Coastal Protection and Sea Level Rise

Solutions for Sustainable Coastal Protection in the Wadden Sea Region

WADDEN SEA ECOSYSTEM No. 21 - 2005

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Colophon

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Solutions for Sustainable Coastal Protection in the Wadden Sea Region

Trilateral Working Group on
Coastal Protection and Sea Level Rise (CPSL)

2005
Common Wadden Sea Secretariat
Working Group on Coastal Protection and Sea Level Rise

Contents

Executive Summary

Questions regarding the consequences of climate change, especially an accelerated sea level rise, for the Wadden Sea ecosystem entered the political agenda of the trilateral Wadden Sea cooperation. In 1997, at the 8th Trilateral Wadden Sea Governmental Conference (Stade, Germany), it was decided to investigate the possible impacts of enhanced sea levels on the Wadden Sea and, on the basis of such an investigation, to develop recommendations for coordinated coastal defence and nature protection policies.

In 1998, a trilateral expert group, the Coastal Protection and Sea Level 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. In a first phase, for three sea level rise scenarios, the impact upon physical, biological, and socio-economic parameters was investigated. Further, a first screening of sustainable coastal defence measures that minimize impacts on the natural system to secure present safety standards in the future was conducted. The results were presented and acknowledged at the 9th Trilateral Governmental Conference in 2001 (Esbjerg, Denmark).

Recognizing the high topicality of sustainable strategies, the ministers decided to continue the work of CPSL. Based upon the screening in the first phase and a description of the natural system, the expert group investigated the following instruments and measures that might contribute to sustainable coastal defence strategies for the Wadden Sea: spatial planning, sand nourishment, dune management, salt marsh management techniques, mussel and sea grass beds, outbanking of summer polders, and sea dikes. The investigations were based upon two geomorphological scenarios: below breakpoint and above breakpoint. Below breakpoint, the Wadden Sea will be able to maintain its present appearance (despite moderate sea-level rise) by sediment redistribution. Above breakpoint, the Wadden Sea will not be able to balance sea-level rise and the tidal basins will start to drown, i.e., evolve in the direction of coastal lagoons (a shallow water area, separated from the open sea by barriers). The main difference to the present Wadden Sea tidal basins is that major parts of the tidal lagoons are permanently water covered.

Concerning spatial planning, the establishment of coastal regional plans that include buffer zones and coastal flood hazard zones is recommended by the group as a promising non-technical BEP measure. In the buffer zones, space can be reserved for future coastal defence measures or retreat of the coastal defence line. In the flood hazard zones, restrictions and/or regulations for spatial utilization aim to reduce the consequences (damages) of storm surges. In the coastal spatial plans, the significance of climate change and its consequences, increased sea level rise and changed storminess, should be duly considered. The determination of buffer zones and flood hazard zones in coastal spatial plans becomes specific significance above the breakpoint. In this case, traditional techniques might become less feasible (technical and/or financial) to maintain present safety standards.

Sand nourishment is seen as a BEP measure that successfully counteracts coastal erosion. Further, it helps to stabilize the dunes (constituting a natural dune-foot protection and as a sand source) and, therewith, their functionality as flood defences. Concerns exist with respect to interferences with nature that result from extraction and deposition of the sand. Hence, the measure should be applied in a way that minimizes the effects on the environment. Compared to other techniques (groynes, revetments) to stabilize sandy coastlines, sand nourishment is, in general, to be preferred. In the long-term and, especially, above the breakpoint, nourishment of sand on strategic locations in the Wadden Sea may help to balance the sand-deficit that results from sea level rise.

Dune management comprises of a number of measures (dune restoration, dune relocation, natural dune dynamics and over-wash) that ensure the functionality of dunes as flood defences. Allowing natural dynamics and over-wash have clear ecological benefits as they add to the naturalness of the environment. Dune restoration and relocation, e.g., by building sand fences or planting marram grass, do interfere with nature. However, from an ecological point of view, these techniques are to be preferred above hard constructions like dikes or groynes that would otherwise become necessary. Especially above breakpoint, dune relocation in combination with sand nourishment might be a BEP measure to maintain defence standards. Even though, there might be a point where the techniques described above do not suffice and, with present safety standards, hard techniques may become necessary to protect inhabited lowlands.

Salt marsh management techniques (i.e., groynes, drainage furrows and grazing) aim at maintaining the flood defence functions of the marshes. At the same time, salt marshes have an outstanding ecological value and should be preferred as dike foot protection compared to hard constructions. Groynes function in that they reduce wave energy and currents, thereby creating an environment where sedimentation prevails and erosion is lessened. Hence, they interfere with natural dynamics. Without groynes, widespread erosion of salt marshes would occur in the Wadden Sea. Natural material (wood) should be applied if feasible. Artificial drainage furrows constitute an interference with natural dynamics as well. They should only be applied to secure dike-foot dewatering (avoiding otherwise necessary hard constructions) and, if necessary, to secure dewatering on grazed salt marshes. Natural structures (creeks) should be used wherever possible as part of the drainage system. Livestock grazing on salt marshes is controversial and still subject to discussion. It is considered to be a BEP measure where, after storm surges, high amounts of flotsam would, otherwise, have to be removed from the outer dike slopes. At present, salt marsh management differs between the countries and is also dependent on the regional and local boundary conditions.

Promoting mussel and sea grass beds aims at stimulating accumulation on, and stabilization of intertidal flats. As it is capable of enhancing biodiversity, it has ecological benefits. From a coastal defence point of view, the measure could only perform a very local and limited effect in that it may reduce wave energy. During storm surges, the large water depths reduce the wave damping effect to zero.

Outbanking of summer polders in estuaries may have, under specific conditions, positive flood defence effects by reducing the height of storm surges upstream. Outside estuaries this effect does not occur. Here, the outbanking allows the surface level of the summer polder to keep pace with sea level rise by increased sedimentation rates. This, however, only functions below breakpoint and if the existing height differences between the polder and the fronting tidal flats or salt marshes are not too large. Extra measures with regard to the main sea dikes behind the summer polder might become necessary due to the failing summer dikes. As the measure can compensate for loss of salt marshes, it has ecological benefits.

Under sea dikes a number of measures (dike-strengthening, dike relocation and second dike line) were investigated that ensure the functionality of dikes as flood defences. Sea dikes constitute the main coastal flood defence measure in the Wadden Sea (on the islands in combination with dunes). Measures that maintain the functionality of the sea dike system in the Wadden Sea are indispensable to secure present safety standards. Sea dikes, on the other hand, strongly interfere with nature. Hence, necessary dike-strengthening measures should be carried out in a way that minimizes the adverse effects on nature, for example by using material from the old dike and by strengthening on the landward side (if possible). Further, on a more local scale of single uninhabited flood units (polders) alternatives like dike-relocation and strengthening the existing or building a new second line should be considered, especially above breakpoint.

The elaborations of the group resulted in a number of conclusions:

- The predicted sea level rise will induce a sediment deficit in the Wadden Sea. Above breakpoint, the Wadden Sea will develop into a number of tidal lagoons.
- A number of measures are identified that contribute to maintaining safety and have limited ecological consequences.
- New coastal defence techniques that are both feasible and have minimal ecological impacts could not be determined.
- All coastal defence techniques constitute, to a varying extent, interferences with nature.
- The application of the identified measures differs among the regions, resulting from the differences that exist in the physical, socio-economic and cultural framework.
- Apart from The Netherlands, no specific regional plans that consider coastal defence and climate change for the Wadden Sea region exist.
- Including buffer and coastal flood hazard zones in spatial plans are a sustainable and flexible way to deal with the effects of sea level rise.

- Sand nourishments successfully balance coastal erosion along the outer coastlines of the barriers.
- Sand nourishment may contribute to the compensation of sediment deficits in the Wadden Sea resulting from sea level rise, but the ecological effects are still unclear.
- Dune management techniques ensure protection against flooding and are, from an ecological point of view, to be preferred above hard constructions.
- Salt marsh management techniques are necessary to prevent most salt marshes from erosion.
- Salt marshes perform an ecologically sound measure to protect the dike foot compared to otherwise necessary hard constructions.
- Mussel beds and sea grass fields enhance biodiversity and may, on a local scale, help safeguarding intertidal areas from drowning.
- Inside estuaries, outbanking of summer polders has positive ecological effects and may, in specific cases, be positive for coastal defence.
- Sea dikes strongly interfere with natural dynamics in the area but are, generally, necessary to secure present safety standards in coastal lowlands.

The CPSL group finally formulated five recommendations:

1. Coastal spatial plans that include buffer and coastal flood hazard zones should be established based on the principles of integrated coastal zone management. Coastal defence and climate change should be duly considered. The feasibility of such plans should be investigated by a follow-up group, comprising trilateral experts from nature protection, spatial planning and coastal defence.
2. Sand nourishment should be applied, wherever feasible, to combat erosion along sandy coastlines.
3. A study should be carried out on the feasibility and effects of sand nourishment to balance the sediment deficit of the Wadden Sea tidal basins under increased sea level rise.
4. Regional salt marsh management plans should be established to harmonize the demands of coastal defence and nature conservation.
5. An evaluation of maintaining present day safety standards with respect to feasibility and ecological consequences, especially above breakpoint, should be carried out.

1. Introduction

Climate change and, in particular, its possible effects, had become a central issue in politics and science in the 1990s. The notion 'climate change' became almost identical with anthropogenic 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, caused by the thermal expansion of the ocean water and the melting of glaciers and polar ice caps, have been predicted. Also changes in storminess 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 Wadden Sea Governmental Conference (Stade, Germany), it was decided to investigate the possible effects of enhanced sea levels and, on the basis of such an investigation, to develop recommendations for coordinated coastal defence and nature protection policies in the Wadden Sea.

In 1998, a trilateral expert group, the Coastal Protection and Sea Level 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. In a first phase, (CPSL I) which lasted from January 1999 till May 2001, the following steps were conducted:

- a common understanding of the Wadden Sea (morphology, biology and coastal defence) was established in the expert group,
- for three scenarios (sea-level rise of 10 cm, of 25 cm and of 50 cm until 2050), the impact upon selected physical, biological, and socio-economic parameters was investigated,
- a first screening of sustainable coastal defence measures, that minimize impacts on the natural system (best environmental practices) to secure present safety standards in the future was conducted, and
- several recommendations for policy, management and research were formulated.

The results of this first phase are available in a report, at www.waddensea-secretariat.org. Further, the results were presented and acknowledged at the 9th Trilateral Governmental Conference in 2001 (Esbjerg, Denmark). Recognizing the high topicality and exigency of sustainable strategies, the ministers decided to continue the work of CPSL. In a second phase (CPSL II), the expert group conducted feasibility studies of integrated coastal defence solutions that aim at maintaining the existing safety standards and anticipate the expected impacts of sea level rise in the long term. At the same time, they should have , at least, no negative effects on natural assets, such as natural dynamics and habitat quality. Further, the solutions should stand a check on technical and financial feasibility, legal aspects, public acceptance, and "harmony" with other interests, e.g. tourism. The solutions in one part of the Wadden Sea (e.g. barrier island) should have no adverse impacts on other areas (e.g. tidal flats). Finally, regional aspects were duly considered. The precise terms of reference of CPSL II are in Annex 1, the members of the group are listed in Annex 2.

In CPSL I there was agreement that, up to a certain "breakpoint" (Figure 1), the Wadden Sea will be able to adapt to external changes (sea level rise, storminess). Above this breakpoint, the

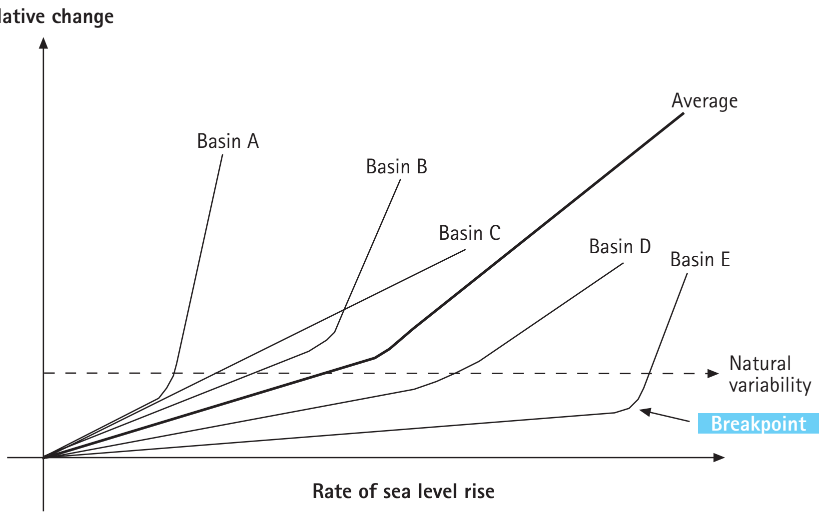


Figure 1: Possible change in geomorphological and biological parameters for individual tidal basins under sea level rise.

Wadden Sea ecosystem will start to develop in the direction of tidal lagoons (i.e., a reduction of intertidal flats). However, the exact level of this breakpoint is not known and differs from basin to basin. Hence, the investigations in CPSL II were based on the two scenarios: below and above breakpoint.

In this report, the results of the work of CPSL II, carried out in the period July 2003 till May 2005, are presented. The report starts with an executive summary. In Chapter 2, the natural system is described in terms of the expected development below and above breakpoint. Chapter 3 elaborates selected coastal defence measures. After a general description of the measure, the coastal defence significance and ecological effects are depicted. In a synthesis, these aspects are evaluated including a breakpoint discussion. Finally, regional aspects are addressed. Chapter 4 includes an overall synthesis of the measures. Finally, in chapter 5, conclusions and recommendations are listed. In box texts, relevant aspects are described in more detail. The report contains three annexes. In addition to the already mentioned annexes 1 (terms of reference) and 2 (members of CPSL II), in Annex 3 the cited literature is listed.

Coastal defence

The Wadden Sea region has been inhabited for thousands of years. In the beginning the population lived mainly from hunting and fishing. Together with the permanent settling, the construction of dikes and the development of agriculture, land reclamation became an important activity. In the second half of the last century other functions became more and more important, e.g. recreation. Land reclamation in the last 50 years or so took place for sea defence purposes only.

In the Wadden Sea region people live, work and recreate. At present approximately 3 million people live in the flood prone lowlands of the Wadden Sea region. There is a fundamental need to protect the local population and the lowlands against storm floods in order to give the inhabitants the possibility to live in safety and to earn their living. It is a precondition of the tri-lateral Wadden Sea Cooperation that sustainable human activities and sustainable economic developments in the area remain possible in the future (Stade declaration, 1997).

Coastal defence aims at safeguarding coastal lowlands, their inhabitants and economic assets against the forces of the sea. It consists of coastal flood defence (protection against coastal flooding) and coastal protection (protection against structural erosion and land loss). Hence, coastal defence implements the claim of the coastal population to be protected against flooding and land loss.

In general, the protection of the flood prone areas along the mainland coast is implemented as a spatially staggered system consisting of barrier islands (i.e., the first line of defence), tidal flats, salt marshes (with or without groynes), a primary sea wall, and, in some cases, a second dike line. On the islands, dunes and revetments are important elements of coastal defence as well. The sea defences are kept in such condition that they can withstand storm surges and that structural erosion of the coast is combated. There are areas, however, where safety standards do not apply. Further, there are differences in safety standards between the count(r)ies (see CPSL I report).

