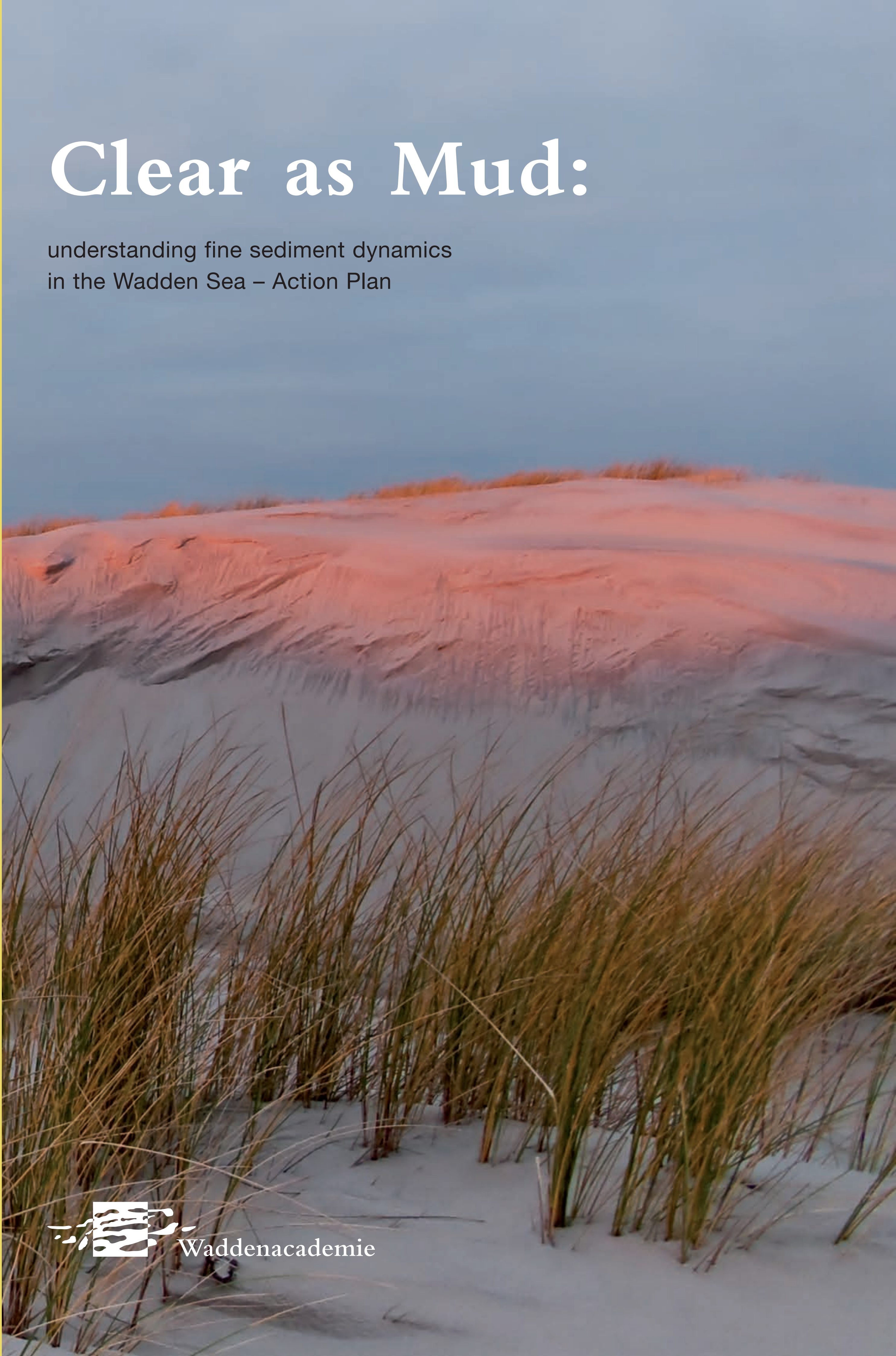
Clear as Mud:

understanding fine sediment dynamics
in the Wadden Sea – Action Plan



Waddenacademie

Clear as Mud:

understanding fine sediment dynamics in the Wadden Sea – Action Plan

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Reviews and comments

A first draft of this action plan regarding fine sediment in the Wadden Sea has been sent out to an international feedback group. This document contains comments by:

name	institute	country	expertise
Morten Pejrup	University of Copenhagen	Denmark	Biofilms, sediment transport, Estuarine sedimentology, Coastal geomorphology, Natural Resource Management, North Sea, OSL dating, Geography, Earth System Science
Justus van Beusekom	AWI	Germany	fine sediment biota, productivity, Wadden Sea
Rolf Riethmüller	HZG (formerly GKSS)	Germany	sediment and turbulence measurements, observatories, COSYNA
Hans Burchard	IOW	Germany	Turbulence modelling, Three-dimensional numerical models, Estuarine, coastal and shelf sea dynamics, Numerical methods
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Their contributions are gratefully acknowledged.

The final draft has been reviewed by:

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1 Problem definition

1.1 Background

The Wadden Academy has defined an ambition in its integrated research agenda to turn the Wadden region into the “best monitored and best understood coastal system in the world” by 2020 (Kabat et al. 2009). This region should be an example how scientists, policy makers and management agencies cooperate in developing sustainable and innovative solutions based on interdisciplinary knowledge. In the same document the Wadden Academy also identifies the dynamics of fine sediment and the interrelationships between fine sediments and biota as major knowledge gaps. These knowledge gaps are not only of importance to scientists who are interested in the geo- and ecosystem functioning, but lack of background knowledge also hampers sustainable management of the Wadden area. This document is concerned with fine sediment dynamics in the whole (international) Wadden Sea. However, as the assignment is given by the Dutch Wadden Academy and financed by the Dutch Programme “Towards a Rich Wadden Sea”, there will be a stronger focus on the Dutch tidal basins than on the German and Danish ones.

1.2 Frame of reference

The Wadden Sea is a large shallow body of water with tidal flats and wetlands, stretching from Den Helder in Netherlands, to Skallingen in Denmark. It is rich in biological diversity, and in all three countries, nature has a very high status of protection. In 2009 the Wadden Sea has received the status of UNESCO World Heritage site (World Heritage Committee 2009). The Wadden Sea countries have thereby committed themselves to protect the natural and cultural heritage of this unique wetland area. This implies that any exploitation of natural resources of this area can only be allowed if sufficient guarantees are available that this exploitation is not compromising the natural and cultural values.

However, like most coastal areas, the system is under considerable pressure from human use and exploitation despite its status. This also has an impact on sediment dynamics. These anthropogenic pressures and influences include:

- Enclosure of former large inlets and salt marsh areas (e.g. the Afsluitdijk, closing off the former Zuiderzee in 1932 and the dyke closing off the former Lauwerszee in 1968). This has changed the tidal amplitude of several tidal basins, as well as the wave exposure of shallow areas within these basins. This is likely to have had and still has a major influence on fine sediment dynamics and although these infrastructural works were completed decades ago, the system is still undergoing substantial morphological changes due to these impacts (Wang et al. submitted).
- Fixing both the position of the islands and the current coastline, rather than allowing these to move naturally also causes changes in fine sediment behaviour.

- Access to the islands and access to harbours (either within the tidal basins, or further inland) with ever increasing sizes of ships requires extensive dredging. This induces morphological changes and an artificial sediment handling system interfering with natural (re-) distribution processes , as well as changes in the fine sediment concentrations in the water column and the bed.
- Both gas and salt extraction from deeper layers underneath the Wadden Sea cause subsidence and increase the sediment demand of the system.
- Bottom trawling (in particular shrimp fishing) disturbs the bed directly, although these direct effects are often short-lived (Simpson & Watling 2006). However these activities also disturb benthic biota (plants and animals) that potentially have an impact on the fine sediment dynamics of the Wadden Sea (Sips & de Leeuw 2009). The same holds for fishing for mussel seed, although this practice is going to be phased out over the coming years.
- Eutrophication causes plankton blooms outside and inside the Wadden Sea. This has been hypothesised as a possible mechanism for changing the flux of material into the Wadden Sea.

Some of these anthropogenic activities may have a significant impact on the fine sediment dynamics of the system, while other activities may be totally undetectable in the "noise" of the natural variability of the system. For example: whether or not the direct and indirect effects of shrimp trawling have a significant effect on fine sediment dynamics is at present impossible to ascertain due to the lack of insight in the major fluxes and the impact of biota on sediment stabilisation. There is a clear need for policy makers and ecosystem managers for a frame of reference against which these various human activities can be evaluated. Our current state of knowledge of the dynamics of fine sediment and organic material within the tidal basins is too limited to ascertain whether or not certain activities ought to be labelled as "harmful" and should thus be banned or restricted to some extent. On one hand, this situation leaves room for unsubstantiated claims of damage and scare stories. On the other hand, it can also be interpreted as a licence for unbridled exploitation – because damage cannot be proven. Neither is desirable. This document aims to determine what level of knowledge is required to provide a frame of reference and recommend specific activities that are required to achieve this level of understanding. Achieving this knowledge will require research using numerical modelling, observations and experiments as integrated research tools.

Other processes that have an impact on fine sediment dynamics and the functioning of the Wadden Sea as a whole are e.g. climate change (accelerated sea level rise, changes in temperature, precipitation as well as storm frequencies and intensities) and the introduction of various exotic species such as Pacific oysters (Crassostrea gigas) and the American Razor Clam (Ensis directus). Human activities are likely to have an effect on such factors, but the extent of human influence is unclear. It is also questionable whether legislation or mitigating measures would have much impact on these more indirect consequences of human activities. However, the impact of the changes in the system has to be understood.

The major knowledge gaps are quite well defined and the need for better observations, better modelling frameworks and better or more specific process knowledge have been clearly identified. In the past few years, a number of documents have been produced, involving many scientists from different institutes detailing the relevance of these gaps. Among the leading scientists there is consensus regarding this issue, although there may be differences of opinion regarding the priorities of tackling particular issues. The most relevant documents are: the integrative research agenda of the Wadden Academy, with the position papers on geosciences and ecology as a basis. These documents focus on fundamental system knowledge. Furthermore, the so-called "building blocks" of the nature restoration programme "Towards a Rich Wadden Sea" focus on knowledge gaps and possible lines of research with a specific goal of improving the natural value of the Wadden Sea. This Plan of Action will take these documents as a starting point. Appendix A contains a digest of the relevant parts of the documents mentioned above. We will not explore further possible knowledge gaps and research topics. However, we will present a stepwise plan to fill in these gaps. The outlook of this plan will span 10 – 20 years, i.e. a similar time-scale as the aim of the Wadden Academy has defined in their ambition and a similar time-scale as programmes such as the conservation programme "Towards a rich Wadden Sea" and the Dutch "Wadden Fund" (a finance stream specifically for the Wadden area).

1.3 Fine sediment

This document is primarily concerned with the behaviour of fine, cohesive sediments in the Wadden Sea (from here on indicated by the term "fine sediment", rather than "silt" or "mud", as these definitions are too narrow). This comprises all the sediment particles, ranging from the finest clay fraction to very fine sand. It is concerned with all the inorganic fractions that can have an impact on turbidity.

The Wadden Sea system is rich in fine sediment. It contains significant fractions of mud. "Mud" is the combination of fine sediment and clay. Silt is defined as: particles between 4 and 63 µm, while clay particles are smaller than 4 µm. The settling behaviour of suspended particles depends on various parameters. Small particles tend to have lower settling velocities than larger ones. Generally, sand (i.e. particles larger than 63 µm and smaller than 2000 µm) sinks fastest because of a high density and a large diameter. Cohesive particles have a stronger tendency to form aggregates. In the Wadden Sea the presence of fine-grained material in the water column leads to turbid water, as this material scatters and absorbs light. Although sandy beds may be very mobile, sand has little impact on water clarity, because it sinks relatively fast, even in turbulent water. Fine, non-cohesive particles are also easier to erode from the bed. However, the minimum force required to erode particles, depends not only on the particle size, but also on the properties of the bed. Cohesive sediments have a higher erosion threshold than non-cohesive ones. In particular the clay fraction of mud makes the bed more cohesive.

Another important property of sediment beds is its permeability. Permeability is strongly affected by the concentration of fine particles and an important parameter determining advective pore water transport and benthic-pelagic exchange (Meysman et al. 2006).

Fine sediment particles also have a tendency to form flocs and aggregates. Due to flocculation the average particle size in the system can increase (Winterwerp et al. 2002). The settling velocity of flocs has a broad spectrum. Therefore, the zonation of Wadden Sea sediments shows an increasing fraction of cohesive particles with attenuated hydrodynamic energies, but the sediments are often not well sorted.

Flocculation can be a purely physical process, but biological processes (algae, bacteria, faecal pellets from zooplankton and benthic species) can significantly increase aggregate formation. Particularly EPS excretion by algae and bacteria has been indicated as an important factor determining the behaviour of fine sediment in the water column and the resuspension probability of particles from the bed (Maerz & Wirtz 2009). These authors hypothesise that biological control mechanisms have a stronger effect on SPM dynamics than currently represented by state-of-the-art SPM transport models.

1.4 Tidal basins as functional units

Although the Wadden Sea as a whole is considered to be one system in terms of legislation and organisation, in terms of fine sediment dynamics there are large differences between the different tidal basins (Zwarts et al. 2004). Lateral transport of water across the watersheds is limited. The bulk of the volume flux of water is via the tidal inlets. The tidal basins tend to show differences in trends, regarding fine sediment. In order to get a first order understanding of fine sediment dynamics within the Wadden Sea, it is imperative that we get an idea about the gross, but particularly also the net fluxes of sediment in each basin. I.e. an important question is: do tidal basins show net accumulation or net export of fine sediments? This very basic question has to be answered first before questions on a more local level can be answered. Quantitative information is required on the horizontal fluxes (transport between the North Sea and the Wadden Sea) and the vertical fluxes (exchange between the bed and the water column).

The level of human impact on tidal basins varies enormously. Dredging is extremely heavy in the Ems estuary and also in some of the German rivers draining into the Wadden Sea. In the Ems estuary, it is clear that deepening due to dredging has changed the tidal amplitude and asymmetry to such an extent that the whole system has seen a dramatic increase in suspended sediments, particularly inside the estuary (de Jonge 2009). Dredging in this basin clearly affects a wider area than its immediate vicinity. Also around Ameland, morphological changes combined with the effects of dredging may have a significant impact on the fine sediment dynamics of the tidal basin. In some other systems, dredging is virtually absent and is therefore not a major influence on the dynamics of fine sediment. Bed disturbance by shrimp fishing is currently wide spread in nearly all Dutch tidal basins, while some of the German ones are completely, or nearly completely closed for all bed-disturbing activities. Much can be learned from detailed comparisons between the systems, although we have to bear in mind that tidal basins not only differ in human exploitation, but also in physical and natural functioning. Cross-basin comparisons therefore always have to be interpreted with caution, but will nevertheless offer very much needed potential for exchange of knowledge and experience.

1.5 Natural dynamics

Fine sediment is a natural and integral part of the Wadden Sea. Without large amounts of fine sediment in suspension or in the sediment, the system would look totally different and the ecosystem would undoubtedly be poorer.

