work out in a positive way both from a financial and a nature protection point of view The fear of loss of safety and the limitation of human activities in buffer zones will lead to difficulties in public acceptance.

The measures selected as BEP for the sandy coast are artificial reefs, beach drainage, dunes creation, relocation and allowing natural dune dynamics, overwash restoration, sand nourishment and spatial planning aiming at creating buffer zones.

6.3.2 Tidal basins

The selection of BEP measures for the tidal basins depends, first of all, on the political choices that have been made for the area under consideration. One extreme is not accepting any change in the character of the tidal basins and the other extreme is accepting all changes as a consequence of changed hydrodynamics. In addition, it must be realized that, on the scale of whole tidal basins, preventing changes in morphology induced by accelerating sea level rise is an impossible job. On a local scale, however, safeguarding intertidal areas from drowning can be done by (re)-installing mussel beds (14) or seagrass beds (15). Locally erosion and damage of constructions or loss of salt marsh area can be prevented by damming gullies (13). Schleswig-Holstein has an example of a successful application of this technique. Where human activities have morphological consequences comparable to those of sea level rise, the reduction of such activities will cause less changes and a postponement of the moment that changes in the system will become distinguishable from natural variability. This holds for mining causing bottom subsidence and sand and shell extraction.

In the estuaries both sea level rise and dredging works cause an easier penetration of the tidal wave and storm surges. A reduction of dredging (12) will diminish this effect leading tot a reduction in costs of maintaining safety along the inner parts of the estuaries. On the other hand this will give problems for navigation between the North Sea and the harbors. This makes this option not feasible from a legal and public point of view. However, in the long term, stimulating the increase of harbor capacity along the more outer deep water parts of the estuaries instead of the inner parts might be a preferred option.

The measures selected as BEP for the tidal area are reinstalling mussel beds and seagrass beds, gullies damming and dredging reduction.

6.3.3 Salt marshes

Outbanking of summer polders (18) can compensate the loss of salt marsh area caused by cliff erosion or drowning as a result of accelerating sea level rise and is, therefore, a good option from the point of view of nature protection. However, in Niedersachsen, where summer polders are important for coastal defense, outbanking will lead to higher expenses for guaranteeing safety. Here, the feasibility is therefore considered low. The outbanking of summer polders along the inner parts of the estuaries will cause a reduction of storm surge levels because the inundation area and, therewith, the storage capacity is increased. The surface of the outbanked area should, however, be substantial compared to the total surface area of the inner estuary.

Applying the already existing method of groyne fields (19) will safeguard salt marsh areas when sea level rise accelerates. If applied, it is clear that a choice has been made for safeguarding the habitat at the cost of natural dynamics. It is an already existing measure which is technically very good applicable. At the moment brushwood is frequently used to build the groynes. In future, with a higher sea level, hard materials may become necessary. The extra sedimentation prevents marsh lands from drowning, also, up to a certain level, with an accelerating sea level rise. Although it may be positive for certain habitats, it interferes with natural dynamics.

Artificial drainage (20) and low intensity grazing (21) stimulate root and swath growth and, consequently, the stability of the salt marsh. There are different opinions about the effectiveness of grazing in reducing the amount of flotsam at the dikes and thus reducing the costs of coastal protection (compare 3.4.2.). From a nature protection point of view both measures cause interference with natural dynamics. Grazing with low to intermediate intensity can, however, result in a more diverse vegetation which is interesting for biodiversity. Here political choices have to be made about the desired kind of nature: natural dynamics versus a high biodiversity. This choice does not necessarily have to be the same for the different countries.

The measures selected as BEP for the creation and maintenance of salt marshes are brushwood groynes and outbanking of summer polders in estuaries.

6.3.4 Dikes

Maintenance and enforcement of existing dikes (23) and revetments (22) is the classical, technically feasible starting point for guaranteeing safety. If alternatives are insufficient or not accepted, the continuation of this kind of protection seems logic. The separation of land and water will, however, become stronger. The question is whether, on the long term, this will still be the cheapest method. One possibility is, for instance, to create a second dike line (24) parallel to the first one with a buffer zone in between. In the long run this may become attractive from a financial point of view, provided no large infrastructural investments take place in the potential buffer zone. From a nature protection point of view such a buffer zone with low human exploitation must be regarded as positive.