Natural references

The Wadden Sea is a highly productive and dynamic ecosystem, in which natural processes proceed and the natural structures of habitats and species are still present. Its function as a stepping-stone for migrating birds and as nursery area for many fish species underlines the world wide ecological importance. The protection of this unique landscape and the aim to achieve, as far as possible, a natural and sustainable ecosystem in which natural processes proceed in an undisturbed way, is the guiding principle of the trilateral Wadden Sea policy as formulated on the 6th Trilateral Governmental Wadden Sea Conference in Esbjerg 1991.

The following natural reference situation represents partly a hypothetical picture of the Wadden Sea, under natural circumstances. This reference is not identical with a desired target situation, but merely reflects a standard, to which, from a nature point of view, the actual or future developments can be compared.

A natural Wadden Sea ecosystem is characterized by barrier islands or high sandbanks at the seaside, tidal flats and, without dikes, a wide transition of salt and brackish marshes along the mainland coast. The tidal waters exchange via gully systems: consisting of tidal inlets with ebb and flood deltas and main channels, which branch into small gullies and creeks inundating or draining tidal flats or salt marshes. The tidal flats are diversely composed of sand or mud and, in the course of the tides, with different exposure times. In interplay of physical and biological processes, salt marshes and dunes are formed. Erosion and sedimentation processes influence the shape and position of the islands.

Some typical structures, especially in the marine environment have a biogenic origin such as oyster and mussel beds, reefs of the tube building worms (Sabellaria) or sea grass fields. The exposed parts of the system are highly dynamic, but even the sheltered parts, the bights at the mainland or the salt marshes behind the dune ridges on the islands change in shape and height in the course of the time. On high sand flats, vegetated dunes may appear and develop to islands.

The plants and animals are adapted to the extreme environmental conditions and often occur in high abundance. On the salt marshes many species are endemic. One strategy to inhabit such an unstable and permanently changing environment is a high reproduction capacity, which is essential for many species of the tidal flats. Sedimentation of organic material and the subsequent decomposition purifies the adjacent coastal waters from their organic load and is one major source for the high biological production.

The high dynamics of abiotic and biotic components of the system and as a consequence its flexibility to changing environmental conditions, its function as a sink for sediment and organic matter and the decomposition capacity, the high biological production and reproduction rates as well as the high degree of specialization of plants and animals, which are partly endemic, are the corner-stones of the Wadden Sea ecosystem. All these functions and features are connected within a network, which to a certain degree has the ability of resilience.

2. The Natural System

2.1 Introduction

In its present state, the Wadden Sea is characterized by 33 adjacent tidal systems, each consisting of a number of distinct morphological elements. With respect to the tasks of the trilateral expert group (annex 2), each tidal system may be divided into three subsystems.

1. The outer North Sea coast consists of the elements: foreshore, barrier island, tidal inlet and the ebb-tidal delta. In this subsystem, offshore wave energy is significantly reduced.
2. The tidal basins consist of the elements: tidal channels, tidal flats and salt marshes. Here, tidal processes dominate the morphology.
3. Finally, the element -reclaimed coastal lowland- is defined as one subsystem. In respect of this element, we aim at preventing that tides and/or waves dominate at any time.

A comprehensive description of the elements (apart from the last one) is given in CPSL (2001).

In this chapter, after a description of the breakpoint, the natural morphologic development in the three subsystems below and above the breakpoint is elaborated.

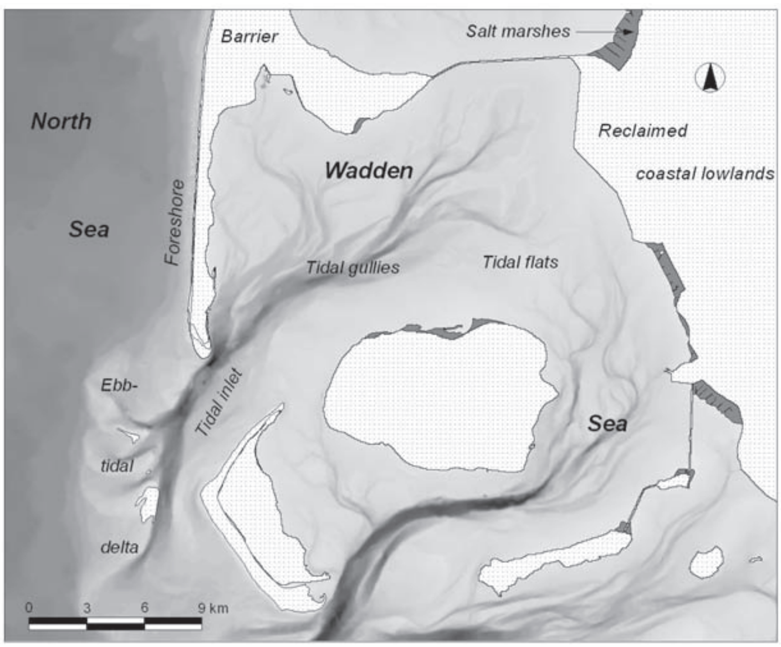
2.2 The breakpoint

Strong interrelations in the Wadden Sea exist between hydrodynamics and the morphology. Each element as well as each tidal system is striving to maintain a dynamic equilibrium, mainly by sediment redistribution. In other words, changes in any part of the system will primarily be compensated by sediment transport to or from the other parts of the same system (CPSL 2001). When changes are temporary, limited and/or moderate, the old dynamic equilibrium will eventually be restored. For example, as a result of a moderate increase in sea level rise, the duration of tidal inundation will increase. This induces a stronger *sediment* accumulation on tidal flats and salt marshes (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 tidal inlet or, rather, sand-sharing system.

To address these different types of morphologic reactions, the *CPSL II group* applied the concept of a breakpoint (Fig. 1). Below the breakpoint, the system will be able to balance. Above breakpoint, a development away from the existing dynamic equilibrium will start. Referring to the tasks, the *CPSL II group* concentrates on sea-level rise being the main cause for exceeding the breakpoint. This concept was chosen because of large uncertainties that still exist concerning future changes in sea level rise and storminess (IPCC 2001). Pending on the socio-economic scenarios and the models that are used, a sea level rise varying among 0.09 and 0.88 m till 2090 is predicted with mean values between 0.3 and 0.5 m.

In the first CPSL report, the group estimated that, under a moderate sea level rise of 25 cm in 50 years, most of the tidal systems will be able to adapt by increased sediment redistribution. Under the worst-case scenario (50 cm in 50 years), it is expected that most systems will not be able to adapt anymore. These will be changes in morphology, which will influence biological parameters and socio-economic parameters as well. The most notable morphologic change might be a reduction in the size of the intertidal area, i.e., an evolution towards coastal lagoons might start (CPSL 2001). The exact rate of sea level rise, at which the dynamic equilibrium among sea level rise and sedimentation is disturbed, might differ significantly from one to another tidal system, depending on e.g. sediment availability. In the Netherlands, investigations with semi-empirical models on how single basins might react to

Figure 2: Geomorphological elements of the North Sea coast (J. Hofstede).



changes in sea-level and wave climate are underway. They suggest that in larger tidal systems, the breakpoint might be situated lower than in smaller systems (Van Goor 2002). In general, the simulations support the assumptions made in the first CPSL report (see above).

In the Wadden Sea Quality Status Report (2005, Ch. 3.4) it is stated that: "tidal flats are expected to be able to keep up with sea level rise due to faster sedimentation up to a critical limit of sea level rise of 3 mm/yr (for large tidal basins) to 6 mm/yr (for small basins). For salt marshes, this critical limit is at least 8.5 mm/yr, and for the pioneer zone 3-6 mm/yr. Above the critical limit flats and marshes will 'drown'. The increasing sediment demand in the tidal basins will trigger a faster erosion of the sandy North Sea coasts. Combined with the direct effect of a rising water level, it is estimated that the total coastal erosion will increase by 250% of the present level of 6 mm/yr and by 330% at 8.5 mm/yr. This can be compensated for by nourishments".

Another aspect that needs to be addressed here, is the inherent natural variability. In a positive sense, it implicates that the Wadden Sea has a high resilience to changes. The intense hydrodynamics and the high sediment mobility enable the system to balance local and/or moderate disruptions from the equilibrium. Due to the variability, however, developments away from the existing dynamic equilibrium are difficult to detect at an early stage. This complicates a timely development of integrated strategies to anticipate negative consequences.

Finally, a number of processes may lead to a development away from the existing dynamic equilibrium. Sea-level rise is one cause, storminess and tidal energy (and human efforts) may be others. Depending on the causes, the development may go even in the opposite direction. For example, following Hayes (1979) the morphology of barrier islands is a function of wave and tidal energy. A strong increase in wave energy (storminess) may lead to the closure of tidal inlets, whereas a strong increase in tidal energy (tidal range and/or volume) may lead to a situation where barrier islands are not sustained anymore. The western coasts of Holland and Denmark, where no tidal inlets interrupt the barrier coast, are examples of wave dominance. The Inner German Bight between Eiderstedt and the Weser estuary is an example of tidal dominance. Here, one tidal inlet more or less borders the next. As stated above, the trilateral expert group concentrates on the effects of sea-level rise.

2.3 Natural development of the tidal systems below the breakpoint

Over the past centuries, numerous local changes occurred in the Wadden Sea. However, the overall physiography, i.e., the relative proportions of each element, remained within a certain band. Enough sediment to balance sea-level rise in the tidal basins came from the foreshores of the barrier islands, from the closed western coasts of Hol-

Figure 3:
Salt marsh cliff erosion (Photo: F. Thorenz).

land and Denmark. The only exceptions were the coastal marshlands. Due to land reclamation, a significant part of these marshes was turned into cultural landscape. Below, the overall morphologic development in the three subsystems is described for the situation below breakpoint, i.e., as it occurred over the last centuries.

2.3.1 Outer North Sea coast

In response to the observed sea-level rise during the last century (0.1 to 0.2 cm per year), the outer North Sea coast generally retreats. However, on the Wadden Sea barrier islands, a number of natural factors (e.g., excessive sediment supply by the littoral drift, Pleistocene subsurface) may counteract this morphologic 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. A further morphological result is a dominant littoral drift in eastward direction for most of the West- and East-Frisian Islands.

In the tidal inlets and ebb-tidal deltas, dynamic equilibriums exist between the tidal currents and the cross-sectional areas of the channels, as well as between the waves and tidal/littoral accumulation at the sand bodies of the delta (Oost 1995, Hofstede 1999). The equilibrium state in the tidal channels is controlled by the scouring potential of the currents, i.e., an increase in currents results in an enlargement of the channel cross-sections until the old current velocities are re-established. On the ebb-tidal delta, sediment is imported by the littoral drift and ebb-tidal currents. With decreasing current velocities, the sediment may settle here. Energy impact of shoaling and breaking waves prevents a continuous growth, i.e. equilibrium between erosion by waves and tidal sedimentation prevails. As long as tidal regime and wave climate remain within a certain band, inlets and deltas will be maintained in its present steady state (given enough sediment supply to balance present sea-level rise).

In synthesis, if hydrologic changes remain below the breakpoint, and external sediment supply into the system from the coasts of Holland and Denmark continue, the present steady state and, therewith, the general physiography and development of the outer North Sea coast will persist.

2.3.2 Tidal basins

The tidal basins are situated landward of the outer North Sea coast. They consist of tidal flats, tidal gullies and salt marshes. The tidal flats normally occupy the largest part of a tidal system. In the long-term, they represent tidal accumulative structures where particles, brought into the area by flood currents, settle. Significant short-term sediment redistribution may occur during storm surges. The maximum elevation of the tidal flats is defined by the ratio between sedimentation during fair weather and erosion during storms (Göhren, 1968). In sheltered areas, sedimentation may prevail, and the tidal flats evolve into salt marshes.

Tidal currents scour tidal gullies into the tidal flats. As in the tidal inlet, a dynamic equilibrium exists between the tidal currents and the cross-sectional areas of the channels, controlled by the scouring potential of the currents. Tidal gullies may show high meandering or migration rates, shifting their position over several hundred meters during one year.

If sedimentation on the tidal flats prevails, eventually a salt marsh will develop. Boundary conditions for establishing and sustaining salt marshes are:

- an adequate supply of fine sediments,
- a low energy environment which allows for sedimentation,
- regular salt-water inundation, and,
- a moderate sea level rise to balance the accumulation and prohibit vegetation succession.

Salt marshes represent an accumulative tidal structure, of which the maximal elevation is limited by the time of tidal inundation. Nowadays, most of the mainland salt marshes in the Wadden Sea are artificial, i.e. developed by salt marsh accretion enhancement techniques (CPSL 2001).

In synthesis, if hydrologic changes remain below the breakpoint, and salt marsh management techniques are continued, the present steady state and therewith the physiography of the tidal basins will persist.

2.3.3 Reclaimed coastal marshes

The reclaimed coastal lowlands consist almost exclusively of former coastal salt and brackish marshes. Their reclamation started more than 1,000 years ago with the construction of so called ring dikes to protect small areas for agricultural purposes. Over the centuries, local population performed a continuous "battle against the sea". This struggle with occasional hard setbacks has significantly influenced their local identity. Nowadays, the former marshes are separated from the sea by an almost continuous line of sea walls. Hence, the situation in the reclaimed coastal lowlands differs fundamentally from the other two subsystems, in a way that natural dynamics and development are negligible. In synthesis, if hydrologic changes remain below the breakpoint, and if present coastal defence strategies remain similar, no significant changes in physiography in the reclaimed coastal marshes are anticipated.

2.4 Natural development of the tidal systems above the breakpoint

Above the breakpoint, a natural development away from the existing dynamic equilibrium will start. For this investigation, a strong sea-level rise is assumed to be the cause for this development. Under this assumption, there is not enough sediment available to maintain a dynamic equilibrium. The system will change towards a new morphological state. Below, the morphologic consequences are described for the three subsystems.

It should be stressed here that, pending on the causes for breakpoint exceeding, the resulting morphologic development may differ significantly or even be the opposite (see also Ch. 2.2).

2.4.1 Outer North Sea coast

As elaborated by, amongst others, Bruun (1988), acceleration in sea-level rise will result in increasing retreat rates of the outer North Sea coast (eroding foreshores). Above breakpoint, probably those barriers that are, at present, stable or even accreting (e.g. Amrum, Rømø) will start to retreat as well.

The tidal flats will start to drown above breakpoint (see below). Hence, larger tidal volumes will have to be transported through the tidal inlets causing erosion in the inlet channels. How the ebb tidal deltas develop, will probably depend on the ratio of sand input by stronger ebb-tidal currents and the rate of sea level rise (drowning effect).

2.4.2 Tidal basins

Part of the released sediment from the foreshores might be deposited on the tidal flats and salt marshes. However, it is postulated that - above breakpoint - this extra sedimentation will not balance the accelerated sea-level rise in these elements. In result, the relative water depths over the tidal flats will increase. A larger part of the tidal volume might be transported over the flats instead of through the tidal channels leading to a silting up of the channels. In the end, tidal lagoons may evolve. A tidal lagoon is a shallow water area, separated from the open sea by, e.g., barrier islands and/or spits. The main difference to the present Wadden Sea tidal basins is that major parts of the tidal lagoons are permanently water covered.