Large amounts of fine sediment are transported in and out of the system with every tide. Also locally, there are large vertical fluxes, with material eroding and settling again. The sediment concentrations in the Wadden Sea are generally higher than in the adjacent North Sea, such that the tidal dispersion of fine sediments out of the Wadden Sea must be balanced by one or more transport processes against the gradient into the Wadden Sea.

The natural morphological development of the Wadden Sea caused islands to migrate within the system, depending on tides, currents, sea level changes and sediment availability. The morphological development of the Wadden Sea is mainly the consequence of sand transport, i.e. strictly speaking outside the remit of this document, although it has an impact on fine sediment dynamics and therefore needs to be considered as a background process. The morphological history of the system includes large estuarine areas with a gradual transition from fresh water to saline conditions, as well as large salt marsh areas and deep channels, capable of capturing and fixing sediment on long time scales. Over the past decades fresh water influx into the Dutch part of the Wadden Sea has been substantially reduced (van Aken 2008). In the German part there are no reports of major changes in freshwater input. As stated before, the Wadden Sea is by its own nature a dynamic area, which over relatively short geological time scales (± 8000 years) has undergone large changes in sea level rise and large changes in its overall morphology. Nevertheless it has kept its basic elements intact (channels, islands, flats, tidal marshes).

Although the large-scale morphology of the Wadden area is primarily determined by sand dynamics, the variability in morphology of the system, e.g. the wandering of gullies, can also mobilise large quantities of fine sediment, locked in deeper layers of the seabed. Changes in the morphological balance of the system (either natural or anthropogenically influenced) are therefore important factors to take into account when considering fine sediment dynamics.

Variability is a natural characteristic of the Wadden Sea. These changes occur at a variety of spatial and temporal scales, such as changes in bed composition and migration of channels, over spring-neap cycles, seasonal variations, and response to larger measures up to decades. This makes, by definition, a fixed frame of reference, and management goals of "no change to the system" neither desirable nor possible.

1.6 Human boundary conditions

The current morphology of the Netherlands includes solid and fixed coastal defences (e.g. the Afsluitdijk) which also create an abrupt transition between large fresh water reservoirs (the IJsselmeer, Lauwersmeer) and the Wadden Sea. These enclosure dykes not only constitute a solid and fixed land – water transition, the closing of these inlets has substantially shortened the coastline. The IJsselmeer is an essential freshwater reservoir, which prevents salt intrusion into important agricultural areas and provides drinking water reservoirs for the Netherlands.

Current legislation prescribes that the Dutch coastline (including the primary sea defences of the Wadden Islands) is fixed. Also, in the German and Danish parts of the Wadden Sea, the natural migration of the islands and the dunes on the islands has been restricted. In some cases (e.g. on Sylt and on Rømø) causeways have been constructed connecting the islands directly to the mainland. Big parts of the islands and causeways are extended by groynes ("Buhnen" and "Lahnungen") that are built to accumulate fine particles during slack tide. These causeways limit exchange of water and sediment across the watersheds. Most of the German East Frisian islands have been fixed with hard substrates and concrete on the tips of the islands. The extension of salt marshes has been significantly reduced over the last century, by extending the dyke line towards the sea. The natural gradient from dunes to saltmarshes to mudflats to sand flats is virtually absent from big parts of the shore and the coastal relief is much steeper than in historic times.

Both the presence of the Afsluitdijk and the fixing of the mainland and island coastlines are factors that are inherently unnatural and will cause morphological counter reactions to redress the sediment balance within the system. These counter effects continue to have an impact on the system many decades after the infrastructural building works have been completed. Keeping the coastline and particularly the islands fixed in place currently requires coastal nourishments and other measures. The changes in the shape of the coastline and the fixing of island locations means that the natural fluxes of fine sediment are also influenced.

Although these artificial measures and constructions contravene the ideal of a "natural system", the importance of them to the human society are so substantial that they are deemed acceptable.

This implies that other human activities in the Wadden Sea should be judged against the background fluxes of fine sediment, while taking the Afsluitdijk and Lauwersmeer into account as reference background for the system.

1.7 Fine sediment interaction with ecology

Although the focus of this document is on understanding fine sediment dynamics, ultimately most questions relate to ecosystem health and possible damaging effects of human activities on nature. The interaction between fine sediment and ecology is a two-way interaction. To ascertain impacts of human activities on the natural system, we need to know how fine sediment in the water and the bed affects biota, to ascertain the causes of certain conditions we also need to be able to quantify the effects of biota on sediment dynamics.

1.7.1 Effects of fine sediment on biota

The presence of fine sediment in the water column and in the seabed has an influence on biota. In the water column, the presence of fine sediment reduces the penetration of light. In general this leads to a reduction of primary productivity. That is: unless the system is limited by other factors, such as nutrients. A strongly nutrient limited system will not react very dramatically to changes in light availability. This is generally not the case in the Wadden Sea, as the system still tends to be eutrophicated. However, in recent years, due to a strong reduction of the phosphate input certain areas may become nutrient limited in certain parts of the year (Philippart et al. 2007). In the bed, the presence of fine sediment cannot be generalised. With regard to benthic primary production, it is fair to say that silty intertidal flats (d50~50 µm) have a higher productivity than sandy ones (d50>63 µm). Sandy flats dry out quickly as soon as the flat emerges. Flats dominated by fine sediment tend to hold both water and nutrients for much longer when the area is dry, i.e. when light availability is maximal. For benthic animals the effects of fine sediment are also not straightforward: certain species may show a strong correlation with silt in the bed within a system, but are actually more directly influenced by hydrodynamics than by fine sediment. Others (particularly burrowing species that ventilate their burrows) do have very specific requirements regarding sediment composition (Gimenez et al. 2006, Berkenbusch & Rowden 2007). Particularly sediment permeability is the factor determining habitat suitability, which is to a large extent determined by the particle composition of the sediment (Meysman et al. 2005). Apart from the composition of inorganic particles, also the organic fraction of the sediment is relevant for benthic animals. Many of them use the organic fraction of the sediment as a major food source. There are still major knowledge gaps regarding the effects of fine sediment in the system on species composition, biodiversity and biomass (Norkko et al. 2010). Within one tidal basin, one will nearly always find a correlation between sediment composition and species distribution. However, this correlation does not always signify a causal relationship. In order to ascertain whether fine sediment (either in the water column or in the sediment) has a direct influence, several tidal basins with different physical driving forces (e.g. different fine sediment concentrations) have to be compared.

Not only the sediment composition, or the sediment concentration in the water column are important. Particularly in relation to human activities such as e.g. dredging or other forms of bed disturbance, the rate of sedimentation or the rate of (re)colonisation of bare sediment is important. Nearly all species in a relatively turbid, shallow environment will have to be able to cope with a certain rate of deposition of sediment. E.g. mussels are sufficiently mobile to "climb out of a layer of sediment". However, if the sedimentation rate is faster than the rate at which mussels can move upwards, the mussel bed will get buried and suffocate (van Dalfsen & Essink 2001).

1.7.2 Effects of biota on fine sediment

Many plant and animal species are so-called ecosystem engineers, i.e. biota that alter the abiotic properties of a habitat (Jones et al. 1994). In the past decade a large body of fundamental studies has been produced, describing significant effects of biota on sedimentation and erosion rates of fine sediment (Le Hir et al. 2007, Andersen et al. 2010). The current line of thinking is that large-scale morphology of the system (mainly sand dynamics) is a purely physical process, and that biota can have a significant effect on the fine sediment dynamics. The exception being saltmarshes, which can trap fine sediment for long time-scales and significantly influence large scale morphology (Morris 2007). However, on local spatial scales and at short (seasonal) time scales biota can certainly have a major effect (Borsje et al. 2008). To what extent, and under which circumstances biota can influence dynamics on larger spatial and temporal scales, remains to be investigated. It is likely that the same ecosystem engineering species may have very different scopes for modifying their environment depending on the characteristics of the system. E.g. in systems with very stable abiotic conditions in terms of seasons, fine sediment exchange, nutrient dynamics etc., such as the Banc d'Arguin, it has been proven that the seagrass species Zostera noltii can have a major influence on sediment composition of the bed (Wolff et al. 1993). However it is, very uncertain and probably unrealistic to expect that in the Wadden Sea, with strong seasonal dynamics, strong variability in fresh water dynamics, fine sediment import-export and nutrient availability, this seagrass will have the same scope for ecosystem engineering. A major difference between these systems being the fact that in Mauretania this seagrass has above-ground shoots all year round, while in the Wadden Sea the species is dormant in the winter months, and any accumulated fine sediment by the seagrass is released back into the system every autumn. In winter in the Wadden Sea only the root systems of Z. noltii may have some effect in preventing erosion. However, lack of understanding of these processes has occasionally lead to far-reaching claims with respect to ecosystem engineering species. Without insight into ecosystem-functioning these claims can neither be substantiated nor can they be dismissed.

Seagrass is only one example where the effect of biogenic structures or activity is known to have an effect on the smaller spatial and temporal scales. There is a large body of work on ecosystem engineering species, both plants and animals, that can either stabilise or destabilise sediment (Jones et al. 1997, Herman et al. 2001, Crain & Bertness 2006). Particularly the interaction between the small-scale processes and the larger ecosystem scale effects needs a lot of attention.

1.8 Societal questions

The Wadden area is also an area where people live and work. Human activity is part of the fabric of the Wadden system. The attractions of the natural system of the Wadden Sea landscape is an important ecosystem service. People like to visit the area for its natural beauty, its peace and its characteristic landscape. Although perhaps not directly appreciated as such by tourists, the fine sediment dynamics are a prerequisite for this natural landscape.

Somehow the effects of human use and exploitation of the area has to be balanced against the natural development of the system and the intrinsic value of the unique ecology of the area. Many of the direct societal questions are immediately concerned with the relatively short term and small to intermediate spatial scales. Examples of such questions are e.g.:

- Fine sediment deposition in the harbour of Harlingen, where continuous and expensive dredging is required to keep the harbour accessible.
- Fine sediment deposition in the “Kikkertgat” near Ameland. Due to the migration of the channels, extensive dredging is required to allow access to the ferry from Holwerd to Ameland and vv.
- The Ems-Dollard system has seen an extreme increase in fine sediment retention over the past decade. There are further plans for widening and deepening of the shipping lane between Eemshaven and Borkum.

In all of these cases the immediate problem is local. Authorities want to know:

- What are the effects of these dredging activities on ecosystem functioning, biodiversity, and ecology?
- Would different dredging strategies be more effective and therefore cheaper?
- Would different dredging strategies have less impact on the environment?

We can make a separation in these questions between the causes of the fine sediment problem (why is dredging required and which dredging strategies are most efficient?) and the effects of fine sediment on ecology. If the effects of fine sediment on ecology are deemed serious and detrimental, authorities have to be able to make a decision whether

- the human benefits of the dredging operation are high enough to warrant them;
- mitigating measures are effective.

It is very important to note that not in all cases policies and technologies will be either effective or feasible to mitigate negative effects.

1.9 Approach

Ultimately, we want to gain full understanding of the processes governing the dynamics of fine sediment in the system, to an extent that we can predict the most probable development of the sediments in the framework of the societal questions put forward above. Observations are always limited in temporal and spatial coverage, but they can deliver the parameterisations for the model algorithms. Models can capture the non-linear feedbacks within the systems. Models can be used as research tools to help us acquire sufficient understanding. They allow us to carry out virtual experiments under controlled conditions.

Ultimately we also want these processes captured in a range of numerical models varying from simple quick-assessment tools to complex 3D numerical models for intermediate to long-term predictive purposes. Such models should be applicable from small scales to total Wadden Sea scale. This is clearly not something that is going to be achieved in a couple of years, this is a long-term goal. As the time-frame for this goal we envisage about two decades. Understanding of ecosystem functioning can only be achieved through a tightly coupled approach of modelling, observations and experimentation, and can only be achieved by a multidisciplinary group of scientists.

Modelling, observations and detailed process knowledge have to work parallel and iteratively: observations, experiments and theoretical reasoning generate ideas; these ideas are converted into models; models are validated with observations; models can indicate what type of observations are lacking and what specific processes need to be quantified in experiments etc. Additionally, models can also show mechanisms that can be validated by observations.

1.9.1 Modelling

It is important to note that although ultimately detailed numerical models may be used as management tools, initially models will serve primarily as research tools. We will also not focus only on complicated 3D numerical models, such as Delft 3D or GETM simulations (van Kessel et al. 2001, van Ledden et al. 2006, Burchard et al. 2008). For testing purposes, numerical experiments with smaller analytical models, or numerical models of reduced spatial complexity are very important to assess whether certain processes may or may not have a system-wide relevance.

1.9.2 Observations

Earlier inventories have indicated that, particularly in the Dutch part of the Wadden Sea, there is a distinct lack of observations on suspended sediment concentrations and fluxes (see also the appendix on knowledge gaps) together with observations of hydrography, waves, currents, turbulent quantities and biogeochemistry. Specific local issues, such as the dredging of a shipping lane or the entrance to a harbour may carry obligations of effect monitoring. While any additional data are welcome and can and should be used by scientists, these smaller scale monitoring efforts within the framework of e.g. environmental impact assessments, are not a substitute for integrated system-scale observational programmes. In short: there is strong a need for large-scale monitoring programme, linked to modelling efforts.

1.9.3 Stepwise action plan - scope

We have devised a modular plan, to achieve sufficient system knowledge for evaluating human activities on the sediment dynamics of the Wadden Sea system. We have primarily concentrated on understanding that drives the dynamics of fine sediment. For many policy frameworks, the relevance of looking at fine sediment dynamics is to evaluate the effects on the ecology of the system. The effects of fine sediment on the ecology of the Wadden Sea system is only covered in so far as it relates directly to ecosystem engineering species that influence sediment dynamics. We have not concerned ourselves with effects on e.g. primary productivity or effects of turbidity on hunting success of diving birds. These effects are relevant for environmental effect studies, but research for these topics should be outlined in a different setting.

From a purely scientific point of view, it makes sense to start with the broader picture, analysing the major background driving forces and quantifying the large-scale fluxes, ultimately zooming in on smaller-scale processes. However, it is arguable that if only the large scales are given priority, many questions relating to the possible role of ecosystem engineers will not be tackled in the short term. Whether ecosystem engineers inside the Wadden Sea will have a major influence on the large-scale transport mechanisms is an important question. Due to the fact that questions regarding the role of ecosystem engineers are high on the agenda, it is still justified to pay due attention and effort to smaller-scale processes even if we have to accept that exact predictions with regard to specific locations and specific species are not going to be feasible in the very near future. However, getting insight in the order of magnitude of biological-physical interactions and getting better insight in the potential effect of ecosystem engineers (species that are capable of modifying the abiotic conditions in their habitat) should be feasible even on short to medium time-scales.

2 Modular action plan

The goal of the fieldwork and modelling program proposed in this document is the generation of knowledge on the functioning of fine sediments in the Wadden Sea, with the ultimate objective to be prepared for answering societal questions with respect to the management of the Wadden Sea. This knowledge should be based on a variety of activities, i.e. field observations and monitoring, field and laboratory experiments, and numerical modelling. The numerical model serves to formalise knowledge built up during the research, and as a tool to generate knowledge through sensitivity analyses and answering what-if questions. The fieldwork is necessary to drive and calibrate the numerical models, as well as to provide information to our system understanding. This system understanding will be made explicit in the form of a conceptual model, which will be updated and refined during the course of the work.