Relocation of the first dike line (25) with rising sea level may be cheaper than guaranteeing safety forever and everywhere. Legally this option is, however, not considered feasible. Also public opinion will be strongly against it. From a nature perspective it is positive because it would mean an extension of the Wadden Sea.

With appropriate spatial planning (26) in the zone landward of the dikes it can be guaranteed that alternative options for guaranteeing safety will not be lost. In general this means that economic developments in areas directly bordering the Wadden Sea are limited.

The measures selected as BEP for dikes are creating different dike lines, dike relocation in estuaries and spatial planning aiming at preserving the possibility to use stretches of land along the coast for future coastal defense.

6.3.5 Mainland

An alternative for creating expensive extra pumping stations (27) or higher sluice capacity (28) for the discharge of increasing amounts of fresh water, is creating storage basins (29) on land. This is positive from a safety, technical feasibility and public opinion point of view. Dependent on the design of the basins they can also have functions for nature. This measure must therefore be regarded as BEP.

7. Conclusions and Recommendations

7.1 Introduction

The CPSL has investigated possible impacts of three sea level rise scenarios:

- Scenario 1 reflects a continuation of current sea level rise of about 10 cm/50 years;
- Scenario 2, the intermediate and most realistic scenario, assumes a sea level rise of 25 cm/ 50 years;
- Scenario 3, the worst case scenario assumes a sea level rise of 50 cm/50 years.

For all scenarios also the additional effects of an increase in storminess have been evaluated.

The analysis was done under the assumption of a continuation of current coastal defense practices (Business As Usual, BAU), taking as the main starting point that current safety standards are maintained. The main conclusions with regard to the anticipated impacts on several physical, biological and socioeconomic parameters are given in 7.2. In general, the intensity of impacts on the elaborated physical, biological and socioeconomic parameters is expected to show a strong regional and temporal variability.

As a second step the CPSL has investigated a large number of alternative measures which may alleviate and reduce the impact of enhanced sea level rise and storminess and which also take into account the environmental impact. Those options that were regarded as both positive from a coastal defense point of view and acceptable or even positive from a nature protection perspective (Best Environmental Practice [BEP] measures), either on a local or on a larger scale, have been listed in 7.2.5 below.

It should be stressed that all measures, both BAU and BEP, needed to counteract the negative effects of sea level rise and increase in storminess, are actually combating symptoms and not the causes.

It should finally be underlined that the assessment of the CPSL is based upon best available knowledge and best expert judgement and that little hard facts are available.

7.2 Conclusions

7.2.1 General conclusions

1. The Wadden Sea system shows a high natural variability. Consequently changes caused by accelerated sea level rise and increased storminess will not easily be distinguishable from natural variability.

2. The Wadden Sea system has a high resilience to changes and will, up to intermediate increases in sea level (25 cm/50 years), which is the most realistic scenario, be able to compensate the increased levels. Within this most realistic scenario costs for coastal defense will be higher than today. Also changes in the ecosystem are expected but these will not be substantial.

3. When sea level rises beyond intermediate levels and storminess increases, there will probably be a point between the intermediate and the worst-case scenarios at which the capacity of the system to balance the changes will be exhausted (breakpoint) and after which significant changes in the system can be expected. These will be changes in the morphology, which will influence biological parameters. The most notable change will be a reduction in the size of the intertidal area. Consequently the Wadden Sea tidal basins may start to evolve into the direction of tidal lagoons.

The reduction of intertidal area will cause a reduction in population sizes of some bird species. Also the costs for coastal defense will increase substantially after the breakpoint has been passed. A more detailed description of the changes is given in Sections 7.2.2 to 7.2.4.

4. In the long term, the application of current and future coastal defense measures may alleviate impacts of sea level rise and storminess but will not be able to prevent such impacts, certainly not under the worst case scenario. Policies will therefore have to adapt to the anticipated changes by starting, as soon as possible, to develop long term interdisciplinary policies for coastal defense, nature protection and economic development in the coastal area.