2.4.3 Reclaimed coastal marshes

As stated in Ch. 2.3.3, the reclaimed coastal marshes are not influenced by the dynamics of the Wadden Sea anymore. Hence, no direct consequences will occur as a result of breakpoint exceeding. However, if present safety standards are to be maintained, changes in the natural dynamics in the other two subsystems will have serious implications for the efforts needed.

3. Integrated BEP Solutions

In this chapter, relevant coastal defence measures in the Wadden Sea are examined. The measures were selected on the basis of the screening, which was performed during the first phase (CPSL, 2001). A description in terms of coastal defence functionality and ecological aspects is followed by a general discussion on their feasibility (incl. breakpoint). Regional aspects from the three countries follow. Some measures like sand nourishment are addressed separately. Others, for example groynes, drainage furrows and grazing are grouped (i.e., into salt marsh management techniques) as they have a combined functionality.

3.1 Spatial planning

3.1.1 Introduction

Spatial planning is a formalized and systematic way to influence (regulate) the distribution of people and activities geographically. The guiding principle of spatial plans and programs is a sustainable spatial utilization and development which balances the social and economic requests upon a region with its ecological functions. Spatial planning is realized at local, regional, national and international levels. In Denmark, Germany and The Netherlands spatial planning is well-established in public administrations on all scales. However, the coastal zone with its specific characteristics is, normally, not seen as a spatial entity of its own.

Of significance for coastal defence is the possibility to reduce the risk in coastal lowlands through spatial planning. The risk is the product of the probability of flooding and its consequences (damages). Thus, by managing the spatial distribution of people and human activities in the coastal regions, the risk may be reduced.

In recognition of the guiding principle (see above), it may be expected that spatial planning has positive ecological effects as well. Almost all national and regional spatial plans and programs include the protection of the natural environment and its ecological functions as one of their main goals.

With respect to coastal defence, the identification of coastal buffer zones and/or coastal hazard zones in spatial plans as well as the establishment of specific spatial plans for the Wadden Sea is of specific interest. These possibilities are described below.

3.1.2 Coastal buffer zones

Coastal buffer zones, demarcated by setback lines in spatial plans may provide protected zones between the sea and the hinterland, where human utilization and development are strongly restricted. As the term "buffer" already implies, this measure provides a spatial buffer zone between the sea and the coastal hinterland, which may either allow for retreat of the coastal defence line or reserves space for necessary coastal defence measures.

Several qualities of buffer zones may be defined, e.g., zones where all human activities are prohibited and zones where certain time-limited activities/investments and "easy to remove" properties are allowed. The zones may be included in all spatial plans and programs, e.g. local building plans (scale ca. 1:5,000), regional plans (scale ca. 1:100,000) or (inter)national programs (scale < 1:1,000,000). Buffer zones are long-term planning measures which have to be considered by planning authorities, decades before they might actually fulfill their function.

3.1.3 Coastal flood hazard zones

Coastal flood hazard zones, demarcated by height contour lines in spatial plans, are areas potentially endangered by storm surges. If no coastal defence structures existed, these coastal lowlands would probably become inundated during extreme events. In the Wadden Sea region, the width (depth) of the flood hazard zones may vary from 0 to more than 50 kilometers inland.

In these zones, human activities can be managed in such a way, that their vulnerability is reduced. This could be realized by specific requirements or recommendations defined in the spatial plans. For example, certain roads could be constructed in elevated position (like dams) to allow for evacuation and to limit the inundated area. Further, information about the hazard should be included in the spatial plan in order to increase the awareness for the risk. As with coastal buffer zones, the zones and requirements may be included in spatial plans and programs at all levels.

3.1.4 Coastal spatial plans

As stated in the introduction, within present spatial planning, the coastal zone with its specific characteristics is, normally, not seen as a spatial entity of its own. No coastal spatial plans exist that substantiate and regulate the spatial distribution of people and activities in a sustainable way. However, the specific characteristics of the Wadden Sea region: (1) one of the last relatively unaffected natural ecosystems in Europe, (2) intensively used and inhabited flood-prone coastal lowlands, and (3) a strong attraction for tourists, call for integrated solutions that aim at a sustainable development in the Wadden Sea.

The plans should be established using the philosophy of Integrated Coastal Zone Management (ICZM), i.e. its three basic principles: (1) the integrative consideration of land and sea, (2) the balancing of ecological, economical and social demands in the coastal zone in accordance with sustainability, and (3) the involvement of all relevant levels of politics, economic actors, social groups, and administration through information, coordination and cooperation. The trilateral Wadden Sea Forum is a good example of such a cooperation structure.

In such plans, the significance of climate change and its consequences, increased sea level rise and changes in storminess, should be duly considered. Coastal buffer zones and flood hazard zones, as described above, should be included in such plans.

3.1.5 Discussion

In many countries, spatial planning systems are well-established and accompanying planning measures have been applied over several decades. Sustainable coordination of coastal defence strategies within spatial planning will, however, gain in importance during the coming decades, while considering the consequences of climate change. Preserving and enhancing the living conditions as well as protecting nature and the man-made environment in the coastal zone during the coming decades, will depend even more on sustainable coastal defence strategies and a careful handling of public means.

The procedure of long-sighted spatial planning, that considers climate change and its consequences, is complicated by the fact that the actual dimension of future sea level rise and changes in storminess are only based on scenarios. However, planning authorities should consider different scenarios when elaborating spatial plans.

Moreover, the question about who will pay for the consequences of climate change is often not considered appropriately. On the one hand spatial planning and newly adopted coastal defence strategies are indispensable for a sustainable development in the coastal zone; but on the other hand these plans and strategies might require large investments. The scale of investments will depend on the consequences and the intended spatial development within a specific area. Below the breakpoint, present sources may be sufficient to pay for the (increasing) costs. Above the breakpoint, financial adjustments (new sources) may be necessary to cope with a significant increase in costs. In general, the necessity to deal with coastal defence in spatial planning, e.g. by defining specific zones, will increase strongly above breakpoint as traditional measures will become less adequate.

3.1.6 Regional aspects

The Netherlands

The prevailing law on spatial planning is the Spatial Planning Act. The National Government, specifically the Minister of the Environment and Public housing, is responsible for the spatial planning on headlines. This national spatial strategy is laid down in a so-called spatial planning key decision. Based on the key decision, the provincial authorities develop their regional spatial plans. They are to be revised every ten years and evaluated every fourth year. The most detailed spatial plans, the local zoning schemes are developed by the local authorities, the municipalities, according to the indications in the regional plans.

The latest national spatial strategy dates back to 2004 (Nota Ruimte) and pays attention to spatial reservation in relation to climate change in order to meet future safety demands:

"The changing climate has major consequences for spatial development in the Netherlands. To keep our heads literally above water, we will have to 'go with the flow' and anticipate expected developments. To ensure public safety from flooding, the national government is allowing more space for the major rivers and the coastal defence systems." Public safety from flooding will be guaranteed by maintaining and improving the coastal foundations (which carry the dunes and dikes). The coastal foundations are bounded at the sea side by the -20m depth line and include, on the landward side, a spatial reservation for 200 years of sea level rise. This may include the whole dune area; in which case the boundaries coincide with those of the areas according to the EU Habitats and Bird Directive, the Nature Conservation Act and the National Ecological Network.

The national government laid down its policy for the Wadden Sea in a separate key document in 1993 ("PKB Waddenzee"). Its revision has been postponed to 2005. The basic principles of the national spatial strategy will also underlie the revised key document on the Wadden Sea.

Climate change and sea level rise are also items in the draft new regional plan of the province of Friesland, which also includes the Frisian Wadden Islands. Outside the coastal towns, it suggests a buffer zone of 125 m on the inside (landward) and 200 m on the outside (seaward), along the Frisian sea defences. In principle, no new infrastructure will be allowed here, unless in case of evident social importance. Within the boundaries of the coastal towns it suggests a buffer zone of 50 m on the inside of the sea defences.

Germany

In Schleswig-Holstein, the overall responsibility for spatial planning lies with the Minister of the Interior. In Lower Saxony, the supreme spatial planning authority is the Minister for Rural Areas, Food, Agriculture and Consumer Protection. The municipalities establish local building plans, which implement the development goals and aims defined in the regional and state spatial plans. The plans and programs have a time-horizon of about 10 to 15 years. In the spatial plans, the aspect of climate change and its possible consequences for the vulnerability of the coastal lowlands are neither elaborated nor managed. A reference towards the sector plan: "integrated coastal defence management in Schleswig-Holstein" is made in the state and regional plans. In the regional plans the flood-prone coastal lowlands are shown in figures. It is stated that, in these lowlands, the interests of coastal defence must be duly considered.

In Lower Saxony, the extension of the state spatial master plan to the 12 sea mile zone is planned. One mayor focus will be on the legal implementation of offshore wind parks and its transmission lines to the mainland coast.

In the Schleswig-Holstein State Water Act, a 100 m buffer zone landward from, respectively, the coastline, the landward toe of sea dikes or the upper cliff face is defined where building is prohibited for coastal defence reasons. The same rule applies for salt marshes.

In the Lower Saxony Dike Law a 50 m buffer zone landward from the landward border of the dike is defined where constructions are not allowed. These buffer zones are included in the municipal building plans. The dike itself and the protective dunes are not permitted to be used except for costal defence purposes. The usage of salt marshes can be regulated with regard to the needs for coastal defence. Exceptions are subject to strong restrictions and need a special permission.

The flood prone areas on the mainland, protected by coastal defences, are defined by ordinance.

Denmark

In Denmark, the Minister of Environment is responsible for the overall planning system. The key legislative basis is the Planning Act of 1992, which defines the responsibilities for spatial planning on

The Danish Storm Council

In Denmark, a non-technical solution for compensating damages exists. This Danish flood insurance scheme was arranged in form of an emergency fund for compensation payments due to flooding. The fund was established in 1990 as a result of several severe inundation events in Denmark. Since September 1, 2000 the fund has also been covering compensation payments for damage in forests.

The Storm Council (SC) is in charge of administrating the emergency fund. It is a governmental council, represented by a board being composed of four members from four Danish ministries (Economy, Transport, Justice, and Environment), a member from the public insurance and pension organization 'Forsikring & Pension', a member from the Danish Regions and the Local Government Denmark, respectively, as well as one member from the Denmark's Consumer Association. All members are appointed by the Ministry of Economics, every four years.

The daily administration of the SC is governed by a secretary being located at the public insurance and pension organization 'Forsikring & Pension'.

Compensation is paid to private persons, companies or farms who have suffered flood damage or forest damage due to severe stormy events. Means for compensation payments are collected by an annual tax payment charged with all private fire insurance policies. An annual amount of 20 DKK (2.7 EURO) is payable with each signed fire policy covering houses/buildings or movable property. This way, the total annual revenue of about 80 million DKK (10.7 million EURO) is deposited at the Danish National Bank.

In case of a severe storm the SC board is advised by experts from the Danish Coastal Authority (DCA), Danish Meteorological Institute and the Danish Forest and Nature Agency. The DCA assesses wind and water level conditions during the storm surge, whereas the Forest and Nature Agency assesses the severity of the storm in case of forest damage. The report by the experts is presented to the board, which afterwards decides whether or not a compensation is paid. Within the board's assessment four criteria must be met in the affected area for justifying compensation payments:

1. Wind of gale force in the area;
2. Water levels that occur, statistically, less than once in 20 years;
3. Flooding must have occurred in a wider geographical area;
4. Extreme wave conditions may play a role.

The decision of the board can not be appealed against.

national, regional and local levels. The planning system covers solely the use of land. Planning measures for the maritime area, as well as coastal protection are not included.

The regional authorities are responsible for regional planning (strategic plans) and for administrating and monitoring the overall environmental conditions of the countryside, including sector land use programs. Regional plans define the overall objectives for development for a 12-year period. These plans must contain guidelines for land use including urban development, nature and environmental protection, as well as the location of large public institutions and transport facilities.

The municipal authorities are responsible for local urban planning (framework plans) as well as for water supply and waste facilities. A municipal plan provides policies, maps and land use regulations for the municipal area. This plan is also developed on the basis of a 12 year perspective. Every fourth year the county council and the municipal council have to prepare and adopt a revised regional/municipal plan

Since the 1930s, a 100-meter buffer zone, in which new development is prohibited, has prevented the Danish coastal areas from intense implementation of construction works close to the beach. Moreover, the buffer zone has allowed a dynamic coastal defence in areas where coastal protection is indispensable. The 100-meter buffer zone was extended to 300 meter in 1999, except for approved summer cottage areas. The objective of the extension has been a more improved protection of the natural environment along the Danish coastline. Coastal defence aspects and possible consequences of climate change have not been a cause for extending the buffer zone.

3.2 Sand nourishment

3.2.1 Introduction

With this technique, sand is placed on the beach or the foreshore in order to compensate sand losses due to erosion (CPSL, 2001). It has been appraised as a quite useful measure to counter the effects of sea-level rise and other sand losses (fig. 2). Also, the natural material sand does not interfere as strongly with natural processes as does for instance a hard construction: natural dynamics are respected to a large extent.

3.2.2 Functionality for coastal defence

The general purpose of nourishments is to counter the effects of coastal erosion by means of a nourishment i.e. an artificial addition of sediment.

Basically, there are two main objectives of sand nourishments that can be distinguished by their outcomes and time scale, taking into account the following aspects:

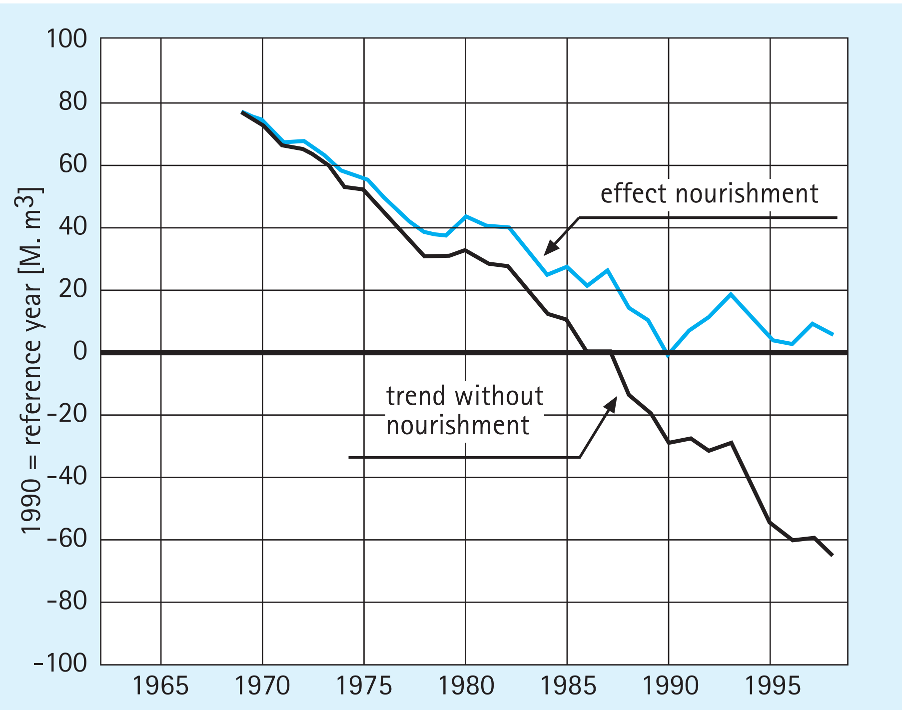


Figure 4: Net sand losses on the Dutch coast with and without nourishments (Ministerie van Verkeer en Waterstaat, 2000).

