



Knowledge for Climate Research Programme

# Hotspot **Wadden Sea**



Natural solutions to cope with  
accelerated sea level rise  
in the Wadden Sea region

Towards an integrated long term adaptation strategy framework



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# Natural solutions to cope with accelerated sea level rise in the Wadden Sea region

Towards an integrated long term adaptation strategy framework

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This project was carried out in close collaboration with Wadden Academy, Delta Programme Wadden Region and Towards a Rich Wadden Sea Programme.



PROGRAMMA **NAAR EEN RIJKE WADDENZEE**







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# Executive summary

## 1 Background and objectives

The Wadden Sea, bordering the South Eastern part of the North Sea along the coasts of Denmark, Germany and the Netherlands over a length of 500 km encompasses the world's largest system of tidal flats and barrier islands. Since 2009, the Wadden Sea area has been listed as a UNESCO World Heritage Site.

The Wadden Sea (WS) is considered an area of extreme ecological importance. Moreover, the WS system performs a key role in the flood protection of its bordering countries by providing a 'shield' of islands, tidal flats and shallow waters that reduces hydraulic forces on the coastal protection systems. Depending on future climate change development, in particular accelerated level rise, it is basically uncertain whether the unique characteristics of the WS can be preserved within a long term time perspective. If sea level rise would exceed critical rates, expectations are that the WS system could enter into a 'drowning' situation and gradually lose its intertidal area.

Concerns about the future development of the WS system are addressed from various perspectives, by different parties and programmes in the Netherlands and in an international context. Among these parties and programmes, the importance of maintaining the Wadden Sea sediment system is generally acknowledged. Additional supply of sediment to the WS by human intervention could be a promising way to prevent the WS from 'drowning', if this were to actually occur.

Within its assignment to study the adaptation to climate change of the WS region as one of its hot spot areas, the national research program Knowledge for Climate (KfC) has taken the initiative to further explore the potential of a sediment-based adaptation strategy from the viewpoint of the long term preservation of the WS system. The basic question addressed in this exploration is: "How to ensure a climate proof Wadden Sea based on a sediment nourishment adaptation strategy?" Specific objectives of this initiative are:

- To explore the need and potential of a sediment nourishment based adaptation strategy.
- To further elaborate on the contents and time aspects of the adaptation strategy.
- To develop an adaptation strategy framework as a basis to trigger and support discussion, research and action towards further adaptation strategy development.

The WS adaptation strategy framework assessment was carried out in the period April 2013 – March 2014. The assessment was mainly based on a consultation of experts in various relevant disciplines, supported by (selective) literature study.

## 2 Wadden Sea system description

The Wadden Sea is a shallow and highly dynamic tidal basin, characterized by:

- A seaward boundary of barrier islands and tidal inlets.
- The presence of relatively large ebb-tidal delta shoals on the seaward side of the inlet channels and island tips.
- A system of channels and (inter)tidal flats in the back-barrier basins.
- The presence of dynamic salt marsh areas bordering the dike systems along the barrier islands' and mainland area coasts.

The KfC exploration is based on the development of the WS sediment system in relation to its main functions and interests. For this purpose, the following subsystems were considered:

- The WS sediment system.
- The WS flood protection system.
- Wadden Sea functions and values related to ecology and landscape.
- Economic functions.

### WS sediment system

Within the WS sediment system, two parts are distinguished i.e. the WS external and internal sediment system. The WS external sediment system refers to the North Sea coastal zone alongside the





barrier islands, including the dune, beach and foreshore areas of the island coasts; the ebb-tidal deltas; and the external tidal inlet channel systems. The WS internal sediment system refers to the internal tidal inlet and distribution channel systems and the related flood-tidal deltas consisting of shallow waters, (inter)tidal flats and salt marsh areas.

### WS flood protection system

A distinction is made between the 'soft' and 'hard' WS flood protection system. The soft flood protection system coincides with the sandy coastal profiles at the North Sea side of the barrier islands, including the foreshore, beach and dune area within the designated coastal protection zone that is to meet required flood protection standards. The condition and performance of the soft flood protection system is directly connected to the preservation of the WS external sediment system. The hard flood protection system includes all man-made dikes and protection structures surrounding the WS, alongside the barrier islands' and mainland coasts. Required flood safety standards of this system are to be maintained within present and future hydraulic conditions, determined by the WS sediment system.

### Ecological and landscape values

Ecological values are closely related to the extent and variety of biotic activity in the WS internal sediment system and its potential to sustain higher life forms, including fish, mammals and birds. Landscape values are associated with the presence of open space, tidal flats and salt marsh land forms (and related natural vegetation). The preservation of the WS internal sediment system is a crucial condition for sustaining these values and functions.

### Economic functions

Main economic functions are gas and salt mining, navigation, (commercial) fisheries and recreation/tourism, providing goods and services as well as income and employment to the WS region and the national economy. There are several ways in which economic functions might affect the WS sediment system or ecological/landscape values, and vice versa.

The figure on the next page presents an integrated overview of causal relationships between the main WS sub-systems, functions and values. This figure distinguishes between three main parts:

1. Economic functions and natural areas.
2. The WS sediment system.
3. Effects on functions and values.

The first part represents the extent of the WS economic functions and natural areas (including biotic activities) in the present, or a particular future, situation. The second part represents the interacting WS external and internal sediment systems. The third part is involved with the effects associated with the main WS functions and values, including flood protection, the ecological functions and landscape values, and the economic functions. The WS (internal) sediment system holds a central position in the system diagram, representing an important basis for essentially all relevant functions and values.

## 3 Development of Wadden Sea sediment system

From a geological perspective, the WS region has been in existence as a tidal basin for a period of some 6000 years. During this period the WS was able to more or less maintain its basic characteristics under conditions that have continually changed. Consequently, WS system behaviour is characterised by a significant degree of robustness and resilience. In the next centuries, accelerated sea level rise may exceed the values occurring in the last 6000 years. Also, natural adaptive system responses may be severely limited as the geometry and dimensions of the basin are now basically fixed. It therefore remains highly uncertain how the WS region will respond to the impacts of climate change becoming manifest in future.

WS sediment demand is mainly driven by the relative **rate** of sea level rise (in cm/yr) and its development in time. In this respect, subsidence rates because of (local) mining activities are expected to provide a relatively modest contribution. Net sediment imports resulting from tidal sediment flows are the main source of supply. In addition there are certain other (smaller) components of the sediment balance related to e.g. dredging activities and the effects of ecosystem engineers.