The research activities should be properly streamlined to optimise the feed-back between the results, which can be achieved by a proper phasing of the work. We anticipate that each phase will produce products (e.g. observational data, reports and papers with insight into the relevance of processes) / tools (specifically models), which can already be used to answer more specific questions. The process of prioritising will involve an analysis of the weakest links in our current knowledge.

The ambition is to make the Wadden Sea the best understood coastal wetland system of the world, an understanding based on the best data set of the world. This ambition implies that one should be able to resolve at least the following issues, related to fine, cohesive sediment:

1 The budget of fine, cohesive sediments and its spatial variations. In particular the import of fine, cohesive sediments through the tidal inlets, sources from historic (Holocene) origin and sinks within the Wadden Sea are to be quantified.

2 Temporal variations in this fine sediment balance over various time scales, such as seasons and years. This should give insight into the natural variability in the fine sediment dynamics, and related sediment balance.

3 The residence and transition time of fine sediments in the Wadden Sea, and its sub basins.

4 The role of freshwater fluxes (run-off from land, groundwater, precipitation, evaporation) into the Wadden Sea for net fluxes of fine sediment in the Wadden Sea.

5 Effects episodic events, such as a single, heavy storm, ice scour or extreme peaks in riverine run-off on the sediment dynamics in the Wadden Sea; or more generic, what is the effect of episodic events in the Wadden Sea.

6 Net transport of fine sediment over the watersheds (wantij), and the conditions at which such net transport occurs. Note that this issue is expected to be addressed implicitly in conjunction with the sediment balance studies. However, because of its inherent difficulties, the watershed transport is referred to separately.

7 The effects of increased sea level rise and/or subsidence on the fine sediment dynamics and balance, as well as effects of climate change on typical wind patterns, freshwater fluxes and water temperature.

8 The effects and efficiency of the salt marsh works along the coast with respect to the trapping of fine sediments (Dijkema et al. 2008).

9 The interaction and sediment exchange between tidal channels and tidal flats via the water column and bed-load transport – these interactions and exchanges may be affected largely by biological effects (bio-stabilization and bio-destabilization).

10 Assessment of historic large infrastructural works on the transport and fate of fine sediments; one can think of the closure of the Zuiderzee (Afsluitdijk) and Lauwersmeer, land reclamation works, the Delta works further south, affecting the fresh water distribution along the coast, etc.

Only when the natural system is understood properly (which will certainly take some time), the impact of human interventions can be established properly; this impact should be weighed against the large natural variations in fine sediment dynamics. Although careful monitoring and modelling of changes surrounding human impacts can also teach us a lot regarding the functioning of the natural system.

We anticipate that various model systems will be used for the numerical modelling, in particular to study the water movement. With respect to modelling sediment transport, we anticipate that the larger amount of work will be carried out with the Delft3D system. However, it is very instructive to use more models simultaneously, as each model has its own merits, stronger and weaker points. But apart from increasing insight in reliability and credibility of the modelling tools, use of different models will also increase our knowledge in the system, analyzing differences in predictions by these models.

Large-scale morphodynamics and (fine) sediment dynamics are strongly interlinked. This document focuses primarily on measurements and models relating to fine sediment dynamics and does not focus on long-term morphological changes. Only where human activities strongly influence the larger scale morphology we also address these issues (e.g. where dredging in the estuaries is concerned). However, these developments have to be considered where these would mobilise fine sediments from the seabed. In the following, we summarize research aspects that have to be addressed.

2.1 Conceptual model

A powerful tool to formalize our knowledge and understanding is a conceptual model of the fine sediment dynamics within the Wadden Sea. A conceptual model is a qualitative/semi-quantitative description of these dynamics in the form of diagrams, cartoons, and some text. A map in which the Wadden Sea is sub-dived in its sub-basins, with numbers representing long-term net import of fines through the tidal inlets, net transports over the watersheds, and net accumulation/erosion within these sub-basins is an example of such a conceptual model. A first step in the development of such a conceptual model is a comprehensive literature study summarising and collating the latest insights regarding sediment dynamics.

Currently, numerical studies on fine sediment dynamics in the Wadden Sea are carried out through long-term simulations (few years), prescribing the actual tidal and weather (wind) conditions over that period. In this way seasonal variations in sediment properties and driving forces can be accounted for. However, it is the question whether this approach is efficient, and whether a full, detailed analysis remains possible when more processes are accounted for in the model. An adequate strategy (or strategies – different problems may require a different approach) for long-term simulations is to be developed, and ultimately incorporated in the conceptual model. A basis for such a strategy should be sensitivity analyses of the currently available models to ascertain the gaps in our data and process knowledge that cause the largest uncertainly in model outcomes.

2.2 Effects of morphological changes and the role of the larger estuaries

The meso- to macrotidal estuaries of the rivers Ems, Weser and Elbe are important elements in the Wadden Sea system with respect to mud, since they are major sinks of fines. On shorter time scales fine sediment may be trapped in estuarine turbidity maxima (ETMs) from which they may be released occasionally into the Wadden Sea and the adjacent North Sea. It is not yet fully clear which are the major processes for the accumulation of fine sediments in ETMs (Jay & Musiak 1994, Burchard & Baumert 1998). All three estuaries in the Wadden Sea are amplified estuaries of which the tidal range in the back is larger than in the mouth. Dredging activity and construction measures in harbours and shipping channels greatly altered the physical processes in the estuaries. River canalisations and river deepening in combination with large-scale dredging operation in the main estuary have led to significantly changed tidal characteristics (De Jonge 1983, Talke et al. 2008). Progressive deepening and streamlining of the rivers and shipping channels has decreased the hydraulic roughness and increased the tidal amplitude, especially in the river part of the estuaries, e.g. in the Elbe (Rolinski & Eichweber 2000) and in the Ems (Winterwerp 2011). On top of that, the system roughness further decreased because of the formation of fluid mud in the lower part of the river Ems (Emden – Papenburg). Increasing amounts of mud and other sediments have been dredged since the nineteen fifties. This has also changed tidal asymmetries and the flood has become much faster contributing to mud import from sea into the estuary (especially in the river part of the estuary). Due to these changes, concentrations of sediment at the ETM in the Ems have increased sometimes as much as by one order of magnitude compared to the mid 1950s (de Jonge pers. comm. and manuscript by de Swart (in preparation). However, for other estuaries (e.g. the Elbe) the situation may be different (Bergemann 2004, Kappenberg & Fanger 2007). In the estuaries fluid mud layers of several meters thickness occur, which can contain enormous amounts of fine sediment e.g. 80-100 million kg for the Elbe (Grabemann et al. 1995). The fluid mud layers in turn decrease friction (Chernetsky et al. 2010). It has even been thought that the fluid mud layer may have led to several profound regime shifts leading to the enhanced import of fine sediment (Winterwerp 2011). The main questions concerning the estuaries with respect to mud are:

1 How much fine sediment is net stored annually in the estuaries?

2 How much fine sediment is stored over longer time scales in the estuaries?

3 How much fine sediment is gross transported in and out of the estuaries by waves and currents annually?

4 What is the annual net fine sediment balance of the estuaries?

5 To what extent do the channelling and deepening of the estuaries lead to stronger imports of fine sediment into the estuaries?

6 What is the influence of the human-induced reworking of large amounts of fines due to dredging on the net fine sediment budgets of the estuaries?

7 To what extent does the fluid mud layer itself act as an enhancer for fine sediment import?

8 How much fine sediments are trapped in ETMs and how frequently and at which rates are these sediments released into the Wadden Sea and the North Sea?

9 To what extent does the increased fine sediment concentration in the waters of the estuaries exert a regional influence and under which conditions (for example: storm surges, peak river discharges?)

10 To what extent does the decrease/increase in the amount of tidal flats play a role in the fine sediment budgets of the estuaries?

11 What are the differences (if any) between the various estuaries and what are the possible causes for it?

12 To what extent do NAO-fluctuations influence the fine sediment household in the estuaries (Talke et al. 2008)?. Insight in the effect of such natural background fluctuations is essential to differentiate between natural trends or cycles and human induced changes.

2.3 Hydrodynamics

The hydrodynamics drive the transport of fine sediments in the Wadden Sea (and elsewhere), and (partly) govern the water - bed exchange processes. Currently, the hydrodynamics in the Wadden Sea are reasonably modelled, but improvements are required for a better understanding of the fine sediment dynamics in the Wadden Sea. Some of these improvements can only be realised when further data become available.

1 The bathymetry of the Wadden Sea is based on five-year surveys by Rijkswaterstaat. For a proper interpretation of the hydrodynamic modelling results, information on the spatial distribution of the errors in the survey data is required – we expect to find the larger relative errors in the shallow, subtidal areas. Most likely such an error map can be retrieved from existing information.

2 The bathymetry of the Wadden Sea is quite complicated, with many channels and shoals, secondary channels, tertiary channels, etc. A proper modelling of the tidal water movement and wave evolution requires a computational grid that can capture the bathymetry with sufficient resolution. Such a detailed grid is not present at this moment. Candidates for resolution improvement are the new developments in unstructured and sub-grid modelling.

3 In addition to points one and 2 described above, the hydrodynamic model should be calibrated against drying and flooding (the water movement over the intertidal flats) – use is to be made of aerial photographs, or remote sensing images from satellite.

4 Currently too few data are available for an adequate calibration of the hydrodynamic model. A proper calibration requires information on the tidal water level variations at a number of stations within the Wadden Sea, and information on flow velocities and flow rates. With respect to sediment transport modelling, and our understanding of net transport fluxes and paths, information on the generation and propagation of sub-tidal components (M4, M6) is required (e.g. tidal asymmetry) – currently no information is available on these components. When this information becomes available, the hydrodynamic model has to be calibrated against mean fluxes and flow velocities, and their sub-tidal components.

5 We have too little, or no information on the residual flows within the Wadden Sea, and their variability) over time (spring-neap cycle, seasons, years?). The TESO-data set provides information on the net water fluxes through the Marsdiep, but no information exists on flow rates through other tidal inlets, or over the water sheds. We expect that these residual fluxes are a strong function of the mean water level (set-up, set-down), wind velocities and direction, and should therefore be measured at a variety of conditions.

6 A possibly important transport mechanism for fine sediments is estuarine circulation due to horizontal density differences that are caused by the input of fresh water. This process may also play a substantial role in the Wadden Sea (Burchard et al. 2008). Also tidal pumping and the transport due to asymmetrical tides can be very important. However, even when tidal processes are dominant, this process can be strongly modified by buoyancy effects (Uncles et al. 1992). The hydrodynamic model should therefore be calibrated properly against observations on fresh water distribution within the Wadden Sea (particularly in the Marsdiep basin and basins with drainage from rivers); possible remote sensing infrared images may add to the required information. This will provide necessary information on horizontal distribution of freshwater in the Wadden Sea, important for both hydrodynamic modelling, but also for the behaviour of fine sediment in the water column.

7 Generation and propagation waves should be modelled properly within the Wadden Sea. With respect to fine sediment transport, wave action is especially important over shallows (i.e. intertidal flats, and close to the shore). Not only the waves during storms are important, also the 'normal' waves play an important role in the shallow areas.

8 Wave propagation and evolution are largely affected by wave-current interaction. The resulting currents are important for the transport of fine sediment, in particular in the shallow areas. Note that above mentioned points 6 and 7, and to a lesser extent point 2 are subject of the ongoing SBW-study, determining the hydraulic boundary conditions along the dykes of the Wadden Sea coast.

2.4 Bottom and sub-bottom constitution

The seabed in the Wadden Sea is partly alluvial, and partly of Holocene origin, the latter certainly with respect to the subsoil conditions. As Holocene deposits may behave differently from alluvial beds with respect to water-bed exchange processes, the subsoil constitution should be mapped, including layers of shells, and other non-alluvial material. The currently available data are not sufficient for sediment transport models.

Distribution maps of benthic biota that influence sediment composition and sediment erodability need to be available. These have to be seasonally specific, as the biomass of different biota may change per season.

2.5 Sediment properties

The sediments within the Wadden Sea are fairly inhomogeneous. Variations in sand-mud content are well-known, but we also expect variations in floc size, organic content, erodability, etc. Further to activity 2.3, presence of other material has to be mapped (shell fields, fine and coarse sand, etc.). Together with the driving forces (water movement and waves) these sediment parameters govern the fine sediment dynamics within the Wadden Sea. In particular, the following sediment parameters have to be assessed through dedicated surveys:

1 Particle size distribution and sediment composition within the bed and its variation over space and time, in conjunction with the bed's bulk density, permeability and organic content,

2 Particle and floc size distributions in the water column, and their variation over space and time, yielding information on temporal and spatial patterns in essential parameters, such as sinking velocities.

3 Settling velocity distribution in the water column, and its variation in space and time,

4 Erosion thresholds and rates of fine sediments from the Wadden Sea seabed, accounting for variations in the bed's composition and history.

The quality and quantity of existing data probably differs among the three Wadden countries.

2.6 Sediment transport

Within this proposal, the fine sediment dynamics in the Wadden Sea are evaluated at time scales of a few years, for given bathymetry. Hence, morphodynamic evolutions are not part of the study. It is anticipated that at least the following processes will have to be incorporated in a numerical sediment transport model – in a number of cases some more fundamental research is required to establish the proper mathematical-physical formulations:

1 Proper maps of the bed shear stress on the Wadden Sea seabed for a variety of hydrodynamic conditions (spring-neap tide, waves, maxima, periods of transgression), as a function of bed composition,

2 Establishment of the relevant number of fractions, and the grain size per fraction, both in the water column, and within the bed. Modelling the interaction between these fractions, and the effect of flocculation.

3 Proper modelling of the water-bed exchange processes (e.g. erosion and deposition), including a proper book-keeping of the bed composition in terms of grain size and mechanical properties,

4 Proper assessment and parameterisation of biological effects on sediment properties (bio-stabilisation by micro-phytobenthos, bioturbation, bio-destabilisation by grazing fauna, etc.). It has been shown that on shorter time scales biological effects can affect the sediment dynamics in for instance the Ems-Dollard to a large extent (de Deckere et al. 2002) or the Wadden Sea (Borsje et al. 2008). However, for the Lister Dyb tidal basin the annual fluxes could be modelled adequately neglecting the effects of biological activity on fine sediment (Lumborg & Pejrup 2005).

5 Modelling the response of the bed to episodic events – very little is known about this response, and further, more fundamental research is required.

Note that it is virtually impossible to calibrate a sediment transport model in detail against observations of suspended matter, bed composition, etc, as the stochastic component in the sediment dynamics is very large. Therefore, another approach is chosen for model calibration:

1 The model should reproduce observed values of suspended fine sediments to the right order of magnitude, including relevant spatial and temporal scales of variability and trends.

2 The model should reproduce observed net and gross fine sediment fluxes through the tidal inlets, through tidal channels, etc. to the right order of magnitude, including relevant spatial and temporal scales of variability and trends.

3 The model should reproduce observed values of channel siltation (dredging numbers) to the right order of magnitude, including relevant spatial and temporal scales of variability and trends.