The first objective is a restoration of sand losses in the beach zone on selected stretches of the coast. The reasons for erosion can be manifold such as large or small scale morphological processes or the permanent influence of artificial structures. Therefore nourishments can be rated as a measure which is orientated on morphological processes.

This kind of nourishment aims at guaranteeing a certain amount of sand in the beach zone in order to prevent dunes from erosion or protect coastal defence elements like revetments or groynes from scouring or heavy wave attack. Therefore it contributes directly to maintaining a defined safety level for coastal defence. In many cases, the application of nourishments makes hard constructions, which can cause negative side effects like lee-erosion, superfluous.

Sand losses in the beach zone can either be restored by bringing sand onto the beach or by bringing sand in deeper water. The efficiency strongly depends on the sediment transport processes in the foreshore and shore area. Generally, it can be stated that the closer to the shore the nourishment is executed the better is the effect (Hillen, 1991). The nourishments should be designed in a way that they are sufficient to last for a certain period of time. The sand can either be extracted from outside the sand sharing system or moved within itself, depending on the hydro-morphological circumstances.

Due to the effects of sea level rise, it is likely that morphological changes within the system and the beaches affected by erosion will increase. Therefore it is expected that the number of nourishments and the amount of sand needed, will rise if only these kinds of nourishments will be executed.

The second objective deals with keeping the volume of water above the sediment surface in the coastal zone constant in case of sea level rise or subsidence due to e.g. gas extraction. The coastal zone is thus defined as a zone lying between a certain depth-contour and a sea wall or dune. Sand nourishments aim at maintaining a dynamic morphological equilibrium in this area to form a sand sharing system (CPSL I, 2001). Therefore enough sand, gained from outside the system, has to be placed within itself by nourishments.

This strategy aims at enhancing the capability of the coastal zone to adapt to sea level rise. Therefore it does not directly contribute to the safety of coastal defence but works more on a large scale and is also long term orientated. It can be assumed that generally, the total area of erosion in the coastal zone will not extend. Due to natural dynamics of the system, additional nourishments to counter erosion on certain stretches of the beach will be further necessary but more limited than with the above mentioned method.

Figure 5: Sand nourishment (Photo: J. Hofstede).

3.2.3 Ecological effects

Sand nourishments have effects on two locations, the location where the sand is extracted and where the sand is deposited.

Depressions produced by extraction, act as traps for fine-grained sediments. During the sand extraction, the turbidity of the water column may locally increase and the bottom will be covered by fine-grained sediments. This change in sediment composition and structure results in a decrease of the oxygen content and the primary production of organic matter and may disrupt the benthic fauna. Turbidity of the water column may potentially lead to a change in the algal species composition, which may be problematic. Restoration of the benthic fauna depends on the duration of the change in sediment composition, the depth of the extraction pit and the water quality within the extraction zone.

Restoration of the bottom (bottom level relative to surroundings and composition) is immanent to the recovering of the benthic fauna. Extraction pits that are deeper than 15 meters will hardly fill up and due to the slow water movements in the pit, recovery chances are remote. Shallow sand extraction over a larger area provides a better chance for recovery. Recolonisation of the area depends on the settling of larvae and the migration of mobile species. The recovery of the macro-fauna, may take between 1,5 and 2 years or even 2-5 years for long living species (Roelse *et al.*, 1991; Essink, 1997; van Dalfsen *et al.*, 2000.

If sand extraction occurred on a very large scale it would probably influence sedimentation processes as well as current velocities, which affects morphology up to distances of several kilometers outside the extraction pit. The effects as well as the implications (see also below) are currently studied by RIKZ.

Sand is deposited on a location where the local flora and fauna will be covered by a sand-layer. Some species cannot survive 1 cm of sediment cover whereas others are able to cope with up to 50 cm of sediment cover (Bijkerk, 1988). This may locally influence the food-availability and, hence, species composition for fish and birds (Wilber *et al.,* 2003). The effects on the beach zone have been studied to some extent and point to recovery times from zero years up to several years (Dankers *et al.,* 1983; Nelson, 1989; Roelse *et al.,*1991). The recovery period of macro-fauna depends on the location, the season in which nourishment takes place (preferably winter), the composition of the sediment and the presence of adjacent beaches. The ecological impact of sand nourishments can be minimized by using sand which is comparable in composition (esp. grain size distribution and organic content) with the original sand (Nelson, 1989; Peterson *et al.,* 2000). The ecological effects of offshore nourishments are still debated. Some think that it is quite comparable to the effects of sand extraction, causing destruction of the benthic fauna followed by recovery, whereas others think that many of the species have large tolerances and are able to cope with the changes, with the exception of being covered by a thick layer of sand. Studies point to full recovery in a period of 1-5 years (Culter en Mahadevan, 1982; Essink, 1997).

Large areas of the Wadden Sea and the coastal zone, north of the Wadden Sea Islands, are designated as Special Protection Areas or Special Areas of Conservation (SPAs or SACs) within the EU Bird Directive and Habitat Directive. The implication is that no activities, which are harmful to bird species or habitats, are allowed. Sand nourishments might affect several bird species such as waders and coastal breeders and coastal habitats like shallow sand banks.

Since March 2002, SPAs and SACs can be designated outside the 12 mile zone. The implication could be that sand extractions should take place outside the future SPAs and SACs. Whether this will limit the sand extraction from the North Sea is unclear.

The OSPAR-convention provides for the designation of Marine Protected Areas (MPA's). By 2010, parts of the North Sea will be designated as MPA's in order to safeguard threatened and declining species, habitats and ecosystem functions. The implication is that large scale sand extraction should not be carried out in areas that qualify as future MPA's.

3.2.4 Discussion

Sand nourishments can be rated as an important measure to guarantee a safety standard for coastal defences especially for sandy coasts. This measure is often a better technical as well as more natural solution than building additional hard constructions since it adapts to morphodynamic processes in the coastal zone, has no negative side effects and interferes less with nature. Despite its effectiveness, larger parts of the public may regard nourishments as a waste of money simply because this measure is not as obviously concrete as hard constructions.

Sand nourishments aiming at bringing additional sand within the Wadden Sea system, contribute to the ability of the coastal zone to keep up with sea-level rise. Thus this measure contributes to protect the present-day ecological character of the area. However, such nourishments may temporarily and locally influence the ecology on and near the locations of both sand extraction and nourishment.

Resuming nourishments can be regarded as BEP measures since, in comparison to other alternatives to keep the present safety standard, in many cases it shows advantages from a technical as well as from a nature conservation point of view.

3.2.5 Regional aspects

The Netherlands

In the Netherlands, the policy is to keep the coastline in its 1991 position and to maintain the amount of water above the sea bottom constant. Sand nourishments are to fulfill these prerequisites. In the Netherlands, beach and foreshore nourishments are common but other new techniques are being studied as well. Examples are channel wall nourishments to protect coastal stretches from erosion caused by (migrating) channels (Oostgat, Western Scheldt; Molengat ebb delta, Texel).

The first nourishments were carried out in 1979 on Texel and Ameland. The total amount of sand nourished over the period 1970 until 2002 amounted 47.6 million m^3 of sand (Roelse, 2002; Kustlijnkaarten 2004). Compared to the present sea level rise (18 cm/century), it is expected that the sand nourishment quantities for the Dutch Wadden Sea will at least have to double (Mulder, 2000).

Lower Saxony

In Lower Saxony, sand nourishments are mainly applied on stretches of the sandy barrier island where the coastal defence strategy is to preserve the present coast line. Nowadays, nourishments are mainly applied on two Eastfriesian islands.

The western part of Norderney is protected by groynes and revetments against waves and currents. Long term erosion occurs due to insufficient sediment supply by the ebb delta of the Norderneyer tidal inlet which reaches the island further east. To guarantee the stability of groynes and revetments a certain height level in the groyne fields is provided by nourishments of the shore and foreshore. The sand is dredged from selected ebb delta shoals westward the islands. The first nourishment was carried out in 1959/51. On the whole, ten nourishments with a total amount of 4.7 million m^3 were executed.

The western part of Langeoog is influenced by a discontinuous sediment supply of the ebb delta of the Wichter Ee tidal inlet. To prevent dune erosion due to storm surges in phases of insufficient sediment supply since 1971, six nourishments with a total amount of 2.9 million m^3 were carried out. Most of the material was dredged in bars located southwest the island, where a positive sediment balance exists.

Schleswig-Holstein

The policy concerning coastal erosion is Schleswig-Holstein is to counteract long-term and structural (irreversible) erosion along inhabited coastal stretches (i.e., where settlements are directly affected). Further, it is stated in the legislation (State Water Act) that the protection of the island basements (as a structure) against erosion is a public obligation. Comprehensive investigations into alternative techniques to stabilize eroding sandy coasts (e.g., beach drainage, artificial reefs, groynes) resulted in the acknowledgement of sand nourishment as the most cost-effective, environmentally friendly and, therewith, sustainable solution (MLR, 2001).

In Schleswig-Holstein, structural erosion occurs along the west coast of the island of Sylt. Without human interference, the coastline would retreat by about 1 m per year. The first nourishment to balance this erosion was conducted in 1972. In all, about 33 million m^3 of sand have been deposited on the beaches of Sylt. Over the last decade, the mean value amounted to 1 million m^3 of sand per year. Further, structural erosion occurs, on a much smaller scale, along the south coast of the island of Föhr. Here, 3.3 million m^3 of sand have been nourished since 1963.

Denmark

No sand nourishment measures have been necessary so far at the North Sea coasts of the barrier islands, primarily because the coastal area is a net sedimentation area. High beach levels are maintained naturally.

At the northern part of the Skallingen peninsula, groynes combined with regular sand nourishments protect against beach erosion. Sand nourishment is carried out every 5 years, the last time in 2000, comprising about 120.500 m^3 of sand. For the southern part of Skallingen, considerations regarding the necessity of coastal protection measures are still ongoing.

3.3 Dune management

3.3.1 Introduction

Dune management comprises a number of techniques that have been developed to maintain and/or enhance dunes and dune areas. The whole spectrum of dune management techniques ranging from dune creation and protection (e.g. planting of marram grass and sand trapping fences) to allowing natural dune dynamics and over-washes are discussed here.

Natural processes like erosion, sedimentation and sand drift are shaping the outer coastline.

Beaches and dunes are important geomorphologic elements. Dunes are formed by aeolic sand transport from dry beach areas. At higher wind velocities, sand is transported in the wind direction. Sand settles and accumulates in areas where the wind speed decreases. This process is encouraged by the settlement of primary dune plants. In further stages of development, dune grasses support these processes and white dunes (bare sand with little vegetation) are formed. Due to succession on the backside brown and grey dunes (referring to the colors of the vegetation cover) can develop.

Dunes are characteristic elements on the North Sea side of the West- and East-Friesian and the Danish Wadden Sea islands as well as on Sylt and Amrum. On some islands, the dunes may extend from the North Sea side to the Wadden Sea side across the island. Younger dune formations and inner dunes mostly consist of single dunes bordered on each other. On the Dutch islands, dune formations are in general very broad, whereas on the Lower Saxon islands, the closed dune lines cover only a width of a few hundred meters.

Dunes reach heights of more than 20 m above sea level. Along major parts of the island coasts, the dunes are formed to one or more closed lines due to long term accretion. However, their location and extent differs very much from island to island. The process of forming dune lines has been promoted for a long time by human activities, such as planting dune grasses and building sand trap fences. Especially in areas of younger and thus lower dune formations with insufficient sand supply, dune breaches and over-washes may occur caused by storm surges and currents, which transport larger amounts of sand through the gaps into the inner part of the island. These gaps are artificially closed in areas where dunes are part of the coastal defence system.

Figure 6: Dune breach (Photo: J. Hofstede).

3.3.2 Functionality for coastal defence

Designated dune areas on the Wadden Sea islands are important elements for coastal defence. Closed dune lines protect coastal lowlands against flooding from the seaward side. Dune management on behalf of coastal defence aims at protecting and maintaining defined parts of the dunes as a coastal flood defence element. Between the different countries along the Wadden Sea, the locations of the dune line, which is part of the coastal defence, differs. In Lower Saxony, the dune row close to the coastline functions as an element of coastal defence, whereas in The Netherlands the inner dune row is designated as the line of defence. This difference is also apparent in the way dune management is executed.

Next to protecting coastal lowlands against flooding, dunes have the function to safeguard the existence of parts of the islands. Depending on the width, number and location of dune lines, the dune formations may protect especially narrow parts or tips of the island from disappearance due to constant coastal erosion.

3.3.3 Dune management techniques

The four main management techniques that are applied today are dune restoration, dune relocation, allowing natural dune dynamics and overwashes. They are described below.

Dune restoration (creation in CPSL I)

Dune restoration encompasses the catching of wind driven sand to create or stimulate the growth of dunes. Building sand trap fences or planting marram grass are examples of dune restoration management. Sand trap fences made of brushwood are constructed at the dune foot in order to heighten and strengthen it and equalize temporary sand losses as a result of storm surges. The accumulated sand is stabilized by the systematic planting with marram grass. The fixing of blowouts is also seen as part of dune restoration. A lot of technical experience with these techniques was gained in the past.

This measure can contribute to the growth and stabilization of dune areas. It can be applied on a relatively large scale, but is only expected to have local influence in strong eroding areas as the supply of sand will be insufficient.

Dune relocation

Dune relocation encompasses the establishment of a new dune line in the rear of the seaward dune row or even further in the inner part of the island, by strengthening the existing inner dunes. This measure can be an option in the case of eroding coasts. In practice, this will mean a gradual retreat of the dune. Compared to maintaining the present coastline, it forms a cheap and technically practical way of sea defence but is only applicable if it does not impact safety and economic assets in the dune area or the area behind it (no buildings or infrastructure) (CPSL, 2001).

Allowing natural dune dynamics

Natural dune dynamics encompass the wind driven transport of sand from the North Sea shore to the inner part of the barrier island where accumulation causes a gradual shift and heightening of part of the barrier island with rising sea level. In the long term, natural dune dynamics provide a positive contribution to coastal defence.

Natural dune dynamics are only applicable when sand is available and in dune areas without a coastal defence function or where the coastal line of defence is located in the more landward dunes or in uninhabited areas

Figure 7:
Dune management
(Photo: J. Hofstede).

where safety is not at stake. Public resistance is expected because there is the impression that the sea defence is not maintained.

Over-wash

When allowing over-washes, water and sand is, during storm surges, transported 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 shift of part of the barrier island with the rising sea level (CPSL I, 2001). Over-wash is a way to use natural dynamic processes to help barrier islands keep above normal high water levels. In practice, over-washes are not created, but they are allowed to occur. Locally, it 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, in the long term, be beneficial because it stimulates island growth on the Wadden Sea side.

Apart from the four main management techniques, indirect preventive measures play an important role in dune protection. Most of these indirect measures aim at minimizing vegetation cover disturbances that could lead to blow-outs which can grow very fast. The most important indirect measures are:

- surfacing of foot-, cycle- and bridle-paths,
- offering certain dune tops as paved observation platforms,
- enclosure of endangered dune areas,
- installation of information panels,
- directive and prohibitive signs,
- informative and custodial work by dune wardens.

Applicability of management techniques

In the description of the management techniques, the applicability of the techniques has been briefly mentioned. The choice of technique depends on (1) whether or not the dune area has a coastal defence function and (2) the sediment budget.