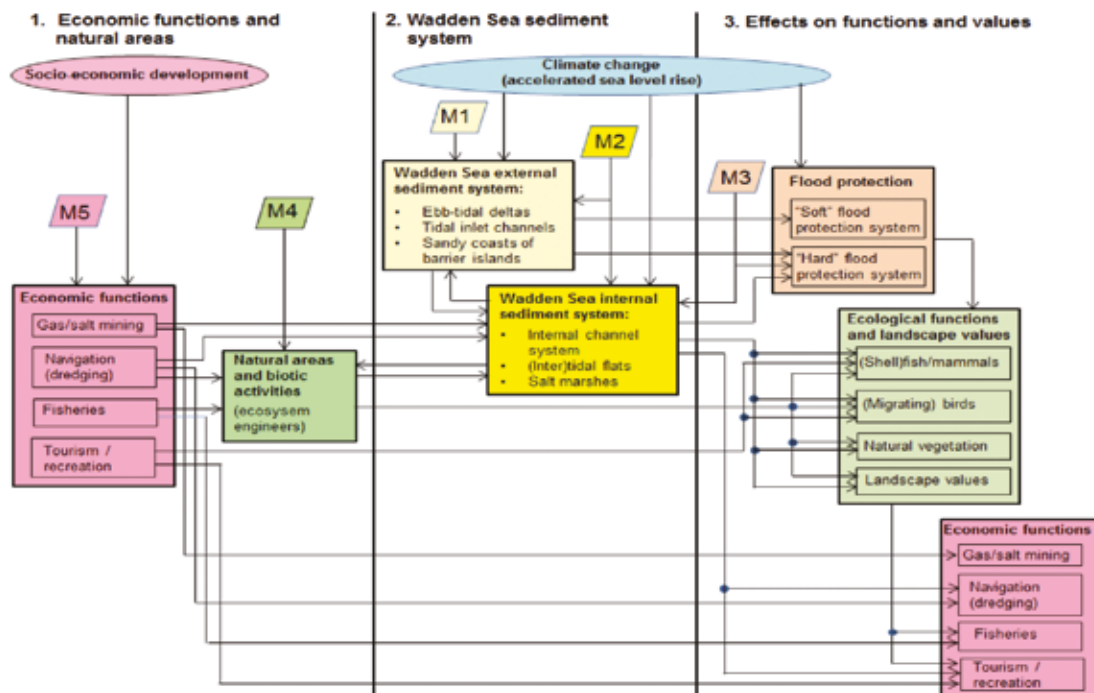
The analysis of available bathymetric measurements has shown that in the last 70 years the Dutch part of the WS was able to keep up with historic sea level rise (approx. 20 cm/century). There is a certain consensus that natural sedimentation processes might be able to keep up with larger rates of sea level rise (presumably up to 50 or 60 cm/century). Beyond these rates there is a risk that the WS might enter into a "drowning" situation. Most experts consulted have emphasized the uncertainties surrounding

the question **if** and **when** the WS system would actually enter into a drowning situation. Presently there are no indications of any emerging drowning problems and available measurements do not yet show an acceleration of the rate of sea level rise along the Dutch coast.

In its 4<sup>th</sup> assessment report (2007), the IPCC provided a range of global sea level rise projections for the year 2100 between 0.18 and 0.59 m. In 2006, KNMI presented four climate scenarios for the Netherlands, covering a range of sea level rise projections for 2100 (versus 1990) between 0.35 and 0.85 m (with a medium value of 0.60 m). In its long term assessment of vulnerability to climate change, the Dutch Delta Committee (2008) has suggested to take account of an absolute sea level rise in 2100 ranging from 0.55 to 1.20 m. So far, Dutch coastal protection policy making has been based on the KNMI scenarios.

Existing projections have all been expressed in

Wadden Sea system diagram





absolute amounts of sea level rise achieved at the end of the century (2100). However, the WS sediment demand is driven by the relative rate of sea level rise (in cm/yr). The comparison of this sediment demand with the net sediment import capacity at a given point in time determines whether or not a sediment balance deficit would emerge. For the medium KNMI scenario (0.60 m sea level rise in 2100), the figure below provides an illustration of the development of both the absolute and relative sea level rise (SLR) in time. The red line represents the development of the absolute SLR in m. The blue line represents the development of the relative SLR in cm/yr. Note that the vertical scale applies to both units (m and cm/yr) pertaining to these two curves. The computation of both curves follows from the assumption that the relative rate of sea level rise amounts to 0.2 cm/yr in the year 2000 and would linearly increase with time. It then follows that the rate of SLR in the year 2100 would have to increase by a factor of 5 (up to 1.0 cm/yr) in order to achieve the absolute sea level rise projected in 2100 (0.60 m). The conclusion is that if such a scenario would actually be realized, the beginning of a "drowning" situation may become manifest in the second half of this century. Different assumptions about the shape of the curve representing the development of relative SLR in time (linear or otherwise) would hardly affect this conclusion.

Total estimates of sediment demands for maintaining the Coastal Foundation zone include the net sediment demands of the Wadden Sea and the Westerschelde. These demands could be approximated by multiplying the areas of the various subsystems with the annual rate of sea level rise. Given the potential changes in the rate of sea level rise as implied by present sea level rise scenarios, sediment demands required to maintain the (total) Coastal Foundation may increase very substantially within the next century.

## 4 Framework for adaptation strategy

The focus of the present assessment is on exploring the possibilities of an adaptation strategy allowing the WS sediment system to keep up with accelerated sea level rise. In addition, other measures may be applied to maintain, enhance or restore more specific ecological values and economic functions of the WS system. A framework was created to support adaptation strategy development. Objectives of this framework are to provide:

- An overview of WS system related measures affecting the overall WS sediment balance.
- A structure for evaluating potential measures and identifying relevant trade-offs.

The Wadden Sea system diagram distinguishes different measure categories as follows:

M1: Maintaining the WS external sediment system.

M2: Preserving the WS internal sediment system.

M3: Upgrading the hard WS flood protection system.

M4: Enhancing natural area and/or biotic potential.

M5: Reducing the adverse effects of economic functions.

All or most of these measures are covered within existing programmes such as the Delta (sub)Programmes Coast and Wadden Region (DP Coast and DP Wadden) and the Programme "Rijke Waddenzee".

### M1: Maintaining the WS external sediment system

The principle objective of the Dutch coastal protection policy is to maintain the Coastal Foundation by applying sand nourishment. Within DP Coast, measures of category M1 are considered following from different visions on the long term protection strategy. With accelerated sea level rise, net sediment imports to the WS internal sediment system may increase within the system's natural transport and distribution capacity limits. Imported sediment quantities will be taken from the CF zone, and may (eventually) have to be supplied by sediment nourishment as part of the na-

tional coastal protection strategy. This strategy therefore provides an important boundary condition for the development and preservation of the WS internal sediment system.

### M2: Preserving the WS internal sediment system

There are certain limits to the WS sediment system's natural capacity to keep pace with rising sea levels. If accelerated sea level rise exceeds these limits the WS would gradually enter into a drowning situation. Drowning could only be prevented by increasing net sediment supplies to the WS. Principle options considered include:

- Options to increase the WS natural sediment import capacity.
- Options to provide additional sediment quantities to the internal WS channel system.
- Options to directly provide additional sediment quantities at specific WS locations.

Trade-offs regarding the execution of alternative nourishment options are involved with nourishment cost and (adverse) ecological effects. Moreover there is a risk of disturbing natural sediment transport processes. In this respect, the consideration of nourishment options 'from outside to inside' the WS system represents a logical 'preference' order.

### M3: Upgrading the hard WS flood protection system

The need for upgrading the hard WS flood protec-

tion system follows from possible changes in flood safety standards and hydraulic loads. Changes in hydraulic loads are subject to large uncertainties related to sea level rise projections and the development of the WS internal sediment system. In case a drowning situation would develop, the cost of measures to maintain required safety standards is likely to increase. This implies a certain trade-off between measures to reinforce existing WS dike systems and measures to preserve the WS internal sediment system. In addition to more traditional reinforcement measures, various types of innovative, multifunctional and dedicated solutions could be considered that may (also) serve a number of other objectives.