5. There is a lack of qualified data to assess possible effects of sea level rise and increase in storminess.

7.2.2 The Tidal Area

Up till an intermediate sea level rise (25 cm/50 years) it is likely that no significant changes will occur in the Tidal Area, at least not such which will be clearly distinguishable from natural variability. Beyond the breakpoint, which may substantially differ between individual tidal basins, significant changes can be expected. The main changes will be:

- A reduction of the intertidal area (because of higher sea level);
- An Increase of flooding time (because of larger water depths);
- A deepening of the channels (because of higher tidal currents);
- An increase of salt marsh edge erosion (because of higher wave impact);
- A decrease in accretion of sediment (because sea level rise will outbalance sedimentation capability).

These physical changes will have the following impacts on biological parameters:

- A reduction of benthic biomass (because of increase in dynamics);
- A decrease of intertidal mussel beds (because of increasing storminess);
- A reduction in population size of bird species (breeding birds mainly because of a reduction of breeding area; migratory birds mainly because of a reduction of feeding time);
- A reduction of the fish nursery function (reduction or disappearance of suitable habitats);
- A reduction of the seal population size (unfavorable haul-out conditions due to storms);
- A decrease in seagrass coverage (decrease of intertidal area, increase of turbulence);
- An increase in the diversity of typical salt marsh flora (mainly in the higher salt marshes because of a higher inundation frequency and inundation time).

7.2.3 The barrier islands

For the barrier islands the changes will have a more linear character because this system reacts more directly to the changes.

The main impacts of increasing sea level rise and increasing storminess will be:

- An increase of barrier retreat (or a reduction of accretion);
- For bird species breeding on beaches and in primary dunes decreasing population sizes are expected, mainly because of increasing storminess.

7.2.4 Socioeconomic impacts

An increase in sea level rise and storminess will have considerable impacts on coastal defense. Because of the breakpoint between the middle and worst-case scenarios (see 7.2.1) the efforts to keep today's safety level will increase in a more than linear way and, under the worst case scenario, efforts may double. More in particular it is expected that, under the worst-case scenario,

- it will be necessary to strengthen dikes and other hard constructions (because of increase in water level and wave energy);
- an increase in sand suppletion will be necessary to combat barrier retreat;
- a strong increase in efforts to maintain salt marshes is needed because of the higher wave energy;
- dredging efforts might become less because of higher water levels, but this reduction may (partly) be nullified by increased efforts due to increased sedimentation as a result of increasing wave energy and a higher sediment-transport capacity;
- increased efforts are needed to discharge fresh water (pumping, sluices, storage basins), because, due to higher water levels in the Wadden Sea, there will be less possibilities for sluicing out fresh water. The situation may be aggravated by more an more irregular precipitation

On the basis of available information no significant impact on salinity in areas behind the dike is expected.

The CPSL furthermore anticipates that changes in tourism and agriculture will be influenced much more by other factors, such as EU policies and development of income.

7.2.5 Best Environmental Practice

On the basis of the criteria "Impact on natural dynamics", "Impact on habitat" and "Contribution to coastal defense" a number of practices was selected. These so-called "Best Environmental Practice" measures are listed below in alphabetical order and are described in more detail in Chapter 6.

It is stressed that there may be considerable legal, financial and/or public perception drawbacks to some of these practices. These aspects will have to play an important role in the assessment of the feasibility of the measures as proposed in Recommendation 2.

Generally, it must be concluded that, in the long term, the application of these measures may alleviate impacts of sea level rise and storminess, but will not be able to prevent such impacts, certainly not under the worst case scenario.

Sandy barrier islands

- Artificial reefs
- Beach drainage
- Dike relocation
- Dunes relocation.
- Overwash.
- Spatial planning, aiming at creating buffer zones where no building is allowed.
- Wider application of sand nourishments.
- Natural dune dynamics.

Tidal basins

- Brushwood groynes
- Dredging reduction
- Gullies damming
- Reinstalling mussel beds

Salt marshes

- Outbanking of summer polders in estuaries

Dikes

- Building/strengthening of 2nd dike line
- Dike relocation in estuaries

Mainland

- Creation of fresh water storage basins
- Spatial planning, aiming at creating buffer zones where no building is allowed.