4 The model response should be consistent with the conceptual picture/model described in Section 2.1. If it turns out to be impossible to reconcile the conceptual model with the numerical transport model, the former should be re-examined.

Sensitivity analyses with sediment transport models should provide insight in the most crucial processes that should get highest priority to be quantified. Uncertainty analysis needs to be applied to obtain insight into the reliability of models and their predictive power.

2.7 Summary modular action plan

The conceptual model is the basis for any research into fine sediment dynamics. This concept of how we think the system works, what the magnitude of the various horizontal and vertical fluxes are, how processes at different spatial and temporal scales interlink is the source for formulating hypotheses, to be tested with various research tools: numerical modelling, observations and experiments. Figure 2.1 shows a graphical representation of the links between the various components.

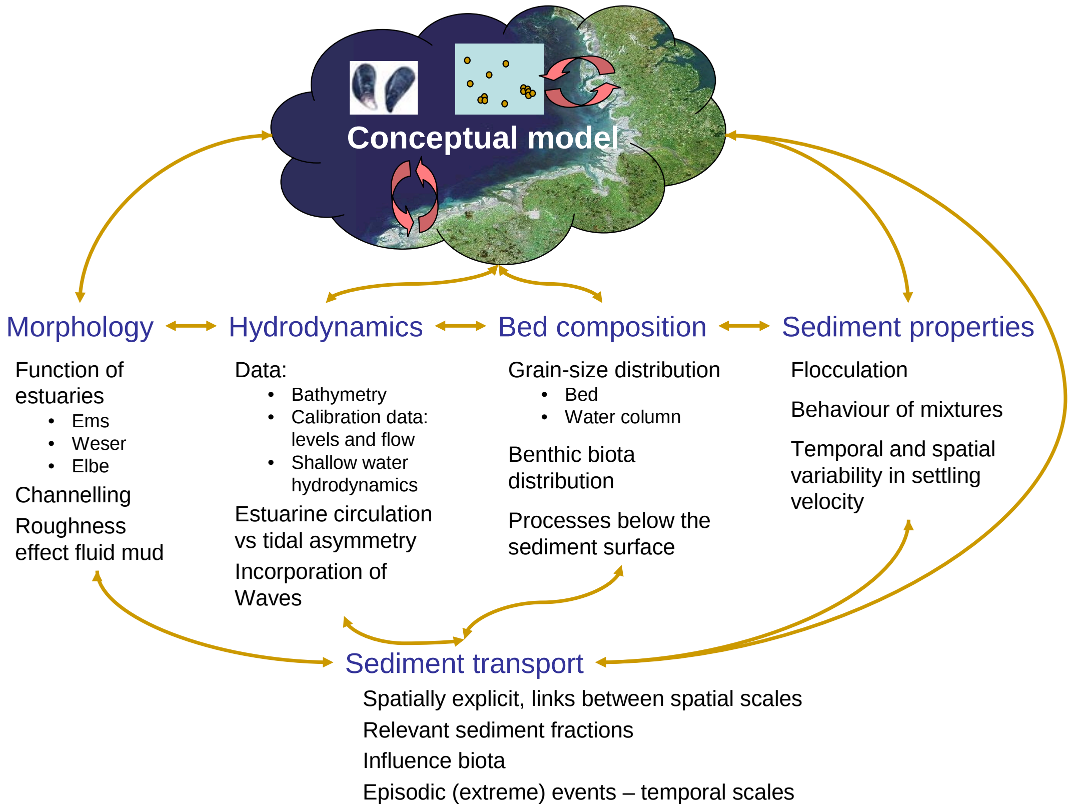

Figure 2.1: Graphic representation of the modular action plan. Note the bullets underneath the different modules are not comprehensive, more detail in the text of chapter 2.

We see this action plan as an iterative process with strong inter-links between the various components.

3 Methods

The aim of this exercise is to develop integrated system knowledge. This requires a suite of investigative techniques, comprising numerical modelling, field and remote sensing observations and laboratory and field experiments. The modelling section below specifically refers to computer models, either relatively simple analytical ones or complex spatially explicit ones.

At least as important as numerical modelling, is developing a conceptual model of what drives sediment dynamics in the Wadden Sea. Such a conceptual model has to be dynamic. It will be constantly updated by progressive insight into the various processes and how these interact, on the basis of results from modelling, observations and experiments.

3.1 Modelling

3.1.1 Classification of models and modelling

Numerical models are of great help in understanding the system, extrapolating trends, determination of human interventions, and interpretation of field observations. Despite the improvements made in the last decades on numerical aspects, parameterisation of processes and model usage, many main mechanisms determining the (fine) sediment dynamics are still poorly simulated, see Chapter 2. This is also caused by the lack of (reliable) field observations and the limited understanding of the system.

We propose the combined use of three types of models, discriminated by the schematization of the geometry: one-dimensional vertical models (1DV); one-dimensional horizontal models (1DH); and two/three-dimensional models (2/3D). Obviously, the level of detail increases from 1D till 3D models. However, also the computation time increases (significantly). Different types of models should not be used in competition, but complementary, enhancing each other (Hommes et al. 2007, Speelman et al. 2009). Another subdivision can be made on the use of models. We distinguish conceptual modelling and prognostic modelling. In conceptual modelling, the interpretation focuses on the mathematical behaviour of the equations and on ordering the mechanisms. This is especially helpful in understanding the system. In prognostic modelling, the emphasis is on determination of parameters for reproduction of data and prediction. This requires data on the same level of detail as the model schematization. Another way of describing is using qualitative modelling for conceptual modelling and quantitative for prognostic modelling. The difference between conceptual and prognostic modelling is not always straightforward. Conceptual modelling also needs some level of calibration and process analysis is also often carried out for prognostic modelling.

To understand the system and to answer the managerial and research questions, different model types and model approaches are to be employed. Especially the combination of models and approaches will give a robust answer.

The applicability of a certain type of model depends on the purpose of the study, the process and parameterisation and the available datasets for calibration and validation. These aspects are discussed below.

3.1.2 Model improvement

1DV models

A (stand-alone) 1DV module (model) is required for testing hypotheses and concepts for vertical exchange processes (i.e. mixing between water column and the bed) and also for mixing within the water column or the bed. It can directly be used for simulation of water-bed exchange processes on e.g. intertidal flats, but also for simulation of laboratory experiments. The simplicity of the geometry of a model allows for consideration of complex flow-sediment-biota interactions.

There are several 1DV model applications described in the literature (Le Hir et al. 2007, Burchard & Hofmeister 2008, van der Wal et al. 2010, van Prooijen & Winterwerp 2010). Direct comparison with field data and laboratory data is made. Figure 3.1 shows an example of the results of a 1DV model, applied at the Holland coast at Noordwijk. The General Ocean Turbulence Model (GOTM, www.gotm.net) is another example of a one-dimensional water column model combining hydrodynamic and turbulence modelling with biogeochemical modelling. Application of 1DV models for simulation of the interaction between hydrodynamics, sediment transport and morphology is done in e.g. (Willows et al. 1998, Orvain 2005, van Prooijen et al. 2011). These studies are still limited in reproducing laboratory experiments. Only a few examples of integrated models combined with field studies are available (Lumborg et al. 2006).

The model should be set up in such a way that it can easily be integrated as module in more complex models (1DH or 2/3D). The turbulence module of GOTM is a good example of such a flexible 1DV model, that is used in many three-dimensional models for the parameterisation of vertical turbulent exchange. In that sense it can be used as quick assessment tool for 1DH and 2D/3D models. At present, a framework for a 1DV model for water-bed exchange is in development within a Building with Nature project. Further model improvements are needed to make the module more general.

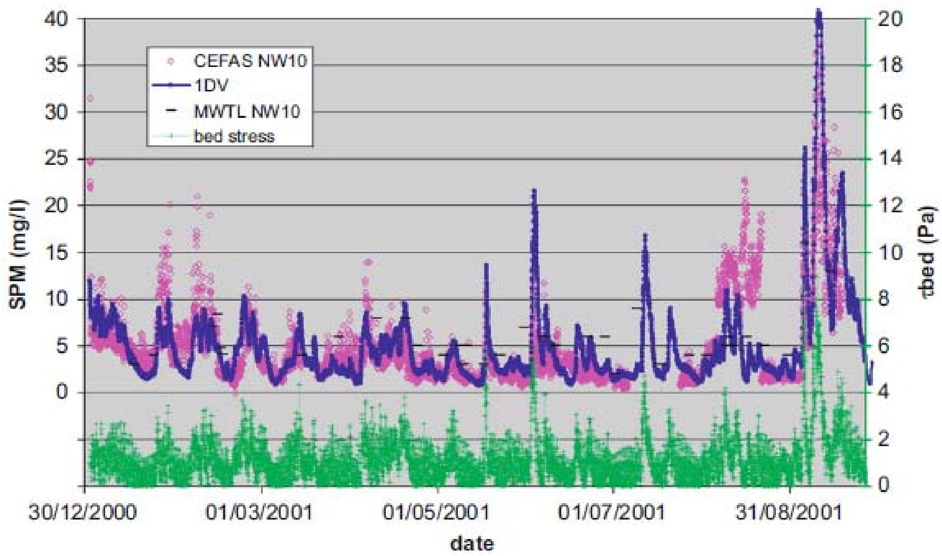

Figure 3.1: SPM values as function of time at Noordwijk. CEFAS NW10 (magenta) refers to the buoy measurements and 1DV (blue) refers to the model outcome. The bed shear stress (green) is plotted below (van Kessel et al. 2010).

1DH models
One-dimensional models are meant to determine the horizontal exchange processes under strongly simplified geometry. These 1DH models give a quick insight in the spatial effects on parameter variation. In that sense, they can also be used as pre-simulations to optimise parameter settings for 2/3D simulations (bearing in mind the differences in model schematization). The water-bed module as suggested in the previous section can directly be used. Different subtypes can be distinguished, from an inlet-bay system (Maas 1997), to a single channel (Schuttelaars & de Swart 2000, van Ledden et al. 2004), to a network of channels (Lorentz 1926). One-dimensional models can also be applied on a transect, e.g. a transect perpendicular to the dyke, covering the saltmarshes and the mud flat. There are examples from a model of a transect in the Humber Estuary (Wood & Widdows 2002).

At present, 1DH models are hardly used for the simulation of fine sediment transport in the Wadden Sea. Especially in combination with observations and 2/3D simulations, this type of modelling can however be of help in understanding the system (Stanev et al. 2009). We therefore propose to use 1DH models on basin scale, in order to get a first estimate of the net sediment fluxes at the mouth and to determine the sediment fluxes between channels and intertidal areas. Specific attention has to be paid to incorporation of waves, as these play a dominant role on the shallow areas. Multiple simulations should be carried out to estimate the sensitivity of the outcome to the specific parameters. Such simulations can be carried out over long periods (decades), which is a major advantage over parameterizations using 2D/3Dmodels.

2D/3D models
The geometries of the Wadden Sea and outer delta are best represented in a 2D schematisation of the bathymetry and geometry. Despite the increase of computer power and development of numerical algorithms, computation time is still limited. For the simulation of fine sediments in the Wadden Sea, three model packages are used: Delft3D, GETM, and MIKE. TRIWAQ/WAQUA has no sediment transport module.

Further model improvement is required for speeding up the simulations (or getting more accuracy).

1 Use of supercomputers. At present many simulations are still carried out on single processors. Parallel computation speeds up the simulations significantly. Improvements are to be made in accessibility of super computers and to improve scalability. More can and should be done to make modellers aware of the possibilities to use these facilities.

2 Sub-grid. Recently multi-grid approaches have been developed (Casulli 2009, Casulli & Stelling 2010). The bathymetry is defined on a high-resolution sub-grid. The computations are however carried out on a coarse grid, but taking into account the bathymetry on sub-grid. Acceleration factors of 10-100 can be achieved with a minimum reduction in accuracy.

3 Unstructured grids. Structured grids (Cartesian or curve-linear) have the disadvantage that some areas have unnecessarily high resolution, and that the bathymetry cannot be followed smoothly. Unstructured numerical grids have the advantage that they are flexible, although they require more computation time per cell. Unstructured grids are not per definition better/faster. Further exploration is however advised.

4 Acceleration factor. Morphological simulations are often accelerated by using a multiplication factor to the bed update. Such a factor is not tested sufficiently yet for simulation of multiple sediment fractions (so including fine sediment). Especially for simulation of the sediment distribution in the bed, it would help if such a procedure can be applied.

5 Additional to the flow and sediment modules, attention is required to the wave modelling. SWAN (Wood et al. 2001, Lettmann et al. 2009) is advised for the wave modelling. Not only the storm conditions, but also the normal conditions have to be considered.

3.1.3 Parameterisation improvement

The equations for hydrodynamics are well established. The transport equation for fine sediment contains however some unknown terms.

1 Erosion. The parameterization of erosion is still poor and highly based on calibration. A better erosion formulation is required, especially for mixed sediments. This should be done by means of a coupling between field campaigns, laboratory experiments and prognostic 1DV modelling.

2 Deposition. The deposition is determined by the flocculation process. Although there are various parameterizations of this process, it is still difficult to model it properly. This part should be coupled with field campaigns, 1DV modelling and laboratory experiments.

3 Multiple sediment fractions. Although it is not difficult to account for different sediment fractions from a numerical point of view, it is difficult from a parameterisation point of view, as cohesive sediments can flocculate, leading to interactions between the classes.

Specifically the effects of biota on sediment transport require more attention.

1 Process-based parameterisation. For many species it is qualitatively known how they influence hydrodynamics and sediment transport. A clear example is: vegetation reduces flow and wave energy, resulting in deposition of sediment. Less clear is the effect of bioturbators. They disturb the bed, but do they also change the critical shear stress and the erosion rate of the sediment? Do they remove the fine sediment only? For incorporation of biota in numerical models, a quantitative description is required. This implies a proper concept and parameterization. Examples of process-based concepts are presented for e.g. Hydrobia ulvae (Orvain et al. 2003) or Macoma balthica (Borsje et al. 2008, van Leeuwen et al. 2010, van Prooijen et al. 2011). Most of these models are however derived for a single species, still fairly complex and requiring multiple parameters. A stronger aggregation level is required for large-scale application. Definition of functional groups is however difficult and still somewhat arbitrary (Okamoto et al. 2009). Certain species, such as e.g. cockles are expected to have a destabilising effect at low to intermediate densities but a stabilising effect at higher densities.

2 Biota-biota interaction. Modelling individual species is not enough for the total effect of biota on sediment transport. For example: deposit feeders like Macoma balthica are hardly influencing the local shear stress. However, by eating and scratching the biofilm, they remove the biofilms and thereby affect the critical shear stress (Widdows et al. 1998, Andersen et al. 2005, Andersen et al. 2010, Weerman et al. 2010). Biota-biota interactions resulting in an effect on sediment transport are therefore important. Van Duren & de Jong (2009) also mention other interactions, such as: mussel beds stimulating the production of microphytobenthos, including biota-biota interactions in sediment transport simulations, requires ecological modelling as well and therefore cooperation with other research projects, such as those running within the NWO-ZKO programme (see for a brief overview appendix B). More fundamental knowledge has to be obtained from field campaigns. Analytical modelling will help in understanding the feedbacks and can give some indication of the spatial and temporal scales over which these interactions can have a significant impact on fine sediment dynamics. Prognostic modelling is, certainly in the short term, not expected to be feasible.

