Deltares

Preparing for climate change: a research framework on the sediment-sharing systems of the Dutch, German and Danish Wadden Sea for the development of an adaptive strategy for flood safety

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Client	**Project**
Delta Programme Wadden Area	1209152-000

Keywords
Delta Program, Wadden Sea, Inlet Systems, Barrier Islands, Tidal Flats, Ebb-tidal Deltas, Climate.

Summary
In 2010 the Delta Program Wadden Area started to look into the effects of climate change on the Wadden area. The following main questions, relevant from a management perspective, were identified:

1. How will the sediment-sharing inlet systems of the Wadden area change under different climate scenarios, in combination with existing human interference? What are the implications of this for: I) Flood safety, II) Natural values, and III) Human use, such as shipping and mining?
2. How can we monitor the hydrodynamic and morphodynamic developments and the associated flood safety risks?
3. How can we adapt to the effects of climate change?

This report provides a research framework showing the way towards developing research programs which successfully may address these questions. The report presents a comprehensive overview of the current scientific insights. It is concluded that currently knowledge of especially the long-term morphological functioning of the sediment-sharing inlet systems is insufficient to answer the above questions. The relevant knowledge gaps have been identified. If these are solved long-term prediction of morphological development of the sediment-sharing inlet systems becomes feasible. The goal should be to develop an operational process-based morpho-dynamic model for inlet systems including ebb-tidal deltas, barrier islands and backbarrier basins, similar to the operational hydrodynamic model for the Dutch Wadden.

The report proposes a research framework which follows a *learning-by-doing* approach along the three research lines: monitoring & data analysis, system research & modelling and field experiments (pilots). All studies together will take several decades, partially due to the many questions, partially because studying changes in the system via the above-mentioned research lines takes time. Research programs developed on basis of this framework may focus on a part of the research issues. Ultimately insights can be brought together and culminate in an operational process-based morpho-dynamic model for the Wadden Sea that can serve as a basis for future management strategies.

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State
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1 Introduction

Textbox 1.1

Delta Program Wadden Area

The Delta Program has an eventful history. The disastrous storm surge (Watersnoodramp) in 1953 led to a strong social and political drive: 'never again'. The resulting Delta Plan provided flood safety in the South-Western Delta. Over the course of time the insight emerged that most of Netherlands can be considered to be one large delta of Ems, Rhine, Meuse and Scheldt. After the extremely high river floods in 1993 and 1995 a set of measures was devised to counteract the dangers of such events: the 'Delta plan large rivers'.

Shortly afterwards, new insights in the effects of climate change led to the establishment of the Delta Committee (also known as Committee Veerman). In 2008 this Committee recommended the creation of a national Delta Programme, focused on long-term flood safety and sufficient availability of fresh water. The Delta Program Wadden Area is one of the local programs within the National Delta program.

1.1 Background

In 2008 the Delta Committee (2008; see Textbox 1.1) stated that flood safety for the whole of the Netherlands has a high priority. The solutions for flood safety should, however, be sustainable, flexible and integral. For the Wadden Sea area the following recommendations were made: *"The beach nourishments along the North Sea coast may contribute to the adaptation of the Wadden Sea area to sea-level rise. The existence of the Wadden Sea area as we know it at present is by no means assured, however, and depends entirely on the actual rate of sea-level rise coming 50 to 100 years. Developments will have to be monitored and analysed in an international context. The protection of the island polders and the North Holland coast must remain assured."*

Starting in 2010, the Delta Program Wadden Area (DPW) followed up on the recommendations of the Delta Committee. The tasks for Delta Program Wadden Area were (Synthesedocument Deltaprogramma Waddengebied, 2014):

1. The development of an integral approach ensuring long-term flood safety of the coast, of the barrier islands and the mainland. Integration of sustainable safety with the ecosystem functions for nature, recreation and sustainable economics is central in this approach.
2. To monitor the developments in the Wadden area with respect to flood safety and ecology in reaction to climate change (in a trilateral context with Germany and Denmark)."

This report is written on request of the Delta Program Wadden Area (DPW). It proposes a research framework on the morphological development of sediment-sharing systems of the Dutch, German and Danish Wadden Sea for the development of an adaptive strategy on flood safety. Such a strategy should ensure that the Wadden Sea Area is prepared to cope with the effects of climate change in the coming century. It should provide a solid base for sustainable management of the Wadden area.

The preferential strategy for sandy coasts and islands aims at maintaining the buffer function of the whole complex of sediment-sharing inlet systems ("Voorkeurstrategie Deltaprogramma Waddengebied", 2014). Keeping the buffer function of the sediment-sharing inlet systems enhances the flood safety of the islands and mainland coast of the Northern Netherlands. In this strategy the natural values of the Wadden area (acknowledged by their World Heritage status) should be respected. This requires a system approach, encompassing all parts of the sediment-sharing inlet systems. It also requires understanding of hard and soft measures to maintain flood safety. To facilitate this, more knowledge has to be developed on the morphological functioning of the Wadden area to reduce uncertainties and to predict its long-term development.

1.2 Development of the research framework

In 2010 the Delta Program Wadden Area started to look into the effects of climate change on the Wadden area (Delta Program Wadden Area, 2010a, b). Based on the studies of 2010 and 2011 it concluded that: 1) climate change and human activities in the area could impair flood safety for inhabitants and economic activities in the coming century and 2) the morphological development of the area plays a key role in it. The following main questions, relevant from a management perspective, were identified:

1. How will the sediment-sharing inlet systems of the Wadden area change under different climate scenarios, in combination with existing human interference? What are the implications of this for: I) Flood safety, II) Natural values, and III) Human use, such as shipping and mining?
2. How can we monitor the hydrodynamic and morphodynamic developments and the associated flood safety risks?
3. How can we adapt to the effects of climate change?

Parallel to this study a second project was carried out via the '*Kennis voor Klimaat*' (Knowledge for Climate) program. The program focuses mainly on the ecological values of the Wadden Sea and on maintaining these values under conditions of acceleration of sea-level rise (Baarse, 2014). This study aimed specifically at providing solutions and developing an adaptive strategy. It highlighted the need for specific research and monitoring. Baarse (2014) concludes: *"The focus of general research should be on the processes underlying the sediment balances of the various interacting subsystems and on improving the modelling capabilities for describing and quantifying these processes. More specific research questions relate to the potential of possible measures to enhance the WS sediment balance. For some of these measures, in view of the complexity of subsystems and processes involved, the execution of large scale field experiments (pilots) would be the most appropriate way to deal with these questions*."

The research framework discussed in this document takes a broader view and addresses the morphological development of the Wadden Sea at large, including barrier islands, foreshore and ebb-tidal deltas. It follows the recommendations of Baarse (2014) and specifies the knowledge development needed to be able to successfully address the main questions stated above.

The framework has been developed after 2012. It was concluded (Delta Program Wadden Area, 2010a&b) that in-depth understanding of the morphological development of the area was essential to answer the above questions relevant to management. Thus, it was decided to focus on the morphological functioning of whole inlet systems as well as parts of them.

In this report the current scientific insights are discussed in some detail and relevant knowledge gaps are identified.

The research framework follows a *learning-by-doing* approach. It combines data analysis, monitoring, system research, modelling and field experiments (pilots) investigating future management strategies.

1.3 Implementation and organization

The research framework presented in this report has, to a large extent, become part of the "Adaptation Agenda for Sand" (Also known as: "de Beslissing Zand"), which is part of the Delta Program (Figure 1.1). The Adaptation Agenda for Sand is formulated by the three regional Delta Programmes dealing with the sandy Dutch coast: Southwest Delta, Holland Coast and Wadden Region. The Dutch coast primarily consists of sand, forming the beaches and dunes. These provide a natural defence of the hinterland and support many other functions. The Agenda proposes to use sand nourishments as a primary means to create a safe, economically robust, ecologically sound and attractive coast. With respect to the functioning of the various parts of the coast, a lot has been learned during the studies carried out within the framework of the coastal maintenance programmes of Rijkswaterstaat. To keep the coastal foundation zone balanced in relation to rising sea levels, sand nourishments will probably have gradually to increase. The rate of increase depends on the rate of sea–level rise, the exact morphological reaction of the sandy system and policy decisions. To understand the sandy system and to predict the effect of (various) alternative nourishment strategies on the system, a multi-year program of knowledge development and monitoring forms part of the Adaptation Agenda. The results of this knowledge development program will ultimately underpin policy decisions regarding flood protection. The program states that pilot projects and monitoring are important elements of the program to obtain the needed knowledge and experience (Dutch Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs, 2013).

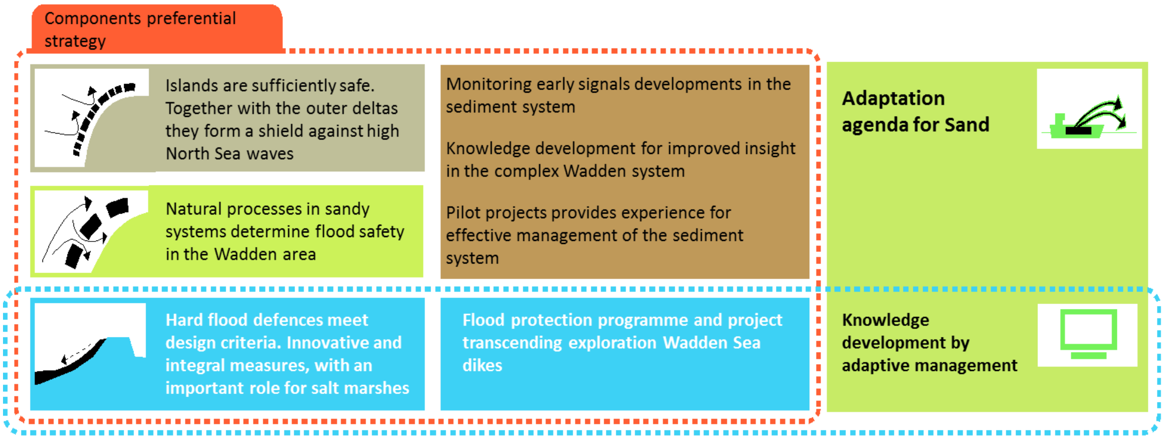

Figure 1.1: The "Preferential strategy" and the "Adaptation Agenda for Sand" in their context.

The science, for the present-day sand nourishment policy was developed in the nineties through the research program Kustgenese 1.0 (Stive et al., 1987). The important research questions of the "Adaptation Agenda for Sand" will be studied in Kustgenese 2.0 under the programme Water and Climate ("Water en klimaat; figure 1.2"). The exact choices on which part of the research proposed by Adaptation Agenda for Sand will be carried out during Kustgenese 2.0 has still to be decided upon. The Delta Program has proposed to form a regional coastal consult group (ROK) and a national coastal consult group (LOK) for policy makers regarding the "Adaptation Agenda for Sand" (fig 1.2) (pers. inf. Hoeksema).

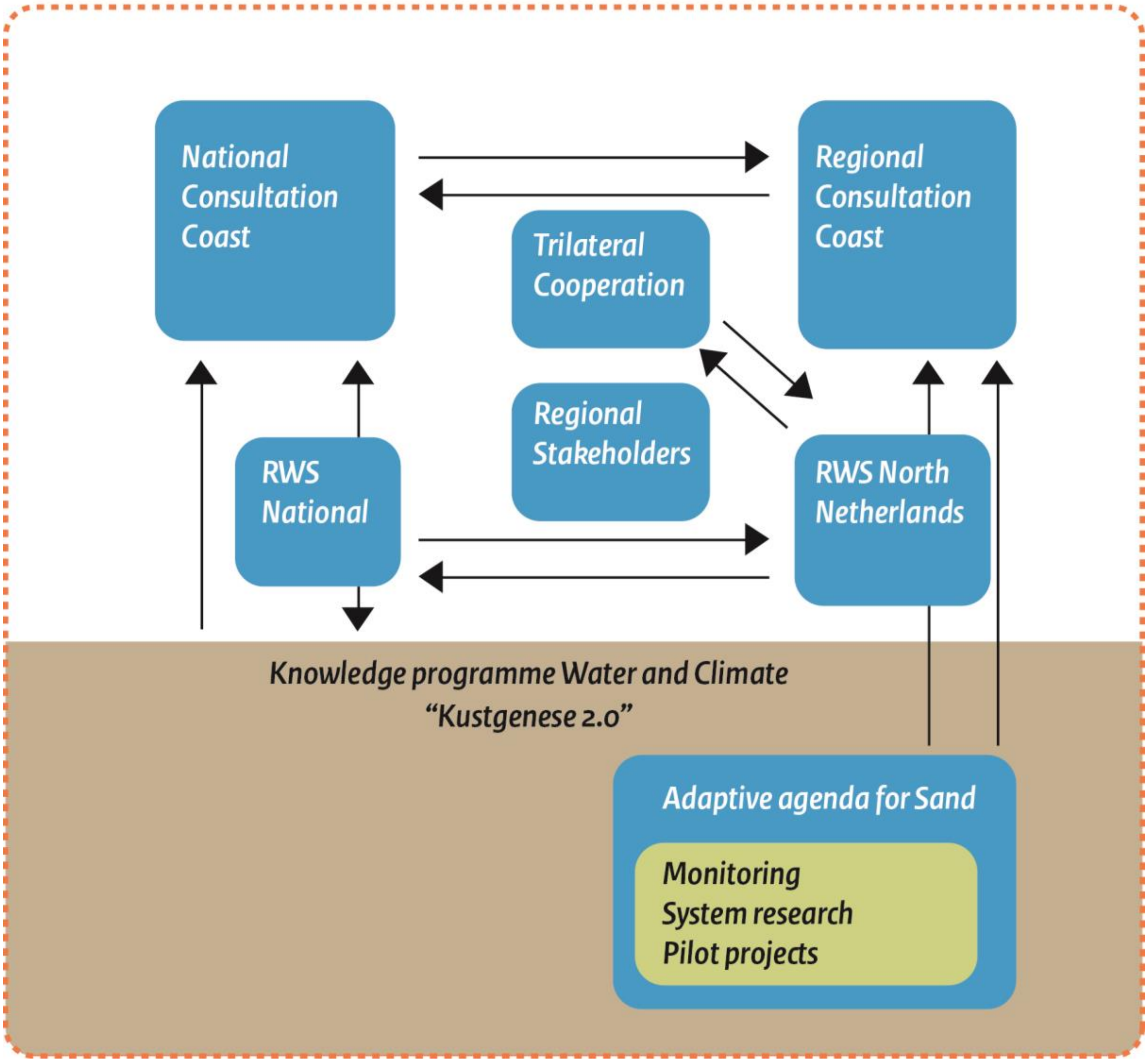

Figure 1.2: overview of the position of the framework on monitoring, system research and pilots as proposed by DPW and the place in the various programs (Source: DPW).