The applied dune management depends sig-

Figure 8:
Brushwood fences
(Photo: F. Thorenz).

nificantly on the hydro-morphological boundary conditions. The sediment budget and thus the development of dunes, beach and foreshore are highly interdependent. Narrow and low-lying beaches suffer from insufficient sediment supply at the foreshore. Severe dune erosion due to storm surges can occur since wave energy dissipation directly affects the outer dune slope. Wide beaches show a typically positive sediment balance. Wave energy dissipates mostly on the beach and the dunes are not or only marginally affected.

In general, three types of sediment budgets and thus developments of dunes can be distinguished:

1. Dune areas with a long term positive sand balance.
   Generally, dunes in these areas are growing or stable. No additional sand retaining measures are taken, as new dunes or a high beach level are established and maintained naturally. When blow outs occur in protective dune lines, dune restoration (e.g. sand trapping fences or planting marram grass) is a possible management technique. Where no safety standards are affected, natural dune dynamics and over-washes can be allowed.
2. Dune areas with a long- term neutral sand balance.
   In these areas, dunes are stable, in the long term, but short term erosion and accumulation phases can occur. Dune restoration techniques are used to heighten and strengthen dunes, especially the dune foot, in order to equalize temporary sand losses for example as a result of storm surges. Should a long-term phase of sand loss occur, beach or foreshore nourishments are suitable measures for protecting the peripheral dunes against storm flood damage and/or for strengthening the dune body by placing additional sand.
3. Dune areas with a long term negative sand balance.
   In these dune areas, long term erosion occurs and measures are necessary to make sure that dunes with a coastal protection function are maintained. In some locations along the Wadden Sea, massive seawalls and groynes have been built since the middle of the 19th century to stop beach and dune erosion. At present, most of these areas are still suffering from erosion. Solid constructions are necessary to safeguard these parts of the islands and have to be maintained and reinforced regularly. Additional beach and foreshore nourishments are carried out in order to prevent undermining of the solid constructions. Where beaches are not protected by hard constructions, the present coastline is often safeguarded by nourishment of the beaches or the foreshore, which prevents or significantly reduces dune erosion. If necessary, these works are combined with strengthening or reconstruction of the dunes. If there is enough space to retreat without reducing the safety standards, the relocation of the dunes will be an alternative.
   Dune creation techniques like sand trapping fences can be an additional measure to re-establish the outer dune foot. Dune relocation can be an option as long as coastal defence objectives and regulations are fulfilled.

3.3.4 Ecological effects

Because of the natural character of the dunes and the valuable habitats, considerable parts of the dunes on the Wadden Sea islands are designated as Special Areas of Conservation (SAC) within the EU Habitat Directive. The implication is that activities that have significant impacts to habitats need to be assessed before they are allowed.

Management techniques that allow natural processes can be seen positive from an ecological point of view, as they add to the naturalness of the environment and can enhance biodiversity. But the natural processes can also cause certain habitats to be replaced by others. For example, in the case of over-washes, (see for a detailed description below) fresh water species are lost in favor of salt or brackish water species.

The other techniques described like e.g. dune restoration, more or less interfere with natural dynamics.

3.3.5 Discussion

As explained above, several management techniques exist and are suitable to be applied in different situations depending on sediment budgets and whether or not the dune is part of the line of coastal defence. With an increasing sea level rise, it is likely that the sediment budgets will develop more negatively. Dune restoration and dune relocation are the dune management measures applicable in case of long term negative sediment budgets and those will become more important as the sea level rises. Beach or foreshore nourishments are important to make sure that there will be enough sand available to stabilize the dunes. Dune restoration and relocation can, on a local scale, be supported by natural dune dynamics as the wind can help the sediment to be transported from the beach to the dunes.

As the sea level rise goes beyond the breakpoint, dune relocation together with sand nourishment will be a way to maintain the safety levels. Perhaps direct nourishments of sand in the dunes in areas where the dunes are too low will be executed to heighten dunes because dune creations techniques are insufficient.

3.3.6 Regional aspects

The Netherlands

In general, the dune area on the Dutch Wadden Sea islands is very broad. In the Netherlands, not all dunes are part of the coastal defence system, only the inner row of dunes is part of the sea defence and should be high and strong enough to protect the island. The dunes on the seaward side help to strengthen this line of defence, but primarily have a natural function. As the dune area is broad, the inner dunes that are part of the coastal protection need no additional measures for coastal defence except from some limited dune creation and allowing natural dune dynamics in the dunes on the seaward side. By allowing natural dynamics, the coastal defence dunes are fed by wind driven sand transport from the dunes on the seaward side. Allowing natural dune dynamics is also possible as the coastline is held in its 1991 position by nourishments, making sure that there is enough sand on the beach to be transported into the dunes. Depending on the location (near villages or not), the width of the dune row and its coastal protection functions, there are 4 classes of dynamics: low, medium high, unlimited dynamics.

In areas where the dunes have no coastal protection function, over-washes are present. Over-washes are present on the eastern tips of Ameland, Schiemonnikoog and on Rottum. In these areas, no maintenance is carried out to keep the coastline or the dunes in a certain position. The over-washes were formed by nature without any help of man. No work is carried out to keep the wash-over channels open. Wash-over channels can disappear when sedimentation (usually by wind driven sediment from the beach) is high.

Lower Saxony

Dune areas in Lower Saxony are only existing on the Eastfriesian Islands. A total length of about 90 km indicates the coastal defence function and the legal status as protective dunes. Most of the dune row is relatively narrow and located close to the coastline. Dune management primarily aims at maintaining safety standards.

At the western part of the island of Juist the protective dune row has been relocated due to strong erosion of the beach and dunes. A new dune row was build in several steps by closing gaps between existing dunes.

Figure 9: Dune erosion on Langeoog (Photo: F. Thorenz).

The inner dunes on the islands of Lower Saxony are not managed as long as blowing sand is not endangering settlements or infrastructure.

On the eastern parts of the islands, no management actions are carried out in significant parts of the dunes and natural dune development including over-washes is allowed. Over-washes are present on the eastern parts of Borkum, Juist, Norderney, Baltrum, Langeoog und Spiekeroog

Schleswig-Holstein

Along the west coast of Schleswig-Holstein, coastal dunes occur on the islands of Sylt and Amrum as well as on the peninsula of Eiderstedt. Although they have, for coastal defence purposes, no official status, they partly function as flood defences for coastal lowlands situated behind them. On Amrum and at Eiderstedt the dunes are, apart from occasional small scale storm surge erosion, not threatened, i.e., no structural erosion occurs. On Sylt, in the course of the regular beach nourishments, sand depots are established in front of the dunes that prevent structural erosion. Occasional storm surge erosion and blow outs are, if necessary, tackled by biotechnical means (planting marram grass, building sand fences).

Denmark

In the Danish Wadden Sea area, dunes protect the inhabited islands Fanø and Rømø against flooding at their North Sea coasts. On the island Mandø, dunes protect only a very small part of the North Sea coast. At the Skallingen peninsula, dunes present the most important form of flood protection, too.

Dune management techniques are not applied at the North Sea coasts of the barrier islands due to a positive sand balance. In most areas, the outer dune rows are growing naturally. No additional sand retaining measures are taken, as a high beach level maintains naturally due to net sedimentation. Especially on Fanø and Rømø, broad dune rows allow natural dune dynamics.

3.4 Salt marsh management techniques

3.4.1 Introduction

Salt marsh management for coastal defence purposes comprises of a number of techniques that have been developed to enhance and maintain salt marshes. For natural salt marsh development and persistence on tidal flats, boundary conditions are an adequate supply of fine sediments, a low-energy environment (waves and currents), regular saltwater conditions, and a moderate sea level rise. At present, about 396 km^2 of salt marshes exist in the Wadden Sea (Essink *et al.*,2005, QSR update 2005). The majority of these are man-made, i.e. developed through management techniques. As a consequence of thousand years of dike building and land reclamation, most of the present mainland coastlines in the Wadden Sea, however, lie in more exposed positions. Hence, it is unlikely that the existing salt marshes would have developed here without the help of management techniques. Investigations on artificial salt marshes in the Dutch sector of the Wadden Sea suggest that the abandonment of the salt marsh works would, even in the present situation, result in a strong erosion or even disintegration of existing salt marshes (Dijkema 1997, Esselink 2000, Jansen-Stelder 2000).

For coastal defence, salt marshes in front of dikes are in the first place a method to transfer the energy-impact of storm waves from the outer dike-slope towards the edge of the salt marsh. Furthermore, salt marshes reduce the wave run up at the dikes. After dike-breaching, salt marshes prevent the continuous flooding (during subsequent normal tides) of the protected areas and provide material for reparation of the dikes. Salt marshes deliver, in restricted areas, the necessary halophytic vegetation sods for the outer dike slopes. Finally, they prevent damage at the outer dike foot by approaching tidal gullies and render the building of expensive slope revetments superfluous.

At the same time, natural or close to natural salt marshes are of a high ecological value. They constitute the habitat for a wide range of halophytic plant species and partly highly specialized invertebrate fauna esp. arthropod species. They provide resting, breeding and feeding grounds for a number of birds. Salt marshes are protected within the EU Habitats and Birds Directives, which provide a European network of special areas of conservation, Natura 2000. Trilateral targets for the salt marshes are (De Jong *et al.*,1999): (1) an increased area of natural salt marshes, (2) an increased natural morphology and dynamics, including natural drainage patterns, of artificial salt marshes, under the condition that the present surface is not reduced, and (3) an improved natural vegetation structure, including the pioneer zone, of artificial salt marshes.

The three main management techniques that are applied today are: (1) the construction of salt

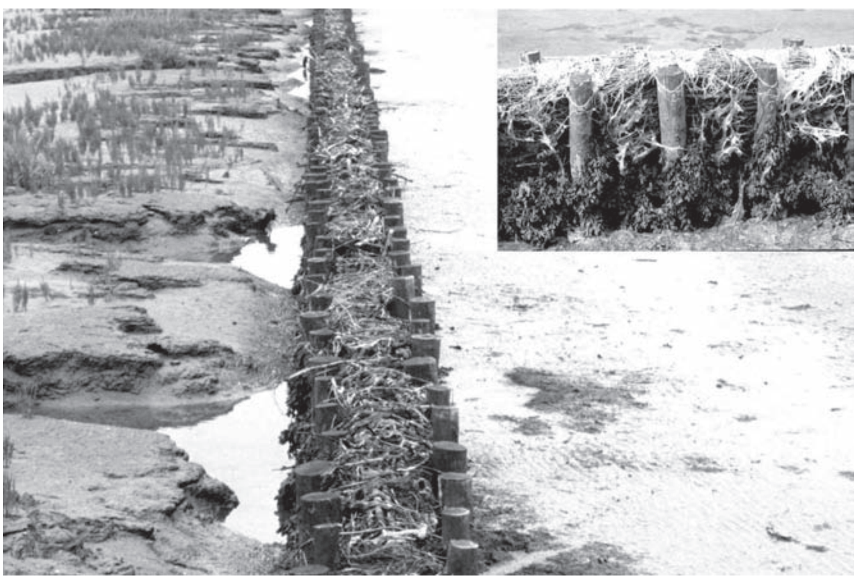


Figure 10: Groyne field and construction (Photo: J. Hofstede).

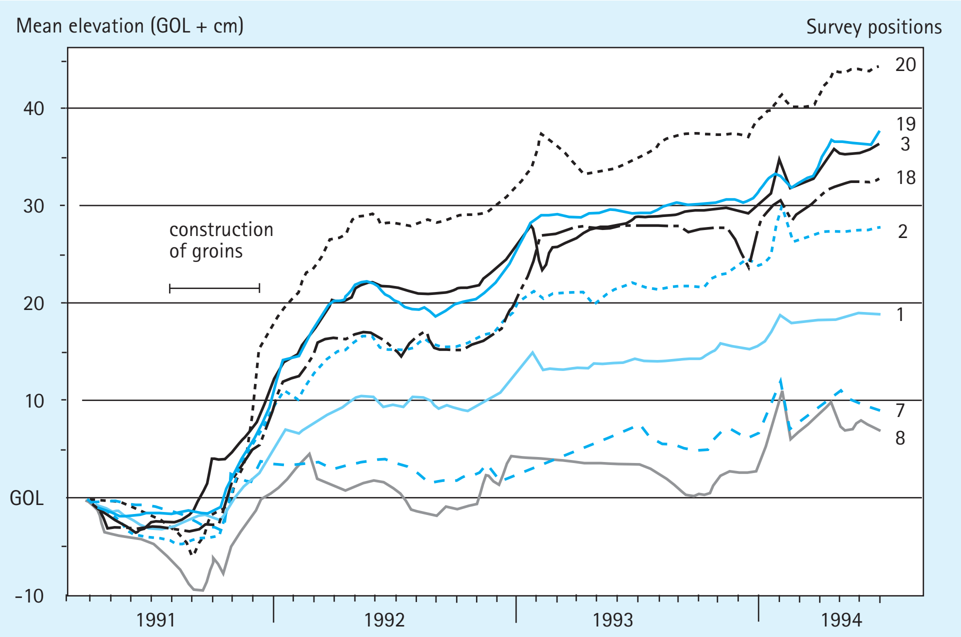


Figure 11: Sedimentation in groyne fields (from: Erchinger *et al.*, 1996).

marsh groynes, (2) the establishment of drainage furrows, and (3) the conduction of grazing. These three techniques are described and evaluated below.

3.4.2 Salt marsh groynes

Description

Salt marsh groynes are permeable fences made of brushwood wedged between parallel rows of wooden poles reaching about 0.3 m above mean high water (Fig. 3). In exposed tidal environments they may consist of stones as well. Normally, the groynes are arranged in fields with a size of about 200 x 200 m combined with a drainage system (see below). The technique of groyne fields is applied extensively in the Dutch and German Wadden Sea, both along the mainland coast and on the back-barrier sides of the islands. In the Danish sector of the Wadden Sea, salt marsh groynes are constructed on a more limited scale.

Salt marsh groynes function in that they reduce wave energy (turbulence) and significantly diminish tidal and storm surge current velocities. As a result, an artificial low-energy environment is created in the groyne fields where the sedimentation of suspended material is enhanced, and erosion of accumulated sediment is hindered. Further, the formation of cliffs along the seaward edge of the salt marshes is prevented, and existing cliffs are stabilized. The positive effect of a groyne field upon sedimentation is demonstrated in Fig. 4 (Erchinger *et al.*, 1996).

Salt marsh groynes or, rather, groyne fields are artificial structures that present an interference with natural dynamics. They create an artificial low-energy environment, which may favor the creation of new salt marshes, but on the other hand reduces the ecologically highly valued area of tidal flats.

Evaluation

Salt marsh groynes indirectly have a positive effect on maintaining safety standards in that they stabilize salt marshes in a highly effective manner. As they influence waves and currents, groynes constitute an interference with natural dynamics. This infringes the trilateral guiding principle of a natural ecosystem in which natural processes should proceed in an undisturbed way (De Jong *et al.*,1999). On the other hand, it is a target of the trilateral co-operation (Esbjerg, 2001) that the present surface of salt marshes is not reduced. As stated above, the abandonment of groynes would induce wide-spread erosion along existing salt marshes in the Wadden Sea. This would affect the sea dike construction. Other measures would be required, e.g., massive dike foot protection or asphalting the outer dike-slopes. Apart from the loss of valuable salt marsh biotopes, these alternatives might have significantly more negative effects for ecology.