7.3 Recommendations

1. Policies

Under the currently most realistic scenario (25 cm in 50 years) it is expected that the system will be able to adapt. There will be increasing costs for coastal defense as well as effects on the ecosystem, but the latter will not be substantial.

However, there is also a chance that the worst-case scenario will become reality. Under the worst-case scenario substantial physical, biological and socioeconomic impacts are expected and it is, therefore, recommended to start developing or to further develop, as soon as possible, long-term interdisciplinary policies for coastal defense , nature protection and economic development in the coastal area, in order to anticipate on impacts caused by increased sea level and storminess. Such policies may, amongst others, include spatial planning in the coastal zone aiming at the creation of buffer zones, the initiation of coastal defense measures which will start to become effective in the long-term and reducing or phasing out activities which enhance the effects of sea level rise.

Obtaining a long term reliability for coastal protection planning into action requires a further harmonization of coastal protection and nature conservation interests. A suitable way is the implementation of regional management plans developed in participation with the various interested parties. In such management plans the question should be addressed whether to introduce more flexibility in the coastal zone in order to reduce the growing costs for coastal defense. The question should be answered which functions of the coast need to be safeguarded at what costs. Another question is where dynamic processes can be reintroduced without losing safety.

2. Best Environmental Practice

In addition, or as an alternative to regular coastal defense measures, it is recommended to seriously investigate the feasibility of the Best Environmental Practice options listed in 7.2.5, within a long-term perspective and taking account of the different sea level rise scenarios, to combat negative effects of enhanced sea level rise and storminess.

3. Public perception

It is recommended to develop a communication strategy with the aim of starting a discussion with the general public about possible future impacts of increased sea level rise and the introduction of measures.

4. Methodology and research

Because all partners in the CPSL apply different methodologies for assessing possible impacts of enhanced sea level rise and storminess, it is necessary to start a process of improving the level of the qualitative assessment. It is in this respect recommended to start a research project in which a detailed sediment budget study is carried out, encompassing all natural and man induced inputs and outputs of sediment and other material (sand, mud, shells) and factors affecting transport processes. It is furthermore recommended to start a study into the links between geomorphological and biological changes.

5. Monitoring

It is recommended to evaluate the parameters of Trilateral Monitoring and Assessment Program (TMAP) for their suitability to assess impacts of climate change, on the basis of the outcome of targeted research mentioned under "4".

6. Other BEP options

It is recommended to continue to survey the literature for possible additional BEP options.

Annex 1: CPSL Terms of Reference

Responsibility

The Working Group acts under the responsibility of the Trilateral Working Group (TWG)

Composition

The Group will consist of representatives of the responsible administrations (coastal protection and nature protection) and/or members of the scientific community, to be nominated by the countries. There is a maximum of two members per country/federal state, not including the Chairperson.

The secretarial work will be carried out by the Common Wadden Sea secretariat.

Tasks

The tasks of the Working Group can be divided into three parts.

1. Definitions and administrative structures

Before starting the work on the issues listed under '2', a common understanding of technical terms must be developed.

Taking into consideration the national differences in coastal protection, it will also be necessary to produce an overview of current national policies and administrative structures relevant for coastal protection.

2. Development of a common knowledge basis

In the past ten years, our knowledge of fundamental geomorphological processes has increased considerably. The Working Group will, as a first step, collect relevant information and work towards a common understanding of facts concerning, in particular:

2.1 The overall sediment budget of the Wadden Sea ecosystem and its subsystems (barrier islands, salt marshes, tidal inlets, estuaries, tidal gullies, tidal flats);

2.2 Changes in storminess and tidal water levels;

2.3 The relevance of the volume of the tidal basin for sedimentation processes;

2.4 The relevance of changes of inundation area (for example through outbankment of summer polders) for sedimentation and/or of wave energy, as well as other factors (i.e. tourism, agriculture, nature protection, biodiversity);

2.5 Possible effects of fixing of (parts of) the islands under different sea level rise scenarios;

2.6 Changes in sediment composition in relation to changes of inundation area (amongst others as a result of the past straightening of the coastline and changes in wave energy);

2.7 Relevance of biogenic structures (mussel beds, seagrass beds, sabellaria reefs, shells) for sediment stability, reduction of current velocities and wave energy;

2.8 Relevance a reduction of wave energy through salt marshes and summer polders for the protection of sea walls;

2.9 Best environmental practices for coastal protection under different hydrological scenarios;

The results will be submitted to the Trilateral Working Group (TWG) by the end of 1999.