1.4 Outline

In chapter 2 the trilateral context in which the research framework Wadden Area has been formed is discussed. The trilateral cooperation was extremely helpful to formulate the research framework. In chapter 3 the main knowledge gaps and research questions are discussed for sediment sharing inlet systems and their various parts. In chapter 4 an outline is given of the research framework giving direction to research which should be carried out to solve the major questions.

2 Research framework in trilateral context

2.1 Introduction

The Wadden area stretches over a distance of 450 km from Den Helder in The Netherlands to the peninsula of Skallingen in Denmark. It has developed over the course of the Holocene transgression and functions as a sediment sink (van Straaten, 1954; Jelgersma, 1979; Bartholdy & Peyrup, 1994; Flemming & Davis, 1994; van der Spek, 1994; Speelman et al., 2009; Wiersma et al., 2009; Elias et al., 2012; Oost et al., 2012). The highly dynamic ecosystem is the result of a combination of sediment availability (local, North Sea, rivers and biogenic (peat, shell material)) and a hydrodynamic regime of tides, wind, waves and storm surges under a moderately rising sea level. The Wadden area ecosystem is structured into 39 adjacent tidal-inlet systems on top of a Pleistocene surface geometry (tidal basins; van der Spek, 1994; Figure 2.1).

Textbox 2.1

Ministerial Council Declaration, 2014

Three points of the Ministerial Council Declaration, 2014, formally addressing the joint cooperation of the Wadden Sea countries:
52 Monitor the implementation of the climate change adaptation strategy and embed the results in long-term trilateral climate change policies, including best practices for adapting to climate change.
53. Recognize that the morphological development under sea level rise is a critical element of the natural resilience of the Wadden Sea and that trilateral cooperation on the exchange of knowledge on this subject is essential.
54. Welcome the successful initiation of a trilateral study on sedimentation behaviour in different tidal basins and acknowledge that the study has already in its first year delivered an exchange of knowledge and expertise between institutions and agencies in the Wadden Sea countries, and support its further continuation.

Trilateral cooperation started with the water management authorities of Denmark and Germany, as part of the assignment of the Delta Program Wadden Area,. First steps were the agreement on common climate scenarios and agreement upon the common knowledge base. The long-term research framework presented here is mainly written from the Dutch perspective of Delta-program Wadden, but it was agreed that studies will be carried out in cooperation with Germany and Denmark. The framework itself should be the common base for other research on the hydrodynamic and morphological responses of the Wadden area to climate change. Over the years this led to cooperation with universities in the three countries. The universities of Delft, Copenhagen and Utrecht, the Leibniz Institute for Baltic Sea Research, IMARES and Deltares are among the main participants. The cooperation was formally welcomed by the responsible ministers during the 12th Trilateral Governmental Conference on the Protection of the Wadden Sea (Anonymous, 2014; see textbox 2.1). The whole process is based on the best available knowledge and trilateral consultation on the needs for knowledge for optimal coastal management. The research proposed is extensive and choices have to be made in the future with respect to implementation.

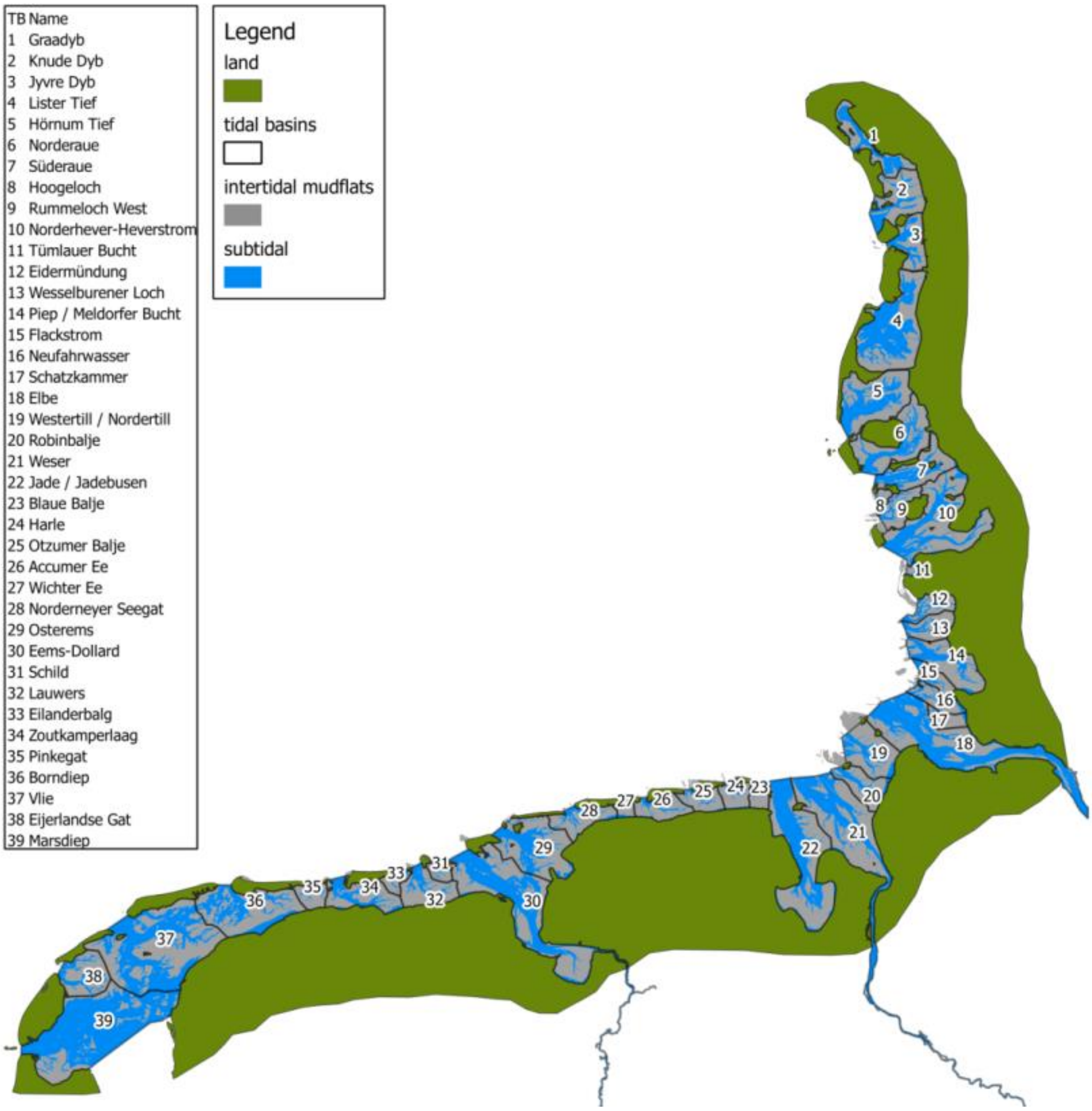

Figure 2.1: Wadden area tidal basins.

2.2 Legislative status Wadden area

The Wadden area is a unique region because of the extraordinary plants, animals and landscapes found here and the special role that the area fulfils globally. It enjoys a high level of protection within the three countries. The protection is regulated through various laws, directives, treaties and agreements. The legislative frameworks are interconnected, ranging from worldwide conventions such as OSPAR and RAMSAR, to European, national and regional authorities, such as the National Parks in Germany. The Wadden area is largely a World Heritage area. The World Heritage status does not change anything in these protective measures; there are no new regulations.

The European regulations consist of guidelines with a specific ultimate goal that the member states must meet after an established number of years. Each member state makes its own laws to accomplish this goal. European directives for the Wadden area are the EU Water Framework Directive and the Birds and Habitats Directives, the latter two forming the basis for Natura 2000.

The three countries bordering the Wadden area, the Netherlands, Germany and Denmark, form the “Trilateral Wadden area Cooperation” which was established in 1978. In 1997, the countries signed their first Wadden Sea Plan to improve and safeguard the protection of the area. It forms the basis for the protection of the Wadden area and is monitored by the Trilateral Monitoring and Assessment Program (TMAP). In March 2010, a renewed plan was signed by the three countries (Common Wadden Sea Secretariat, 2010).

The Danish part is also a National Park, which enjoys special protection via the Nature Protection Act and the Statutory Order on Nature Conservation and a Nature Reserve in the Wadden Sea. Furthermore, the special order of fishing regulations and conservation zones in the Wadden Sea and in some streams in southern Jutland provides the overall framework for regulating fishing in saltwater and freshwater. It creates a coherent set of rules for commercial and recreational fishing. The Spatial Planning Act ensures that the overall planning synthesizes the interests of society with respect to land use and contributes to protecting the country’s nature and environment, securing sustainable development.

In Germany, the Wadden Sea is protected by the National Park laws of the federal states. This concerns: the National Park Schleswig-Holsteinisches Wattenmeer, the National Park Hamburgisches Wattenmeer and the National Park Niedersächsisches Wattenmeer. The national parks of the Wadden Sea receive the highest protection. In this zone, nature has priority over human activities. Management of the region is covered by the federal states and nature conservation organisations.

In the Netherlands, the Core Planning Decision Wadden Sea, 3rd Policy Document Wadden Sea (PKB) and the Main Ecological structure (EHS) form the basis for protection and management of the Wadden area. These policy documents detail how the Wadden area should be, which role the region fulfils and which human activities are allowed (such as fisheries and recreation). They form the foundation for legislation, such as the Nature Protection Act and the Flora and Fauna Act. The Nature Protection Act (NB-wet) is directed at protecting areas, while the Flora and Fauna Act is for protecting plants and animal species. Management of the Dutch Wadden area is in the hands of the national government, provinces, municipalities and several private nature organisations.

It is believed by the trilateral partners who helped to prepare this proposal that the insights, the models and data-bases becoming available and the monitoring developed will provide a far stronger base for policy advice on the effects of climate change for the Wadden area.

2.3 Rationale for a trilateral approach

The entire Wadden area forms one coherent coastal ecosystem, subject to the same basic geomorphological processes. Consequently, cooperation on a trilateral level on the impacts of climate change will allow more efficient use of data, the use of expertise and dissemination of results. The regional differences can help making the research more generic. The following Danish, German and Dutch coastal administrations have been working together since 2012 (figure 2.2):

- Kystendirektoratet
- Ministerium für Energiewende, Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein
- Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz,
- Rijkswaterstaat Noord-Nederland;

The cooperation may lead to a common strategy on coping with safety issues and nature conservation issues in a changing Wadden area. The following issues were thought of high relevance in the future cooperation:

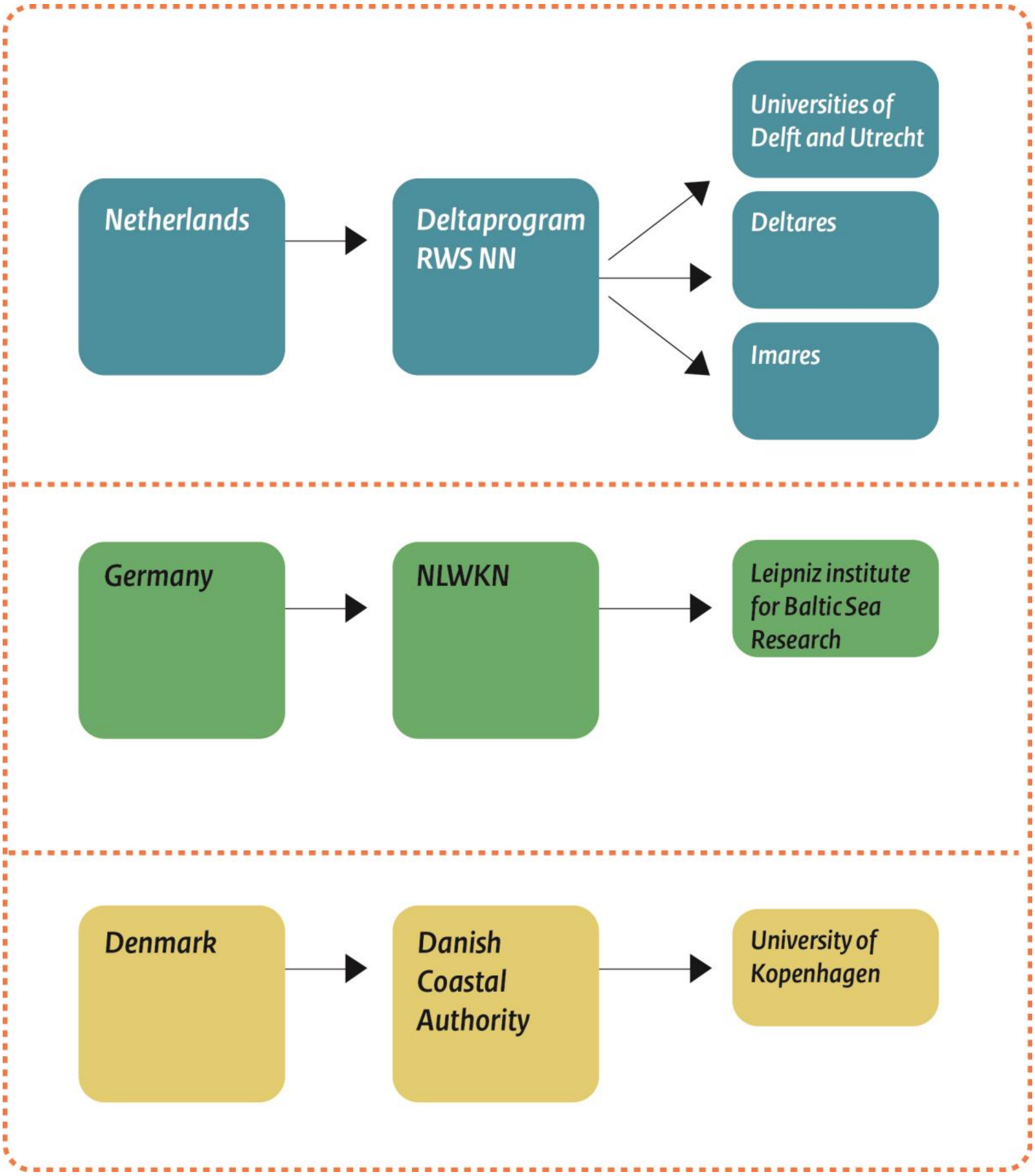

Figure 2.2: Overview of trilateral cooperation up to 2014 on the Wadden sea hydro-morphodynamics.