3 Spatial variation. Detailed numerical models for the Wadden Sea have typical grid sizes of ca 200m. Essential parameters such as bathymetry, sediment composition and biota vary over much smaller scales. E.g. mussel beds are in the order of 100m, with strong variations over meters (Figure 3.2). It will not be feasible to run the numerical models comprising the full Wadden Sea, over such small scales, but averaging the parameters over a full grid cell might result in errors as well. For example: averaging two sub areas with different critical shear stresses will not have the same effect as averaging the erosion rate of these areas. Spatial averaging of the processes is an essential, but difficult task. A multi-grid approach (Casulli 2009, Casulli & Stelling 2010) is advised. In such a method, the biology is taken into account on a small grid, whereas the hydrodynamics are computed on a coarser grid.

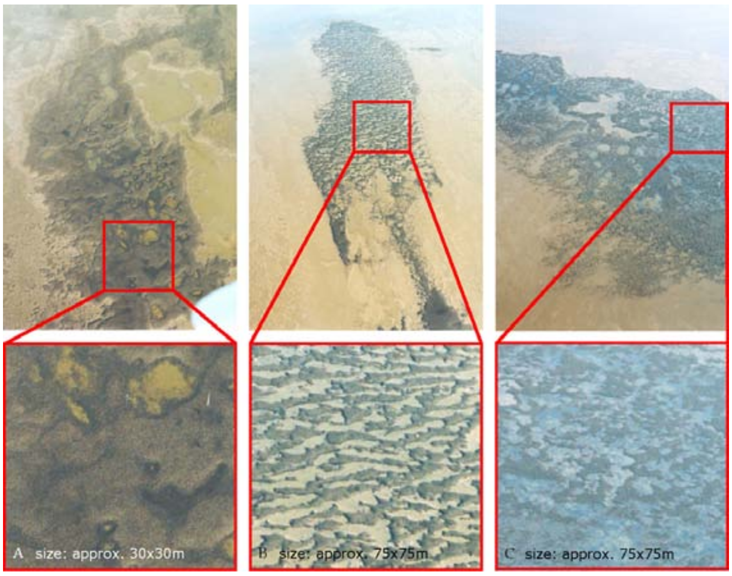

Figure 3.2: Spatial variation in a mussel bed (van Leeuwen et al. 2010).

4 Temporal variation The general perception is that biota influences sediment transport and morphology on seasonal scale and that abiotic processes dominate the long-term morphology (Le Hir et al. 2007). The small influence on long-term morphology is however questionable, as the calibrated “abiotic” parameters include biotic influences as well. Long-term biotic changes can result in a long-term morphological change. Further research is required to determine long-term effects of biota. A seasonal effect on sediment transport is expected, roughly: fine sediment is on the flats during summer and in the channels during winter. Storm events play an important role as well, for example on the effectiveness of biostabilisers. Important is the residence time of the fine sediments. Large areas of biofilms can be destroyed during a single storm. The same holds for mussel banks. Consideration of these events in the simulation is therefore important. The interaction between processes acting on different time scales requires further investigation.

3.1.4 Model usage

The outcome of the models is determined by the quality of the model (i.e. the parameterisation of the processes, resolution etc.), but also by the input and settings. Significant improvement is needed in the model usage:

1 Process reduction. A wide range of processes determine the transport of fine sediments. Taking into account all processes leads to unnecessarily long computation times. Proper knowledge of the dominant processes is required, examples are: “How many tidal components are required?”; “How important is wave-driven flow?”; “What is the influence of fresh water input by rain (run-off)?”; or “What is the effect of bio engineers on sediment dynamics on various time-scales?”.

2 Storm events. Storms can have a major (instantaneous) impact on sediment transport. The impact on longer term is less known. Simulations over longer times require schematization of the storm events. This schematization is especially difficult as the basins are dominated by locally generated waves, whereas the outer delta is more vulnerable for swell from the North Sea.

3 Sensitivity analyses. Most parameters in the model have an uncertainty range, one bigger than the other. The impact of the uncertainty is however not equal. An important aspect is therefore to determine the uncertainty of a parameter and the following impact on the results. The result of such an analysis helps in prioritizing future research.

It is advised to use all three types of models: 1DV; 1DH and 2/3D.

3.2 Field observations

Field observations are essential to help us understand the system. They are the basis for models and are necessary to validate model results. Field observations are urgently needed on fine sediment transport, coupled to data on parameters that will influence these transport processes such as flow, wind, waves, precipitation, as well as ecosystem engineering biota. It has become clear that the parameters that characterise the suspended sediments are important, not just data from the surface layers. It has also become clear that extreme events, such as major storms, which may be rare in occurrence, are very important for the average fluxes of fine sediment in the system. There is no single technique that will cover all data requirements. An integrated measuring programme is required with automated observation techniques that operate with high frequency, techniques that have a large spatial resolution. This combination unfortunately does not exist in one single instrument or technique, but has to be achieved through a combination of techniques (Doerffer et al. 2008).

In addition to automated operational observations, dedicated ship-based campaigns will still be needed to quantitatively investigate processes in the Wadden Sea relevant to sediment transport.

Certain processes such as sediment transport across water sheds are difficult to measure directly. Combining direct observations with indirect measurements will help to quantify these important parameters.

3.2.1 Observation poles and platforms

Presently, long-term observations on the amount of SPM in the water column in the Dutch Wadden Sea are available only from the monitoring that has been done by Rijkswaterstaat during the past decades. There is some additional information from other programmes (Marsdiep series, BOEDE, Eastern Wadden Sea and Ems estuary), but these often cover a limited area and some of these data series are several decades old. This present monitoring program consists of monthly surveys with a vessel where at a number of locations in the Wadden Sea water samples are collected. Subsequently a standard set of parameters, amongst which suspended particulate matter (SPM), is measured in these water samples.

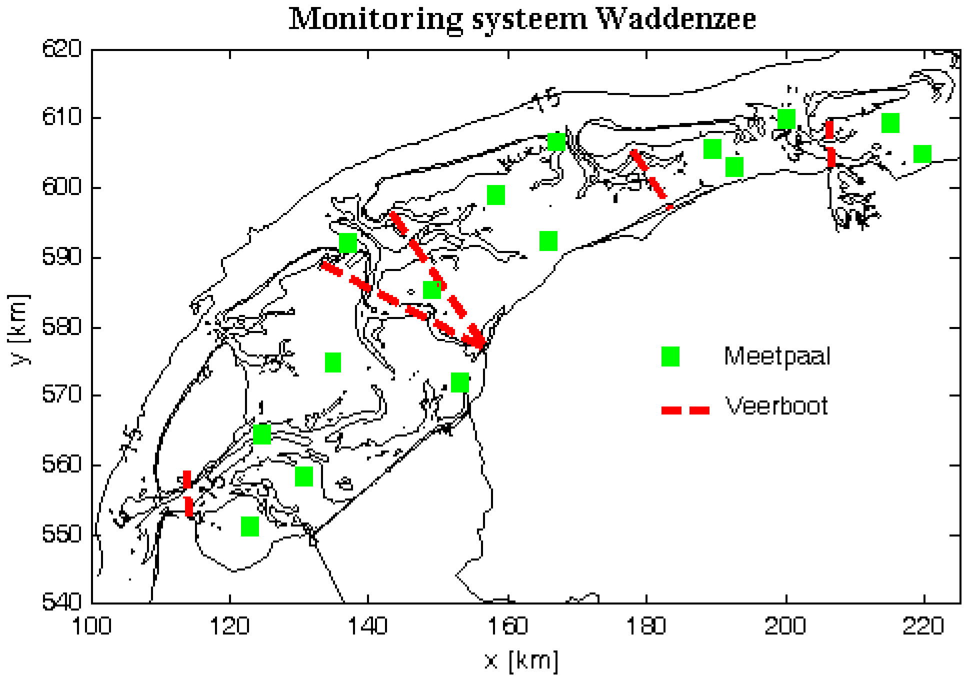

Figure 3.3: Indication of an optimal configuration of measuring poles (green squares) and ferry boxes (red dashed lines) throughout the Dutch Wadden Sea. This configuration ensures cover of several important inlets as well as areas further into the system.

However, technical developments during the past decades have given the possibility to obtain such observations, mainly by the introduction of sensors that can measure continuously. For instance, in the German Wadden Sea, a series of poles have been placed some 10 years ago, that measure parameters such as SPM and variables continuously. Such an observational system can provide information on the variability in the observed parameters. In the beginning of 2011 one similar pole will be placed on a tidal flat in the western Dutch Wadden Sea in the framework of a ZKO funded monitoring program.

Other possibilities are the use of ferries as a measuring platform. Since 1998 such a system has been installed on the ferries that sail between Den Helder and Texel through the Marsdiep inlet.

In order to obtain information for the entire Dutch Wadden Sea this system has to be extended, both by placing more measurement poles and by installing sensors on other ferries.

Figure 3.3 (above) sketches the desired, final, situation: sensors installed on all ferries in the Dutch Wadden Sea and measurement poles in all more or less separate tidal basins. In the sketched final situation we envision that in each of the 7 tidal basins both a pole is placed on a representative location in a tidal channel and similarly on a tidal flat. Of course, the exact location of these poles has to be determined after consultation with experts.

Such a system of continuous observations can provide the backbone of a Wadden Sea observatory. These observations will give the necessary information on the (natural) spatial and temporal variability of SPM concentrations (and fluxes) that are urgently needed in order to develop numerical models and to quantify the relative importance of all kind of anthropogenic influences.

Moreover, the necessarily uniform infrastructure (poles, communication etc.) will offer excellent possibilities to perform detailed process studies, e.g. on the effect of biota on SPM dynamics.

3.2.2 Hydrodynamic measurements

Sediment transport is enforced by the hydrodynamic shear stress due to tidal flow and waves. At present, these stresses are poorly known. Numerical models are not/hardly calibrated on flow velocities on the shallow areas. Measurements of both tidal flow and waves are therefore essential. With recent technical improvement in ADCP technology, stand-alone equipment, suitable for measuring in very shallow water has become available and affordable. Such devices are already in use in a regular monitoring programme in the Westerschelde in Zeeland. Such portable, stand-alone devices for flow as well as for waves should yield essential information for model calibration and validation. Where possible they can be used in combination with a pole. Beside standard observations of currents and sediment concentrations, measurements of temperature, salinity and turbulent quantities are also needed to better quantify the driving forces for sediment transport.

Another technique that is successfully employed in other coastal observatories, yielding a synoptic view of surface flow velocities and waves is radar (Wyatt et al., Howarth et al. 2006). HF-radar has been tried and tested in coastal observatories (Howarth et al. 2006). In the tidal inlet of Ameland X-band radar has been used successfully, which has a smaller range but a much finer resolution, making this technique suitable for use in areas with high spatial diversity in hydrodynamic conditions. The technique still needs extensive validation but it has great potential for validating and calibrating models (Doerffer et al. 2008).

3.2.3 Sediment composition

It is essential to obtain comprehensive information on sediment composition. Within the NIOZ SIBES (Synoptic Intertidal Benthic Survey of the Wadden Sea, funded by NWO-ZKO and the NAM) programme the Dutch Wadden Sea is sampled for benthic biota and sediment composition on a 500*500 m grid. This is done annually. Currently, the bulk of the sediment samples still need to be analysed. However, as the samples are already taken, this would be an important and relatively low-cost action to obtain a reasonably fine-scaled dataset on surface sediment composition. We have not yet made an inventory of data sets available in Germany and Denmark. This is a first step to be taken.

In addition to datasets based on samples, remote sensing can be used to get a synoptic image of sediment distribution and silt content of mudflats (van der Wal & Herman 2007). However, particularly for sediment composition, this technique needs ample ground truthing as the error on such measurements is relatively large due to effects of e.g. interference with water on the flats and the presence of biogenic structures.

3.2.4 Benthic species composition

Data need to be available regarding the distribution in space and time of ecosystem engineering species. Ecosystem engineers work at different spatial and temporal scales (Le Hir et al. 2007). Only saltmarshes can work as a more or less permanent sink for fine sediment, epibenthic shellfish beds have a ‘life expectancy’ of a few decades, while the cover of sediment with diatom mats changes with the season and the tides. However, diatom mats can cover vast areas of intertidal mudflat, while e.g. shellfish beds will seldom cover more than 5% of the total surface area. It is therefore essential that we have information on the distribution of those species that are either able to fix fine sediment over long time scales and thereby may have an effect on landscape morphology, or on those species that have a very wide distribution and are capable of changing important parameters such as critical shear stress for fine sediment over a large surface area. The latter species may not have a long term effect on sediment fluxes, but if they have an effect over e.g. the summer season, when benthic primary productivity is highest, they may have an influence on ecosystem functioning.

Species groups, such as benthic diatom mats, may cover a very substantial part of the intertidal area, but these structures can be ephemeral in nature. Appearing rapidly in spring, disappearing after storms or when hyper benthic grazers increase in density. Particularly for benthic diatoms remote sensing techniques offer excellent possibilities, as these techniques yield wide spatial coverage (van der Wal et al. 2010). However, remote sensing data are restricted by the presence of cloud cover. This means that in periods immediately following large storms, when major changes are expected, remote sensing may have limited use. This technique on its own will not cover all the data requirements.

The NIOZ programme SIBES (mentioned above) collects data from the whole of the intertidal part of the Wadden Sea. The subtidal parts are much less extensively sampled (an exception being the IMARES, subtidal mussel bed surveys). There is certainly a need for more spatially explicit data of the deeper channels. Some areas are known to be covered by old layers of shells and also the position and cover of subtidal mussel and oyster beds tends to show large variability, but is much less well mapped compared to intertidal beds. There are also some other gaps in this current database. The method of sampling under-estimates large deep-living species such as Ensis and Mya. Due to the influx of very high numbers of the invasive species Ensis directus, and the more or less simultaneous disappearance of the shellfish Spisula subtruncata, there has been substantial effort in recent years to develop new sampling gear that allows quantitative sampling of Ensis. However, currently there is no comprehensive current overview of the densities of deep living fauna in the Dutch Wadden Sea. Some older data sets are available (Mulder & van Arkel 1980), however these tend to pre-date the changes in the composition of benthic fauna due to invasions such as the (Crassostrea gigas – the Pacific Oyster and Ensis directus -- the American Razor Clam.

Seagrass meadows (Zostera noltii, Zostera marina and Ruppia maritima) are extensively and regularly monitored (van Katwijk et al. 2006). Until 2011 this monitoring was carried out on an annual basis. From 2011 this will be reduced to once every 3 years. At present there is no longer any perennial submerged population of Zostera marina in the Dutch Wadden Sea, as there has been before the nineteen thirties. The extensive fields of seagrass then may well have influenced sediment dynamics within some tidal basins of the western Wadden Sea. The current relatively sparse populations are located in the intertidal. Z. marina is only present in summer and has to re-grow every year from seed, while Z. noltii is a perennial species but it has no above ground biomass in winter (only extensive root systems). Currently for the Dutch part at least no extra monitoring is required for seagrass, nor in Germany (Doerffer et al., 2008).