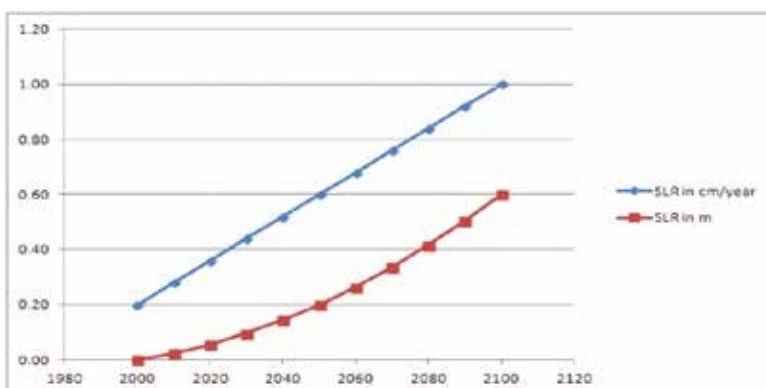
### M4: Enhancing natural areas and/or biotic potential

Within the boundary conditions provided by the existing or future WS internal sediment system, a variety of options are available for enhancing the potential of the WS ecological values and functions, some of which have already been implemented within the Programme 'Rijke Waddenzee'. A number of these options, in particular the measures related to restoring and expanding areas and activities of ecosystem engineers, will provide positive contributions to the WS internal sediment balance.

### M5: Reducing the adverse effects of economic functions

Illustrative sea level rise development (in cm/yr and m)

For absolute sea level rise of 0.60 m in 2100





The WS main economic functions may adversely affect the WS natural values and sediment balance in various ways. Within the Programme 'Rijke Waddenzee' a number of actions and projects have been defined that aim to reduce these adverse effects, in most cases by restricting the extent or location of activity levels or by changing management practices.

### Evaluating measures and trade-offs

Strategy development is to be based on an evaluation of the costs and benefits of potential measures and measure combinations, taking into account the relevant interactions and trade-offs. For this purpose, an evaluation framework was developed providing an overview of impacts for a representative set of measure options considered within different existing programmes (as reflected in the above categories M1 through M5). The evaluation framework considers a number of impact groups such as 'costs of measures', 'ecological functions and values' and 'costs and values of economic functions'. A specific focus is on the impact assessment of ecological functions and values which explicitly considers the Wadden Sea sediment system; natural areas and biotic activities; animal species (fish, mammals and birds), vegetation and landscape; and the ecological aspects related to the soft and hard flood protection systems. The framework developed was used for presenting the impacts in a qualitative way, allowing an interpretation of measure options and potential strategies from the viewpoint of the overall WS sediment system and providing a basis for identifying relevant trade-offs, win-win situations and potential conflicts.

## 5 Adaptation strategy development

### Time aspects and phasing

The crucial driver for strategy development is the behaviour of the WS internal sediment system under different scenarios of accelerated sea level rise. The phasing of strategy development is governed by a number of critical questions. The key question is: "Can the WS internal sediment system keep pace with emerging sea level rise within its

natural sedimentation transport and distribution capacity?" If it would become clear that the answer to this question is 'no', further questions are:

- What additional measures would be most appropriate in sustaining the WS internal sediment balance?
- Will these measures be effective in preventing the WS system from entering into a drowning situation?

If it would become clear that the answer to the final question is 'no', a soft adaptation strategy will not (or no longer) be able to ensure the preservation of the WS sediment system. Following this conclusion, the question arises what other feasible options would remain.

Resulting phases to be considered in strategy development are:

- Phase 1: period to assess if the WS system will be entering into a drowning situation.
- Phase 2: period to assess if a soft adaptation strategy will be adequate.
- Phase 3: transition period from a soft adaptation strategy to an alternative strategy.

The time periods involved with each of these phases, if they become at all relevant, may be very substantial (from decades to centuries).

### Activities and measures by phase

At the present stage, further steps to prepare for a long term adaptation strategy should merely concentrate on Phase 1. Key actions to be considered are:

- Improving the understanding of WS system sediment balance and transport processes through execution of general research and monitoring programmes.
- Identifying feasible measure options through specific research activities and/or pilot execution with a focus on nourishment options of the WS system. Additional measures to augment the WS sediment balance would follow from other objectives, such as reinforcing hard flood protection systems and enhancing ecological values and functions.
- Selective implementation of measures. These include required (high priority) measures for flood protection (from the nHWBP); other attractive measures combining different objectives (win-win); or measures of which the ben-

efits are beyond doubt (no regret).

### Specification of research and monitoring requirements

Research and monitoring requirements have been identified within different WS subsystems. With regard to the nature of the research requirements, a distinction is made into:

- General research requirements related to WS system processes.
- Measure and pilot related research requirements.

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 specification of adequate monitoring programmes is an explicit part of research execution. Within the specification of general monitoring requirements, particular attention should be given to the possibilities of developing 'early warning' indicators for detecting the early stages of a possible drowning process.

## 6 Conclusions and recommendations

### Conclusions

- In the last century, natural WS sedimentation processes have kept pace with historic sea level rise. There is a certain consensus that the WS system may be able to keep up with larger rates of sea level rise (up to 0.5 or 0.6 cm/yr). Beyond these rates there is a risk that the WS might "drown". Given the state of available knowledge and data it is basically uncertain **if** and **when** the WS system would actually enter into a 'drowning' situation.
- Changes in future (annual) sediment demand

will be driven by changes in the **rate** of relative sea level rise (in cm/yr). Present sea level rise scenarios have been expressed in terms of absolute sea level rise achieved in a given target year and do not provide explicit information on the development of the rate of sea level rise over time.

- Present sea level rise scenarios would imply a quite drastic increase in the rate of sea level rise over time. **If** these scenarios would actually materialize, the WS sediment system could enter into a 'drowning' situation in the second half of this century.
- Options to increase the WS natural sediment import capacity may be found in changing nourishment schemes in the WS external sediment system. Additional options could be to directly apply nourishment measures within the WS sediment system, i.e. into the main channel system or to more specific locations (such as (inter)tidal flats).
- Based on nourishment costs and potential effects, the consideration of nourishment options 'from outside to inside' the WS represents a logical preference order.
- Various 'building with nature' measures would positively affect the WS sediment balance. The execution of such measures offers an important 'win-win' potential.
- Present and anticipated policies within ongoing programmes in the Netherlands are generally very much in line with the concept of applying natural solutions to preserve coastal systems. Therefore, in the foreseeable future, there is no need to consider additional measures to preserve the WS sediment system.
- Available time should be used to anticipate further measures that may be required on longer term. For now, the focus of adaptation strategy development should be on research and monitoring; identifying feasible measure options (through pilot execution); and selective measure implementation (win-win and no-regret).

### Recommendations

- Research and monitoring programmes to be further specified, should be aimed at a better understanding of the WS sediment balance and at accommodating specific measure and pilot related research questions. It is essential



that research requirements following from adaptation strategy development needs will be embedded in existing national and international research agendas.

- An evaluation framework is to be created to support strategy development. This framework should provide an integrated view on the effects of relevant measures on WS sediment transport processes and balances and facilitate the identification and analysis of measure trade-offs, win-win situations and potential conflicts.
- In order to ensure the coherence and continuity of future policy making regarding the WS system, more specific institutional arrangements are to be developed. In particular, such arrangements should provide a clear organizational structure for the execution of tasks related to policy development and implementation.







1

# Background and objectives

The Wadden Sea, bordering the South Eastern part of the North Sea along the coasts of Denmark, Germany and the Netherlands over a length of 500 km encompasses the world's largest system of tidal flats and barrier islands. Since 2009, the Wadden Sea area has been listed as a UNESCO World Heritage Site.