<u>I)</u> Sharing scientific data, knowledge and expertise

A large number of national and regional institutions gather, store and analyse Wadden area data. Cooperation on these matters with respect to morphological and hydrodynamic data is currently moderately developed and mainly as part of the Trilateral Monitoring and Assessment Programme. Individual countries may increase their knowledge base considerably if they can make use of all data and generated knowledge.

II) Sharing management expertise

Trilateral cooperation also ensures that management expertise will be exchanged. For each participant this cuts costs (it avoids double work). Furthermore, important advantages can be gained from managing the Wadden area as one interconnected area. The Trilateral Working Group on Coastal Protection and Sea Level Rise (CPSL, 2005, 2008 & 2010) expertise exchange already made clear that such approaches work well. The work on how to deal with the problems related to climate change from a management point-of-view led to intense exchange of ideas and some improvements in management practice.

III) Consideration of regional variability

Due to varying geomorphologic and physiographic characteristics, both the challenges of climate change and optimal adaptation strategies may differ in the 39 tidal-inlet systems. For example, a northward shift in storm wind direction may lead to higher storm surges in the Netherlands and Lower-Saxony, but to lower storm water levels in Denmark and Schleswig-Holstein. Trilateral cooperation facilitates consideration of this variance. Lessons can be learned on what more extreme conditions may bring. An example is the observed lowering of ebb-tidal deltas when storm surges become more important as was observed in Schleswig-Holstein (pers. com. Hofstede).

The joint trilateral research framework aims to address the long-term management issues regarding safety and sustainability of the entire Wadden area at large, excluding the estuaries. The parties have agreed to join forces to reach this generic coastal-management goal. At the same time, the work should help to provide answers to the more specific aims of each individual country.

3 Scientific basis and knowledge gaps

3.1 Introduction

The Wadden area is a highly dynamic ecosystem that has evolved as the result of a combination of the sedimentary past (morphology, local sediment composition), sediment availability (local, North Sea, rivers and biogenic) and a regime of tides, wind, waves and storm surges under conditions of moderate sea-level rise. The Wadden area is structured into 39 tidal-inlet systems (figure 2.1), each consisting of a set of characteristic morphological elements: barrier islands, ebb-tidal deltas and back-barrier basins (consisting of salt marshes, tidal flats and tidal channels; figure 3.1).

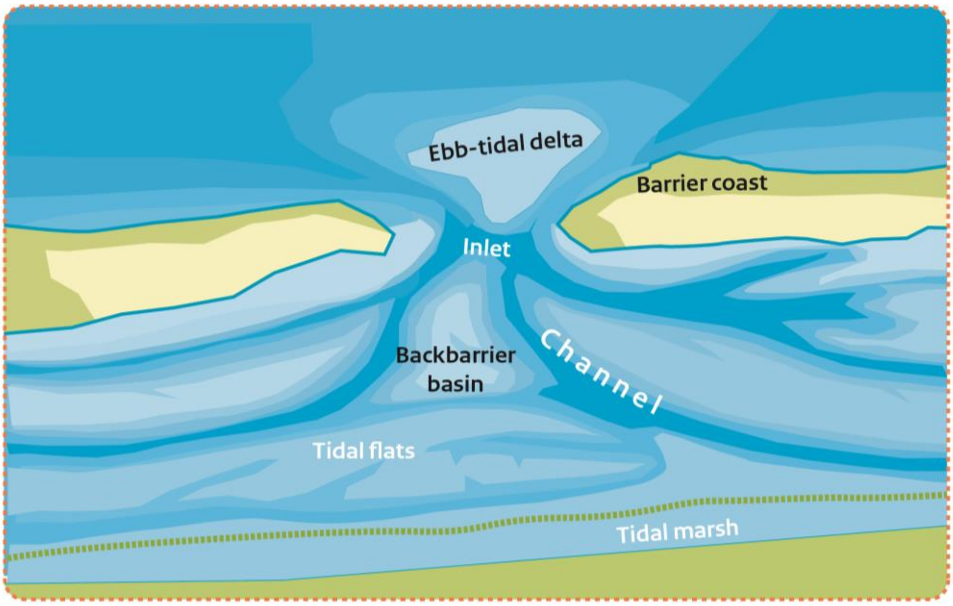

Figure 3.1: schematic overview giving the three main elements of the sediment-sharing inlet system (black font) and some minor elements (white font).

In this chapter an overview is given of the knowledge basis and the scientific questions which need to be answered to understand the behaviour of the Wadden Sea area and to predict its response to future climate change. Such knowledge will enable us to manage the area optimally. The focus is on the hydrodynamic and particularly the morphodynamic problems of the sediment sharing inlet systems, as these to a large extent determine flood safety. This overview addresses the sediment sharing inlet system as a whole (paragraph 3.2), the ebb-tidal deltas (3.3), barrier islands and their North Sea coasts (3.4), back-barrier basins (3.5) and the migration of channels (3.6).

The knowledge gaps were partly taken from extensive inventory studies and overviews and various position papers (CPSL, 2001, 2005, 2010; Oost, 2009; Speelman et al., 2009; Elias et al., 2012a&b; Oost et al., 2012; Wang et al., 2012;). Other gaps emerged during the discussions on the trilateral cooperation meetings with water management authorities and knowledge institutions of Denmark and Germany who are facing similar challenges with regard to climate change.

3.2 Sediment sharing inlet system

3.2.1 Current insights

Each individual tidal system can be considered to form a sediment-sharing inlet system. It consists of an ebb-tidal delta, an updrift and a downdrift barrier island, and the back-barrier basin (figure 3.1). The latter consists of tidal channels, tidal flats and tidal marshes (figure 3.1). All elements of the system are coupled and are assumed to be in, or developing towards, a dynamic equilibrium with the hydrodynamic conditions (Dean, 1988; Eysink, 1991; Eysink & Biegel, 1992; CPSL, 2001). Changes in any part of a tidal-inlet system will primarily be compensated by sediment transport (mainly sand) to or from the other parts of the same system (Figure 3.2; Oost et al., 1998; 2012; Elias et al., 2012a; Wang et al., 2013).

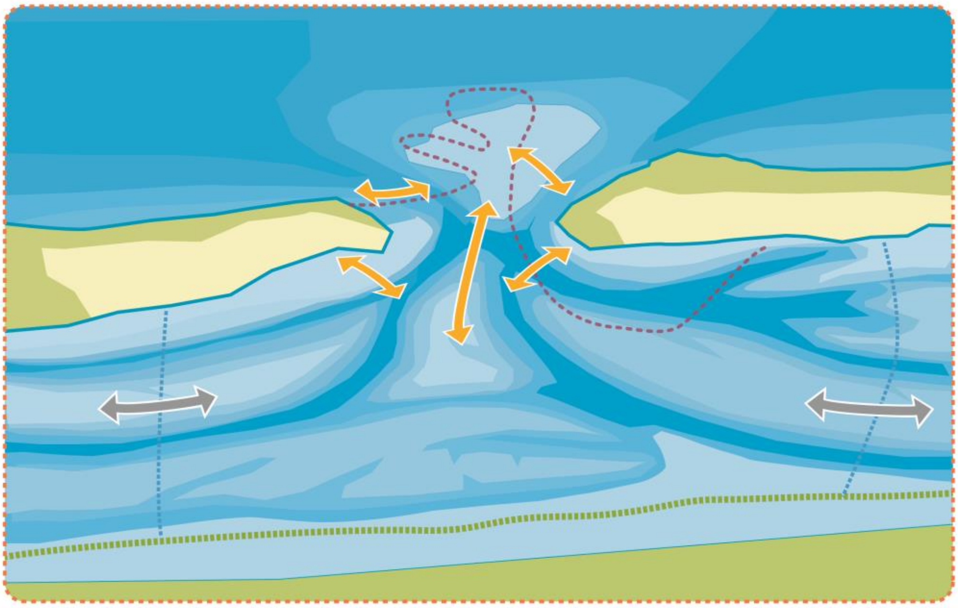

Figure 3.2: Schematic sediment exchange between the three main elements of an inlet system given in black. In reality sediment exchange paths can be very complicated, which is illustrated by a schematic path of sediment exchange given in purple. Furthermore, the tidal inlet systems also exchange sediment via the watersheds; here illustrated with a grey arrow.

When such changes are temporary or limited, the dynamic quasi-equilibrium will be restored. For example, subsidence due to gas extraction induces a stronger accumulation on tidal flats and salt marshes. This is a result of longer tidal inundation and diminished wave action (i.e., sediment has more possibility to settle). As a result, the elevation of the flats and salt marshes increases and the water depth decreases again until the old dynamic equilibrium is restored.

If changes are more permanent or intense, a new dynamic equilibrium can develop if sufficient sediment transport capacity and time is available. The length of time for a new dynamic equilibrium to occur depends on the magnitude of the perturbation. For instance, damming of a part of the back-barrier basin (e.g. Lauwers Sea) may reduce the flow velocities in tidal channels through a permanent reduction in tidal prism. This leads to infilling of the channels until erosion and deposition is in balance (Oost, 1995).

To reach this new dynamic equilibrium, sediment may be imported from or exported to areas outside the sediment-sharing inlet system. The sediment is not lost, but becomes available to other sediment-sharing inlet systems.

From paleo-reconstructions, large-scale sediment budget analyses, and many studies, conducted throughout the Wadden area, some general conclusions can be drawn:

- During the larger part of the past 5000 years of the existence of the Wadden Sea the ebb-tidal deltas, barrier islands and back-barrier basins were not significantly restricted by human interferences. The flooded area could increase and decrease in size depending on the rate of relative sea-level rise, peat erosion and sediment supply (van Straaten, 1954; Bartholdy & Peyrup, 1994; Flemming & Davis, 1994; van der Spek, 1994; Oost et al., 2012).

- Only in the past 1000 years dikes were built to protect the inhabited areas and large areas were reclaimed, especially the land inward oriented channels and embayments. It changed the orientation of many basins from perpendicular to the coast to parallel to the coast. During the past 500 years the general appearance of the Wadden area (figure 3.3 to 3.5), has mainly changed due to the diking of the bigger landward embayments (Zuiderzee, Lauwerszee, Dollard, Leybucht, etc.). But the general appearance of the remaining part has not changed profoundly. Ebb-tidal deltas and barrier islands were present. For the larger part of the period (up to 1880) the coast was mainly retreating in a landward direction at a rate of ca. 1-1.5 m/yr. In the back-barrier area the channel-shoal distribution was rather comparable to the present state (Wiersma et al., 2009), suggesting near equilibrium conditions.

- From 1850 (Norderney) coastal erosion at the North Sea was counteracted by groynes, dune enhancement and sand nourishments. The latter were particularly used in the Netherlands, starting in the 1950's and increasing significantly after 1990. The historically observed roll-over mechanisms of landward barrier and coastline retreat can no longer be sustained, due to numerous erosion control measures that have fixed the tidal basin and barrier dimensions (Elias et al., 2012a). This changed the character of the North Sea coasts from a landward retreating system into a system which is basically stable for large parts. As a result sea-level rise is less strongly expressed in the horizontal plane but only in the vertical. The large sedimentation in the Dutch tidal basins (nearly 600 Mm^3 between 1935-2005), the retained inlets and the similar channel-shoal characteristics of the basins during the observation period indicate that the Wadden Sea is to some extent resilient to anthropogenic influence and moderate sea-level rise (Elias et al., 2012a).

- Most of the Wadden Sea basins capture sediment as the result of sea-level rise and human-induced coastal interventions in the past (Elias et al., 2012a; Wang et al., 2012; Oost et al., 2012). The current sedimentation rate in many of the back-barrier basins is higher than the observed sea-level rise (Stive, 1987; Oost et al., 1998; Hoeksema et al., 2004; CPSL, 2010; Elias et al., 2012a; Wang et al., 2012). Hence, the Wadden Sea is an important long-term sediment sink.

  It is generally assumed that the import of sediment to the Wadden Sea causes erosion along the North Sea coasts (Stive, 1987; Stive and Eysink, 1989; Mulder, 2000; De Ronde, 2008; Van Koningsveld et al., 2008). There is only a thin layer of Holocene sediments present up to water depths of -20 m NAP in front of the North Sea coasts (Sha, 1990b).

Based on erosion during the past 5000 years over several km the Wadden area forms a nearly closed system for sand transport: sand eroded at the North Sea side is largely transported into the back-barrier areas (Oost et al., 1998, Elias et al., 2012).

- Several of the ebb-tidal deltas show an erosive trend over the last decades (Elias et al., 2012a; trilateral meetings: Hofstede pers. Com.). The causes seem to vary regionally and are not always understood. There appear to be the conflicting explanations on the erosion and re-orientation of the Dutch ebb-tidal delta's (Elias et al., 2012a; Ridderinkhof et al., submitted, a&b).

- There are some unexplained differences in the development of the barrier islands. Some islands tend to migrate landward (Trischen, Rottumeroog) and/or in a down-drift direction (Spiekeroog), others are rather stable (Terschelling), or accreting (Rømø) (Oost et al., 2012).

- The various tidal-inlets systems cannot be considered as separate systems with fixed boundaries. Transports occur across the natural tidal divides and these tend to migrate over time.