3. Development of proposals for common coastal protection strategies

Pending the decisions of the TWG the Working Group will, as a second step, draft proposals for future integrated policies regarding the above mentioned issues, on the basis of the commonly agreed facts Specific attention should be given to safety and nature protection aspects. However, other interests in the coastal zone that affect coastal and nature protection (e.g. tourism, agriculture) should be considered in an adequate way.

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Annex 3: Technical Terms

Accretion
The accumulation of mineral material in a particular locality or environment, e.g. tidal muds in a shallow coastal sea.

Amphidromic point
The area around which the tidal wave is turning and therefore without any tidal difference itself.

Barrier island (Barrier)
An elongated sand or shingle bank, either with or without dunes, which lies parallel to the coastline and is not submerged by the tide.

Best Environmental Practice (BEP)
The application of the most appropriate combination of measures, eliminating or minimizing environmental impact.

Biogenic structure
A structure that is created by living organisms, either animal or plant.

Bottom subsidence (Subsidence)
The setting of the bottom by
1. gravitational forces following accumulation of material,
2. the extraction of mineral deposits, e.g. salt or coal subsidence,
3. large-scale structural readjustment of the Earth's surface, as in basin down warping or rift valley formation.

Coastal protection
The protection of coasts against loss of land by marine erosive forces (tidal and wind waves). (see also Coastal Defense and Flood Defense)

Coastal defense
The protection of coastal lowlands against flooding by the sea, to a certain limit.

Coastline
The line forming the boundary between the land and the water.

Damming
The building sea walls for the protection of coastal lowlands against flooding by storm surges.

Design water level
Storm water level with a certain frequency of occurrence (return interval, e.g. 100 year) that is taken as a design criterion to establish/calculate the necessary dike height.

Dredging works
Works carried out in order to maintain the function of shipping channels or to maintain a certain water flow in a channel or belt.

Ecosystem
A functioning, interacting system composed of one or more living organisms and their effective environment, in a biological, chemical and physical sense. It is applicable at any scale (Fosberg 1963) Natural functional unit of organism, as well as, natural and artificial abiotic compartments which are interconnected concerning the exchange of energy, substances and information. (Ref. Glossary Stade Declaration)

Embankment
The activity by which a former flood-prone area becomes protection against flooding.

Erosion
The processes of wearing away the land surface by the mechanical action of the debris which is being transported by the various agents of erosion.

Eulittoral (eulitoral)
The zone between high and low spring tide marks

Eustatic sea level change
Change in sea level not considering changes in bottom level (see also sea level rise).

Flood defense
The protection of lowlands against flooding.

Geostrophic wind
The wind blowing parallel to isobars and representing the first-order approximation of the real wind. It is a measure for the driving force of the air pressure gradient on the real wind. Other factors, e.g. friction an centrifugal forces, are neglected.

Greenhouse effect
The ability of the atmosphere to allow shortwave radiation to reach the Earth's surface whereas outgoing long-wave radiation is absorbed and reradiated by water vapor, droplets, carbon dioxide and other radiative gases.

Intertidal flats (tidal flats)
That part of a tidal coastal landscape that is situated between the mean low and mean high tidal water level. Consequently, the area is submerged at high tide and emerged at low tide.

Inundation area
The area exposed to flooding without protective measures (damming).

Littoral sand transport
Nearshore parallel transport of sand by waves.

Low water level (low tidal water level)
The water level reached at low tide.

Mean Sea Level
The average level of the surface of the sea, determined by averaging recorded tidal levels over a one-year interval.

Mean Tidal Range (MTR)
The difference between the level of the surface of the sea at high tide and low tide, determined by averaging all high and low tidal water levels recorded over a one-year interval.

Mud flat
Tidal flat composed mainly of muds.

Natural dynamics of the coastal zone
The principle by which all natural (biological, chemical and physical) processes in the coastal zone be allowed, i.e. no human interference.