3.4.3 Drainage furrows

Description

Drainage furrows are artificial ditches in salt marshes. Normally, they are structured in a hierarchical drainage system with a straight and evenly distributed channel pattern (Fig. 5). The

Figure 12: Drainage system (Photo: J. Hofstede).

spacing and the cross sections of the drains vary significantly depending upon local circumstances. In areas with the most dense drainage patterns, the furrows may be spaced about 10 to 15 m. The width of drainage furrows varies between 2.0 and 0.4 m, the depth between 0.4 and 0.15 m. Drainage systems are applied extensively in the Dutch and German Wadden Sea, both along the mainland coast and on artificially influenced salt marshes of the back-barrier sides of the islands. In the Danish sector of the Wadden Sea, drainage furrows are applied on a more limited scale.

Drainage furrows in the salt marsh pioneer zone function in that they improve the consolidation and aeration of the upper layer of the mud flats. Therewith, the ability for pioneer vegetation (Salicornia-Spartina communities) to germinate and grow is enhanced (Houwink 1999). As the aerated zone is shifted to a lower level in relation to the mean high water level, a seaward shift of the salt marsh edge of up to 200 m may occur (Dijkema *et al.*,1990). Thus, an indirect positive effect on sedimentation by increased vegetation growth is achieved. A direct positive effect of ditches on sedimentation rates, as sometimes stated, seems implausible. In order to function, they need to be cleaned as necessary.

In those parts of the salt marshes, where a closed vegetation cover already exists, a furrow system is maintained to guarantee an appropriate drainage of the outer dike foot and to provide the possibility of grazing by cattle (see below). Drainage has no direct functionality for the protection of the salt marshes.

Drainage furrows are artificial morphological structures that present an interference with natural dynamics. They boost the dewatering of the pioneer zone which results in a seaward shift of the area suitable for salt marsh development. They affect natural morphology, and, in existing salt marshes, they reduce the periods of salt water inundation (especially after storm surges) which influences the natural vegetation structure and the fauna.

Evaluation

A drainage system in the pioneer zone positively influences the circumstances for salt marsh development. Without artificial drainage it would, at least, take longer to establish a pioneer vegetation cover. In an existing salt marsh with a permanent and closed vegetation cover, a drainage system is needed to prevent water logging of the dike-foot (which is normally situated lower than the seaward edge of the salt marsh). Without drainage, the stability of the dike and, therewith, safety would be impaired and countermeasures, e.g., concrete revetments, become necessary. Further, grazing with cattle (see below) may be negatively affected by diseases (e.g., hoof decay) if the water remains too long on the salt marsh surface after tidal and/or storm surge inundation.

As a result, the maintenance of an artificial drainage system to dewater the dike foot is considered a BEP, especially compared to the otherwise necessary techniques. If natural drainage is not sufficient, grazed salt marshes should be artificially dewatered as well (making use of natural structures as much as possible). In the pioneer zone, creation and maintenance of drainage furrows might be reduced. As a positive side-effect, this would reduce the costs, and improve the aesthetic and, therewith, recreational quality of the landscape.

However, dewatering of the dike foot and, for grazing purposes, of the salt marshes (see below) must still be guaranteed.

3.4.4 Grazing

Description

Livestock grazing (mostly extensively by sheep or cattle) is implemented on parts of the salt marshes and summer polders in front of dikes. In former times, land reclamation by groyne construction and controlled drainage aimed at creating new pasture mainly for agricultural purposes. The need of pasture decreased significantly in the recent years.

For coastal defence, the main function of livestock grazing is the reduction of biomass. The remains of dead salt marsh vegetation are transported during storm surges to the outer dike slope. There it settles as flotsam and endangers the grass cover of dikes. Flotsam also provides a hiding and resting place for mice, which dig burrows into the dike. Significant effects of grazing, i.e., a reduction in the amount of flotsam on the dikes, can be demonstrated especially in areas with a tall herb vegetation. Extensive grazing enhances the soil stability against erosion whereas very intensive grazing affects the soil stability in a negative way (Erchinger *et al.,* 1996). Even without grazing, salt marshes surfaces will not be eroded during storm surges. Where livestock grazing occurs, artificial drainage may become necessary if natural drainage is not sufficient (see above).

Livestock grazing interferes with the natural development of salt marshes. It influences the stability and permeability of the soil as well as the vegetation structure. Extensive grazing in selected areas may increase the diversity of plant and animal species (QSR 2005, chapter 7.5.2).

Evaluation

There is a continuous and, partly, controversial discussion about the role of livestock grazing in salt marshes. The positive effect of reducing the amount of flotsam on the dikes is discussed in respect of its interference with nature. Without grazing the salt marshes, technical efforts (i.e., gathering and transport by vehicles) are needed to remove flotsam from the outer dike slopes. Livestock grazing can be used in selected areas as a management tool to create heterogeneity of the vegetation structure and to enhance biodiversity. It is expected that, due to natural succession, the biodiversity of salt marshes will decrease. In result, livestock grazing is considered to be a BEP in selected areas.

3.4.5 Breakpoint discussion

Above breakpoint, not enough sediment will be available within the ecosystem to balance the sea level rise (Ch. 2). In that case, the salt marshes will start to drown, with or without salt marsh management techniques. Thus, salt marsh management techniques will only function below breakpoint. On the other hand, salt marshes need a certain sea level rise in order to survive as halophytic vegetation communities. With stable sea levels, the sedimentation will induce a reduction in salt water coverage and, therewith, a succession towards brackish and fresh water biotopes.

Investigations imply that mainland salt marshes in the Wadden Sea may be able to balance a sea level rise of about 1 cm per year by enhanced sedimentation (providing that groyne fields stabilize the pioneer zone, see below). Island salt marshes may already start to drown if the sea level rise exceeds 0.5 cm per year (Dijkema 1997). As a first effect of increased sea level rise, an accretion deficit in the pioneer zone is expected. This zone lies in an elevation, which is mostly affected by wave action and currents, and lacks the protection of a closed vegetation cover. Vertical erosion in the pioneer zone may lead to horizontal cliff erosion at the seaward edge and, in the end, to a disintegration of the salt marshes. As a general conclusion (Dijkema, 1997), salt marsh management techniques (groynes) have to direct most attention to the pioneer zone in order to prevent negative effects of sea level rise below breakpoint.

3.4.6 Regional aspects

The Netherlands

Salt marshes officially have no coastal defence function. They are managed for ecological reasons only. Extensive livestock grazing for nature conservation is applied to make salt marshes more attractive to bird species, and to create heterogeneity of the vegetation structure. As an environmental goal, 1250 ha of salt marsh area shall be secured in the Dutch Wadden Sea. Groynes fields with drainage systems are maintained to achieve this goal. Dikes will be constructed in such a manner that safety standards are guaranteed even if the salt marshes do not persist. The maintenance of ditches on mainland salt marshes stopped in 2001, due to a more natural management (Dijkema *et al.,*2001). It is too early to know if and how natural creeks will develop in the long run, in artificially drained salt marshes after the cessation of drainage measures.

Lower Saxony

Salt marshes in front of main dikes are defined by law as elements of coastal protection. The salt marshes have to be preserved in a defined width and maintained as a protection element for the main dike as a legal obligation. Groynes also stabilize the dike foot against erosion were salt marshes are absent and therefore can enhance salt marsh creation.

Drainage furrows and ditches are maintained in parts of the salt marshes to secure drainage of the dike foot and make grazing possible in defined areas. No artificial drainage is needed where natural drainage systems e. g. tidal creeks exist. Salt marsh management plans are developed to harmonize the demands of coastal defence and nature conservation.

The reduction or cessation of systematic drainage in the salt marsh accretion zone has proven a good method to increase the natural morphology. From an ecological point of view, the reduction of drainage is considered to be more positive than its maintenance.

In a natural salt marsh, meandering creeks develop, functioning both as transport routes for sediments towards the salt marshes and as dissipation zones for tidal energy (Pethick 1992, Pye 1992). The present artificial drainage system has a straight and evenly distributed channel pattern which differs strongly from the natural situation. According to Esselink *et al.*,(1998), this may be an explanation for the lower spatial variation of elevation, soil conditions and vegetation in man-made salt marshes.

Schleswig-Holstein

In Schleswig-Holstein, it is prescribed by law to secure salt marshes appropriately to sustain their protective function (see above) for the state dikes. For this reason, about 550 km of groynes, and 6,300 km of drainage furrows are maintained to secure the 10,000 ha of salt marshes. To anticipate possible conflicts, a common salt marsh management concept was established in 1995 by the coastal defence and environmental administration in conjunction with the dike and water boards. The common goal of coastal defence as well as of the environmental authorities is the preservation of the existing salt marshes. Where there are no salt marshes existing in front of dikes they shall be created. The techniques used to reach this goal depend upon local circumstances. They must be carried out as ecologically sound as possible. Local circumstances permitting, technical measures are abandoned. An integrated board that includes (apart from the institutes mentioned above) local administration and NGOs monitors the implementation of the plan. As stated in the first five-year evaluation report, the plan has been implemented successfully (Hofstede, 2003, Stock *et al.* 2005).

Denmark

In Denmark, an area of 2,000 ha of salt marshes is maintained for coastal defence purposes. On a local level, salt marshes are grazed, drained, and protected by groyne fields. It is aimed at a 250-300 m wide salt marsh area in front of the sea dikes (approximately 2,000 ha). Half of the salt marsh area has a natural drainage system. The other half is artificially drained. At the moment, an area of approximately 800 ha of salt marshes is protected by groyne fields.

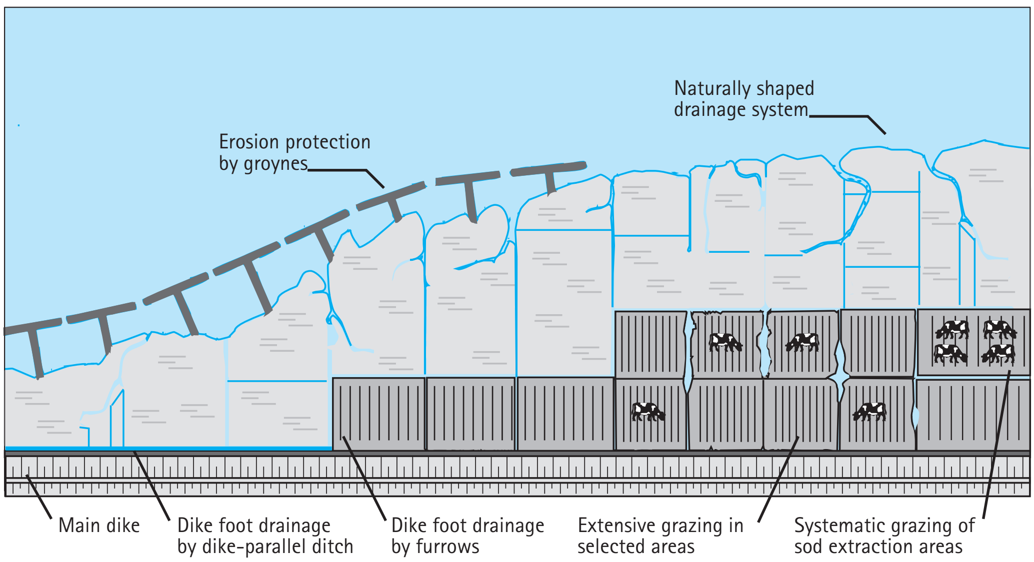


Figure 13: Salt marsh management techniques (F. Thorenz).

3.5 Mussel and sea grass beds

3.5.1 Introduction

This measure encompasses the promotion of the settling of mussel beds or sea grass fields in order to stimulate sediment accumulation and stabilization. This measure includes the protection of existing beds and fields or potential locations for these beds.

In the Wadden Sea, the natural development of mussel beds differs locally and has also changed over the years.. In the 1930s, large areas of sea grass fields disappeared, probably because of a disease. In the Northern part of the Wadden Sea, the sea grass fields have recovered and show stable conditions. In the Southern part, sea grass fields are still scarce but the areas have slightly increased during the recent years.

3.5.2 Functionality for coastal defence

Because, under normal weather conditions, mussel and sea grass beds stimulate accumulation and stabilization of the sediments, they might diminish wave energy. Especially the older, stable mussel banks may have positive influence as they are very resistant to storms. During storm surges this effect is reduced to zero because of the large water depth. Promoting the settling of mussel beds and sea grass fields are measures that are applicable on sheltered locations in the tidal basins of the Wadden Sea.

Mussel and sea grass beds may, on a local scale, help safeguarding inter-tidal areas from drowning. It has to be realized, however, that on the scale of the whole tidal basins, preventing morphological changes, induced by an accelerated sea level rise, is impossible by using this measure.

3.5.3 Ecological effects

Both sea grass fields and mussel beds provide favorable conditions for other species and are therefore capable of enhancing biodiversity.

3.5.4 Discussion

Below breakpoint, the system can keep up with the sea level rise. Mussel beds and sea grass fields can help stabilizing inter-tidal areas. Above breakpoint, not enough sediment will be available within the ecosystem to balance the sea-level rise. In that case, mussel beds and sea grass fields can, on a local scale, help safeguarding inter-tidal areas from drowning. It has to be realized, however, that on the scale of the whole tidal basins, preventing morphological changes induced by an accelerated sea level rise is impossible. Active re-introduction of mussel beds and sea grass fields would not be in line with the current concept of naturalness in nature conservation policy, but might enhance the biodiversity.

Figure 14: Mussel beds (Photo: G. Millat).

3.5.5 Regional aspects

The Netherlands

In the Netherlands, approximately 30% of all inter-tidal mudflats, the most promising areas for recovery, are closed for soil disturbing fisheries (since 1993). The aim is recovery and conservation of an area of 2000 tot 4000 ha of stable mussel banks. Largely due to a rich spetfall, 2002 showed an increase to 2500 ha; however, the stability remains to be seen, as recently formed beds tend to dissolve in their first winter. The installation of the closed areas seems to favor the recovery of mussel beds (EVA II, 2003). However, also in less favorable areas, mussel beds returned.

Reintroduction of species which used to be part of the wild flora or fauna is only seen as a sensible nature conservation measure under certain specified conditions: the causes of their local extinction must be eliminated, the environmental conditions must have improved and the chances for natural reinstallation must be low. Reintroduction of sea grass may, in certain regions, meet these criteria. In general, active reinstallation of biotic structures is seen as gardening in a nature conservation area and therefore interfering with natural dynamics. In the case of sea grass, reintroduction is seen as a contribution to biodiversity.

In the Dutch Wadden Sea, two sea grass species occur. (Zostera marina and Zostera noltii). In general, the sea grass beds have recovered after the 1930s, but especially in the western Wadden Sea of The Netherlands, sea grass did not show any recovery. The closure of the Zuiderzee by the Afsluitdijk probably changed the conditions unfavorably towards the recovery of sea grass in that area. The chances that sea grass will spontaneously return to the western Wadden Sea are small as the net circulation patterns make it difficult for seed to get from the eastern part to the western part. In The Netherlands, a project trying to reintroduce sea grass beds in the western Wadden Sea by replanting sea grass started in 2002. Sea grass from the Ems estuary is replanted in the western Wadden Sea (in the area 'Balgzand'). Mussel beds and low brushwood groynes were erected to create calm areas for the sea grass. The first results (replanting in 2002) were disappointing, as the mussels were eaten by birds, the brushwood groynes deteriorated, the plants were planted too deep and weather conditions were unfavorable just after replanting. A second phase of replanting in 2003 seems to have been more successful (www.zeegras.nl).