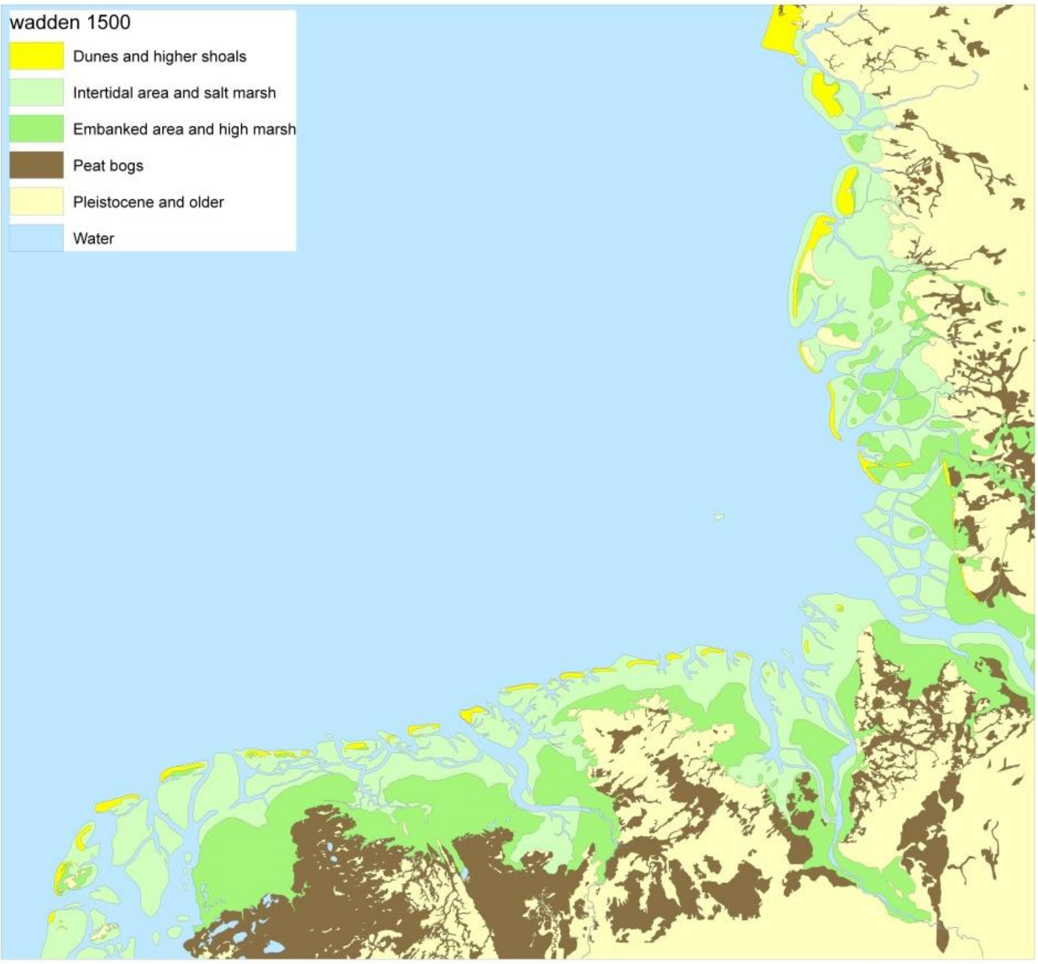

Figure 3.3: Reconstruction of the trilateral Wadden area in 1500 (Oost et al, 2012).

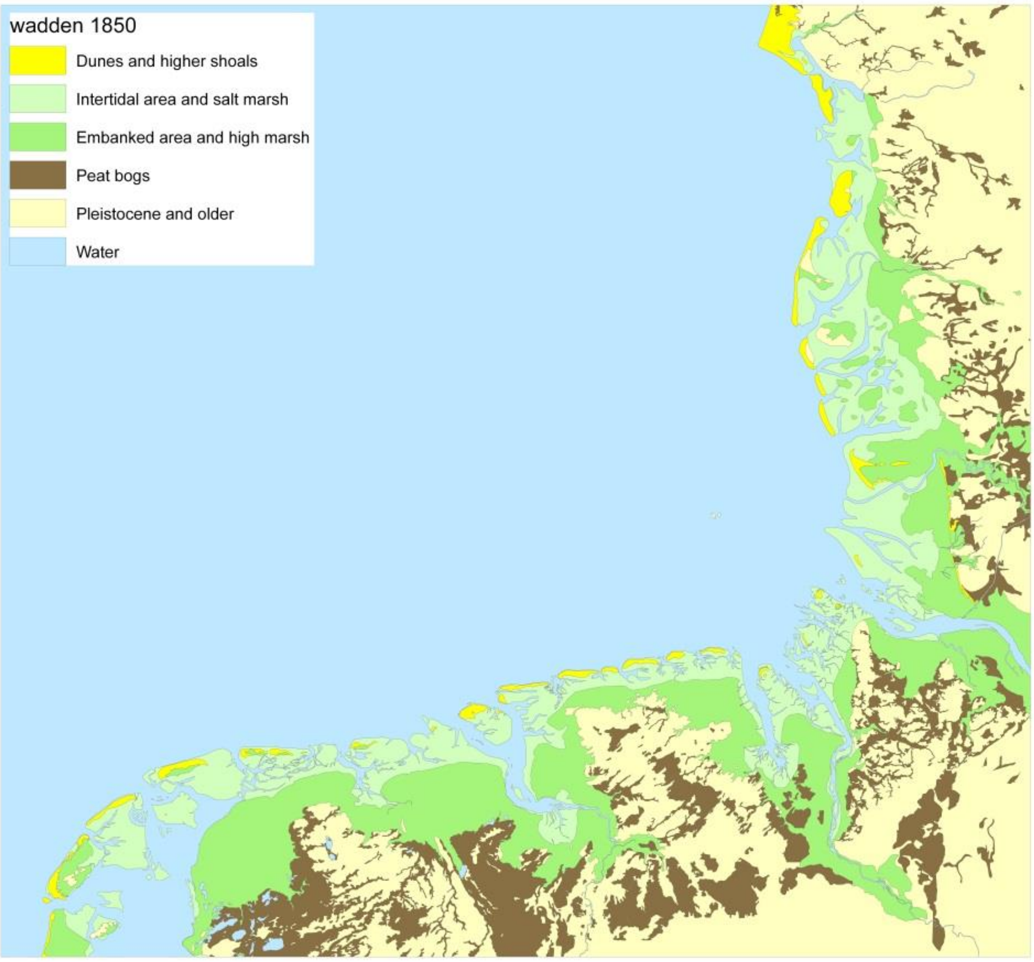

Figure 3.4: Reconstruction of the trilateral Wadden area in 1850 (Oost et al, 2012).

Figure 3.5: Map of the trilateral Wadden area in 2000 (Oost et al, 2012).

Sediment is continually redistributed from the coast, ebb-tidal deltas and perhaps tidal channels to the tidal flats and salt marshes. The North Sea coasts of barrier islands and ebb-tidal deltas are influenced in two ways. Firstly, they have to deliver the sand needed for the back-barrier in response to sea-level rise. Secondly, they have to keep up with rising sea-level, as retreat is societally not acceptable. As the coastal foundation (the part above -20 m NAP) is not receiving much sand from deeper water it will mainly gain sand via nourishments. The long-term redistribution pattern is the result of sea-level rise combined with an increase in tidal range and, especially after 1900, human interferences (Elias et al., 2012a; Oost et al., 2012). In the light of accelerated sea-level rise the question arises: are there limits to the sedimentation rates in the back-barrier area and if so, what determines these?

There are strong indications that sediment transport capacity via the inlets is an important limiting factor for the sedimentation rates in the back-barrier area (see: Hofstede 1991, 2002; Eysink, 1993; Bartholdy & Pejrup; 1994; van der Spek, 1994; Oost et al., 1998; van Goor et al., 2003; Kragtwijk et al., 2004). Disturbances in the back-barrier, such as sea-level rise, closure works, dredging, gas extraction, managed retreat, etc. merely generate the accommodation space: a place to deposit sediments. A very large disturbance however, will not lead to even higher inputs. This is illustrated by the large sediment demand of the Marsdiep-Eijerlandsche Gat-Vlie back-barrier area. Over the period 1935-2005 426 Mm^3 was deposited (Elias, 2012). Depending on the assumptions regarding the equilibrium state, the total sediment demand might be in the order of 10^9 m^3 resulting from the closure of the Zuiderzee. The area, however, is filled in at an average rate of only $6*10^6$ m^3/yr since 1935 (Elias et al., 2012). In many basins it was observed that only the minimal estimate of the gross suspended sand import could be net deposited (Textbox 3.1).

Most Wadden area basins are more or less closed basins with limited fresh water input from the land or rivers. This implies that the amount of water that flows into the basin during flood (flood volume) is more or less equal to the amount of water that flows out of the basin during ebb (ebb volume). Residual sediment transport seems to be caused by secondary properties of the flow, e.g. tidal asymmetry and density flow (estuarine circulation). Furthermore, residual sediment transport occurs over the watersheds. There are various main processes and mechanisms that can cause residual sediment transport into the Wadden Sea, but the exact contributions of the various processes and mechanisms are not sufficiently known (Wang et al., 2012). Modelling attempts have thus far failed to satisfactorily model sediment imports. Next to mapping the development of the sediment-sharing inlet systems in terms of hydrodynamics and morphodynamics, process-based models should be improved so that these are able to predict the sediment transports leading to the observed developments.

At first sight the back-barrier area seems robust and resilient with respect to morphological response to hydrological changes. However, it must be kept in mind that accelerated sea-level rise (SLR) may lead to a situation in which sediment transport capacity and perhaps (locally) sediment availability is insufficient to balance the rising sea level. This would lead to a relative lowering of tidal flats and perhaps the salt marshes with respect to sea level. Because tidal basins have different geomorphological characteristics, the SLR tipping point, or the threshold at which drowning will occur, will differ (see Figure 3.6; CPSL, 2010).

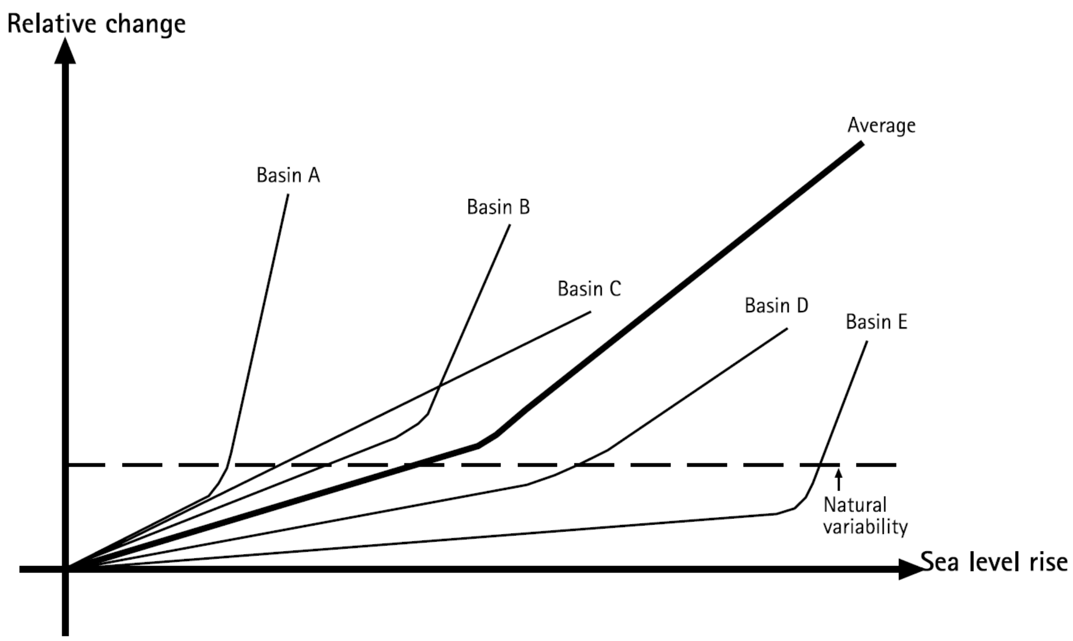

Figure 3.6: Response of various hypothetical tidal basins to sea-level rise. Above a certain rate of sea-level rise the basins start to develop differently with respect to their characteristics. The exact value of these so-called "tipping-points" varies for the different basins. Differences in the basins A to E may for instance be: the net sediment transport into the basin (e.g. Lister Tief, where it is negative), the size of the basin (Oost et al., 1998; Ridderinkhof et al., submitted, a&b), subsidence rates (Oost et al., 1998), or grain size characteristics (Wang et al., 2012). It is expected that tidal shoals will no longer be able to keep up with sea-level rise above the threshold (CPSL, 2010).

Exceeding a tipping point may have serious implications for ecological functioning and ecosystem services of the Wadden area. For instance the Wadden Sea intertidal flats might change into a subtidal lagoon. Furthermore, the potential of storm-wave energy dissipation within the Wadden Sea might decrease, due to reduction in shoal and tidal marsh (relative) heights and surface area. It leads to higher waves at the flood defences surrounding the basin. In addition to SLR, climate change may lead to other changes in driving forces, such as changes in wave climate, in storm surge set-up, river run-off, precipitation and temperature (figure 3.7).

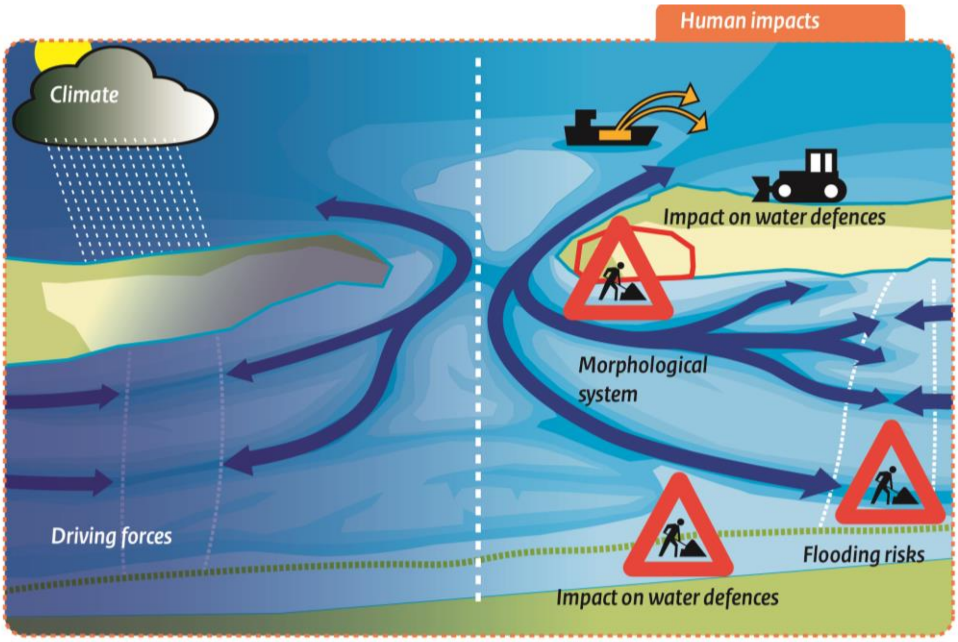

Figure 3.7: overview of the determining factors and human impacts which influence the morphological system which together determine the impact on water defences and with that the flooding risks.