Nourishment
The activity of artificially replenishing the sandy coast

Outer delta (ebb-tidal delta)
An accumulative structure formed by the deposition of material transported into the area by ebb-tidal currents. As soon as the ebb currents leave the tidal inlet the bulk of the load is deposited as a result of decreasing current velocities.

Salt marshes
A coastal ecosystem, composed of marine sediments, occupied by salt tolerant and/or salt resistant vegetation, that is regularly inundated by salt water.

Sand balance
The net amount of material carried into or out of a specific area over a certain time interval. It is often established by the comparison of high resolution topographic maps for different epochs.

Sand flat
Tidal flat composed mainly of sand.

Sand sharing system
Coastal systems and tidal basins within which sand is relocated and between which sand is exchanged without a net lost of sand.

Sea level rise (change)
The long-term (secular) rise (change) of mean sea level. Different processes, e.g. eustatic, isostatic, etc. may be responsible for this change.

Sea level rise scenario
A scenario for future sea level rise. It is a hypothetical series of possible future sea levels that is constructed to evaluate causal correlations.

Secular sea level rise
See "Sea level Rise"

Sediment budget
The amount of material that is redistributed in a specific area over a certain time interval. The gross amount is the turnover volume, the net amount the sand balance.

Sediment importing system
Area with a net accumulation of sediments.

Storm flood
High water caused by a storm.

Storm surge
The elevation of the sea water level resulting from meteorological forcing (wind) on the water surface in shallow coastal seas

Storminess
The force, duration and frequency of storms, characterized by significant state variables.

Sublitoral = (Sublittoral)
That part of a tidal coastal ecosystem that is permanently water covered (subtidal area).

Summer polder
Former salt marsh which is now protected by a low dike (summer dike) against flooding by high tides during summer.

Tidal basin
That part of a coastal sea that is drained by one unitary channel network. Its perimeter is marked by tidal drainage divides, terrestrial environments and/or artificial constructions like sea walls.

Tidal channel
A channel in a tidal system that functions to transport tidal water masses.

Tidal current
The movement of sea water in response to the rise and fall of the tide.

Tidal flats
See intertidal flats

Tidal inlet
A large tidal channel that is often situated between two barrier islands through which the tidal waters may enter or leave a tidal basin during flood- or ebb-tide.

Tidal prism
The amount of water between high water and low water, excluding any freshwater flow.

Tidal range
The difference between consecutive low tide and high tide.

Tidal system
(Behind barrier islands) System of (a tidal inlet) tidal channels and tidal flats between two tidal drainage divides, ranging from the dike to approximately the 20 m depth line.

Tidal volume
The sum of the amounts of water that a flood-tide carries into, and an ebb-tide carries out of, a tidal basin.

Tidal wave
The oscillation, generated by the gravitational attractions on the earth's surface of the moon and the sun and the magnitude, in proportion to the planetary pull, the local water depth and the distance from the amphidromic point (see also wind wave)

Tide
The regular rise and fall of water level in the world's oceans, resulting from the gravitational attraction that is exerted upon the earth by the sun and the moon.

Water shed (tidal divide)
Hypothetical line connecting the highest points of the upper tidal flats, separating neighboring tidal basins. It is the first to fall dry on the ebbing tide.

Wave climate
The average wave conditions at a specific place over a lengthy period of time (> 30 years), including absolute extremes, means and frequencies of given departures from these means.

Wind climate
The average wind conditions at a specific place over a lengthy period of time (> 30 years), including absolute extremes, means and frequencies of given departures from these means.

Wind wave
A deformation of a water surface in the form of an oscillatory movement which manifests itself by an alternating fall and rise of that surface. The oscillation is generated by the wind pressure on the water surface and the wave magnitude is in proportion to the speed of the wind, its duration and the length of fetch.

Annex 4: Relevant Running Projects

1. Evaluation study of the coastal lowlands in Schleswig-Holstein

Area: coastal lowlands of Schleswig-Holstein
Project period: 1997 - 2000
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Contents: this projects aims at establishing the damage potential for the coastal lowlands using a GIS and a digital terrain mode
2. MERK - micro scale evaluation of the risks in coastal lowlands.
Area: four coastal flood units in Schleswig-Holstein.
Project period: 01.01.2000 - 31.12.2002.
Contact: Prof. Dr. H. Sterr (see address project 1).
Contents: this project focusses on establishing a common method to evaluate the (future) risk of coastal flooding on a micro scale using GIS and DTM.