The Wadden Sea is a shallow and highly dynamic tidal basin, characterized by:

- A seaward boundary of barrier islands and tidal inlets.
- The presence of relatively large ebb-tidal delta shoals on the seaward side of the inlet channels and island tips.
- A system of channels and (inter)tidal flats in the back-barrier basins.
- The presence of dynamic salt marsh areas bordering the dike systems along the barrier islands' and mainland area coasts.

The Wadden Sea (WS) is considered an area of extreme ecological importance. Moreover, the WS system performs a key role in the flood protection of its bordering countries by providing a 'shield' of islands, tidal flats and shallow waters that reduces hydraulic forces on the coastal protection systems. Depending on future climate change development, in particular accelerated level rise, it is basically uncertain whether the unique characteristics of the WS can be preserved within a long term time perspective. This mainly depends on the question whether natural sediment supply to the WS will be able to keep up with accelerated sea level rise. If sea level rise would exceed critical rates, expectations are that the WS system would enter into a 'drowning' situation and gradually lose its intertidal area.

Concerns about the future development of the WS system are addressed from various perspectives, by different parties and programmes in the Netherlands and in an international context. These include:

- The Delta (sub)Programme Wadden Region.
- The Programme "Rijke Waddenzee" (Rich Wadden Sea).
- The national research programme 'Knowledge for Climate'.
- The Wadden Academy.
- Trilateral Wadden Sea Cooperation.

The Delta (sub)Programme Wadden Region (DP Wadden), which is part of the national Delta Programme, is involved with the flood protection of the WS barrier islands and mainland area coasts. In particular, the DP Wadden aims to develop a coastal protection strategy within the context of climate change and sea level rise from a long term perspective. While ensuring future safety from flooding is the key objective, the DP Wadden also explicitly considers the other interests associated with the WS system, such as ecological, landscape and cultural values and the various economic functions.

The Programme "Rijke Waddenzee" (PRW) was initiated at the end of 2008 as part of a covenant on mussel sector transition and nature recovery between nature organizations, the mussel sector and the Ministry of Agriculture (now part of Ministry of Economic Affairs). Concrete objectives formulated in the covenant were (1) to achieve a sustainable mussel sector (by ending harvesting mussel seed from 2020 onwards) and (2) the development and implementation of a Nature Recovery Plan. A PRW project bureau was established to initiate and support concrete nature recovery and other projects within a jointly defined target scenario for WS ecological and economic development.

The mission of the independent national research programme 'Knowledge for Climate' (KfC) is to develop scientific and applied knowledge aimed at adapting Dutch society to climate change and the creation of a knowledge infrastructure to support this process. The KfC programme structure considers 8 different themes and 8 hot spot areas. Knowledge development is centred around the various themes. Hot spot areas represent the focal points of knowledge application and concrete development of adaptation strategies. The Wadden Sea area is one of the hot spot areas considered in KfC.

The Wadden Academy is a facilitating, scientific organisation, financed by the Dutch Wadden Fund, that is involved with identifying knowledge gaps and programming research within a broad range of WS-relevant research areas. The prime objective of the Wadden Academy is to support



the development of a comprehensive and sustainable WS knowledge base, through cooperation and knowledge-sharing with all relevant parties.

The Trilateral Wadden Sea Cooperation is an administrative agreement between the WS countries (Germany, Denmark and the Netherlands) aiming to conserve and protect the WS as an ecological entity. The focus of the cooperation is on the specification and execution of a joint research programme, through establishing a trilateral research agenda, research platform and research fund. The governing body of the cooperation is formed by the Wadden Sea Board, supported by specific Task Groups and a Common Wadden Sea Secretariat.

All above parties and programmes acknowledge the importance of maintaining the Wadden Sea sediment system. Also, there seems to be general agreement that additional supply of sediment to the WS by human intervention could be a promising way to prevent the WS from 'drowning', if this were to actually occur. It is noted that the use of sediment nourishment measures to preserve coastal sediment systems has played a central role in Dutch coastal policy making for the last decades and will continue to do so in future coastal protection strategy development. This has triggered the idea of further exploring the possibilities of an adaptation strategy which is based on augmenting natural sediment flows into the Wadden Sea system to keep up with accelerated sea level rise.

Within its assignment to study the adaptation to climate change of the Wadden Sea region as one of its hot spot areas, KfC has taken the initiative to further explore the potential of a sediment-based adaptation strategy from the viewpoint of the long term preservation of the WS system and all related ecological and economic values. This idea was presented and discussed at the 13th International Scientific Wadden Sea Symposium held in November 2012 in Leeuwarden, The Netherlands. As existing time constraints and budget limits within KfC did not allow to undertake a substantial research effort, the exploration was based on an assessment of existing information and the views of experts in the

field. The basic question addressed in this exploration is: "How to ensure a climate proof Wadden Sea based on a sediment nourishment adaptation strategy"? More specific objectives of this initiative are:

- To explore the feasibility of a sediment nourishment based adaptation strategy.
- To further elaborate on the contents and time aspects of the adaptation strategy.
- To develop an adaptation strategy framework as a basis to trigger and support discussion, research and action towards further adaptation strategy development.

Regarding the above exploration, it is acknowledged that there is considerable overlap with the objectives and assignments of the other parties and programmes mentioned above. From the viewpoint of possible measures to be explored there is a particularly strong relation with the DP Wadden (developing a coastal protection strategy for the WS system) and the PRW (involved with measures and projects for nature recovery and ecological/economic development). With respect to the Wadden Academy and the Trilateral WS Cooperation, the overlaps mainly pertain to the identification and programming of research requirements.

For this reason, a continued and close cooperation between the various programmes and parties in the process of developing and applying the adaptation strategy framework will be required.

The WS adaptation strategy framework assessment was carried out in the period April 2013 – March 2014. The assessment was mainly based on a consultation of experts in various relevant disciplines supported by (selective) literature study. In principle, the study area includes the entire WS area along the coasts of Denmark, Germany and the Netherlands, between Esbjerg and Texel. Practically speaking, the assessment was based on the Netherlands part of the WS. At a later stage, the results and conclusions of the assessment may be broadened and generalised through further discussions with national and international experts. For this purpose, the results of the assessment have been reported in the English language.

The present report describes the findings and results of the literature study and expert consultations and provides an elaboration of the WS adaptation strategy framework. Chapter 2 of this report describes the main features of the WS system and the set-up of the present assessment. More detailed descriptions of the relevant WS subsystems and functions, leading to a coherent WS system diagram, are provided in Chapter 3. In Chapter 4, an interpretation is given of the present insights regarding the possible development of the WS sediment system under the influence of accelerated sea level rise. The framework for the WS adaptation strategy is developed in Chapter 5, while Chapter 6 further elaborates the process of adaptation strategy development. Main conclusions and recommendations are summarized in Chapter 7.



# 2

## Wadden Sea system and adaptation strategy framework assessment

## 2.1 Overview of Wadden Sea system

The Wadden Sea is a highly dynamic tidal basin including a well-developed system of channels and intertidal areas in the flood-tidal deltas, providing the boundary conditions for ecosystem development. The existence of such an intertidal basin is subject to conditions of sea level rise within relatively narrow bands. If rates of relative sea level rise are too low, the tidal system will eventually turn into land; if sea level rise is too high, the intertidal area will be gradually reduced and the system may enter into a 'drowning' situation. The incidence of sea level rise triggers a sediment demand of the intertidal basin to keep up with rising waters. Natural sediment transport and distribution processes driven by tide result in a net sediment flow to the WS system, at the expense of sediment buffers present in tidal inlet zones (the ebb-tidal deltas and the foreshores and beaches of island tips and adjacent coastal areas). Developments during the last 70 years have shown that the Dutch part of the WS was able to keep up with historic sea level rise (approx. 20 cm/century) and in fact a significant net sedimentation has taken place, mainly triggered by the closure of the 'Zuiderzee' through the construction of the 'Afsluitdijk' in 1932 and the closure of the 'Lauwersmeer' in 1969 (Elias E.P.L. et al., 2006 and 2012a; Wang, Z.B. et al., 2012).