Textbox 3.1

Estimating the maximum net sediment transport capacity in an inlet system

The transport capacity of an inlet defines the annual amount of sediment which migrates in and out of an inlet. Eysink (1993) calculated the amount of sediment as follows: measurements during a spring tide under calm weather conditions in the Vlie Inlet (Terschelling Inlet) indicate that in suspension an amount of $25\text{-}35*10^6$ kg sand and $25\text{-}40*10^6$ kg of fines is transported. For an average tide the amount is multiplied by a factor 0.75. The gross amount which annually flows through the Vlie is hence $13.5\text{-}18.5*10^9$ kg/yr. Assuming comparable flow velocities in other inlets, the gross annual imports per inlet can be calculated.

The gross import, which is only partially deposited (Eysink, 1991), is an average upper limit to what an inlet theoretically could deposit in a year. The sand import in an inlet can be compared based on depth soundings (after 1958) with the calculations of Eysink. It shows that the minimal estimates of Eysink are comparable to the maxima in net annual deposition. Based on an average mud content of the Dutch Wadden Sea sediments (outside the tidal marshes) of 8% it is hypothesized that mud deposition plays on average a minor role and will “drown” in the errors of the depth soundings.

Inlet system	Calculated gross annual sand import (10^6 m^3/yr)	Measured maximum sedimentation ($10^6 m^3$/yr) after 1958
Marsdiep (Texel Inlet)	6.1-8.4	7.7
Eijerlandsche Gat (Vlieland Inlet)	3.2-4.5	0.5
Zeegat van het Vlie (Terschelling Inlet)	8.7-11.9	8.6
Borndiep (Ameland Inlet)	3.5-4.8	2.9
Pinkegat	1.9-2.6	1.4
Zoutkamperlaag after closure Lauwerszee (Schiermonnikoog Inlet)	2.9-4.2	3.0
Eilanderbalg	1.5-1.9	1.4
Lauwers	2.9-3.9	1.2
Schild	1.3-1.7	0.4
Wester Eems	8.4-11.6	5.2
TOTAL	40.6-55.5	

Table I: see also textbox 3.1. Overview of calculated annual gross annual sand import (Eysink, 1991; and measured maximum sedimentation (data of various studies up to 2002 (Oost, 1995; Hoeksema et al., 2004; Elias et al., 2012).

Many relations between hydrodynamics and morphological dimensions, such as the volume of the ebb-tidal deltas, the length of barrier islands and the dimensions of the tidal channels, have been observed in the Wadden Sea of the Netherlands and Niedersachsen (Eysink, 1991; Eysink & Biegel, 1992). Furthermore it was found that these relations might be more complicated than previously thought, especially for longer basins (Sha & Van den Berg, 1993; Ridderinkhof et al., submitted, a&b).

3.2.2 Knowledge gaps

A series of major knowledge gaps is identified considering the functioning of the sediment sharing tidal system. The overview is partially based on the various trilateral discussions and on recent inventory studies and overviews (Speelman et al., 2009; Oost et al., 2012; Elias et al., 2012a&b; Wang et al., 2012):

- *With regard to water movement:*
  - What role do storms play in the exchange of water and sediment between the neighbouring basins and between the Wadden Sea and the North Sea (Wang et al., 2012)?

- *With regard to sediment transport:*
  - The major question is how the observed sediment import is generated and what will be the reactions to climate change effects, especially sea-level rise. More in detail (mainly after Wang et al., 2012):
  - The processes and mechanisms leading to net sediment transport – either import or export -, such as: residual flow, tidal asymmetry, density currents, etc. seem to be relatively well known, except for their relative importance. Thus a central issue is: what is the relative importance of the major sediment transport mechanisms in a Wadden Sea tidal inlet system and what causes the local differences?
  - What role do extreme events such as storms play in erosion and deposition of sediment?
  - What are the consequences of various aspects of climate change (sea-level rise, global warming, changing wind patterns, changing precipitation/evaporation patterns) to the net sediment transport into the Wadden Sea?
  - What determines the exchange of sediment between adjacent tidal basins?
  - How much import of each sediment type occurs in each sediment-sharing tidal inlet system?

- *With regard to morphodynamics:*
  - Which factors determine whether a tidal basin can keep up with sea-level rise?
  - Which other tipping points might occur either due to changes in drivers or due to inherent evolution after which the sediment sharing inlet system can follow a different morphological development? (e.g. Ridderinkhof, submitted, a&b)
  - What is the role of barrier islands as a source and sink for sediment as part of the sediment-sharing inlet system on the scale of decades to centuries?

- *Models*
  At the moment, most models are aimed at the development of (parts of) inlet systems over the period of years. Although the direction of development can be determined in this way, the exact development over a timespan of several decades cannot be calculated. Also, the uncertainties in this development (due to for instance stochastic processes and the uncertainties in the model itself) cannot be assessed. There are several causes for this. On one hand there is insufficient theoretical knowledge leading to inherent limitations in the models, such as the exact schematizations for driving forces; closure for turbulence and mixing in 3D modelling. At the moment, models are not capable of satisfactorily reaching morphological equilibrium state. On the other hand, the models are also limited due to the lack of accurate measurements over longer time spans (10-20 years), such as fresh-water discharges, currents and waves, which are needed to validate the models. For the semi-empirical models which are able to predict general behaviour of the sediment-sharing inlet system over longer spans of time, such as ASMITA, the parameter settings are still unsatisfactory addressed (Wang et al., 2013).

3.3 Ebb-tidal deltas

3.3.1 Current insights

Ebb-tidal deltas (figure 3.8) play an essential role in the sedimentary development of inlet systems and in flood safety. They form the link between the open sea, the barrier islands and the back-barrier basins. Also they dissipate the wave energy and provide shelter to parts of the islands and to the adjacent back-barrier area. Driving forces (tide, wind and waves) exert a strong influence on the morphology of the ebb-tidal deltas (Sha & Van den Bergh, 1993). Changes in the driving forces will therefore lead to morphological change. In turn it may influence the development of other parts of the system. Thus knowledge about ebb-delta development is essential to our understanding of the sediment sharing inlet system.

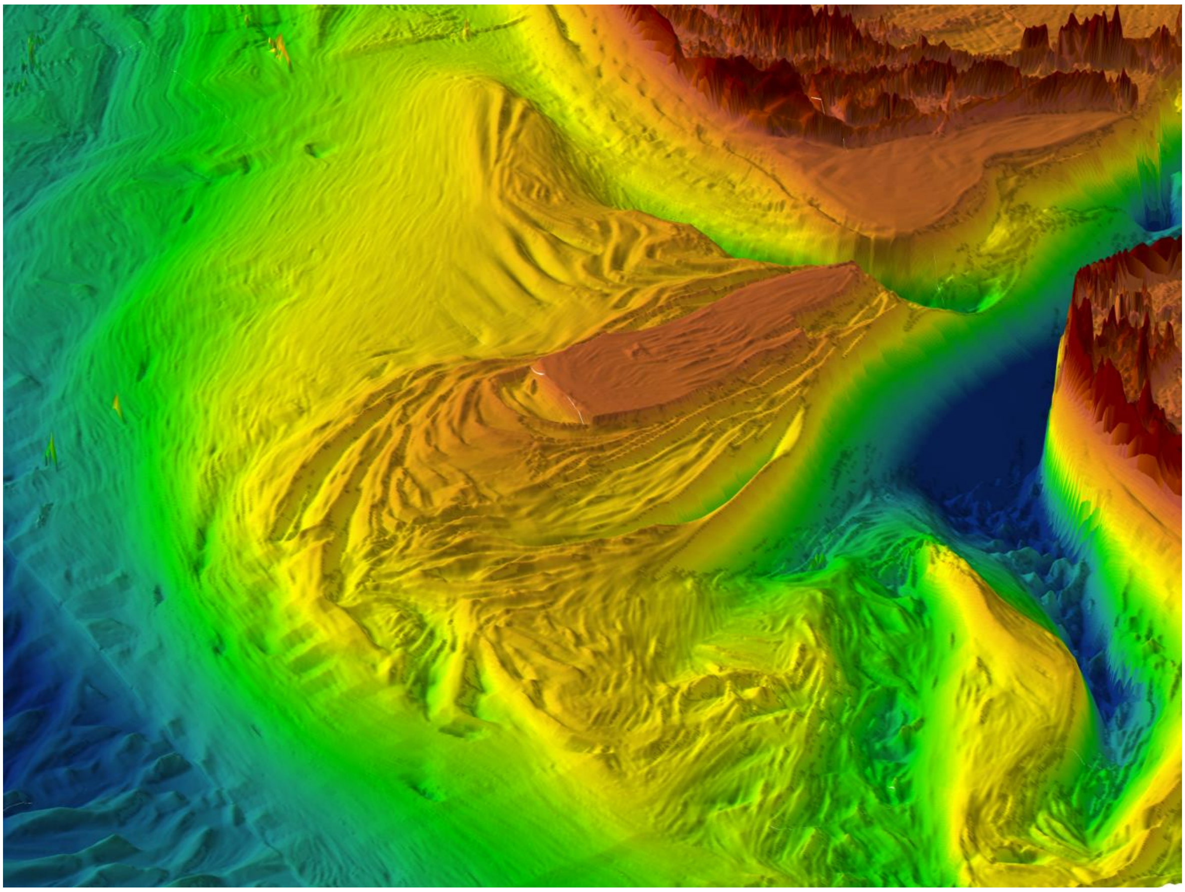

Figure 3.8: Oblique picture of the ebb-tidal delta of Texel Inlet (Marsdiep), based on 2004 depth soundings; colours indicate depths (blue deepest) (source: RWS).

In general, a bigger tidal prism results in a larger sediment volume of the ebb-tidal delta (Eysink & Biegel, 1992). However, it was observed that in the western part of the Dutch Wadden Sea the development of the ebb-tidal deltas was different. From volumetric developments of Dutch inlet systems since ca. 1927, it was concluded that the ebb-tidal deltas lose sand to the back-barrier areas. Especially the ebb-tidal deltas of the Marsdiep and Vlie inlet systems which are strongly influenced by the building of the Afsluitdijk deliver large amounts of sand (Elias, 2006, 2012; Elias et al., 2005, 2012a). Furthermore, the ebb-tidal deltas of Marsdiep and Vlie appear to have stopped their cyclic behaviour of the past centuries (Sha, 1990b) and have maintained an up-drift orientation since 1930 (Elias, 2006). The development of the tidal channel which developed along the Holland coast causes erosion. The causes for volume and orientation changes of the ebb-tidal delta of the Marsdiep are still under debate: phase shifts between the horizontal and vertical tides coming from the back-barrier basin and in the North Sea have been suggested as well as increasing tidal volumes (Sha, 1990a; Elias, 2006; Ridderinkhof et al., 2014a&b).

Still, if the hypothesis that sediment demand in the back-barrier basin also determines the size of the ebb-tidal delta is true, then the larger sediment demand due to accelerated sea-level rise can result in more ebb-tidal delta’s being eroded faster than at present. This may also have consequences for the barrier islands.

A likely example is the fast erosion over more than 1 km of West-Vlieland in the 16-17th century, after the strong decrease in size of the ebb-tidal delta (as was described by contemporaneous sources; Abogado Rios, 2009). Something similar was observed during the 19-20th century reorientation of Marsdiep ebb-tidal delta, coinciding with a landward retreat over 1.5 km of SW Texel. Under present-day conditions the barrier islands are no longer allowed to retreat and are kept in place by nourishments if possible. At some places sufficiently large nourishments are already difficult to place into the rather small coastal profile (West Ameland); an increase of nourishments would make the problem worse. Also, the costs for an increase in nourishments may increase to an unacceptably high level. The question is if nourishment policies have to be altered when ebb-tidal deltas erode faster under conditions of accelerated sea-level rise.

It is not fully clear what will be the effect of a further decrease in sediment volume of the ebb-tidal deltas on the adjacent barrier islands and back-barrier basin. Two issues are important:

1) *Sediment supply*
   A reduction of the ebb-tidal delta volume to zero would obviously result in a reduction in sediment transport from the ebb-tidal delta to the down-drift island (for the Dutch situation: to the north or to the east). Also, the back-barrier area would probably receive less sand. The situation of a total disappearance of the ebb-tidal delta is however not likely: some volume will always be there. Whether this volume is sufficient to provide the down-drift coast and back-barrier area with sediment is not known.

2) *Sheltering effects*
   This is a complicated issue. In general a lowering of the ebb-tidal delta shoals will result in less shelter and waves might penetrate deeper into the back-barrier area or larger waves might reach the barrier coasts. Lowering of the ebb-delta shoals has been observed in Hörnum inlet, Schleswig Holstein (Hofstede, 1999b). Erosion of the back-barrier island Föhr due to extra wave-attack is identified as a likely consequence of that (Hofstede, pers. com.). Reversely, vertical growth of shoals has been observed on most of the Dutch ebb-tidal deltas, thus providing extra shelter. Furthermore, a shift of the ebb-delta away from the coast may result in less sheltering effects and lead to erosion (e.g. 1.5 km since 1880 on south Texel when the Molengat channel opened). The same may hold for a decrease in size, if this is not counteracted by shoal formation and/or reduction in inlet size. From a flood safety point-of-view a reduction in shelter for waves implies an increase in wave periods and heights. At the moment it is not possible to predict if and how ebb-tidal deltas will change due to climate change effects (i.e. sea-level rise and change of wind patterns) and we therefore cannot predict changes in wave attack.

   A broader angle over which waves come in from the open North Sea onto the island's coast does not automatically lead to stronger erosion: waves from the new directions may counteract the sediment loss by the waves coming from the old directions. This can be illustrated by the coastal erosion resulting from the northward expansion of a shoal along the coast of south Texel (Cleveringa, 2001). Also here, present-day insights and modelling tools lack the capability to predict if and where erosion will increase (see also Elias et al, 2012b; de Ronde & van Oeveren, 2013).

Denmark has at the moment hardly any problems with its ebb-tidal deltas, in contrast to Schleswig-Holstein. There, accretion is in general dominant in front of and in between the barrier islands. This is due to a positive sediment budget, resulting from onshore transport from the North Sea and substantial long-shore transport from the Jutland peninsula (Nielsen

& Nielsen, 2006; Madsen et al., 2010). Except for the ebb-tidal delta off the Grådyb Inlet which is dredged, the other ebb-tidal deltas are currently stable in volume or even growing.