3. Programs to optimize the long-term stability of the Wadden Sea

Area: Wadden Sea of Schleswig-Holstein
Project period: 1998 - 2001
Contact: P. Witez, Landesamt für Natur und Umwelt des Landes Schleswig-Holstein, Hamburger Chaussee 25, D-24220 Flintbek, Tel.: +49 4347 704461, e-mail: pwitez@lanu.landsh.de
Contents: This projects aims at the prediction of morphological changes in the Wadden Sea for different hydrographic scenarios using digital terrain models. Further, methods to counteract possible negative developments are described and evaluated.

4. Regeneration of sediment source areas for beach nourishments

Area: German North Sea
Project period: 1999 - 2002
Contact: Dr. Figge, Bundesamt für Seeschiffahrt und Hydrographie, Postfach 301220, D-20305 Hamburg, Tel.: +49 40 31903240.
Contents: This project deals with the establishment and the analysis of the long-term development (hydro-, morpho- and ecological) of sediment source areas for beach nourishments.

5. PRODEICH - probabilistic design of sea walls

Area: German North and Baltic Sea coasts.
Project period: 01.02.2000 - 01.01.2002.
Contact: Prof. Dr.-INg. Hocine Oumeraci, Leichtweiß-Inst. TU Braunschweig, Beethovenstr. 51a, D-38106 Braunschweig, Germany, Tel.: +49 531-391 3930, e-mail: h.oumeraci@tu-bs.de.
Contents: this project aims at establishing probabilistic design criteria for sea walls as well as increasing the knowledge about the probability of failure of coastal flood defence systems under given hydrographic scenarios.

6. NOURTEC (Innovative nourishment techniques evaluation)

Type of project: co-sponsored by EU-MAST II (MAS2-CT93-0049)
Co-ordinator and partners: RWS-RIKZ (National Institute for Coastal and Marine Management, The Netherlands), CRS (Coastal Research Station, Germany), DCA (Danish Coastal Authority, Denmark) and UU (University of Utrecht, The Netherlands)
Area: Terschelling (The Netherlands), Torsminde (Danmark) and Nordeney (Germany)
Project period: 1993-1996
Contact: dr. R. Spanhoff, RWS RIKZ, Kortenaerkade 1, P.O. Box 20907, 2500 EX, The Hague,
Tel: +31 70 114230,
e-mail: R.Spanhoff@rikz.rws.minvenw.nl.
Contents: Description and explanation of three experimental nourishments (complete or partly on the shoreface). Conclusions on the feasibility and effectiveness of shoreface nourishments. Design recommendations for shoreface nourishments in different coastal environments. The development of a database for future model tests.

7. RIACON (Risk analysis of coastal nourishment techniques)

Type of project: co-sponsored by EU-MAST II (MAS2-CT94-0084
Co-ordinator: RWS-RIKZ (National Institute for Coastal and Marine Management, The Netherlands)
Area: Terschelling (The Netherlands), Torsminde (Danmark), De Haan (Belgium), Costa Daurada

(Spain) and Nordeney (Germany).
Project period: 1994-1997
Contact: dr. K. Essink, RWS RIKZ, Kerklaan 30, P.O. Box 207, 9750 AE, Haren, tel: +31 50 533 1373, e-mail: K.Essink@rikz.rws.minvenw.nl.
Contents: Evaluation of the risk of shoreface nourishments and offshore subaqueous sand extraction for the marine zoobenthic community of the foreshore.

8. NWO-ALW Outer Delta Dynamics project

Type of project: NWO (National Science Foundation) sponsored acandemic research program.
Participants: Utrecht University, Delft University, Netherland Insitute for Sea Research (NIOZ), and support from RWS-RIKZ (National Institute for Coastal and Marine Management, The Netherlands) and WL|Delft Hydraulics.
Area: Tidal inlets in the Wadden Sea.
Project period: 2000-2004
Contact: dr. H.E. de Swart, Institute for Marine and Atmospheric Research (IMAU), Utrecht University,
P.O. Box 80005 Utrecht, The Netherlands, e-mail: H.E.deSwart@phys.uu.nl
Contents: The aim of this programme is to gain more fundamental knowledge about the dynamics of the outer deltas by addressing the following questions:
1. what is the role of outer deltas in the sand balance of the coastal zone;
2. what is the morphodynamic relationship between the outer delta and the inner basin;
3. how to model and understand the cyclic channel-shoal behaviour and related sediment bypassing over the outer delta.