The processes involving the sediment (sand) movement in channel systems and the interactions between channels and tidal flats can be largely explained by abiotic factors, including the dynamics of tidal water movement, currents, waves and wind. Sedimentation processes within the shallow and (inter)tidal parts of the WS, including the finer sediment fractions (silt, mud), are much more complex and also governed by the interplay of abiotic and biotic factors. The role of biotic factors pertains to the activity of a variety of 'ecosystem engineers' that have the ability to increase sedimentation processes while creating structures that will keep sediments in place. Most important ecosystem engineers are: mussel and cockle beds, oyster reefs, sea grass fields and salt marsh vegetation.

The key to the present and future functioning of the WS is in the characteristics and preservation of the WS sediment system. Most important functions and interests of the WS system relate to:

- The flood protection of the barrier islands and mainland areas surrounding the WS.
- Ecological and landscape values.
- A number of economic functions providing different goods and services.

The exploration will be based on the development of the WS sediment system in relation to these functions and interests. For this purpose the following subsystems will be considered:

- The WS sediment system.
- The WS flood protection system.
- Wadden Sea functions and values related to ecology and landscape.
- Economic functions.

### WS sediment system

Within the overall WS sediment system, for the purpose of this assessment, two parts have been distinguished i.e. the WS external and internal sediment system. The WS external sediment system refers to the North Sea coastal zone alongside the barrier islands, including the dune, beach and foreshore areas of the island coasts and island tips; the ebb-tidal deltas; and the external tidal inlet channel systems. The WS external sediment is to be considered an integral part of the active coastal sediment system. The WS internal sediment system refers to the internal tidal inlet and distribution channel systems and the related flood-tidal deltas consisting of shallow waters, (inter)tidal flats and salt marsh areas. It is noted that both the external and internal subsystem are part of a common sediment-sharing system.

### WS flood protection system

A distinction is made between the 'soft' and 'hard' WS flood protection system. The soft flood protection system coincides with the sandy coastal profiles at the North Sea side of the barrier islands, including the foreshore, beach and dune area within the designated coastal protection zone meeting required flood protection standards. The condition and performance of the soft flood protection system is directly connected to the preservation of the WS external sediment sys-



tem. The hard flood protection system includes all man-made dikes and specific protection structures surrounding the WS, alongside the barrier islands' and mainland coasts. Required flood safety standards of the hard flood protection system are to be maintained within present and future hydraulic conditions, depending on the condition and characteristics of the WS sediment system.

### Ecological and landscape values

Ecological values are closely related to the extent and variety of biotic activity in the WS internal sediment system and its potential to sustain higher life forms, including fish, mammals and birds. Landscape values are associated with the presence of open space, tidal flat and salt marsh land forms (and related natural vegetation). The preservation of the WS internal sediment system is a crucial condition for sustaining these values and functions.

### Economic functions

Main economic functions are gas and salt mining, navigation, (commercial) fisheries and recreation/tourism, providing goods and services as well as income and employment to the WS region and the national economy. There are several ways in which economic functions might affect the WS sediment system or ecological/landscape values, and vice versa.

## 2.2 Steps in adaptation strategy framework assessment

Main assumptions and boundary conditions underlying the strategy framework assessment :

- The adaptation strategy framework will be aimed at preserving the WS sediment system from the viewpoint of maintaining the present main functions of the WS system (related to flood protection, ecological and landscape values, and economic functions).
- The study area includes the entire WS area along the coasts of Denmark, Germany and the Netherlands, between Esbjerg and Texel. From the viewpoint of practical execution, the focus is on the Netherlands part of the WS.

- The time horizon is 100-200 years; rates of accelerated sea level rise to be considered in this period will be between 1 – 2 m.
- The assessment will be based on existing knowledge to be made available from literature and expert consultation.

Steps in the assessment include:

- 1) Literature review and interview preparation.
- 2) Expert consultation.
- 3) Adaptation strategy framework development.
- 4) National feedback and discussion based on a Working Conference.
- 5) Final reporting on adaptation strategy framework.

### Re 1) Literature review and interview preparation

A considerable amount of literature is available on the characteristics and functioning of the WS and its possible responses to climate change and accelerated sea level rise. In preparation of the expert consultation a brief literature review was conducted, identifying main topics and questions to be further discussed. During the exploration, the list of literature to be reviewed was extended based on suggestions of consulted experts.

### Re 2) Expert consultation

Candidates for expert consultation in the Netherlands have been identified within various relevant disciplines, including geomorphology and physical geography; flood protection and safety; aquatic and terrestrial ecology; other user functions and interests; design and implementation of nourishment, protection and preservation measures. Expert consultations by means of interviews were held in two rounds, allowing the selection of candidates for the second round to be based on suggestions of experts consulted in the first round. Results of all interviews were recorded in separate interview reports, endorsed by the experts consulted. In addition to available literature sources, the information and opinions provided by the various experts has formed an important basis for the present assessment. An overview of experts consulted is provided in Appendix 1 of this report.

### Re 3) Adaptation strategy framework development

Following the consultation rounds, a draft report was produced on the results of the interviews and the development of an adaptation strategy framework. The draft report was used as a main input for the preparation of a Working Conference (see re 4).

### Re 4) National feedback and discussion

A Working Conference was organized to facilitate a round of national feedback and discussion (held in Leeuwarden on 25th March 2014). Specific objectives of the conference were to further discuss the adaptation strategy framework in relation to ongoing programmes and research activities. Most relevant programmes are the national Delta Programme (in particular the sub Programmes Wadden Region and Coast) and the Programme "Rijke Waddenzee". From the viewpoint of the national/international research agenda, the Wadden Academy has taken a leading role in the organization of the Working Conference.

### Re 5) Final reporting on adaptation strategy framework

Following the Working Conference, the final report was completed, taking into account the findings, results and responses following from the national feedback and discussion. The focus of the final report is on the adaptation strategy framework and possible further steps for its elaboration and implementation, within the context of ongoing developments in national/international policy-making and research programmes.





# 3

## Wadden Sea system description

### 3.1 External sediment system

Since 1990, the national Dutch coastal protection policy is governed by the principle of 'dynamic preservation'. According to this principle, a Basal Coast Line (BCL) was defined representing the desired state and position of the Dutch sandy coast. The basic principle is that the position of the BCL will be maintained. This means that, if the actual (observed or projected) coastline shifts landward of the BCL, an intervention takes place, usually by increasing the sediment budget through sand nourishment. At a later stage, this approach was extended to include the entire 'active' coastal zone in which changes in sediment budgets may have an impact on the natural (sandy) coastal protection system. This zone has been defined as the area shoreward of the -20 m depth contour and is referred to as the 'Coastal Foundation' (CF) zone. In principle, the present national coastal protection policy is based on maintaining the sediment budget in the CF zone by compensating sediment losses (including the sediment demands following from sea level rise) by means of sand nourishment.