Saltmarshes are also well mapped and for most locations there is reasonably good data available on accretion rates of sediment inside the saltmarshes (Dijkema et al. 2008).

3.2.5 Measurements on sediment erodability and erosion rates

Sediment composition alone and sediment composition combined with data on the presence of biota will give some indication of actual sediment erodability in the field, but other factors, such as sediment consolidation, and compaction will also determine how easily particles can be resuspended. Until recently the most common approach was to combine techniques for hydrodynamics measurements with high-resolution acoustic techniques to record bed level heights (Andersen et al. 2006). Several techniques have become available in recent years to quantify critical shear stresses in the field for resuspension and sedimentation of sediment and for shear strength of sediment. Acoustic methods, originally developed to analyse hydrodynamics (ADV) have been successfully deployed to assess thresholds for erosion and deposition (Andersen et al. 2007). Deltares has a new method, using injection of gas bubbles into the sediment and analysing the failure thresholds (i.e. critical forces required to erode sediment) that can be deployed in the field.

Also, the Centre for Estuarine and Marine Ecology is busy developing a field wave tank that can be placed in situ on various types of sediments and biota and used to estimate critical erosion thresholds. Other techniques that can be deployed in the field include the EROMES device, which also determines critical shear stress for erosion (Andersen et al. 2010).

Despite these new developments, no objective and widely accepted instrument is yet available for determination of the critical shear stress.

3.2.6 Indirect methods for assessing transport rates

In particular transport across watersheds is difficult to measure directly. However, due to the characteristics of cohesive sediment, particles not only easily bind to each other, but they also easily adsorb contaminants, such as heavy metals. These heavy metals do not decay in the system and are quantifiable in minute concentrations. Over the past decades fine sediment contaminated with cadmium gradually “travelled” from the Western Wadden Sea towards the eastern part. These analyses on contaminants can help provide additional information regarding net transport rates of fine sediment on the time-scale of decades (Laane et al. 1999). From some of the transport patterns we may deduce whether transport took place over the watershed, or via the North Sea.

3.3 Experiments

We know that there are many processes that need better quantification in order to develop models that can ultimately be used as management tools. It is not possible to present an exhaustive list of these processes and what particular methodology is required to quantify them. Prioritising these processes will be largely dictated by insights gained from the combination of observed correlations of processes in the field and modelling. In particular modelling should be the main tool to ascertain which gaps in our process knowledge are most pressing.

Certain gaps regarding erosion parameters can already be identified as being relevant on a large scale: effects of consolidation, drying out and rewetting (e.g. over a tidal cycle) and effects of freshwater and rainfall on the erodability and net transport of sediment. Most models are currently based on sediment composition. However, this parameter on its own is not sufficient to accurately describe erosion thresholds. Another factor is the behaviour of mixtures of different sediment fractions and the effect this has on sediment transport and the effects of organic carbon compounds on the behaviour of fine sediment, both in the water column and in (or on) the bed.

Regarding biota, it is likely that in an early stage attention will be drawn to certain groups of species that have recently colonised the Wadden Sea in very large numbers, but require further investigation regarding their net effect on sediment stability. Examples are e.g. Pacific oysters (C. gigas) and the American Razor Clam (E. directus). Other species groups that will probably require further experiments are those that are likely to have a system-wide impact due to the large spatial cover, such as diatom mats. There are likely to be seasonal variations in microphytobenthic binding of fine particles, which will in turn affect the critical shear stress of the bed over very large surface areas.

In addition to lab experiments, (relatively) large-scale field experiments are very valuable to give insight in the larger scale effects of biota. Exclusion experiments and defaunation experiments can yield important information on the bulk effect of biota under natural conditions, that cannot be obtained in lab facilities (Volkenborn et al. 2009).

Identifying what type of experiments are most essential to get a grip on fine sediment dynamics in the Wadden Sea will be an iterative process, requiring strong cooperation between researchers of different disciplines.

3.4 Integrated large-scale pilots

For certain specific problems, large infrastructural measures may mitigate or even solve the problem. For some of these issues large scale pilots, preceded by model exercises and surrounded with targeted monitoring campaigns can yield very valuable knowledge. This is only feasible for problems where the cause of the problem is already largely identified and particularly, if the cause of the problem is human induced. A good example is the large increase in fine sediment in the tidal basin and the mouth of the Ems-Dollard (Chernetsky et al. 2010). As described in section 2.2 the most likely cause for these problems lie in the extensive dredging of the shipping lanes, which has, over time changed the morphology of the system and thereby changed tidal asymmetry and the hydraulic roughness of the system (De Jonge 1983, De Jonge & De Jong 2002, Chernetsky et al. 2010). In such cases, changes to e.g. the width of the mouth of the estuary, combined with adaptive dredging strategies (as are currently developed in the Schelde Estuary) may be extremely useful. However, this is only advisable when there is consensus among the experts about the factors behind the problem. Such large-scale experiments also carry a certain amount of risk. Before contemplating such measures we have to be reasonably sure that the cure is not worse than the disease. Although the basic driving forces are known, for most tidal basins of the Wadden Sea we do not know how they quantitatively influence fine sediment dynamics. I.e. we lack information on the ratio of effects of various horizontal and vertical transport mechanisms and we lack essential knowledge on boundary conditions. Therefore the scope for such large-scale pilot experiments is limited.

4 Phasing of the work

4.1 Highest priorities (first 2-3 years)

The priorities of the various activities are defined by the questions addressed in the introduction to Section 2.

The first aim of the project is to obtain a proper understanding and quantification of the temporal (daily, seasonal, annual) and spatial variation of suspended sediment concentration and fine sediment fraction in the bed. This includes modelling and field measurements.

The largest unknown concerns the fine sediment budget of the Wadden Sea, its sub-basins, and fine sediment import and export through the tidal inlets, and over the water sheds between the sub-basins. Currently no single (measuring) method exists to resolve this issue. Therefore, we have to rely on a combination of methods, each of which should resolve a piece of the puzzle. In particular, the following activities are anticipated in the first phase of the study:

- Install two measuring poles (anchor stations) on two watersheds in the Wadden Sea to measure water levels, flow velocities, wave conditions and SPM-concentrations over longer time periods, assessing sediment fluxes as a function of ambient conditions. In the German part of the Wadden Sea several such stations are already in place (Flöser et al. 2009) and the data accessible through the Internet (www.cosyna.de). Due to the expected differences in functioning of tidal basins it is imperative that such observational data become available from the Dutch tidal basins as well. Within the framework of the NWO project "In Place" (see Appendix B, section 2.1) one such station has recently become operational on the Balgzand. One other one should be placed in one of the eastern tidal basins.
- Velocity and wave measurements on the tidal flats. This information is essential for calibration of the numerical models. At present, the hydrodynamic models are only calibrated on measurements in the deeper channels.
- An urgent action concerns improvement of the computations of the water movement, as today the quality of the results hampers improvement of the modelling of transport and fate of fine sediments. One issue is a proper representation of the bathymetry at sufficient detail. This modelling is also programmed within the framework of the SBW program, a project to improve water level and wave height predictions along the Wadden Sea coast. A joint effort would speed up progress of this activity.
- Determine sediment composition in the Wadden Sea seabed, and their seasonal variations. As it is not possible to carry out a space-covering sampling program, we propose two approaches:
    - Analyse the samples from the SIBES monitoring programme as soon as possible.
    - Select limited areas around the two measuring poles, from where samples are to be taken twice a year. These sites (and their extension) to be assessed from preliminary model simulations,

- Develop and use innovative techniques to establish sediment composition from remote sensing techniques. One possibility is the use of multi-beam surveys – this technique cannot be applied everywhere because of depth limitations. A second method was developed at NIOO (Daphne van der Wal) using reflectance as a proxy for sediment composition. An excellent summary of the state of development of various novel technologies can be found in the "Atlas of Advanced Monitoring techniques" (Doerffer et al. 2008).
- Check the availability of such datasets in Denmark and Germany. For the Hörnum basin there are data available (Riethmüller, pers comm.).

- Establish properties of sediments in water column and within seabed – currently we have no data at all on these important physical parameters:
    - Grain size and settling velocity distribution with the new "slib camera" of Deltares,
    - Erodability of the seabed through analyzing a variety of soil mechanical parameters.
- Analysis of the dispersion of cadmium-containing sediments – the legacy cadmium contamination disperses slowly through the Wadden Sea, and as such forms a tracer for large scale and long term transport of fine sediment and some additional information on transport routes.
- Sensitivity analyses with the available numerical tools to assess the response of the model results to variations in boundary conditions, meteorological forcing, sediment composition and properties, etc. A model system that includes flow, waves, salinity, turbulence and sediment transport for the entire Wadden Sea needs to be developed in a stepwise approach.
- Sensitivity analysis to properties of variables in the model that can be influenced by biota, such as critical shear stresses over large scales (i.e. possible effects of diatom mats) and smaller patches (e.g. effects of mussel beds), sinking velocities of flocs outside the Wadden Sea (i.e. possible effects of algal blooms on transport rates of fine sediment to the Wadden Sea)

4.2 Mid-term activities (3-7 years)

The results of this phase of the study will guide developments and improvements of the fine sediment transport model. As stated before this will be an iterative process between model development and observations. These two 'pillars' will fuel our understanding of the main drivers and interactions of drivers working on sediment dynamics. These will also determine the priorities for additional experiments to quantify certain parameters.

The period 3-7 years from now should see a strong merging of ideas and methods from the more fundamentally driven research under the NWO-ZKO programme, including the cross-border projects with German counterparts.

4.2.1 Model development

Within the current larger modelling packages (Delft 3D, GETM and Mike) a start should be made to incorporate not only a multilayered parameterisation of movement of sediment in the water column, but a start should be made with coupling the water domain to dynamic processes within the sediment that influence essential parameters such as critical shear stresses. Furthermore in this stage coupling should commence between biological processes and sediment dynamics.

4.2.2 Observations

After 2014 the Waddenfonds project WaLTER should have delivered better access to existing data sets and set out a plan for a comprehensive monitoring programme for the Wadden Sea. This comprehensive programme should obviously include hydrodynamic and fine sediment measurements, although for certain activities additional measurements will remain important. Links should be established and extended between de Dutch scientific community and the German groups involved in the COSYNA network (see www.cosyna.de). In the SedOBS section there several new methods are developed for sediment water exchange processes, e.g. small scale morphological and sediment related measurements with a Lander, ADCPs, Nortek Velocimeter, LISST 100X, UNISENSE Eddy Correlation Scanning Sonar etc.).

4.3 Long-term activities (7-15 years)

The exact longer term activities will strongly depend on the progress made in the first two stages. By 2018 we already should have much better insight into the fluxes in and out of the system and how these vary over longer and shorter timescales, as well as insight into the temporal and spatial variability of the vertical fluxes. This should already be a major step forward in a frame of reference for assessing whether certain human activities have a significant effect on fine sediment, or whether these effects are negligible in comparison to the natural dynamics of the system.

5 Research coordination

This document was instigated by the Wadden Academy. In the Netherlands the Wadden Academy (http://www.waddenacademie.knaw.nl) has established itself as an influential advisory body bringing much needed coordination in ecosystem research in the Wadden Sea. The Wadden Academy was established in 2008 and has already proved its worth in bringing together scientists from different disciplines, as well as establishing an integrated ecosystem approach to research. The Wadden Academy is meanwhile recognised both by the scientific community and by policy makers and ecosystem managers as a suitable body to advise on research priorities and possibilities for cooperation.

The issues discussed in this document make clear that there is a substantial amount of work required to gain sufficient insight in fine sediment dynamics in the Wadden Sea. It is clear that there is no single large fund available to fund this type of research, but that researchers and policy makers will have to combine funds and projects as efficiently as possible. A good balance will have to be found between making opportunistic use of possibilities and funds that crop up and a solid backbone of ecosystem monitoring and modelling from regular funds. Only making use of local monitoring efforts and pressing local problems is not going to yield the required integrated ecosystem knowledge.

With the regular symposia of the Wadden Academy and the many consortia that are formed for Waddenfonds projects, coordination of research within the Netherlands is logistically not too difficult. However, there would certainly be a lot to gain from more international cooperation and international coordination. There appears to be a lot of cross-border cooperation among individual scientists in various projects. However, an international platform where both scientists and policy makers can meet and discuss priorities in questions and in research to provide answers would be very useful.

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A Appendix A: Knowledge gaps

Over the past years a number of developments have taken place in the Netherlands that are relevant to the management and research of the Wadden Sea. Established on 30 July 2008, the Wadden Academy has the task of providing a sound scientific basis for the management of the natural and social values represented by the Wadden Sea Region. They have produced a research agenda aimed at integrating not only the various disciplines of the natural sciences, but also promote integration between natural scientists and economists, historians, sociologists, psychologists, anthropologists and cultural scientists. The Integrated research agenda is built on various position papers on various sub-disciplines. These position papers identified the most important knowledge gaps in the specific fields. Both the position paper on geosciences (edited by Hessel Speelman) and the one on ecology (edited by Peter Herman) have immediate relevance to the dynamics of fine sediment in the system. The essential points for this plan of action are summarised below.

Furthermore from negotiations between the shellfish sector and various nature conservation NGOs, a nature restoration programme has been set up in 2009. This programme was entitled “Towards a Rich Wadden Sea”. The earlier name “Nature Restoration Programme – Wadden Sea” was abandoned in recognition of the fact that “restoration” is a redundant term in a system where many autonomous factors and anthropogenic influences ensure that the system is continuously changing and reversal to a historic situation will never be possible. This programme was based on 5 “building blocks”, two of which have an immediate relation with fine sediment dynamics. These building blocks also identified the need for gaining more information regarding fine sediment dynamics and identified possible lines of action to improve the natural quality of the Wadden Sea while improving our understanding of the system.

A.1 Wadden Academy

Overarching theme in the research agenda is the need for better integration of disciplines. Both the Geosciences paper and the Ecology paper stress the need to quantify essential fluxes, horizontal and vertical of water, sediment and biota.

A.1.1 Geosciences

The theme of Wadden Sea Region Evolution

- The natural dynamics on the islands (overwash, storm erosion and aeolian sand transport) and the robustness of the islands in different sea-level rise scenarios.
- The dynamics of salt marshes, flats and channels and outer deltas in different sea-level rise scenarios.

- The effect of humankind as a ‘geological force’ on the Wadden Sea Region from Roman times up to and including the twenty-first century.

Theme of Wadden Sea Morphodynamics

- Detailing of the sediment balance for both sand and fine sediment (including the impact of sand nourishments) of the Wadden Sea Region related, inter alia, to the erosion of the North Sea coast. Aspects of this are the inaccuracies and uncertainties of available data, the frequency of bathymetric measurements and the classifications used in the Wadden Sea classification systems.
- Forecast of the dynamics of the tidal inlet systems likely to occur in the Wadden Sea Region. An outer delta, the adjacent island points, the tidal inlet, the channels and the flats of a tidal inlet system form a single unit.
- Quantification of the processes over an engineering timescale, interaction between these processes (water movement, sand and fine sediment transport, soil changes) in the Wadden Sea.
- Development of modelling tools both through the implementation of improvements in physical-mathematical formulations and improved data.