At the moment there seem to be no insurmountable problems along the Wadden coasts due to changes in ebb-tidal deltas, although some may have gone unnoticed. However, if sediment demand increases in other sediment sharing inlet systems, it is plausible that ebb-tidal delta's may retreat faster. This may affect the barrier island coasts and result in more management measures to maintain the coasts. To tackle future problems and look for cost-effective solutions to prevent coastline retreat of the Wadden islands, locations for and volumes of sand nourishments may have to be reconsidered. North Sea coast nourishments are nowadays usually put on the shallow foreshore, but perhaps they could be partially shifted towards the ebb-tidal deltas, or should be given a different shape. For example, mega-nourishments and closures of an ebb-tidal delta outer-channel are being considered (Elias et al, 2012b; de Ronde & van Oeveren, 2013). However, it is concluded that the present knowledge is insufficient to carry out such measures without risks. Particularly knowledge on system behaviour over the medium term (1 to 25 years) is insufficient. Predictive models for this would greatly benefit from datasets for validation, including data on discharge, currents and waves (de Ronde & van Oeveren, 2013).

3.3.2 Knowledge gaps

In summary the research questions concerning ebb-tidal deltas are:

- *With regard to water movement (mainly following from discussions):*
  - What is the relative role of waves and currents in different parts of the ebb-tidal delta?
  - What changes in wave conditions along the barrier coast and in the back barrier area can be brought about by changes in size and/or orientation of an ebb-tidal delta?

- *With regards to sediment transport (mainly following from discussions):*
  - What is the relative importance of the various sediment transport mechanisms on ebb-tidal deltas and how does sediment exchange between the ebb-tidal deltas and the barrier islands and back-barrier occur?
  - What will be the resulting sedimentation-erosion patterns on the barrier islands and in the back-barrier area due to changes in configuration or sediment volume of ebb-tidal deltas?
  - What will be the development of sand nourishments on ebb-tidal deltas?

- *With regard to morphodynamics (Wang et al., 2012):*
  - How is an ebb-tidal delta generated?
  - What factors determine the size and shape of the ebb-tidal delta?
  - Why do the sandbanks on the ebb-tidal delta show a cyclic behaviour in time?
  - When will the reduction of sediment volume of the ebb-tidal deltas stop?

3.4 Barrier islands

3.4.1 Current insights

The barrier islands are closely coupled to the ebb-tidal deltas and inlets (figure 3.9). Ebb-tidal deltas provide sediment to the islands, but ebb-delta channels may also cause erosion, as do shifting inlets. Given this continuous exchange of sediments, the heads and tails of the barrier islands might be considered part of the ebb-tidal delta. The North Sea coasts of barrier islands and ebb-tidal deltas have to deliver the sand needed for the back-barrier. Next to that the islands themselves need sediments to keep up with rising sea-levels, while they are not allowed to retreat. To compensate both, sediment import is needed. When natural sediment import is small to zero, the coastal foundation will mainly gain sand via nourishments. How, where and when these nourishments should be placed can be decided better when the role of barrier islands in the sediment exchange of the sediment sharing inlet systems is understood.

Sediment exchange
Barrier islands play an important role in the long-term exchange of sediment, as a source or sink of sediment (mud and sand). Historical observations show that the long-term development of barrier island volumes is especially related to (Davis, 1994):

- shifts in position of the inlets (Dean, 1988; Sha, 1990b; Elias, 2006);
- shifts of marginal ebb-tidal delta channels (van Veen, 1936; Joustra, 1971; Oertel, 1977; Oost, 1995; Schoorl 1999a&b; van Heteren et al., 2006);
- coastal erosion (Hofstede, 1994a; Elias et al., 2012);
- back-barrier erosion by barrier-ward channel migration (Oost, 1995);
- sediment delivery from the ebb-tidal delta (Van Veen, 1936; Oertel, 1977; Sha, 1990b; Israel & Dunsbergen, 1999; Schoorl, 1999a&b; Van Heteren et al., 2006);
- wind driven sediment transports (Arens, 1999; Arens et al., 2007, 2008a&b);
- storm-surge driven sediment transports (Ten Haaf et al., 2006; Hoekstra et al., 1999, 2009);
- tidal marsh sedimentation.

The development of barrier islands over longer periods of decades to centuries is only partially known. Large amounts of sediment are involved (e.g. the increase over 4 km in length of east-Schiermonnikoog since 1970; or the erosion of east-Terschelling over 2 km since 1990; see also: Schoorl, 1999a&b, 2000a&b; Ehlers, 1988; Oost, 2012; Oost et al., 2012). In all large-scale sediment budget analysis for the Wadden area up to now the development of sediment budgets of the barrier islands are not fully taken into account. This is especially due to the lack of precise data before Lidar became available. At the moment Lidar is mainly concentrated on the areas with a so-called reference coastline. This results in uncovered areas on most of the islands. A better knowledge and monitoring of the barrier islands is essential for predicting their future development.

Many of the barrier islands have a drumstick shape with a broad head at the updrift side and a thinner tail at the downdrift side (Figure 3.9; FitzGerald et al., 1984). As a result, the island beaches are somewhat different in morphology and behaviour compared to the Holland coast beaches. Most beaches are very wide and dissipative. The wave field is 3D in character as it is strongly affected by the near-shore morphology and bathymetry of the ebb-tidal delta. It results in specific refraction patterns and the convergence and divergence of wave energy. Due to the complexity of the coast, the safety levels of this part of the islands are difficult to assess (Wang et al, 2012). Sediment transport is reasonably well understood. However, it is still an open question to what extent a beach-ward sand transport is generated on these dissipative beaches by the dominant low-frequency (or infragravity) waves (Ruessink et al., 1998, 2012).

Figure 3.9: Barrier island Schiermonnikoog view towards the east, 2-8-2011: the island has significantly shifted in an eastward direction. At several periods it was a major sink for sediment whereas during others it acted as a source.

On most islands, natural development (inlet and ebb-delta channel migration, dune migration and washover development) has been hampered or strongly influenced by man, especially since 1900. This will undoubtedly have consequences for the resilience of the islands and the sediment sharing to the effects of climate change. These consequences are, until now, poorly understood. A short overview of some important points is given below:

Halting channel migration.

On many of the German islands ebb-delta channel and inlet migration is stopped by massive stone works, especially on the island heads. In the Netherlands this is the case at Den Helder, north-Texel, the east part of Vlieland and west-Ameland. The sand and mud covered with stonework are no longer part of the exchange of sediments within the sediment sharing inlet systems. The influence on the functioning of the inlet system in terms of sediment exchange and natural dynamics is not known.

Eolian transport

Large-scale marram planting and the building of sand fences led to the formation of massive and often fully closed sand drift dikes along the beachfront (Arens, 1999; Löffler et al., 2011). Currently, on the 5 inhabited Dutch barrier islands in total about 1 Mm^3/year sand is trapped in the managed dunes at the North Sea side (Arens et al., 2007). Consequently, eolian sand transport from the beach further into the interior of the barrier islands is hindered. This is strengthened further by marram grass planting, stopping migration of inlands dunes. Originally, eolian sand transport was a main mechanism to allow the barrier areas to accrete vertically (see a.o. De Jong, 1984). The lack of sediment import from the beach may ultimately result in a falling behind of barrier elevation with respect to sea level. This is locally already observed in an area on Ameland which is subsiding due to gas extraction. The lack of eolian dynamics also resulted in a strong loss of ecosystem values due to fast plant succession (Löffler et al., 2011).

Recently several authors have advocated to look into the restoration of dune processes to increase eolian sediment transport to rejuvenate the ecosystem. (Arens et al., 2008a&b; Löffler et al., 2011; Oost et al., 2012). At the same time resilience to sea-level rise increases due to the increasing dune volumes which can also safeguard the inhabited behind the dunes. Locally on all barrier islands re-activation is tried at both the small (a few dunes; e.g. Schiermonnikoog) and the large (km of dune face; e.g. Terschelling) scale. Until now no comprehensive studies are available to evaluate all of these attempts. Eolian sediment transport over the beach is currently studied in the Netherlands. Eolian transport from the dune face into the barrier islands is not understood in sufficient detail to model it satisfactorily with programs such as X-Dune. If vertical accretion via eolian transport is going to be used successfully to create a natural answer to sea-level rise, such knowledge is essential.

Overwash transport
The washover environments often consist of low areas which are topped by waves (the overwash transport proper) and flooded (flooding phase) during storm surges. In this way water and sediments are transported from the North Sea onto and over the island. Similar to eolian transport, overwash transport under natural conditions is a normal phenomenon on the Wadden barrier islands. From the few observations available (Nielsen & Nielsen, 2006) it appears that overwash on the Wadden Sea barrier islands is especially important in eroding and redepositing sediment of the beach and dune-face. During the period thereafter eolian transport takes over (Hoekstra et al., 2009; Ten Haaf et al, 2011). Washover deposits and sediments taken from the beach are transported deep into land via the overwash areas. As such, eolian transport appears to be the dominant factor. It is also another way in which barrier islands can keep up with sea-level rise, at least locally. The formation of sand drift dikes along the beach area blocked many of the washovers and ended their dynamics. Due to this also the pioneer species which were depending on the extremely harsh environmental conditions brought about by overwash disappeared. Plant succession was accelerated and natural values of the areas are declining strongly.

Currently PhD-research is carried out at Utrecht and Nijmegen Universities to study the feasibility of restoration of washovers, supported by environmental organizations. Based on the outcome, pilot studies realising restoration are expected in 2018. The PhD-studies as well as the pilot studies will improve our understanding of the functioning of this part of the sediment-sharing inlet system and the feasibility to restore natural dynamics.

Development of tidal marshes
In the lee of both natural and artificial dunes, tidal marshes developed while fine-grained sediments accumulated. Volume calculations for the Dutch islands indicate that these salt marshes are an important sink for cohesive sediment and fine sand (De Groot et al., 2014a). The accumulation of sediments in tidal marshes might be one of the keys to compensate for sea-level rise on the islands through extra sedimentation. It is not known yet whether the normal feedback mechanisms between sea level and salt-marsh sedimentation will be sufficient to let mature salt marshes grow with sea-level rise, or if additional measures are necessary. An important matter is whether salt marshes on barrier islands exhibit the same natural cycles of lateral growth and erosion as estuarine tidal marshes, i.e. whether lateral erosion is a long-term threat or not. Also, the hindered sediment supply from the North Sea by sand drift dikes is not compensated everywhere by extra input from fines from the Wadden Sea. This leads to relative deepening of the areas directly landward from the dike. It is not clear if it is possible to restore the original processes successfully, due to the massive changes in the area.

3.4.2 Knowledge gaps

Main research questions to be resolved are:

- *Role of barrier islands as part of the sediment sharing inlet system*. What are the principal mechanisms of sediment exchange between the island and the other parts of the sediment sharing inlet system? What volumes are involved?

- *Sediment transport to the islands*. What role does infragravity wave-related sediment transport play on the broad dissipative barrier coasts of the Wadden? What is the magnitude of the eolian transport onto the barrier islands?

- *Dune development*. Can we reconstruct the developments of dunes on the barrier islands in the past and can we predict future developments? More specific: to what extent are these related to landward barrier retreat, ebb delta developments or to island head shifts? Furthermore, how do dune areas develop?

- *Tidal marsh development.* What is the magnitude of the various sediment transporting processes which are important to accumulation on tidal marshes (i.e. washover, eolian transport and back-barrier flooding-related processes)? Do salt marshes on barrier islands exhibit the same natural cycles of lateral growth and erosion as estuarine tidal marshes, i.e. is lateral erosion a long-term threat or not?

- *Washover development.* How can we successfully restore washovers and migration of dunes? Which dimensions are needed? Can physical and ecological changes which occurred after the formation of sand drift dikes be successfully reversed?

- *Nourishments.* What are the optimal locations, frequencies and volumes for nourishments in the future in terms of morphology, ecology etc.?

3.5 Back-barrier basins

3.5.1 Current insights

The Wadden Sea has become UNESCO World Heritage due to its ecological values as well as its morphology, especially its extensive tidal flats (figure 3.10; Reise et al, 2010), which are a major factor behind the ecology of the area (Herman et al., 2009). Especially the flats are considered vulnerable to climate change (Sips & de Leeuw, 2009). Both recent direct observations as well as geological observations show that net sediment import is limited due to a limit on gross sediment transport capacity and accommodation space (see text box 3.1; Beets & van der Spek, 2000; Madsen et al., 2010). Under dynamic equilibrium conditions mostly only a small percentage of the gross amount of sediment which is transported during each tide is net deposited (Nummedal & Penland, 1981; Wang et al., 1995; Reise et al., 1996). Therefore, it is assumed that higher rates of relative sea-level rise can, in most cases, still be compensated by higher sedimentation rates and a new equilibrium can be established in the back-barrier area. But as discussed in paragraph 3.2.1 sediment import via the inlet has most likely an upper limit. Thus, the capability to vertically grow with increasing rates of sea-level rise is limited. Much focus is therefore on the determination of (possible) critical limits which may lead to regime change. It requires solving the following fundamental problems in morphodynamics of the Wadden Sea system (mainly Wang et al., 2012):

Figure 3.10: Back-barrier area of Spiekeroog: tidal flats consisting mainly of fine sand and to a lesser extent cohesive sediments, provide feeding grounds for many invertebrates and vertebrates (Photo by C. de Leeuw).

Sediment import

Based on the long-term rate of coastal erosion of the barrier islands in The Netherlands and Lower Saxony it was concluded that a sea-level rise of at least 3 mm/yr can be compensated by sedimentation by bigger inlet systems and as much as 6 mm/yr by small inlet systems (Oost et al., 1998). Probably the rates of SLR which can be compensated by sedimentation are higher. Rates have been mentioned of 5 mm/yr (CPSL, 2010; now TG Climate), which is considered statistically likely based on field data by Hoeksema et al., (2004); 7 to 8 mm/yr based on geological investigations of the former tidal flats in the western Netherlands (Beets & Van der Spek, 2000). Some ASMITA model studies indicate that the tipping points may be as high as 10 mm/yr (van Goor et al., 2003). The latter figures are confirmed for the zone of the upper tidal flats near the mainland by precise sedimentation rate measurements which give long-term (8-10 yr periods) average figures around 10 (-6 to 20) mm/yr (Dijkema, 2007). There is thus still no consensus on the critical rate of sea-level rise at which the different back-barrier basins can just keep pace with. The maximum rate of sediment import to a Wadden Sea basin is thus still not sufficiently known.