9. Delft Cluster Research program: theme Coasts and Rivers.

Type of project:: NWO (National Science Foundation) sponsored acandemic research program.
Participants: Delft University, WL|Delft Hydraulics, TNO-NITG, Alkyon and RWS-RIKZ (National Institute for Coastal and Marine Management, The Netherlands).
Area: Tidal basins in the Netherlands
Project period: 2000-
Contact: Delft Cluster, Postbus 69, 2600 AB Delft, Tel: +31 15-2693793,
Contents: To identify and further develop data, knowledge and models regarding the medium and long-term morphological evolution of coast-basin interaction based on the coastal cascade concept. The Delft Cluster Theme 3-Project Coasts focuses on the morphological interaction between the coast and tidal/estuarine basins.

Ongoing research

Sediment transport and morphological development in a barrier/lagoon system: This project focuses on the Skalling barrier spit with the following key issues:
Offshore: The role of flocculation in possible fluff layer formation during calm weather situations in the North Sea. Resuspension during storm of fluffy material and its import to the Wadden Sea.
Coastal zone: Understanding the 3-D nature of the bar system, morphological evolution in both cross-shore and longshore directions. Sediment transport in the surf zone. Exchange of sediment between the surf zone and offshore. Eolian transport processes and resulting morphology on beach face and in dunes. Hydrodynamics and sediment budget of wash-over fans.
Inlets: Examining when and how episodic transport takes place. Import/export balancing of suspended matter. Bedform migration with time.
Tidal flats and salt marsh areas: Tidal flat dynamics and their role as temporal storages for fine grained material. Resuspension effects of biological activity. Salt marsh development with time and its connection to sea-level variations. Drainage pattern evolution and effects on salt marsh growth. Retention of fine grained material, nutrients and heavy minerals on salt marshes.
Barrier evolution: Surface sediments and their stratigraphic relations. Morphological evolution from cores and shallow seismic.

INTERMUD. EU MAST III project
The Morphological Development of Intertidal Mudflats
The objectives of the project are: To investigate the characteristics of intertidal mudflats in NW Europe in order to establish a classification which reflects the morphological effect of variations in such parameters as: tidal range and phase, wave climate, sediment physical and biological properties, biological communication structure etc. This will propose a series of conceptual models of mudflat development. To carry out experiments on a number of type-mudflats, using harmonized methods, to quantify the processor, and their interactions, their ranges and time scales of variation. To formalize the relationships in statistical descriptions, and test the validity of the concepts by computer modeling, using the experimental field data. To provide a basis of understanding, which can be used in management of mudflats, in order to maintain ecological health, particularly under changing climatic, sea level, and anthropogenic pressures.

DECO (Danish Research Councils Danish Environmental Monitoring of Coastal Waters) The objectives of the project are: The project encompasses two major objectives. The first being the development and validation of the spectral fingerprint technique, and the set-up of a spectral library of key parameters for the Danish coastal waters. This goal will involve the integration of sea truth measurements, remote observations, statistical analysis, and modeling, leading to a unique data library pertaining specifically to the Danish marine environment. The second major objective of this program is the application of the spectral fingerprint information to specific problems and processes relevant to research and monitoring questions. The specific questions to be addressed include: Distinction between different phytoplankton pigment and determination of their concentration. Determination of suspended sediment concentrations and size distribution Sediment resuspension and transport in coastal waters Classification of different bottom types in shallow waters including vegetation and mussel beds.

Within RWS RIKZ (National Institute for Coastal and Marine Management, The Netherlands) several research projects address aspects of the subjects mentioned in the CPSL Final Report. The subjects include: subsidence due to ongoing and possible future mining projects, the future sediment budget of the Wadden Sea, including the effects of sea-level rise, improved nourishment techniques, and more.

Annex 5: Literature

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