Cross-domain gaps
Gaps in knowledge that extend across disciplines and domains are of a higher order. Such gaps can only be reduced by combining data and knowledge from different domains. From the point of view of the physical development of the Wadden Sea Region in time and space, these include:

- together with the ecology domain: The effect of biological processes (ecosystem engineers) on soil characteristics and vice versa (biogeomorphology).The statement and prediction of insight into the Wadden Sea is closely connected to this. The interactions of terrestrial vegetation with changing fresh-salt gradients in response to seepage and infiltration;
- together with the climate domain: The impact of climate change (sea-level rise, storm regimes) on the morphodynamics of the tidal flats resulting in swamping, silting up or the continuation of the current situation. Reconstruction of paleoclimate trends. Design and evaluation of interventions to improve coastal defences.

A.1.2 Ecology

Below is a summary of the major knowledge gaps identified in this position paper. Some points have only an indirect relationship with the dynamics of fine sediment in the system (such as processes related to food web dynamics). However, also in these bullet points references are made to the need to quantify vertical transport (i.e. benthic-pelagic exchange) and horizontal fluxes.

- A better understanding of bottom-up processes in the food web. Greater attention focused on pelagic processes and benthic-pelagic exchange. Predictive capacity. Attention focused on exchanges at the boundaries, with the adjoining North Sea and international parts of the Wadden Sea Region.
- A better understanding of the interaction between organisms and physical processes, particularly as regards the dynamics of fine sediment in the system.

- The biological interactions in the system, particularly those interactions that can show a positive feedback, which could give rise to threshold values in the dynamics, require further research.
- Comparative research with other tidal flat systems. This provides an opportunity to subject 'top-down regulation' mechanisms to a critical examination, to compare different types of management and to study a sequence of system conditions at different levels of human pressure.
- International connections of the Dutch Wadden Sea. Analysis of functional relation between habitats connected to the Wadden Sea. Important connections are migratory birds that form a link between Arctic breeding grounds, tropical wintering areas and the (international) Wadden Sea, but current patterns, nutrients and climate also connect the water in the Wadden Sea to processes on a much larger scale.
- Changes can be expected in the Wadden Sea as a result of global change but the form they will take is almost completely unpredictable. Targeted long-term monitoring is required. This could also form the ideal background for process-oriented research. The environmental consequences of mitigation measures such as sand nourishments must be monitored.
- There is a need for an integrated strategic vision and an evaluation process for human activity in the region. To do so, attention must be paid to the cumulative aspects and the interconnections between different activities; the evaluation must be interdisciplinary, aiming at future sustainable development, taking into account external and diffuse disturbances and concentrate on the Wadden Sea as a whole. Evaluations must seek international attention by treating the Wadden Sea as an example of regions essential to the global ecosystem. There is a need for a much clearer definition of ecological values in the Wadden Sea that takes account of expected future changes, governance structures and the need to safeguard the essential qualities of the region.

The main interfaces with other disciplines are:

- Biogeomorphological processes and their integration into the modelling of the dynamics of fine sediment, sand and geomorphology, both on the supra-littoral areas and on the tidal flats.
- Development of probable scenarios for climate change and its consequences for the ecology of the Wadden Sea Area. Integration of ecological studies with monitoring efforts and process studies directed at the causes and effects of climate change.
- Research into the basis of the ecological values in the Wadden Sea, taking into account the cultural, social and economic dimensions of the problem; iconising species in relation to image creation and policy.
- Integration of ecological and economic aspects of research into human interventions in the system, focusing particular attention on the integration of natural values as a non-use value in the economic estimates.
- Research into governance structures in which the unique role of the Wadden Sea Region for the world ecosystem can be given a correct valuation and in which the management of the Wadden Sea Region can serve as a model for other ecosystems of world importance.

Infrastructural preconditions for bridging these knowledge gaps are:

- Consistent monitoring of basic variables in the ecosystem, linked to modelling bottom-up processes in the food chain.

- Extrapolation of observations in time and space and consistent modelling of exchanges with peripheral areas are required.
- Integration of geomorphological and ecological research, modelling and monitoring. Developing a methodology and tradition of integrated long-term policy development and evaluation, combining natural, social and economic sciences. This requires a great effort from the natural sciences to incorporate their observations in an evaluation process.
- A meeting place for natural scientists, social scientists, artists and opinion leaders in which the value system around the natural environment in the Wadden Sea Area can be studied and examined more explicitly.

A.2 Programme Towards a Rich Wadden Sea.

A.2.1 Building block “sea bed and water column”

The Programme “towards a Rich Wadden Sea has formulated an objective that it is desirable that the Wadden Sea should have less fine sediment in suspension. This report states that there are considerable amounts of sediment transported in and out of the system through the tidal inlets, but the largest source of sediment in the water column originates from resuspended local material. Fine sediment in the bed can be resuspended by erosion. Biota can either reduce or enhance resuspension. Also anthropogenic effects can have an effect. Most notably, the closing off of (parts of tidal basins, reducing the volume of basins changed flow patterns and reduced the surface area of shallow sheltered intertidal area, where fine sediment can settle. Also, dredging and bed disturbing activities such as (shrimp) fishing can affect sedimentation.

From the available measurements it is not possible to conclude univocally whether the system has become more turbid over the past decades or not, apart from the Eems-Dollard estuary, where long-term morphological changes due to land reclamation, channelling and deepening have lead to substantial morphological and ecological changes.

This document advises to

- Tackle the problems with fine sediment in de Eems-Dollard estuary in a separate project and to give this project high priority.
- Integrated system monitoring and analysis of the rest of the Wadden Sea to assess what drives the sediment dynamics in the system.
- Measures to reduce the need for dredging in the system
- Look for opportunities to apply more natural structures as coastal defences (e.g. saltmarshes) that increase the ability of the system to adapt to processes such as sea level rise.

A.2.2 Building Block “ecosystem engineers”

The Programme Towards a Rich Wadden Sea has currently formulated the objective to increase the number of species and the cover of sediment stabilising ecosystem engineering species. The arguments for promoting such species are not only concerned with their function in fixing fine sediments. An important function of many of these ecosystem engineers is that the biogenic structures of these organisms provide a habitat for other organisms. Within this document (van Duren & de Jong 2009) a table has been compiled listing the major groups of ecosystem engineers, the spatial and temporal scales on which they act and whether they are sediment stabilisers or destabilisers. This table should provide a good first directive on which species to focus. It is reproduced on the next page with the addition of Ensis directus as a potentially powerful ecosystem engineer of which little is known about its net effect on sediment stability. This building block has furthermore looked at several groups of sediment stabilising ecosystem-engineering species such as:

- benthic microalgae
- seagrasses
- mussel beds and oyster reefs in the littoral zone
- mussel beds and oyster reefs in the sub-littoral zone
- other invertebrates such as Sabellaria spinulosa, Lanice conchilega en Sertularia cupressina

There are still a lot of unknowns regarding processes influenced by ecosystem engineers and interaction between biota and ecosystem engineers. Specifically, factors influencing the settlement of these species are identified as important.

One of the factors that is likely to limit the probability that ecosystem engineers can settle in an area is direct bed disturbance. This document also recommends research into the effects of bed disturbance on the carrying capacity for various ecosystem engineers.

Ecosystem engineers in the Wadden Sea

Group	Species	Type of effect (abiotic)	impact on sediment dynamics	magnitude of impact	Type of effect (biotic)	Current state	restricting factors	probability of population increase
Microalgae	Diatoms	reducing critical shear stress, gluing sediment particles together	sediment stabiliser, reduces turbidity	minor, local, seasonal	food for shellfish and other invertebrates	sand flats less productive than mudflats with high silt content	light, silt availability, nutrients	++
Seagrasses	*Ruppia maritima*	alters near bed fluid dynamics, reduces sediment resuspension	sediment stabiliser, reduces turbidity	minor, local	refuge for juvenile fish, settlement of invertebrates	expanding	light, salinity, bed disturbance by fisheries	+++
	Zostera noltii	alters near bed fluid dynamics, reduces sediment resuspension	sediment stabiliser, reduces turbidity	minor, local	refuge for juvenile fish, settlement of invertebrates	slightly increasing trend over the last decade, small populations. Some replanting efforts successful	light, nutrients, hydrodynamics, bed disturbance by fisheries, seed populations	++
	Zostera marina (flexible)	alters near bed fluid dynamics, reduces sediment resuspension	sediment stabiliser, reduces turbidity	moderate, local	refuge for juvenile fish, settlement of invertebrates	Limited number of small populations present, restricted mainly to eastern part. Restoration efforts thus far not successful	light, nutrients, hydrodynamics, bed disturbance by fisheries, seed populations	+
	Zostera marina (robust)	alters near bed fluid dynamics, reduces sediment resuspension	sediment stabiliser, reduces turbidity	significant	refuge for juvenile fish, settlement of invertebrates	extinct	light, nutrients, hydrodynamics, bed disturbance by fisheries, seed populations	-
Shellfish	*Mytilus edulis*	reef building, alters near bed fluid dynamics, reduces sediment resuspension, filtration of algae and sediment, changes in sediment composition, changes in nutrient recycling rates	sediment stabiliser, reduces turbidity	very high, larger scale	Protection of mussels against dislodgement, settlement of mussel larvae and other invertebrates, food for birds	Increase after nineties, stabilisation over the past decade, recruitment strongly variable	mussel (seed) fishing, primary production, presence of Pacific Oyster???	++
	Crassostrea gigas	reef building, alters near bed fluid dynamics, reduces sediment resuspension, filtration of algae and sediment, changes in sediment composition, changes in nutrient recycling rates	sediment stabiliser, reduces turbidity	very high larger scale	Protection against dislodgement, promotes settlement of Pacific oyster larvae and other invertebrates, captures mussel larvae	expanding rapidly	not much	+++
	Ostrea edulis	reef building, alters near bed fluid dynamics, reduces sediment resuspension, filtration of algae and sediment, changes in sediment composition, changes in nutrient recycling rates	sediment stabiliser, reduces turbidity	significant	Protection against dislodgement, promotes settlement of flat oyster larvae and other invertebrates, captures mussel larvae	extinct	primary production, fisheries, competition, notably by *C. gigas*	--
	Ensis directus	bioturbator, very active in the sediment, tends to bury deep into the sediment	toally unknown, effects probably density dependent	totally unknown, likely to occupy a large area		expanding rapidly		
	Cerastoderma edule	bioturbation, active resuspension of fine sediment, reduction of stabilising benthic algae	sediment destabiliser, increases turbidity, stabilising at very high densities	moderate - significant	food for birds	strong fluctuations in recruitment and total available biomass	mechanised cockle fishing (prohibited), primary production, bed disturbance by fisheries	++
Other invertebrates	*Sertularia cupressina*	alters near bed fluid dynamics, reduces sediment resuspension	sediment stabiliser, reduces turbidity	very minor (species occurs on hard substrate)	settlement of invertebrates	large meadows have completely disappeared, seed populations available in North Sea	Presence of suitable hard substrate, other factors not well established	++
	Sabellaria spinulosa	reef building, small-scale fluid alteration near the bed, reduces sediment resuspension, particle capture	sediment stabiliser, reduces turbidity	moderate - significant	Habitat for certain epibenthic fauna	extinct	bed disturbance by shellfish fisheries and dredging, substrate, hydrodynamics	+
	Balanus sp.	none	none	very minor (species occurs on hard substrate)	encrusting relatively smooth surface, excluding other species form hard substrate	strong fluctuations in recruitment and total available biomass	Availability hard substrate	++
	Lanice conchilega	small-scale fluid alteration near the bed, reduces sediment resuspension, particle capture	sediment stabiliser, reduces turbidity	minor, local	protection against dislodgement	strong fluctuations in recruitment and total available biomass	bed disturbance, availability sandy sediment, primary production, temperature	++
	Arenicola marina	small-scale fluid alteration near the bed, bioturbation, increases sediment resuspension, particle capture	sediment destabiliser, particle capture, reduces turbidity (?)	moderate - significant	food for birds, excludes macrophyte and invertebrate settlement		presence of suitable sediment	++

A.3 Symposium “Clear about mud”

On the 24th of June 2010 a symposium was held within the framework of the Rijkswaterstaat duties regarding the European Water Framework Directive (WFD) with respect to the fine sediment dynamics in the Wadden Sea. This symposium focussed mainly on the tidal basins of the Dutch Wadden Sea, with exception of the Eems-Dollard estuary. A document was compiled before this conference, also stressing the pressing need for a multidisciplinary approach.

In the background document several questions were identified with immediate relevance for human impact on the Wadden Sea system:

- What are the effects of the large-scale closures (Zuiderzee and Lauwerszee) and how do these relate to other forms of ecosystem use.
- What is the role of dykes near salt marshes and vice versa on the dynamics of fine sediment?
- What are the effects of dredging and coastal nourishments and do these activities have any large-scale impacts on the sediment dynamics of the tidal basins? If there are any significant impacts, can they be mitigated by different dredging or nourishment strategies?
- What are the effects of other forms of bed-disturbance (e.g. shrimp fishing) on the fine sediment dynamics?
- How do biota influence sediment dynamics?

The symposium concluded that to answer these questions, better insight is needed into the functioning of the system as a whole. At the same symposium Prof. Herman Ridderinkhof showed the importance of better measurements. The monitoring data coming from the national monitoring programme (MWTL) are collected at biweekly intervals and only from the surface. The data from the TESO ferrybox and some isolated other measuring campaigns have shown that the bulk of the fine sediment transport occurs near the bed. The MWTL measurements severely underestimate the gross fluxes and make estimates of the net fluxes nearly impossible. Some of the other ferries have meanwhile been kitted out with ADCPs. During one of the discussion sessions some fishermen have also offered to allow measuring equipment on board. This would be interesting since these ships tend to go near edges of mudflats, where a great lack of information is required. it may take some adaptations in measuring protocols to get these measurements done with ADCPs suitable for very shallow water, and this may also create some goodwill within an industrial sector that is often sceptical against scientific research, conservation and policy measurements. However, although opportunistic ‘hitchhiking’ is always to be encouraged, it will not be sufficient to generate a synoptic overview required to gain insight into sediment dynamics for the Wadden Sea as a whole. A well structured overarching monitoring programme is certainly required.

B Appendix B: Running initiatives

B.1 Wadden fund projects

B.1.1 WaLTER

WaLTER is the acronym for Wadden Sea Long Term Ecological Research. The overall aim of WaLTER is to provide a basic contribution to the sustainable future of the Wadden Sea region through increasing the effectiveness of the use of knowledge, necessary for planning processes, policy and project development, and adaptive management. The aim will be achieved by

- Establishing a web-based, low-threshold, user-friendly central knowledge platform, for making available existing and new knowledge.
- Achieve consensus about a basic system of monitoring, i.e. which basic system variables (ecologic and socio-economic) must be monitored to be able to understand the functioning and development of the Wadden Sea system.
- Achieve a good tuning between running and future monitoring programmes, measuring networks and data portals.

This proposal was submitted for financing by the Dutch “Wadden Fund” and has been awarded in December 2010.