Sediment demand

The import rate needed for a basin to keep pace with the rising sea level can, as a first approximation, be calculated as the surface area of the basin multiplied by the rate of sea-level rise. Judging from the long term development (1500-present) under conditions of slow sea-level rise, this seems a good first approximation. However, this straight-forward approach is only valid under the assumption that the basin does not change its shape (more channel volume or fewer shoals; Hofstede, pers. com.). As pointed out by Hofstede (trilateral discussions) the height distribution (hypsometry) of the back-barrier area might change under the influence of changing driving factors. There are indeed indications that the tidal channels of several tidal systems in the German Wadden Sea are increasing in average depth (Hofstede, pers. com.). All such changes may change the sediment demand of the back-barrier basin. This may differ from basin to basin, due to factors such as its shape, hydrodynamic and sedimentary characteristics and the management. At the moment there is insufficient knowledge of the long-term morphodynamics of the tidal basins to predict its future sediment demand under conditions of accelerated sea-level rise.

Until now, sediment budget studies mainly determine the total amounts of sedimentation and erosion. Little is known about which sediment fractions have caused the changes. For instance the ratio between non-cohesive and cohesive sediment in the Dutch Wadden Sea is 10:1 in general, but important regional differences occur (Flemming & Nyandwi, 1994; Delafontaine et al., 2000; Vos & van Kesteren, 2000; van Ledden, 2003; Wang et al., 2012). These differences have a profound influence on sediment deposition and on the quality and nature of Wadden Sea habitats. In fact, a budget is needed per sediment fraction and at least a distinction is required between cohesive sediments (which are mainly imported in suspension from outside of the Wadden area) and non-cohesive sediments (which are mainly locally reworked sand) (Wang et al., 2012). Furthermore the shoals of the Wadden area are characterised by fine sands (120-160 µm), whereas the channels have coarser material (280-340 µm). The fine sands are mainly transported as suspended load. Such differences might be a reason to distinguish them in models.

Tidal marshes form an important sink for cohesive sediments and fine sands (Dijkema, 1980; Hoffmann, 2004, De Groot et al., in prep.). The bio-accumulation of sediment volumes by tidal marshes might be one of the keys to compensate sea-level rise in front of dikes of the mainland. The tidal marshes play a role in the reduction of waves in front of dikes (van Loon-Steensma et al., 2012). It is however, not well known which management practices will optimise the accumulation processes and maintain the ecological quality at the same time.

Channel-shoal interaction
At the moment the net exchange mechanisms of sediments between shoals and channels is still an unsolved problem in morphodynamics of tidal systems such as estuaries and tidal lagoons (Wang et al., 2005). It is therefore not known how development of shoals will proceed when rates of sea-level rise increase. Also there is no clear idea how such changes might be mitigated.

Sufficient import through the inlet is a prerequisite, but for tidal flats of the back-barrier basin to keep pace with (accelerating) sea-level rise also net transport from the channels onto the shoals is needed. The local annual gross vertical dynamics are a few to a hundred times (cm to m/yr) bigger than the net sedimentation rates on shoals (Hoeksema et al., 2004). This implies a strong exchange of sediments between channels and shoals. The exchange is brought about by wave- wind- and tidally driven currents in combination with the (often dominant) bottom shear stress exerted by waves which tend to “whirl” the sediment up from the shoals. On top of that several other factors are probably important such as: settling lag and scour lag effects (van Straaten & Kuenen, 1957; Postma, 1961); biotic effects; sieve deposit effects and the influence of the many small inter- and just subtidal channels on the shoals. The special phenomenon of drying during ebb and flooding during flood tide in such areas is still difficult to handle in models. Pilot studies in the Oosterschelde have proven that field measurements may greatly help to obtain a better understanding of the relative importance of the mechanisms which play a role and determine the sedimentation rates of the shoals.

Models
For the management of the effects of sea-level rise in combination with human interference, predictions are needed over decades. At the moment it is not possible to make model predictions in detail over such long periods. If a dynamic morphological equilibrium will establish, the basin keeps pace with sea-level rise. The average depth, however, will increase with increasing rate of sea-level rise. On the aggregated scale this can already be simulated with semi-empirical models such as ASMITA. However, there is a drawback in the ASMITA models. They do not take into account the possible changes of the tidal amplification with the changed sea-level. High sea-level rise will result in larger over-depth in the Wadden Sea, which might cause stronger amplification of the tide (Wang et al., 2012). A changed tidal range will influence the (absolute) morphological equilibrium and therefore the dynamic morphological equilibrium. At more detailed spatial scales, process-based models are required to evaluate the morphological development under influence of accelerating sea-level rise over sufficiently long time spans (decades). Given the diverse spatial patterns of Wadden sea inlet systems, 2D/3D modelling is needed to provide insights for safety-related management questions (such as: will this shoal remain in front of this dike for the coming decade?). Much still needs to be done in this field. Recently a new 1D schematisation is presented by Van Prooijen and Wang (2013), which is expected to be very useful for solving this issue.

3.5.2 Knowledge gaps

In summary the main research questions to be resolved are:

- *What drives the changes in hypsometry of tidal basins? Can these change under changing external drivers?*
- *How do channels and shoals interact? What is the relative importance of the various known mechanisms?*
- *How can the back-barriers with their channels and shoals be modelled better on both an aggregated scale and, at more detailed spatial scales, to predict their morphological development under various regimes of accelerating sea-level rise and wave conditions?*
- *What measures can be effective in controlling undesired developments such as local drowning of shoals and tidal flats in response to accelerated sea-level rise?*

3.6 Migration of channels

3.6.1 Current insights

Migration of channels in both the ebb-tidal deltas and in the back-barrier basins can results in serious problems for safety against flooding (figure 3.11). When a channel migrates towards a flood defence structure failure may occur due to stability problems. Also this may increase wave attack on the tidal marshes in front of dikes or on dikes themselves (Janssen-Stelder, 2000). In many cases a channel which has migrated to the dike will not migrate away from it again and cause damage from time to time. Various examples of such (near-) events are known in the Dutch coastal system and also in the Wadden Sea region. Also in Zeeland channels migration leading to dike instability is a problem. We still do not quite know how such problems can be prevented and mitigated.

Within the Wadden area, channels branch in a regular manner and transport the water to and from the various sub- and intertidal flat areas (Cleveringa & Oost, 1999). In general tidal channel structure is reasonably well understood. However, channel migration is still not sufficiently understood.

Figure 3.11: Morphologic dredging and protection of the dike near Vierhuizergat a channel which came perilously near to the dike (source: site Hoogwaterbeschermingsprogramma).

3.6.2 Knowledge gaps

Main research questions to be resolved are:

- Which processes govern the behaviour of tidal channel migration near dikes?
- What causes failure of flood defence structures due to erosion caused by migrating channels?

4 Research Framework

4.1 Set up of the research framework

In this section the tasks are further specified along three lines: monitoring & data analysis, system research & modelling and field experiments.

As stated in paragraph 1.2, the following main questions, relevant from a management perspective, were identified:

1. How will the sediment-sharing inlet systems of the Wadden area change under different climate scenarios, in combination with existing human interference? What are the implications of this for: I) Flood safety, II) Natural values, and III) Human use, such as shipping and mining?
2. How can we monitor the hydrodynamic and morphodynamic developments and the associated flood safety risks?
3. How can we adapt to the effects of climate change?

To answer the questions a better insight in the long-term morphological functioning of the system is needed in which the knowledge gaps identified in chapter 3 have to disappear. To this end three research lines are proposed, which combined will constitute an integrated system research framework. The research and modelling will be based on data analysis combined with monitoring. This will lead to hypothesis formulation and model development. These will be tested with pilot studies. At the same time the pilot studies should deliver new data.

The framework of the proposed program is shown in Figure 4.1, indicating how the three main management questions are dealt with along the three research lines: data analysis & monitoring, system, research & modelling and field experiments (pilots).

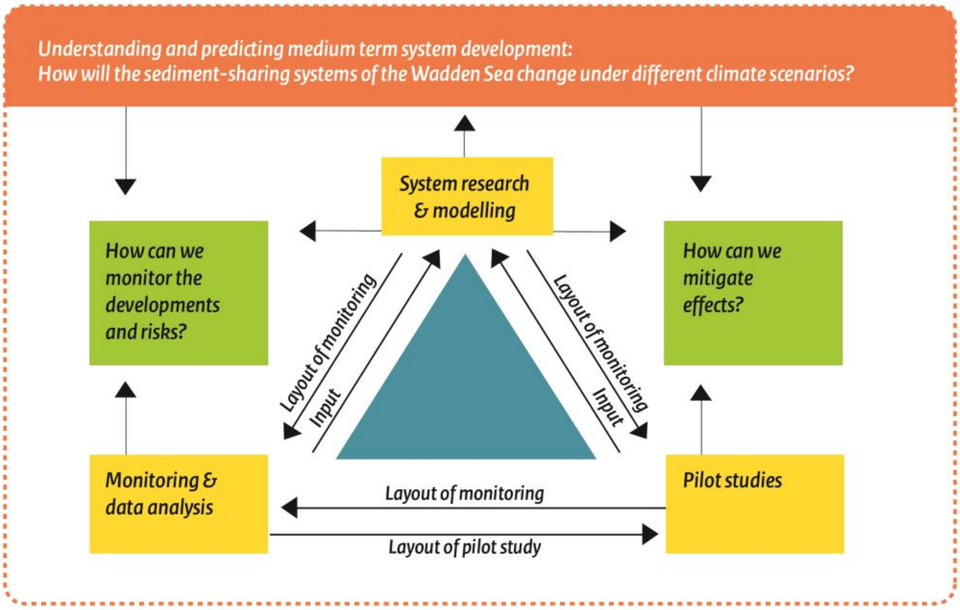

Figure 4.1: The three proposed research lines: system research & modelling, monitoring & data analysis and field experiments / pilots and their mutual interconnections.

It is important to realise that the three lines each serve several goals and are also closely interlinked (figure 4.1). Monitoring and data analysis should shed light on the changes that are occurring as a result of climate change (in combination with human impacts). Also, they should help in the layout of the pilot studies, while reversely the pilot studies consist partly of monitoring and data analysis. Long-term monitoring as well as pilot study-related monitoring should also provide the data needed for modelling and system research.

Furthermore, data analysis and modelling should help to determine the layout of both monitoring and the pilot studies. The data gained from monitoring the pilot studies will underpin the system research and modelling. The pilot studies will help answering the question how to mitigate negative effects: will this or that measure work? The pilot studies will contribute to the system research and partially determine the layout of the pilot-related monitoring.

It is expected that, to answer all the questions which have to be answered, much time is needed: several decades rather than years. Partially this is due to the great amount of knowledge gaps. Partially it is also due to the fact that gathering sufficient morphological data and analysing them, carrying out pilots and studying them and developing the system knowledge and models needed takes decades. Fortunately such time is still available: climate change is predicted to develop at a slow rate up to at least 2050 (http://www.klimaatscenarios.nl/).

In the following three sections the three research lines are described in more detail.

4.2 System research & modelling

To increase our capability to predict the changes in the Wadden Sea system and the effect of mitigation measures, we require better modelling tools. This requires improvement of the modelling tools themselves, but even more importantly, it requires improved process knowledge of the system. Models can also be research tools, improving our knowledge of the system. The research line ‘system research and modelling’ serves both purposes: to improve the fundamental knowledge of the system and to improve the modelling tools. System research and modelling can only be carried out in conjunction, as they mutually depend on each other.

System research

The research questions (knowledge gaps) outlined above in chapter 3 are to be used as guidelines for the fundamental research. Note that the summarizing description below is not meant to be exhaustive.

Considering the morphological functioning of the sediment sharing tidal system, system research has to focus on the interrelation between the ebb-tidal delta’s, the barrier islands and the backbarrier basin (see also paragraph 3.1). A special focus is needed on the identification of tipping points in morphological development in the light of climate change and human alterations of the system, such as: what defines the limits to net sediment input into the backbarrier areas?

For the ebb-tidal delta an important focus point is the development of the ebb-tidal delta’s due to changing tidal volumes or increased sediment demand of the back-barrier area. A better understanding of sediment transport mechanisms is crucial (see also paragraph 3.2). The effects of changes in the configuration of the ebb-tidal delta for the adjacent barrier islands and the backbarrier in terms of sediment supply and shelter is another crucial issue.

The role of barrier islands in the sediment sharing inlet-systems of the Wadden Sea and the principal mechanisms of sediment exchange between the island and the other parts should be and important issue in system research. For possible pathways to increase resilience of the barrier islands themselves important sub-issues are dune - , washover - and tidal marsh development (see also paragraph 3.3).

For back-barrier basins the relative importance of external drivers causing changes in height distribution should be determined. Within the basin the interaction of channels and shoals has to be understood in more depth. The research should also make clear what is the best way to mitigate unwanted developments due to climate change (see also paragraph 3.4).

For tidal channels it is important that processes governing the behaviour of tidal channel migration near dikes and the causes of failure of the dike during such migration are better understood.

<u>*Modelling*</u>
Dutch, German and Danish coastal administrators are currently working with a suite of models. Improvement and further development of three model types are envisaged.

Semi-empirical models[1]
At present, modelling the long-term morphological development still relies on, to a large extent, semi-empirical and aggregated models such as ASMITA. The ASMITA models for the tidal inlets of the Dutch Wadden area were set up in the 1990's and were most recently updated at the beginning of this century. Therefore the following updates and improvements of the models should be carried out:

- Update the parameter settings. Wang et al. (2007) show that parameter settings of the models were not fully correct due to the restrictions of the used data sets for the calibration/verification of the models. This shortcoming causes a limitation of the applicability of the models. The parameter settings should be updated by a new calibration of the model following the rules outlined in Wang et al. (2007).
- Include basin-basin interaction. At present a separate ASMITA model is available for each of the Dutch tidal inlets in the Wadden area, where each of the tidal inlets is considered as a closed system. However, research has shown that the tidal divides are not fixed in their positions and exchanges of water and sediment take place over the tidal divides. Therefore such basin-basin interactions ought to be incorporated in the semi-empirical morphological models for the Wadden area tidal inlets.
- Include changes in tidal range. Tidal range in the Wadden Sea changes over the course of decades and longer due to two mechanisms: the change at the North Sea and the change of tidal amplification because of changed morphology in the Wadden Sea. The present ASMITA models can only include the changes of the tidal range through a time-series as input. This means that the changes of the tidal range at the North Sea can be taken into account but the changed tidal amplification following the morphological changes cannot be included. It is suggested to extend the ASMITA model by implementing a relation between the morphology and the tidal range in the tidal basin.