The WS external sediment system can be regarded as the part of the CF zone alongside the barrier islands of the WS system, forming an integral part of the entire national CF zone. The particularly active parts of this system consist of the dynamic zones around the tidal inlet channels in between the barrier islands, including the ebb-tidal deltas, island tips and adjacent sandy beaches and foreshores (referred to as the 'tidal inlet zones' of the WS external sediment system).

Sea level rise will lead to a sediment demand of the WS internal sediment system to keep up with rising waters. The sediment amounts to meet these demands will be taken from the WS external sediment system, in particular from the tidal inlet zones. Whether or not the sea level rise related sediment demand of the WS internal sediment system can/will be actually provided depends on (1) sediment availability in the tidal inlet zones of the WS external sediment system and (2) the natural capacity to transport sediment quantities from the external to the WS internal sediment system and to distribute these quantities within the WS internal sediment system.

Expectations are that the present national Dutch coastal protection policy regarding the preservation of the BCL and the CF zone will be continued. Through the continuation of this policy it will be ensured that sufficient sediment (sand) quantities will remain available in the tidal inlet zones of the WS external sediment system. The question whether the WS internal sediment system will be able to keep up with future sea level rise (within a range of sea level rise scenarios) then basically depends upon the natural sediment transport and distribution capacity of the WS sediment system and the resulting net sediment imports to the WS internal sediment system.

### 3.2 Internal sediment system

The WS internal sediment system, comprising the internal tidal channel network systems and flood-tidal deltas, is basically built from sand, resulting from the tide-driven sediment flows from the WS external to the internal sediment system and vice versa. A relatively limited part of the total WS sediment budget consist of fine sediments, i.e. cohesive, smaller sediment fractions ( $< 63 \mu$ ), including both organic and inorganic components. These are the fractions that remain in the water column for a longer time, contributing to turbidity. Considerable amounts of fine sediments are transported in and out of the system with every tide. Although fine sediment concentrations in the WS are higher than in the North Sea, the WS system is a 'net importer' of fine sediments. In terms of fine sediment dynamics, there are large differences between the various tidal basins, however (Van Duren, L. et al, 2011).

Fine sediments are mostly deposited within relatively shallow waters that are sheltered from currents and waves, forming a top layer on tidal flats. Quantities of fine sediments present in the upper layers of the WS internal sediment system are modest compared to the volume of the larger (sand) sediment fractions (of the order of 5%). Considering fine sediment fluxes in the WS system, the internal, annual amounts brought in suspension by tide and wave action are large compared to the net import of fine sediments from the



North Sea. Most of the internal fine sediment movement takes place within the WS internal channel network system.

The availability of sufficient amounts of fine sediments is a necessary condition for the development of a variety of life forms that support the WS system's unique ecological values. This particularly holds for the role of a number of important ecosystem engineers (such as mussel and cockle beds, oyster reefs, diatom mats, sea grass fields and salt marsh vegetation) providing a habitat and source of food for other organisms. Moreover, ecosystem engineers may have significant effects on local sedimentation processes, owing to their capacity of trapping and holding fine sediment fractions (Waddenacademie, 2009b).

Measures aimed to expand the accumulation of fine sediments through the activity of ecosystem engineers could greatly enhance the system's ecological values. With the exception of salt marsh formation, the (fine) sediment retention potential of ecosystem engineers is expected to be rather limited, however. Main reasons for this are found in the temporal and spatial characteristics of the presence of ecosystem engineers. Mussels, for example, form temporary structures that have a limited life span (on average 6 years). Moreover, these structures only cover a relatively limited surface area of the Wadden Sea. Other possible structures such as diatom mats may cover more substantial areas, but these effects are essentially limited to the spring and summer period.

The process of salt marsh formation is the potentially most important sink of fine sediments and might provide a substantial contribution to the retention of fine sediments in the WS system. In addition, the formation of natural, dynamic salt marshes may contribute to ecological and landscape values and may provide a buffer zone to dissipate wave energy and reduce hydraulic loads to existing dike systems. In principle, there is considerable potential for preserving or expanding the extent of salt marsh area, which could be accomplished by applying various techniques to improve conditions for salt marsh development, making use of natural availability of fine sediments.

### 3.3 'Soft' flood protection system

The soft WS flood protection system consists of the natural foreshore, beach and dune systems at the North Sea side of the WS barrier islands, forming an integral part of the WS external sediment system. Given expected sea level rise, required safety standards of the soft flood protection system need to be met at all times. This is ensured by the present national coastal protection policy and its expected continuation in the foreseeable future, aimed at maintaining the position of the entire Basal Coast Line (BCL).

The present coastal protection policy has been implemented from 1995 onwards. In the beginning period an average annual volume of 6 Mm<sup>3</sup> of sand nourishments was applied. This volume has increased over time to 12 Mm<sup>3</sup> and is expected to be further increased as part of future policy development. The bulk of the present volume is applied to specific coastal locations to keep the BCL in place. The remaining part is used for sand nourishments in other locations within the wider Coastal Foundation zone, supporting the sediment balance of the overall sediment-sharing system. Initially all nourishments took place within the beach or dune area. In the last ten years, the majority of nourishments (some 60% of the total volume) take place in the foreshore area, making use of natural transport mechanisms for sediment distribution within the coastal profile (Rijkswaterstaat, 2012). This has considerably reduced nourishment cost (roughly speaking the cost per m<sup>3</sup> of dune, beach and foreshore nourishment are of the order of €10, €5-6 and €2-3 per m<sup>3</sup>, respectively).

From observed developments in the last 20 years it can be concluded that the national Dutch coastal protection policy based on dynamic preservation has been very successful. In the last decade, the BCL was maintained in more than 90% of all coastal sections (while in many coastal sections the position of the BCL is at considerable surplus). A significant proportion of the sediments supplied by sand nourishment is also reaching the beach and dune parts of the coastal protection zone and has effectively reinforced the dune profile (with local increases in dune elevation up to 2 m). For the closed coastline of Holland, estimates

are that some 20% of nourishment volumes supplied have ended up in the dune profile. For the WS barrier islands this may even be as high as 45%.

With regard to future nourishment measures in the WS external sediment system, a number of other objectives could be considered. One of these objectives would be to look into the possibilities of applying alternative nourishment options that may increase sediment flows to the WS internal sediment system (while meeting the nourishment objectives and safety standards of the soft flood protection system). Another objective relates to the possibilities of enhancing the natural dynamics of the barrier island sediment system proper, in particular the water and wind driven processes involved with beach, dune and salt marsh formation. Due to human interventions and changes in land use, natural dynamics and resilience of the barrier islands have been significantly reduced. The notion is that barrier island related processes and interactions with the WS sediment system should be considered as an integral part of the overall sediment-sharing system. The potential of management practices that benefit from natural forces was recently investigated by a group of experts working in several nature conservation and management agencies and research institutions (ERA Foundation, 2011).

### 3.4 'Hard' flood protection system

#### Existing hard WS flood protection system

The barrier island sides and mainland areas surrounding the WS are protected from flooding by a man-made system of dikes and other structures. The total length of the dike system on the WS side of the barrier islands is approx. 65 km. The total length of the mainland dike systems bordering the WS is approx. 200 km (30 km in the province of 'Noord-Holland' and 170 km in the provinces of 'Groningen' and 'Friesland'). A total of 83 structures (such as sluices, locks and pumping stations) are included in the dike systems, forming an integral part of the flood protection system. The

'Afsluitdijk' with a length of 32 km connects the mainland coasts of 'Noord-Holland' and 'Groningen', separating the fresh water basin 'IJsselmeer' from the Wadden Sea. A large complex of sluices and locks is situated on either side of this closure dam (Deltaprogramma Waddengebied, 2013).