Lower Saxony, Schleswig-Holstein and Denmark

In Germany and Denmark, the promotion of settling mussel beds or sea grass fields in order to stimulate sediment accumulation and stabilization is not applied as coastal protection measure.

3.6 Outbanking summer polders

3.6.1 Introduction

Outbanking of summer polders is the complete or partial removal of summer dikes in order to allow normal tides to enter the summer polder. A summer dike protects a summer polder from flooding by moderate (summer) storm surges. Higher (winter) floods may overtop the summer dikes. The outbanking of summer polders by opening summer dikes will result in a more frequent flooding of the area and higher sedimentation rates. By allowing the sea into the summer polders, these areas could keep up with sea level rise through higher sedimentation rates.

Summer polders occur in The Netherlands and Lower Saxony. Several pilot studies are in preparation or underway in The Netherlands. Here, summer dikes are or will be, partially, removed. The development towards more natural conditions (creek system and vegetation) is monitored. In Germany, the generally small summer polders have a function in sea defence. Outbanking would lead to higher expenses for guaranteeing safety. Here, the feasibility is thought to be low. Despite this, outbanking was realized in some summer polders in Lower Saxony, too.

3.6.2 Functionality for coastal defence

In the inner parts of estuaries, outbanking of summer polders may reduce storm surge levels because of the increase in storage capacity. In order to be effective, however, the surface area of the outbankment should be substantial, compared to the total surface area of the inner estuary. Further, the location of the polder is essential to influence the tidal dynamics in the desired way.

In the Wadden Sea, from a sea defence point of view, outbanking of summer polders may be interesting in the long-term because it will allow low-lying outbanked summer polders to keep up with sea level rise in a natural way. As a result, a high area (possibly high salt marsh) in front of the sea wall will remain. With rising sea level and sinking land, the height of the summer polders, if not outbanked, will become lower and lower with respect to both sea level and seaward salt marsh. Outbanking of summer polders could induce extra cost for sea defence, as the strengthening and extra maintenance of the current sea dike might be necessary.

It is advisable that summer polders are outbanked only when the difference between the summer polder and both sea level and seaward salt marsh is not too big. If this difference is too big, outbanking will result in the polder to be flooded permanently and the chances for salt marsh regeneration are low. In such a case the summer polder could start to function as a weak spot, because of a weaker soil structure. Investigations in whether this is the case are planned in The Netherlands.

3.6.3 Ecological effects

Outbanking of summer polders can compensate for the loss of salt marsh areas through cliff erosion or drowning caused by accelerated sea level rise and is therefore interesting from a nature protection point of view. Besides higher sedimentation rates, such a measure could make up for the loss of salt marsh habitat caused by sea level rise. In Dutch nature conservation, the outbanking of summer polders is seen as a possibility to increase the area of mainland salt marshes, enhance nature quality and to compensate for the loss of salt marsh habitat on the islands due to sea level rise. It is thought beneficial to the plant and bird species related to this type of habitat.

3.6.4 Evaluation

The positive effects of outbanking of summer polders in the Wadden Sea area for coastal defence are questionable. If executed, the protective function of summer dikes for the main dike disappears and additional measures to strengthen and maintain the coastal defences especially for grass dikes are likely to be necessary. Therefore, presently, outbanking of summer polders can mainly be regarded as an environmental measure with the objective to change the polder areas into valuable habitats.

In the long term, outbanking of low lying summer polders might be useful for coastal defence in order to keep up the ability of the polder marshes to adapt their elevation to sea level rise. From an environmental point of view, this measure may help to compensate the loss of salt marshes due to cliff erosion.

Outbanking of summer polders in estuaries might help to influence hydrodynamics of storm tides and especially water levels positively. The effect of such measures is strongly interdependent on the shape and location of the polders. Additional maintenance and strengthening measures on the dikes as well as positive effects on nature can be expected.

Above breakpoint, on a longer time scale, outbanking of summer polders in the Wadden Sea might be a coastal defence option with positive ecological side-effects.

Public resistance is expected, especially if summer polders are private property. In these cases finances are needed for acquisition.

3.6.5 Regional aspects

The Netherlands

Several pilot studies are in preparation or underway in The Netherlands. In the Dutch Wadden Sea, in the area 'Noord-Friesland Buitendijks', a landscape of summer polders, salt marshes and salt marsh accretion works has developed seaward of the dikes. The summer polders are used as pasturage for cattle. In this area, it is feared that due to erosion of the salt marsh accretion works at the seaside and summer polders and past land reclamation, tidal marshes might decrease in area. As a solution, the provincial association for nature conservation 'It Fryske Gea' initiated a plan, converting parts of the summer polders into salt marshes with brackish vegetation which are flooded by salt water at high tide. In 2000 and 2001 a pilot project was undertaken in the Noorderleech polder (135 hectares). The landward sea dike was raised, while holes were made in the seaward summer dike, allowing salt water to enter the polder at high tide. As they are situated rather low, everywhere in the outbanked polder, sedimentation is taking place. Straight ditches have started to fill up and change in more windy creeks. The vegetation is starting to change towards salt marsh vegetation.

Another plan in The Netherlands is the outbanking of the summer polder 'Peazummerlannen'. Unlike the 'Noord-Friesland Buitendijks' area, where the distance between the sea dike and the outbanked summer polder is large, the summer polder to be outbanked in the 'Peazummerlannen' plan is situated directly in front of the sea wall. A study into the consequences of outbanking this relative narrow and sea dike near summer polder regarding its safety and maintenance is undertaken. If outbanking means that, for safety reasons, the sea dike needs another construction, the costs for sea defence will rise significantly (millions of Euros).

Lower Saxony

In Lower Saxony, summer dikes are regarded to have positive effects on the main dike. They allow e.g. to construct a dike foot of the main dike with clay and reduce maintenance works on the main dike. Therefore outbankings for coastal defence purposes are not executed.

In the last decades, only a few smaller outbankings of summer polders on selected sites were implemented in order to compensate for environmental impacts of dike strengthening measures, located directly behind the summer polders. A recent example of outbanking is the relocation of a summer dike on the island of Langeoog, as a compensation measure which covers a total area of 210 ha. The summer dike was located in front of a dune area and therefore had no direct positive effect on coastal defences.

At present, the outbanking of the Langwarder Groden summer polder as a compensation measure is under discussion

Schleswig-Holstein

In Schleswig-Holstein, no summer polders exist along the mainland coastline. The so called Halligen (small marsh islands in the Wadden Sea of North-Frisia) are protected by summer dikes and/ or stone revetments. About 350 people live here on dwelling mounds. The Halligen are inherent parts of the cultural heritage of Schleswig-Holstein. Without protective measures, the Halligen would erode due to natural dynamics and, in the end, disintegrate. According to the Schleswig-Holstein State Water Act, the Halligen must be protected.

Denmark

In Denmark, no summer polders exist along the mainland coastline in connection with the sea dikes. In the area of Ballum-Kolby, a summer dike, of about 6 km, protects agricultural land against flooding during months of cultivation. The complete or partial removal of the summer dike would expose the hinterland to more frequent flooding including an increase of crop failure. On the barrier islands, summer polders and summer dikes do not exist.

3.7 Sea dikes

3.7.1 Introduction

Sea dikes are artificial wall-like accumulations of earth with affixed slopes (e.g., grass, asphalt), situated at or near the seashore. Normally, revetments at the outer dike-foot and transport roads along the inner dike foot are inherent parts of the structure. The gradients of the outer and inner slopes should be low enough to prevent erosion by breaking and overtopping waves. Almost the entire mainland coastline in the Wadden Sea and parts of the back-barrier coasts of the islands are occupied by dikes. About 1200 years ago, people built the first ring dikes in the Wadden Sea region. In the twelfth century, for the first time, a more or less continuous dike-line protected the mainland marshes from flooding. Since than, dikes have grown bigger and stronger with increasing technical possibilities and higher storm surges. At present, the height of primary sea dikes in the Wadden Sea region is between 6 and 9.5 m above mean sea level. Until the middle of the last century, land reclamation was – apart from flood defence – an important motivation for building dikes in the Wadden Sea region. Since the twelfth century, about one third of the Wadden Sea ecosystem (i.e. coastal marshes) has gradually turned into cultivated land. About 3.3 million people live in this reclaimed area. Sea dikes constitute the main coastal flood defence measure in the Wadden Sea. On the Wadden Sea islands, dunes constitute a main flood defence measure as well. Sea dikes effectively prevent the flooding of coastal lowlands by storm surges. As a result, people and assets are protected up to a defined safety standard. However, dikes cannot, guarantee absolute protection. In case of flooding, older dikes situated inland may function as a second defence line and confine the area that is flooded (see below).

Sea dikes are artificial structures that interfere with natural dynamics. They exclude natural dynamics (incl. regular flooding) from the diked marshlands, and influence dynamics in front of the dikes. Further, they exclude naturally wide brackish water transition zones with various habitats and partly endemic species. The actual dike-line is, on a Wadden Sea scale, seaward from the coastline, under natural circumstances. Nearly all natural bights are embanked or closed and the mud flats as an important Wadden Sea habitat are reduced.

The three main measures discussed in the context of sea dikes are: (1) dike strengthening, (2) dike relocation, and (3) second dike line. These three measures are described and evaluated below.

3.7.2 Dike strengthening

Description

Dike strengthening is the measure, in which the dike dimensions are modified (in height, in width, by armoring, etc.) in order to maintain or improve its flood defence function. To guarantee present safety standards in the long-term, dike strengthening measures are underway in Denmark, Schleswig-Holstein, Lower-Saxony and The Netherlands. Further, investigations about the effects of climate change on safety are carried out. The results may necessitate further strengthening campaigns.

Strengthening a dike has several environmental implications. Apart from the ecological impacts during the measure, salt marshes might become build-over. Further, tidal flats and salt marshes may be impaired due to the extraction of sand and/or clay necessary for the enforcement.

Evaluation

On a Wadden Sea scale, despite their possible effect on ecology, sea dikes and, if necessary, dike-strengthening is indispensable (protecting more than three million people and their assets from flooding). On a more local scale of single uninhabited flood units (Polders, Köge), alternatives to dike strengthening (second dike line, dike relocation; see below) might be an alternative. In this case, however, aspects like safety, costs and/or public acceptance must be taken into account (see also breakpoint discussion).

A number of measures may (and already are under present legislation) be undertaken to minimize adverse effects on nature. Material for dike-strengthening should, wherever technically and financially feasible, be taken from the old dike profile and from inland sources. Normally, a new dike needs more space than the old one. In this case, the dike-strengthening should occur on the landward side of the old dike. If this is not feasible (e.g. housing, costs), the dimensioning of the new dike should occur in a way that minimizes the build-over of valuable biotopes.

3.7.3 Dike relocation

Description

Dike relocation is a combined measure, in which:

- an existing primary sea dike is dismantled,
- a new dike is built or an already existent (second) dike is strengthened landward of the old one.

In other words, dike relocation normally is equivalent to the retreat of a primary sea dike.

In the last centuries, no relocations of primary sea dikes have been conducted in the Wadden Sea region.

Evaluation

Dike relocation usually implies legal and financial complications as well as public resistance, which make its application less feasible. It might become more realistic if it turns out to be cheaper than strengthening the existing dike, as it will often be the case in coastal areas, where no or only very few people live between the old and new primary sea dike.

Obviously, dike relocation will require a resettlement of the people living between the old and new primary sea dike in order to maintain their present safety standard. Major resettlements and reimbursements will probably abate the feasibility of relocation.

On the other hand, environmental aspects may support the relocation of a flood defence system further inland due to the wish of returning embanked areas back to natural hydrodynamic processes such as flooding during storm surge. Valuable (tidal) biotopes may become re-established promoting the enlargement of biodiversity. However, as with summer polders, the differences in elevation among the fronting tidal flats and the embanked area should not be too large.

Sea dikes protect more than three million people and their assets against flooding and are, therefore, indispensable in the Wadden Sea area. However, sea level rise and increase in storminess will put the existing dike structures under increased pressure. At the same time, the demand on guaranteed safety standards will imply a significant financial burden on public means. Depending on the scale of changes in sea level and storminess, financial aspects might get more prevalent than today. Together with demands for more long-sighted defence strategies, the measure of dike relocation might gain more focus in future, mainly as an alternative for unsettled or low-settled areas. However, public acceptance must particularly be considered.

3.7.4 Second dike line

Description

Secondary dikes are situated landward of a primary sea dike. Normally, they are former primary sea dikes, which shifted into their present status as a new dike was built in front of them. These secondary dikes may be several centuries old and lack the dimensions of modern sea dikes. Further, as the coastal defence interest is normally focused on primary dikes, the state of maintenance may be poor. Small stretches may even be removed or lowered for, e.g., roads or houses. Secondary dikes are widespread along the Dutch and German mainland coast. In some areas, several secondary dikes are arranged in a row as a result of repeated reclamations.

An absolute protection against storm floods is not possible. Independent of the safety standards defined, there will always be a residual flood hazard in the protected lowlands. In this context, a secondary dike functions as an extra defence line to minimize the consequences of a breach in the primary dike system. If a breach occurs, the flooding may be restricted to the area enclosed by the primary and secondary dikes, i.e., to one flood unit. Hence, the risk of storm floods (being the product of breach probability and consequences) is reduced. Apart from this function, secondary dikes may, in case of emergencies, be used as escape and evacuation routes. In order to function, they should be dimensioned to withstand certain water levels. Further, they should be maintained on a regular basis (e.g. grazing, pest and weed control).

Secondary dike lines have no direct environmental implications for the Wadden Sea itself. As it may reduce or avoid the strengthening of primary sea dikes, indirect positive ecological effects may be expected.

Evaluation

A secondary dike minimizes the flood hazard of the people and assets situated landward of the structure, thereby reducing the overall risk in the coastal lowlands. The measure has no function with respect to maintaining present safety standards in the polders between the first and the second dike-line, as people and assets seaward of the structure do not achieve any extra protection (which might have negative implications for public acceptance). Hence, this measure would implicate a strategic (and societal) shift from safety towards risk based management.

In synthesis, it appears that a secondary dike line might become an option for single flood units, especially above breakpoint. In this case, comprehensive measures like strengthening the second dike to specified standards, adapting the infrastructure (roads, cables, etc.), heightening buildings (dwelling mounds) and/or resettlement would become necessary in the flood units. Some additional measures along the first dike-line would become necessary too.

3.7.5 Breakpoint discussion

Below and above breakpoint, dike strengthening is a technically feasible method to maintain safety standards even in the long term. Sea dikes of up to 12 meter above mean sea level exist in the Netherlands (e.g. Hondsbossche zeewering). River dikes may even be higher. In specific cases (i.e. where the present primary dikes protect uninhabited flood units), alternatives like a staggered flood defence system might become financially feasible above breakpoint. In this case, public opinion has to be taken into account as well as ecological considerations.