[1] *These models make explicit use of empirical relations to define the morphological equilibrium. An important assumption is that the morphological system after a disturbance (through natural evolution or by human interference) always tends to develop into a state satisfying the empirical equilibrium relations.*

- Distinction of various sediment fractions. The present ASMITA models consider sediment as a single fraction. An extension/improvement of the models by implementing multi-fraction sediment transport module should be considered. To start with, a distinction between the cohesive and non-cohesive sediments fractions should be made.

2DH/3D Process-based models[2]

The process-based models DELFT-3D and GETM are open-source and are presently the best models for predictions of short-term morphodynamic evolution. At the moment Dflow FM is under construction and will become the future successor of DELFT-3D. For convenience we will refer to both models as DELFT-3D in this proposal.

Recent developments on the process-based morphodynamic models (see e.g. Dastgheib et al., 2008; Dastgheib, 2012) show that process-based morphodynamic modelling has also high potential for simulating long-term development, but operational models of this type for the Wadden area still need to be set up. The current models cannot predict morphological development over long spans of time. The aim is to be able to predict the development of the tidal inlet systems over several decades so that implications of climate change (safety, natural values, use) for management can properly be understood.

To be prepared for future questions regarding management of the Wadden system an operational process-based morphodynamic model for the Wadden area is needed, similar to the operational hydrodynamic model for the Dutch Wadden. The model should be able to carry out real-time simulations with detailed forcing-input, as well as to carry out long-term simulations such as hind casting the development since the closure of the Zuiderzee and forecasting the effect of various sea-level scenarios. The idea is to continuously carry out simulations and compare with the up to date field data in order to improve the model. Over time (e.g. over 15 years) a reliable operational process-based morphodynamic model for the (Dutch) Wadden area should be available. The model can then be used for supporting the sustainable management and monitoring of the Wadden area. In Wang and Elias (2014) this part of the work is worked out in more detail.

For sediment transport onto and on barrier islands it is recommended to extend the modelling with the “Xbeach” model to simulate hydrodynamics, sediment transport and the interaction with vegetation. The improved XBeach model has extensively been validated for dune erosion along the Dutch coast (including the Wadden area), both for normative conditions and historic extreme events (e.g., Van Thiel de Vries, 2009; Roelvink et al., 2009, 2010; Van de Werf et al, 2011; Van Santen et al, 2012). The model has also been successfully applied to quantitatively simulate the morphological impact of hurricanes, e.g. at Santa Rosa Island (McCall et al., 2009). In this project we propose to use the new features, including the attenuation of waves and flow by vegetation (according to Mendez and Losada, 2004) and coupling with the operational morphodynamic model. For eolian transport it is recommended to extend the existing model Xdune and to couple this to Delft 3D.

A new 1D model

The large, spatially explicit models such as Delft-3D and X-Beach are computationally very demanding. These models often require difficult choices regarding the balance of spatial resolution, temporal resolution and periods covered by model runs, in order to keep

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[2] Such models aim at the best possible description of the relevant processes by numerical solution of mathematical equations.

calculation times within acceptable limits. Running many scenarios with these models is therefore not always an option.
Recently a 1D morphodynamic model has been developed based on a new schematisation (Van Prooijen and Wang, 2013). The new schematisation includes a very innovative method to accurately represent the tidal flats. The application of the model to the Vlie shows that the model can reproduce the correct hypsometry of the basin, demonstrating the high potential of the model concept. This model runs very fast and offers the opportunity to run large numbers of simulations over long periods of time. Such a model can be used alongside the computationally more demanding 2D/3D models.

4.3 Monitoring & data analysis

Monitoring aims at registering the development of parameters. Field data give insight in the morphological development and processes as function of the various drivers, provided the drivers are monitored as well. Furthermore, monitoring is needed to provide data to calibrate and validate the models and to timely register the effects of climate change. Data analyses should help to build a firm common (trilateral) knowledge base.

Data needs include: meteorological parameters, geology, hydrodynamics, sediment transports, grain-size distributions, bathymetry/topography, salt-marsh and dune development, nourishments and sediment dumping, sediment extraction and changes in the spatial extent of the back-barrier basins. Next to that additional monitoring is needed for the pilot studies (see paragraph 4.4)

These data have to be collected, processed and made available by the participating countries. Collecting monitoring data is important, and well-organised, trilateral data management should provide access to each other's data. This will reduce the effort required from individual member states. Cycles of monitoring and input of new data into the modelling activities are expected to support the adaptive climate change management that the countries need to develop. An important step is to create a data-base in the (semi-)public domain, allowing other groups to join the modelling studies. For the Dutch Wadden area, close cooperation with the WaLTER program has been established for the purpose of data dissemination.

An extensive elaboration of monitoring can be found in the Monitoring Report (De Groot et al., 2014b). It addresses additional long-term monitoring which should become part of the regular monitoring schemes, as well as pilot-study related monitoring (which is partly also addressed in Kustgenese II).

4.4 Pilot studies

Pilot studies on ebb-tidal deltas, barrier islands (eolian and overwash processes) and back-barrier shoals and channels are advised in order to understand if, and how, we can mitigate impacts of climate change. Pilots should ideally combine two aims. Firstly: to test innovative methods to maintain flood safety. In other words: give insight in the applicability of the various envisaged measures. Examples are: mega-nourishments, channel displacements and promoting natural dynamics on the islands. Secondly: to provide data for system research and modelling the system and its components. The focus is on the value of the ebb-tidal deltas in wave reduction and redistribution of sand in the sediment sharing inlet systems, the redistribution of sediment over the islands and the timely management of channels migrating towards dikes.

Field observations are essential for calibration and validation of models and for gaining insight into the functioning of the system. The concept of learning-by-doing takes this one step further: at locations with urgent management issues, promising, novel solutions can be tested. However, in all cases such full-scale experiments and pilots should be prepared well, given the extremely high value of the area for nature and to ensure flood safety. Only if there is a reasonably well supported hypothesis of how a particular measure is going to work such studies might be carried out with little risk. If the main processes driving sediment dynamics in a certain area are really unknown, then large pilots might pose too much of a risk (Van Duren et al., 2012). Modelling and monitoring before, during and after such a pilot will ensure design optimisation and optimal knowledge gain.

Considering the concerns about the on-going erosion of the ebb-tidal deltas in the Dutch Wadden area, the idea of a pilot combined with a large-scale nourishment at or around an ebb-tidal delta was proposed. Such a pilot is meant to investigate how large-scale (mega) nourishments at or around ebb-tidal deltas will be effective in supplying sediment to the ebb-tidal deltas and the coastal foundation and to potentially increase the sediment delivery from the ebb-tidal delta to the barrier or back-barrier basin. The investigations will be based on a combined modelling and monitoring effort.

Following an inventory in 2012 (Elias et al, 2012b), in 2013 a first quick scan on the necessity and feasibility of such a pilot was carried out as a combined action of Delta Program Coast and Delta Program Wadden Area (De Ronde & Van Oeveren, 2013). Subsequent steps might be design and optimisation as well as setting up the required monitoring and research. The research related to the pilot should be closely related to the other two research line data analyses (see previous section) and modelling.

Another field where a pilot project would yield valuable information concerns the sediment transport towards and over a barrier island (by eolian and overwash transport). Much can be learned from the sand-engine and other dune reactivation projects, but the situation of the Wadden Sea barrier islands has its own characteristics (for instance geochemical and morphological). A third option for a pilot is where the behaviour of channels near coasts is still problematic and needs to be investigated in more detail. A pilot would yield knowledge on the processes underlying channel migration and would give input to manage coastal defences more cost-effectively. On all forms of pilot studies discussions are needed on the feasibility and the desirability.

For the moment the following possible pilots are identified (figure 4.2):
1. The small channel slope nourishment Stortemelk;
2. The small channel slope nourishment Borndiep/Ameland;
3. Ebb-delta Sand Engine;
4. Restoration washover or eolian transport;
5. Channel system shift Vierhuizergat.

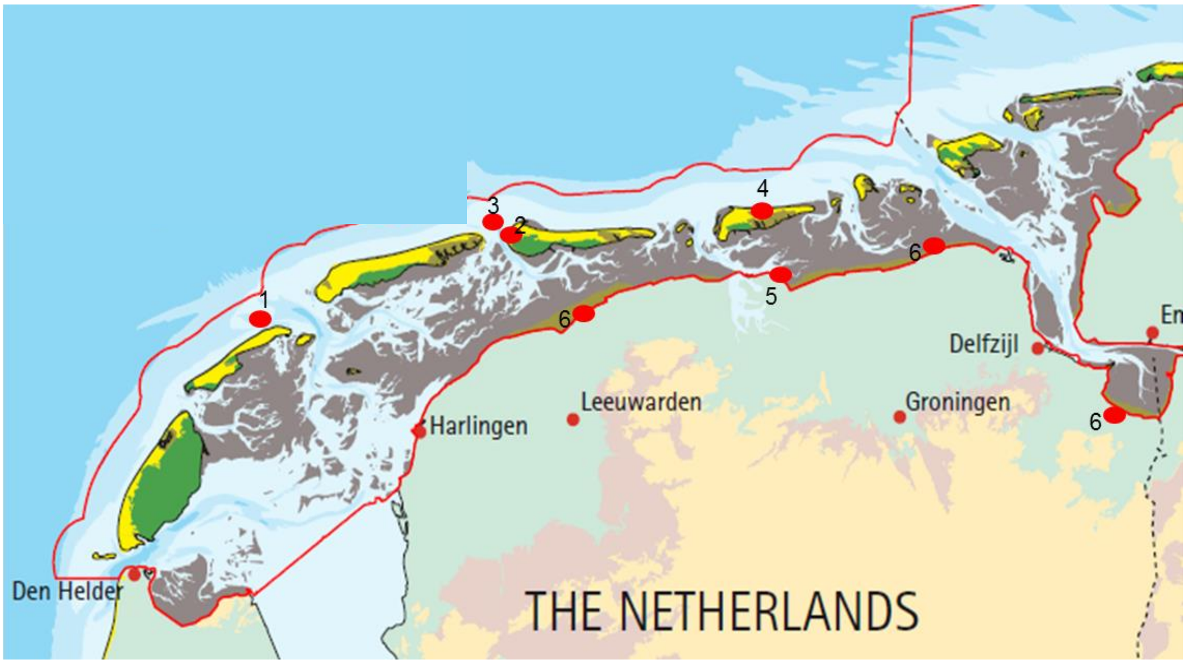

Figure 4.2: Overview of possible pilots. (for numbers see text; no. 6 relates to dike pilots. These are not discusses here).

4.5 Preparing for climate change: towards research programs

The first phase of the cooperation of the Wadden countries started in 2012. The proposed research framework is a continuation of this. Based on it research programs can be formed. From chapters 3 and 4 it will be clear that, in order to obtain the insights needed to be able to predict the long-term morphological development, it will take several decades. An example of how such a program might look like is given in table 4.1. Fortunately there is still time to develop the knowledge which is needed to be prepared for climate change: current climate scenarios predict rather small changes up to at least 2050.

It is also becoming clear that it is not likely that one research program will answer all the questions which will have to be answered. Fortunately parts can be addressed in separate studies which for instance concentrate on barrier islands, ebb-tidal deltas or even smaller issues. Programs such as the Hoogwaterbeschermingsprogramma, Kustgenese 2.0 and trilateral studies, as well as PhD-studies may provide platforms for such partial studies. On the long-run the insights of the various studies have to be amalgamated. Based on this an operational long-term process-based morpho-dynamic model for the Wadden Sea can be developed: The model that can serve as a basis for future management strategies.

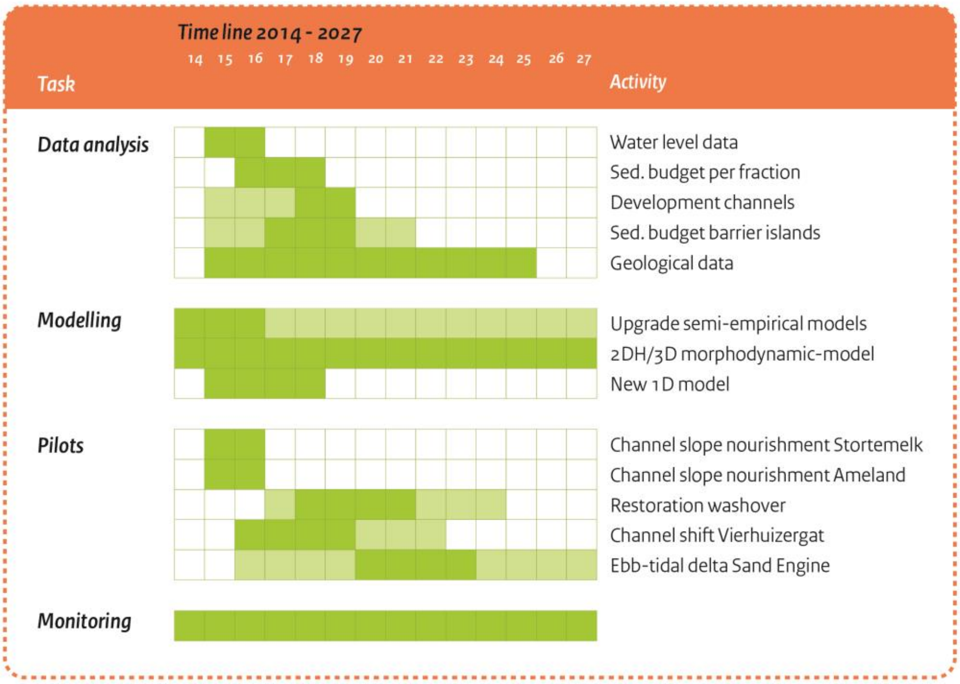

Table 4.1 overview of a possible set-up of future research based on the research framework (light green is minor work, dark green is main body of work).

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