#### Development of flood protection requirements

According to legislative requirements as formulated in the Dutch Water Act, the national flood protection system is subjected to a periodical Technical Assessment which is executed every 6 years. This assessment is involved with checking the compliancy of the entire national flood protection systems with technical standards and design criteria. Following this assessment, the various parts of the national flood protection system (dike sections and structures) are found to be either compliant or non-compliant. For sections that are non-compliant an upgrading of the flood protection system is required. The results of the third Technical Assessment (completed in 2011) have shown that a considerable part of the hard WS flood protection system does not comply and would need upgrading. Most common problems relate to deficiencies in the strength of dike revetments (IVW, 2011). Required measures to strengthen the national flood protection system following from the periodical Technical Assessment are included in the so-called new Flood Protection Programme (nHWBP). Given the extent of this multi-billion euro programme and the existing limitations in available budgets and technical/organisational capacity, the actual implementation of these measures is subject to further prioritisation.

Present flood safety standards have been formulated in terms of the frequency of exceeding design water levels. In the WS system a number of different safety standards apply (1:2000, 1:4000 and 1:10000). In the last decade, a new methodology has been developed for the assessment and application of flood safety standards based on an assessment of flooding probability and flood risk, rather than probability of exceeding critical (design) water levels. The new methodology considers all mechanisms that may lead to dike failure (i.e. a flooding event) and all relevant parameters



determining these failure mechanisms (such as dike overtopping (dike elevation), strength of dike revetments, piping and (macro)stability). According to a ministerial decision of April 2013, a new set of flood safety standards will be developed that is to be based on the new methodology according to the flooding probability and flood risk concept (Ministerie I&M, 2013). Presumably, these standards will be developed and applied on the level of different dike ring sections. In addition, the flood safety concept will be broadened to not only consider measures aimed at flood prevention but to also include measures reducing the consequences if a flooding situation would occur (e.g. measures related to spatial planning, adaptation of buildings and structures and enhancing evacuation possibilities). This broadening of possible measures is referred to as the 'multi-layered safety concept'.

The development and introduction of the new flood risk assessment methodology and the related system of flood safety standards is to be considered an ongoing process. As part of this process, a national analysis was executed to assess optimal flooding probabilities on the level of dike ring sections, based on a cost-benefit analysis comparing long term projected flood protection cost and prevented damages (Deltares, 2011). It is expected that the insights provided by the further development and application of the new flood safety standards will play an important role in the further prioritisation process of the measures identified in the new Flood Protection Programme, which may potentially lead to a reduction or re-definition of measures to be actually implemented in the WS area.

In future, the existing hard flood protection system needs to be further adjusted due to increases in hydraulic loads following from climate change and accelerated sea level rise. The development of the WS internal sediment budget, in particular regarding the extent to which the WS sediment system of tidal flats and salt marshes would be able to keep pace with rising sea levels, is an important boundary condition in this respect. If the WS system would enter into a drowning situation, increases in wave attack resulting from larger water depths could lead to an additional increase in

hydraulic loads which could have significant consequences for future dike profile and dike revetment requirements. It is noted however, that these future changes will only slowly develop over a long time span. Hence, within existing safety buffers there will generally be ample time to anticipate future scenario developments and to prepare for further required adjustments of the dike systems.

### 3.5 Ecological functions and landscape values

The WS is a shallow and highly dynamic tidal basin consisting of a number of flood-tidal deltas. Owing to the large scale geomorphological processes, a variety of land forms have developed within the flood tidal deltas, including an extensive system of shallow waters, (inter)tidal flats and salt marshes, connected by tidal channel networks.

The presence of benthic life and ecosystem engineers (such as mussel and cockle beds, oyster reefs, sea grass fields and salt marsh vegetation) in the fine sediment layers of the flood tidal deltas have created a variety of rich habitats to support other, higher life forms. The WS habitats offer nursery and spawning grounds for a range of marine fish species and house a large colony of seals, feeding on the fish population and resting on the (inter)tidal flats. In particular, the WS is extremely important for a great variety of migrating birds, providing an abundance of food, as well as places for breeding and high tide refuge.

In view of its extensive ecological and landscape values, the entire WS system has been designated as an international nature preservation area. Mainly because of its overriding importance for migratory birds, since 2009 the WS has been listed as a UNESCO World Heritage Site. If due to accelerated sea level rise the WS would enter into a drowning situation, many or most of the above values and functions could eventually be lost. From this perspective, the preservation of the WS sediment system should be regarded as a high priority objective.

### 3.6 Economic functions

Main economic functions related to the WS system include:

- Mining of gas, salt and sand.
- Navigation.
- Commercial fisheries.
- Tourism/recreation.

It is noted that the function of the WS barrier islands as the residence of people and business activities represents a very important 'driver' of the above economic functions in terms of demands (transport, recreation) and employment opportunities. Similarly, the residence function determines the flood protection requirements that need to be fulfilled by the flood protection system. But in terms of the physical processes, the residence function does not directly affect the physical interactions between the WS subsystems that are to be considered in relation to the WS sediment system.

Gas mining has started in the eighties at location 'Zuidwal' in the western part of the WS and several locations around 'Ameland'. From 2007 onwards production has started from a number of new locations in the Lauwersmeer area. A Dutch company (ESCO/Frisia) has applied for a permit for salt mining at a depth of 2-3 km below the "Ballastp-laat", an intertidal flat located Northwest of Harlingen. A decision on this will probably be taken on short term. A small amount of sand resulting from dredging navigation channels is not returned to the sediment system but sold at the sand market. This amount is estimated at 0.6 million m<sup>3</sup>/year (De Ronde, J.G., 2008).

Main navigation activities relate to the ferry services between the barrier island and the mainland, for which maintenance (dredging) of harbour basins and navigation channels is required. Presently, the total annual dredging volume in WS harbour basins and navigation channels (excluding the Eems-Dollard estuary) is of the order of 4 million m<sup>3</sup> per year (Van Duren, L. en B. van der Valk, 2010).

Commercial fisheries in the WS are presently limited to shrimp and shellfish. Mussel fishing is still

allowed, but based on a covenant concluded with the mussel sector, the harvesting of mussel seed will be ended from 2020 onwards. Covenants for the transition of the shrimp and cockle sectors are presently under negotiation.

Large numbers of tourists visit the barrier islands for longer and shorter periods, providing an important source of income. In addition, there is a considerable amount of recreational boating activity in the WS system.

Economic functions may affect the WS system in various ways. The concession for salt mining that may be obtained by ESCO/Frisia raises concern with certain parties from the viewpoint of increasing sediment demands of the WS system through inducing subsidence and the potential effects on sediment composition and food availability on the (inter)tidal flats. As a result of ongoing gas mining activities, estimates are that maximum (local) subsidence rates up to 40 or 50 cm may occur. So far, for the older fields around the island of 'Ameland', subsidence could be compensated by natural sedimentation. For the present fields, computations have been made of maximum admissible amounts of subsidence, given expected rates of sea level rise during the production period and estimates of natural sedimentation capacity. Elevation of tidal flats are continually monitored and if subsidence rates exceed admissible amounts, gas production will be reduced ("hand aan de kraan beleid"). Recently, a Long Term Subsidence Study was started to determine subsidence rates based on available measurements and geotechnical modelling. These study results could be used as an input for the assessment of sediment deficits caused by subsidence.