The first phase of the project (2011-2012) is the inventory phase. In this phase the knowledge requirements of all potential users will be inventoried and the necessary monitoring parameters determined. In addition an inventory and evaluation of conceptual ecological and economical models will be carried out, resulting in an overview of necessary monitoring requirements. In phase two (2013-2014), the data portal will be developed and the results from phase one analysed, focusing on a comparison of data needs and data availability. The analysis will reveal overlaps and redundancies in current monitoring practices and make recommendations for improving effectiveness. Finally a monitoring programme for ecological and socio-economic parameters will be developed, based upon the outcome of the analyses regarding customer needs and effectiveness.

The project will be carried out by a consortium of NIOZ, IMARES, SOVON Vogelonderzoek Nederland, the Radboud University Nijmegen, the University of Groningen and the Common Wadden Sea Secretariat. It will involve close cooperation with organisations and authorities responsible for monitoring programmes such as the ministry of Economic affairs, Agriculture and Innovation, NAM (the Netherlands Petroleum Company), Natuurmonumenten, Province of Friesland, Rijkswaterstaat and Staatsbosbeheer (the National Forestry commission).

B.1.2 Mosselwad

In the Wadden Sea, the area covered by stable mussel beds shows large spatial and temporal variability, in particular in the Western Wadden Sea. The stability of mussel beds is determined by a range of physical and ecological processes and conditions. MOSSELWAD will be testing a number of hypotheses for the (lack of) stability of mussel beds and will consider aspects such as cover, density and predation. The coastal research group of Utrecht University will focus on the physical / hydrodynamical processes and conditions that can play a decisive role in the development of stable mussel beds.

Objectives

- Determine the effect of waves, in combination with wind and tides in eroding mussel beds;
- Establish the hydrodynamic boundary conditions for the settlement and stable development of mussel beds;
- Evaluate the effect of mussel bed patterns in relation to stability;
- Understand the mussel bed – sediment interactions, both in terms of erosion (resuspension of suspended matter) and biodeposition.

Approach:

- Three major mussel beds will be selected in the Wadden Sea and each site will be fitted with a large pole (top about 10 m above the surrounding tidal shoals and flats of the Wadden Sea) to make video-based observations of the mussel bed morphology (hourly and daily basis). The video data will also be used to observe the local hydrodynamic conditions at the measuring plots; this includes wave propagation (direction) and breaking (percentage of breaking waves, type of breakers) during more energetic conditions. At each site an Acoustic Doppler Velocity (ADV) meter is deployed to measure time-averaged and orbital velocities. Local, stand-alone pressure sensors are added to measure tidal water levels and wave characteristics.
- At a relatively stable mussel bed, more detailed measurements will be performed to determine detailed flow and turbulence patterns, to measure wave propagation over mussel beds, to record the suspended load sediment transport and to measure detailed bed level changes due to erosion and deposition.
- A third generation wave model (SWAN) will be used to explore the potential areas for the development of stable mussel beds in the Western Wadden Sea.

B.1.3 Waddensleutels

This project focuses on mussel beds as ecosystem engineers and restoration of key processes in the Wadden Sea. The project consists of two major parts:

- A large-scale restoration experiment to restore mussel beds
- Food web research based on stable isotope analysis.

The latter will be used to develop a set of process indicators to evaluate the success of restoration of the food web structure in the Wadden Sea. A specific link is made between the open mudflat part of the Wadden Sea and the fringing saltmarshes. Both habitat types are functionally closely linked through sedimentary processes. One of the aims is to ascertain the capacity of saltmarshes to capture fine sediment. This can be used as a foundation for expansion of the Saltmarsh area. This is not only relevant from an ecological viewpoint, but also from a viewpoint of coastal protection against increasing sea levels.

B.2 NWO-ZKO programme

B.2.1 Integrated Network for Production and Loss Assessment in the Coastal Environment (IN PLACE)

In shallow seas, such as the Wadden Sea, phytoplankton and microphytobenthos are at the base of the food chain and are the source of food for most other marine organisms. The carrying capacity of ecosystems in terms of biomass per trophic level is highly dependent on the production, abundance, timing and assemblage composition of microscopic algae. Statistical analyses of long-term (> 30 yrs) field observations indicate that changes in nutrient loads were followed by changes in biomass, in species composition, and in the productivity of phytoplankton. The spatially and temporally scattered observations to date on primary production and biomass of higher trophic levels suggest that the carrying capacity of coastal ecosystems, such as the Wadden Sea, is largely under bottom-up control, i.e. photosynthesis. Despite the eminent role of primary production in setting the upper bound to the carrying capacity of the Wadden Sea, consistent measurements of pelagic primary production are limited to a single station only, whereas data on benthic primary production are virtually lacking.

Through this proposal, a 2192 k€ grant is requested for setup, maintenance, and exploitation of a monitoring network of two permanent stations in the western Wadden Sea, and one ferry box in the Marsdiep tidal inlet. This network will monitor the western-most basin of the Dutch Wadden Sea, the only basin for which coherent long-term records on hydrography, nutrients, phytoplankton primary production and macrozoobenthos are available. A selection of meteorological, hydrological, physical, chemical and biological state variables will be monitored, using sensor packages that have proven successful in existing long-term monitoring programs in coastal environments. Fluorometric techniques will be used in situ to monitor microalgal biomass and production after calibration against standard techniques. Quarterly surveys will be organized to measure phytoplankton and microphytobenthos primary production and for additional mapping of water column and sediment characteristics. Basin-wide assessment of phototrophic biomass and sediment characteristics will be obtained from satellite observations and airborne images. Algorithms will be developed for interpolation of field data and satellite images, yielding basin-wide estimates of benthic and pelagic primary production7. Results will be tailored to support habitat studies of higher trophic levels. After quality assessment and calibration, the monitoring data will be made available to the public, using the infrastructure and expertise of the NIOZ' Data Management Group. The resulting long-term, open access database will provide the community of coastal researchers with the key variables to address specific products (e.g., Water Framework Directive) and research questions. These questions will be detailed in parallel research proposals focusing on main rate variables, noticeably the basin-wide assessment of primary production, of carbon and nutrient dynamics, of particle transport including larval transport, and of erosion and sedimentation balance; all key processes in determining the carrying capacity of the western Wadden Sea.

The requested budget for this program of 2192 k€ includes the purchase of automated sensors (628 k€), the construction and maintenance of the automated network (155 k€), the research costs of the field surveys and remote sensing (255 k€), and personnel costs for technicians in charge of design and setup the automated sensor network (1 technician for 1 yr), testing and maintenance of the automated sensors (1 technician for 5 yrs), data quality control and output editing (½ technician for 5 yrs), field-survey sampling and analyses (1 technician for 4 yrs), and for PostDocs for the inter-calibration of raw sensor data and field surveys (1 PostDoc for 3 yrs) and inter-calibration of calibrated sensor data, aerial surveys and satellite images (1 PostDoc for 3 yrs). If successful, the network proposed, will gradually be extended to cover the entire Wadden Sea and will be further tuned and integrated to existing networks in surrounding waters, e.g. the Trilateral Monitoring and Assessment Program (coordinated by the Common Wadden Sea Secretariat).

B.2.2 Integrated monitoring of the carrying capacity of coastal waters

The North Sea and the coastal areas as the Wadden Sea and southwest Netherlands are exceptional areas. The characteristics are under pressure during the last hundred years due to increasing human influences. The negative effects have initiated (inter)national action. The central aim of the (inter)national policy is to maintain the specific ecological characteristics and to be able to explore the systems. In the 1970s the monitoring of the water quality started with the aim to describe the state, to follow the effectiveness of measures and to forecast developments. It is recognized that knowledge about the state of the ecosystem (monitoring) is essential to detect and forecast the dynamic response of the carrying capacity by for instance climate change, fisheries and eutrophication/ oligotrophication processes. Despite the relatively long record and the broad effort of scientists, policy makers and managers, the current monitoring programs of the Dutch coastal waters are yet under pressure, because they are expensive and essentially the methodology and logistics have not been updated since the 1970s. Also the outcome doesn’t fulfil the information needs of policy makers and managers. Therefore, a major renewal of the Dutch coastal monitoring strategy seems desirable. During the past few decades important technological and scientific developments have taken place to advance monitoring efforts. New on-line instruments have been developed for scientific and applied monitoring purposes. Remote sensing combined with GIS analysis has enriched the spatial information available to coastal managers. New molecular techniques have enabled recognition of a wide array of marine micro-organisms and their activities. Advances in computation power, statistical techniques, datamodel integration and data-assimilation procedures have improved the analysis of monitoring data. From a scientific point of view more is known about the behaviour of complex open dynamic systems. However, these new techniques, insights and methods have not yet been applied to optimize the monitoring programs for the water quality and carrying capacity of the Dutch coastal zone. The current project aims at reaching two goals:

Scientific analysis of temporal and spatial trends and fluctuations of nutrients, suspended matter, phytoplankton and where possible zooplankton and shellfish in existing time-series data of the Dutch coastal waters, using recent advances in (nonlinear) statistical techniques and process-based models,

Design of an advanced, cost-effective monitoring network of the Dutch coastal waters for the next decades, integrating new methodologies and techniques with existing monitoring efforts. The area covers the Wadden Sea, the Dutch coastal zone and the estuarine waters in southwest of the Netherlands. There is a close collaboration between the other NWO-ZKO projects. In addition to its scientific goals, the proposal brings together scientists, coastal managers, and policy makers, by creating a national team and strengthening the Dutch position in international marine organizations.

Results will be disseminated through scientific publications, symposia, and participation in international organizations as the EU, TMAP, ICES, EUROGOOS and OSPAR. The interim results and the final results will give policy makers and managers various options to choose for an integrated, innovative and effective monitoring network for the coming decades.

B.2.3 A human-driven regime shift through the loss of ecosystem engineers: consequences for the trophic structure and recovery potential of the Wadden Sea ecosystem

Across the world, human-dominated marine ecosystems are experiencing an accelerating loss of populations and species, with a strong risk of permanently impairing key ecosystem functions and recovery potential. In The Netherlands, the Wadden Sea ecosystem experienced similar deterioration over the last few centuries due to strong intensification of human activities, causing the extinction of many species, strong modification of ecological and landscape processes, and large alterations in the carrying capacity for the remaining characteristic bird, fish, mammal and invertebrate species.

The Wadden Sea has been subject of numerous scientific studies focused on specific landscape-forming (e.g., sedimentation, hydrodynamics), biogeochemical and ecosystem processes (as primary production), as well as on several individual species and their specific ecological interactions (e.g., knots-bivalves). This would suggest that overall ecosystem functioning and trophic structure are well understood, allowing confident predictions on future harvesting of marine resources and optimal locations for restoration of key ecological phenomena, as mussel banks. Unfortunately, this is not true. Surprisingly, no study has yet been successful in putting available knowledge on the interactions among all of the different trophic groups together; jointly with the associated changes in the key environmental factors. The few large-scale, mostly conceptual/theoretical studies on ecosystem functioning of the Wadden Sea that are available, are based on observations combined with modelling only. There is clear need for further identification of the processes that determine ecosystem functioning at large spatial scales, and experimental validation of mechanisms and predictions.

We hypothesize that this lack of a synthetic framework of the functioning of the Wadden Sea is due to an important, but still poorly understood property of soft-bottom intertidal communities: the dependence between the dominant benthic consumers low in the food web (as bivalves and worms), and their main environmental determinants (as sediment texture and stability, water turbulence and geomorphology). Species with such a bi-directional interplay with their environmental factors are called ecosystem engineers. We propose the novel hypothesis that two types of ecosystem engineers can potentially dominate the same habitat in the Wadden Sea. The first group contains filter-feeding reef builders (bivalves) that stabilize the sediment, and promote the local settlement of fine-grained material. The second group consists of deposit feeders (as lugworms) that destabilize the sediment and promote resuspension of fine-textured sediments. Through data compilation, modelling and experiments we will test the hypothesis that overexploitation of the Wadden Sea has induced a regime shift from a spatially heterogeneous state dominated of sediment-stabilizing ecosystem engineers to a more homogenous state dominated by sediment-destabilizing ecosystem engineers. The thought that ecosystem engineers, such as mussels and sea grasses, have historically played a key role in maintaining biodiversity in the Wadden Sea, is not new. What is however new is our planned full reconstruction and experimental testing of how the structure of the food web depends on the abundance and distribution of these ecosystem engineers, and how the food web in turn determines the abundance of specific engineering species. This has important consequences for understanding changes in carrying capacity, as sometimes irreversible responses are expected to further reductions in fishing, to climate change and to reduction of nutrient loads.

We will use existing long-term data collected by our research groups, historical and novel spatial data and GIS methods to analyze them, modelling and large-scale field experiments to test the two main ideas/hypothesis indicated in bold above. We emphasize the importance of our experimental approach, despite its costs. A combination of just monitoring and modelling is insufficient to identify multiple stable states and regime shifts in ecosystem as it does not allow the discrimination against alternative hypotheses, as 'unseen' sudden changes in external forcing factors, or fixed, imposed abiotic heterogeneity causing patchiness Deliverables of the program will include maps of predicted (potential) occurrence of key ecosystem engineers, expected shifts in spatial distributions under alternative scenarios of use, experimental data that allow validation of the hypothesis on regime shifts in ecosystem engineers, and a full construction of the Wadden Sea food web, with identification of the main drivers of the different species groups.

B.3 Coastal defence programmes

B.3.1 Delta programme

The aim of the new-style Delta Plan (the Delta Works of the future) is to protect our country form high water and secure its freshwater supply, for today and the future. Many aspects play a role in this, ranging from the living environment and the economy to nature, agriculture and recreation. The Netherlands is a low-lying, prosperous and densely populated delta that is vulnerable to flooding.

Sub-programmes

The implementation of the Delta Programme is already taking place in various ongoing implementation programmes: by implementing dyke strengthening and coastal defence strengthening projects and making room for rivers, while at the same time examining in the nine sub-programmes what is needed in the long term.

The sub-programmes that apply to the whole of the Netherlands are:

- Safety
- Freshwater
- New construction and restructuring

The regional sub-programmes are:

- Rhine Estuary-Drechtsteden
- South-western delta
- IJsselmeer Region
- Rivers
- Coast
- Wadden Region

In the implementation of the Delta Programme the Netherlands is cooperating closely with neighbouring countries in the flood basins of the Schelde, Meuse, Rhine and Eems. European regulations like the Flood Risk Regulations (EU FRR) are an important reference point for international cooperation. Specifically, the sub-programme for the Wadden Region and the cross border programme regarding the Eems estuary have strong links with e.g. Programme Towards a rich Wadden Sea and other coastal defence programmes, such as SBW (see below).

B.3.2 SBW Programme ("Sterkte & Belastingen Waterkeringen" – Hydraulic Boundary Conditions)

This is a research programme geared towards improving our knowledge regarding fail mechanisms of embankments and other coastal defence mechanisms

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It is the ambition of the Wadden Academy to develop the Wadden Sea Region into an incubator for widely applicable integrated knowledge of sustainable development of a coastal area, in which natural values are a key element and form the foundations of the local and regional economy. The region is a meeting place for scientists from the Netherlands and elsewhere, administrators, policy makers and management agencies. Together, they develop sustainable and innovative solutions based on interdisciplinary knowledge. By 2020, the trilateral Wadden Sea Region will be the best monitored and best understood coastal system in the world.

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