3.7.6 Regional aspects

The Netherlands

In the Netherlands the Ministry of Transport, Public Works and Water management provides the hydraulic boundary conditions for the primary sea defences. The water boards maintain the sea defences and check whether the defences comply with the hydraulic boundary conditions. Based on these checks dike strengthening plans are made by the water boards. The minister of Transport, Public Works and Water management decides which plans are to be executed. The government pays for the strengthening, water boards are responsible for day to day maintenance.

Dike strengthening projects for Schiermonnikoog and the town of Harlingen are being prepared. On Schiermonnikoog the replacement of the sea wall surface is likely to be carried out in 2005-2006. For the sea defence strengthening in Harlingen an environmental impact assessment is being carried out.

Lower Saxony

In Lower Saxony, the mainland coast including the estuaries is protected by sea dikes. Additionally main dikes exist on the Wadden Sea side of the islands. According to the Lower Saxony coastal defence policy, dike strengthening is one of the mayor tasks to maintain safety standards. In the last decades, the dike line on the mainland coast, has been significantly shortened in the estuaries by building storm surge barriers in the Ems (finished in 2002) and in tributaries of the Weser and Elbe River. Secondary dike lines have a legal coastal defence function but only exist along some stretches of the coast.

Schleswig-Holstein

A comprehensive dike-strengthening campaign (anticipating climate change) is underway. About 77 km of primary sea dikes (of a total of 364 km) have to be strengthened along the west coast in order to maintain safety standards until the year 2100 (considering a sea level rise of 50 cm). Landward of the primary dikes, an almost uninterrupted secondary dike line with a total length of about 570 km is situated. As a result, about 2,000 km^2 of flood-prone coastal lowlands (of a total of 3,400 km^2), is protected by two dike lines. The function of the second dike line is acknowledged in the Schleswig-Holstein State Water Act. Dike relocation is, according to the master plan: "integrated coastal defence in Schleswig-Holstein" possible under three preconditions: (1) that safety standards are maintained, (2) that no extra costs arise for coastal defence administration, and (3) that the measure is accepted by the local population.

Denmark

In Denmark, a dike-strengthening project for the Rejsby Dike and Ballum Dike is being carried out in 2004-2007. First attempts are made to apply probabilistic risk analysis methods to establish more transparent and consistent design/safety standards for the Danish sea dikes. The mainland bordering the Wadden Sea is protected against flooding by 72 km sea dike. At the barrier islands Mandø, Rømø and Fanø, about 28 km sea dike protect inhabitants and their assets from flooding. Landward of the primary dike, being just located north of the Danish-German border, a secondary dike line with a total length of 9 km protects the low-lying hinterland including the town Tønder.

4. Synthesis

Figure 15:
Sluice (Photo: M. Vollmer).

4.1 Introduction

In general, the measures described in Chapter 3 vary significantly in their regional, technical and financial feasibility as well as ecological consequences. Some measures like the installation of mussel and sea grass beds may have ecological benefits but are only locally applicable and have limited coastal defence significance. Other measures like sea dikes imply significant ecological interferences but are, from a coastal defence perspective, often without alternatives in order to maintain present safety standards. Further, the measures differ strongly with respect to their technical effectiveness above the breakpoint. This shows that there is not one single solution that fits all demands for the whole Wadden Sea. The group assessed the measures described below as those which are most recommendable, both for coastal defence purposes and with respect to their ecological consequences.

4.2 BEP measures

Concerning **spatial planning**, the establishment of coastal regional plans that include buffer zones and coastal flood hazard zones is recommended as a promising non-technical BEP measure. Spatial planning aims at a sustainable spatial utilization and development that balances the social and economic requests upon a region with its ecological functions. In the buffer zones, space can be reserved for future coastal defence measures or retreat of the coastal defence line. In the flood hazard zones, restrictions and/or regulations for spatial utilization aim to reduce the consequences (damages) of storm surges. In the coastal spatial plans, the significance of climate change and its consequences, increasing of sea level rise and changes in storminess, should be duly considered. The determination of buffer zones and flood hazard zones in coastal spatial plans becomes specifically significant above the breakpoint. In this case, traditional techniques might become less feasible (technical and/or financial) to maintain present safety standards. The plans should be established on the basis of the principles of Integrated Coastal Zone Management: (1) an integrative consideration of land and sea, (2) a balanced consideration of ecological, economical and social demands, and (3) an active involvement of all relevant groups through information and participation.

Sand nourishment is seen as a BEP measure that successfully counteracts coastal erosion. Further, it helps to stabilize the dunes (constituting a natural dune-foot protection and as a sand source) and, therewith, their functionality as flood defences (see below). Concerns exist with respect to interferences with nature that result from extraction and deposition of the sand. Hence, the measure should be applied in a way that minimizes the effects on the environment. Compared to other techniques (groynes, revetments) to stabilize sandy coastlines, sand nourishment is, in general, to be preferred. With increasing rates of sea level rise (i.e., above breakpoint), the amount of sand needed will increase correspondingly. In the long-term and, especially, above the breakpoint, nourishment of sand on strategic locations in the

Wadden Sea may help to balance the sand-deficit that results from sea level rise.

Dune management comprises of a number of measures (dune restoration, dune relocation, natural dune dynamics and over-wash) that ensure the functionality of dunes as flood defences. Allowing natural dynamics and over-wash have clear ecological benefits as they add to the naturalness of the environment. Dune restoration and relocation, e.g., by building sand fences or planting marram grass, do interfere with nature. However, from an ecological point of view, these techniques are to be preferred above hard constructions like dikes or groynes that would otherwise become necessary. Especially above breakpoint, dune relocation in combination with sand nourishment might be a BEP measure to maintain defence standards. Even though, there might be a point where the techniques described above do not suffice and, with present safety standards, hard techniques may become necessary to protect inhabited lowlands.

Salt marsh management techniques (i.e., groynes, drainage furrows and grazing) aim at maintaining the flood defence functions of the marshes. At the same time, salt marshes have an outstanding ecological value and should be preferred as dike foot protection compared to hard constructions. Groynes function in that they reduce wave energy and currents, thereby creating an environment where sedimentation prevails and erosion is lessened. Hence, they interfere with natural dynamics. Without groynes, widespread erosion of salt marshes would occur in the Wadden Sea. Natural material (wood) should be applied if feasible. Artificial drainage furrows constitute an interference with natural dynamics as well. They should only be applied to secure dike-foot dewatering (avoiding otherwise necessary hard constructions) and, if necessary, to secure dewatering on grazed salt marshes. Natural structures (creeks) should be used wherever possible as part of the drainage system. Livestock grazing on salt marshes is controversial and still subject to discussion. It is considered to be a BEP measure where, after storm surges, high amounts of flotsam would, otherwise, have to be removed from the outer dike slopes. At present, salt marsh management differs between the countries and is also dependent on the regional and local boundary conditions.

Above breakpoint, there will not be enough sediment available in the Wadden Sea to balance sea level rise. Hence, the salt marshes would start to drown and the management techniques described above would loose their functionality. Investigations imply that mainland salt marshes might be able to balance a yearly sea level rise of up to about 1 cm. Island salt marshes may start to drown if sea level rise exceeds 0,5 cm per year. As a first sign, accretion deficits are expected in the pioneer zone, confirming the importance of groynes.

As an option, the feasibility of **promoting mussel and sea grass beds** was elaborated. This measure aims at stimulating accumulation on, and stabilization of intertidal flats. As it is capable of enhancing biodiversity, it has ecological benefits. From a coastal defence point of view, the measure could only perform a very local and limited effect in that it may reduce wave energy. During storm surges, the large water depths reduce the wave damping effect to zero. Above breakpoint, there will not be enough sediment in the system to balance the sea level rise, with

Figure 16:
Sand trap fences
(Photo: F. Thorenz).

or without mussel and/or sea grass beds.

Outbanking of summer polders in estuaries may have, under specific conditions, positive flood defence effects by reducing the height of storm surges upstream. Outside estuaries this effect does not occur. Here, the outbanking allows the surface level of the summer polder to keep pace with sea level rise by increased sedimentation rates. This, however, only functions below breakpoint and if the existing height differences between the polder and the fronting tidal flats or salt marshes are not too large. Extra measures with regard to the main sea dikes behind the summer polder might become necessary due to the failing summer dikes. As the measure can compensate for loss of salt marshes, it has ecological benefits.

Under **sea dikes** a number of measures (dike-strengthening, dike relocation and second dike line) are listed that ensure the functionality of dikes as flood defences. Sea dikes constitute the main coastal flood defence measure in the Wadden Sea (on the islands in combination with dunes). Measures that maintain the functionality of the sea dike system in the Wadden Sea are indispensable to secure present safety standards. Sea dikes, on the other hand, strongly interfere with nature, for example by excluding natural dynamics from the diked marshlands and by influencing the dynamics seaward. On top of that, dike-strengthening measures constitute time-limited interferences with nature. Hence, necessary dike-strengthening measures should be carried out in a way that minimizes the adverse effects on nature, for example by using material from the old dike and by strengthening on the landward side (if possible). Further, on a more local scale of single uninhabited flood units (polders) alternatives like dike-relocation and strengthening the existing or building a new second line should be considered, especially above breakpoint.

4.3 Combination of measures

The group elaborated on combination of measures into integrated strategies. Some of the BEP measures are natural combinations. Sand nourishment and dune management measures can be combined successfully as sand nourishments can provide the source of the sand needed to protect the dune foot and provide the sand for more natural dune dynamics. The functionality of sea dikes is related to salt marsh management and a combined approach can be considered.

Figure 17: Beach (Photo: J. Hofstede).

Spatial planning is a BEP measure that should underlie the application of all other BEP measures. Spatial planning should provide the long term framework in which future sea defence is one of the items dealt with. Including buffer and coastal flood hazard zones in spatial plans are a sustainable and flexible way to deal with the effects of sea level rise.

4.4 Final considerations

The regional aspects showed that a large variety exists in the present application of BEP measures. The defences in present and future application of the identified measures is the result of differences that exist in physical, socio-economic and cultural framework.

With respect to coastal flood defences, the group elaborated on the existing safety standards (i.e., the water level that the defences should withstand without damage) in the three counties. Depending on the physical, socio-economic and cultural context the safety standards vary significantly. Especially above breakpoint, there may be specific situations where maintaining the present safety standards could be re-evaluated with respect to technical and financial feasibility as well as ecological consequences. This would, however, call for a broad discussion as it implies a shift from safety towards risk based management. The feasibility of such a strategic modification certainly varies from country to country. As an example, risk (benefit-cost) based coastal defence is implemented in the United Kingdom. An evaluation of maintaining present safety standards with respect to feasibility and ecological consequences, especially above the breakpoint, should be carried out.

5. Conclusions / Recommendations

In this chapter, general and specific conclusions are listed. On the basis of these conclusions, recommendations are made. In the general conclusions, results from CPSL I are considered as appropriate.

General conclusions:

- The predicted sea level rise will induce a sediment deficit in the Wadden Sea. Above breakpoint, the Wadden Sea will develop into a number of tidal lagoons.
- A number of measures are identified that contribute to maintaining safety and have limited ecological consequences.
- New coastal defence techniques that are both feasible and have minimal ecological impacts could not be determined.
- All coastal defence techniques constitute, to a varying extent, interferences with nature.
- The application of the identified measures differs among the regions, resulting from the differences that exist in the physical, socio-economic and cultural framework.

Specific conclusions:

- Apart from The Netherlands, no specific regional plans that consider coastal defence and climate change for the Wadden Sea region exist.
- Including buffer and coastal flood hazard zones in spatial plans is a sustainable and flexible way to deal with the effects of sea level rise.
- Sand nourishments successfully balance coastal erosion along the outer coastlines of the barriers.
- Sand nourishment may contribute to the compensation of sediment deficits resulting from sea level rise, although the ecological effects are still unclear.
- Dune management techniques ensure protection against flooding and are, from an ecological point of view, to be preferred above hard constructions.
- Salt marsh management techniques are necessary to prevent most salt marshes from erosion.
- Salt marshes perform an ecologically sound measure to protect the dike foot compared to otherwise necessary hard constructions.
- Mussel beds and sea grass fields enhance biodiversity and may, on a local scale, help safeguarding intertidal areas from drowning.
- Inside estuaries, outbanking of summer polders has positive ecological effects and may, in specific cases, be positive for coastal defence.
- Sea dikes strongly interfere with natural dynamics in the area but are, generally, necessary to secure present safety standards in coastal lowlands.

Recommendations:

Coastal spatial plans that include buffer and coastal flood hazard zones should be established based on the principles of integrated coastal zone management. Coastal defence and climate change should be duly considered. The feasibility of such plans should be investigated by a follow-up group, comprising trilateral experts from coastal defence, nature protection and spatial planning.

Sand nourishment should be applied, wherever feasible, to combat erosion along sandy coastlines.

A study should be carried out on the feasibility and effects of sand nourishment to balance the sediment deficit of the Wadden Sea tidal basins under increased sea level rise (e.g., volumes needed and costs, search for optimal locations, ecological impacts).

Regional salt marsh management plans should be established to harmonize the demands of coastal defence and nature conservation.

An evaluation of maintaining present day safety standards with respect to feasibility and ecological consequences, especially above breakpoint, should be carried out.

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Annex 1: CPSL II Terms of Reference

As a contribution to the 9th Trilateral Governmental Wadden Sea Conference (Esbjerg, Denmark), a trilateral expert group (CPSL I) elaborated on the subject coastal protection and sea-level rise. The main outcomes were included in the Esbjerg Declaration of 2001. The CPSL II Terms of Reference are based on §75 and §76 of the Esbjerg Declaration:

75. To investigate, therefore
    - 75.1 The feasibility of Best Environmental Practice (BEP) for coastal protection measures.
    - 75.2 Which measures and/or integrated policies could be appropriate to increase the flexibility to cope with sea level rise and climate change.
    - 75.3 At which degree of sea level rise the breakpoint will be reached.
76. To support the continued close cooperation between the coastal defence and nature protection authorities in this matter, including communication with the stakeholders.

Responsibility

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

Composition

The CPSL II Group will consist of representatives of the responsible administrations (coastal defence and nature protection). The secretarial work will be carried out by the Common Wadden Sea Secretariat.

Timetable

The work of the CPSL II group has been conducted since summer 2003, until early 2005. The draft final report shall be available to the TWG by **June 2005.**

Tasks

- BEP measures
  The CPSL II group shall elaborate on BEP measures and, if feasible, their combination into integrated strategies. Regional differences will be duly considered. The elaborations will be based on two scenarios: below and above breakpoint (the point where the Wadden Sea ecosystem starts to develop away from its present dynamic equilibrium state). Other aspects like cost-benefit and public acceptance will also be taken into account.
- Communication plan
  To inform the public, the CPSL II group shall prepare a leaflet in Danish, Dutch, English, and German with the main outcomes of the work of the CPSL I group. Further activities to inform the public (Internet, magazines) shall be undertaken by the group members as appropriate.
- Quality Status Report
  The CPSL II group shall prepare contributions for the 2004 update of the Quality Status Report on the following topics: (1) climate change, and (2) coastal protection.
- Wadden Sea Forum
  Some activities of the Wadden Sea Forum (WSF), especially of the Thematic Group "Policy and Management", have close links to task one of the CPSL II group. In order to optimize co-ordination and achieve synergy, the chairperson of the CPSL II group will become observer status in the Wadden Sea Forum and the respective WSF thematic group. As an input to the WSF report, the CPSL II group shall prepare a chapter on coastal protection.

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Issues of the Publication Series „Wadden Sea Ecosystem"

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