Dredging activities in harbours and navigation channels may have significant local effects on the WS (sediment) system and cause other (temporary) adverse effects on ecological values related to benthic life and water quality (turbidity). Commercial fisheries leads to adverse effects on ecological values that are more or less similar to the effects of dredging. Recreational activities may lead to certain other adverse effects on ecological values, e.g. by disturbing birds or causing aquatic pollution.



### 3.7 Wadden Sea system diagram

Figure 1 presents an integrated overview of causal relationships between main WS sub-systems, functions and values (WS system diagram). This figure distinguishes between three main parts:

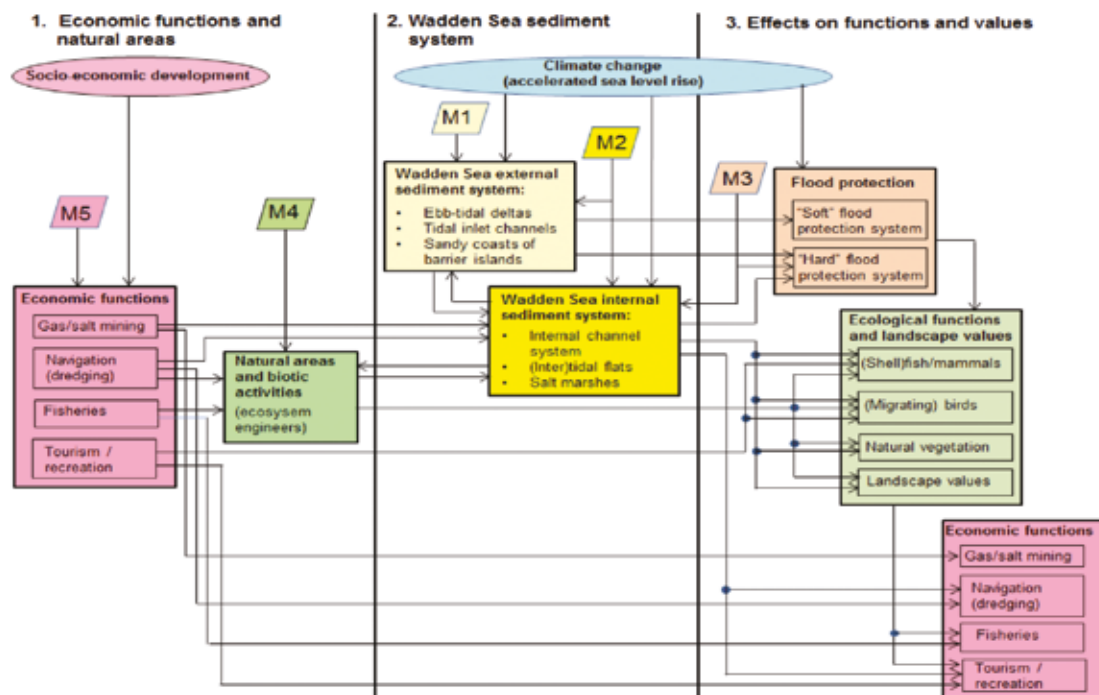
1. Economic functions and natural areas.
2. The WS sediment system.
3. Effects on functions and values.

The first part represents the extent of the WS economic functions and natural areas in the present, or a particular future, situation and related activity levels. For natural areas, these include the biotic activities of different types of ecosystem engineers. The second part represents the interacting WS external and internal sediment systems. The third part is involved with the effects associated with the main WS functions and values, including the flood protection function, the ecological functions and landscape values, and the economic functions. Activity levels related to

economic functions are driven by socio-economic development. From the viewpoint of the WS adaptation strategy, climate change (and in particular accelerated sea level rise) is the main driver affecting the abiotic system components of the WS system.

The WS sediment system holds a central position in the system diagram of Figure 1. The WS external sediment system directly determines the condition of the soft flood protection system at the North Sea side of the barrier islands. Both the external and internal sediment system determine the boundary conditions for the hydraulic loads to the hard flood protection system. The development potential of the WS ecological functions and landscape values are dependent on the WS internal sediment system. In addition, the WS internal sediment system may also affect the economic functions navigation and recreational boating (through available water depths).

Figure 1 Wadden Sea system diagram: causal relationships between WS subsystems, functions and values



Ecological functions and landscape values may be affected by changes in the nature of the soft and hard flood protection systems (e.g. in case of innovative solutions aimed to establish multifunctional protection zones). The extent of natural areas and biotic activities (ecosystem engineers) have a direct effect on ecological values related to (shell)fish and mammals, migrating birds, natural vegetation and landscape values. Ecological values may also be affected by tourism/recreation through aquatic pollution or by disturbing mammals or birds.

Economic activity levels, driven by socio-economic development (related to the barrier island's residence function), largely determine the outcomes of the economic functions. Ecological and landscape values provide important boundary conditions for certain economic functions, such as (commercial) fisheries and tourism/recreation.

The WS internal sediment system is influenced by the nature and extent of biotic activities (ecosystem engineers), while the potential for biotic activities, in turn, depends on the characteristics of the WS internal sediment system (such as the availability of fine sediments and hydraulic conditions). The WS internal sediment system may also be directly affected by economic functions such as gas and salt mining (through subsidence) and navigation (dredging). Certain economic activities (such as dredging and fisheries) can have a direct adverse effect on biotic activity.

From the overview of Figure 1 it becomes clear that the main potential effects are related to the WS sediment system, in particular to the development and condition of the WS internal sediment system. Consequently, the key to the adaptation strategy framework to be developed lies in the possibilities to preserve the WS sediment system, given the interplay of the external and internal sediment systems. The development of the WS external sediment system provides an important boundary condition for the WS internal sediment system. In this respect it is noted that the WS external sediment system is part of the larger, national coastal sediment-sharing system that is referred to as the 'Coastal Foundation'. Developments related to the coastal foundation

depend on the present and future national coastal protection strategy, which is outside the direct scope of the WS adaptation strategy.

In addition to measures aimed at preserving the WS sediment system, a number of other potential measures apply to other parts of the WS system. These include the measures needed to maintain required safety standards of the hard WS flood protection system, as well as a variety of other, more specific measures to enhance specific ecological and landscape values and/or to reduce the adverse effects of economic functions. The potential measures to be considered within the adaptation strategy framework are further described in Section 5.2 of this report.





# 4

## Development of Wadden Sea sediment system

## 4.1 Wadden Sea development from a geological perspective

A comprehensive description of the Wadden Sea historical development is provided in a special issue of *Ocean & Coastal Management on the Wadden Sea Region* (Volume 68 of November 2012), in particular the articles: Bazelmans, J. et al, 2012; Kabat, P. et al, 2012; and Oost, A.P. et al, 2012. In addition, a number of other sources were consulted, including: Elias, E.P.L. et al, 2012a; Oost, A.P. en P.A.H. Kleine Punte, 2003; and Waddenacademie, 2009a.

In the last glacial period, most of the southern North Sea was part of a vast plain, which was largely formed during the Pleistocene. The end of this glacial period marks the beginning of the Holocene, some 11,700 years ago. At this time, the sea level was very much lower than today (many tenths of metres). With increasing temperatures during the Holocene, and the subsequent melting of the icecaps, the sea level rapidly rose (initially at rates of over 1 m/century) and inundated the lowland plains. In the first half of the Holocene (roughly the first 6000 years), sand and clay deposits following from sediment distribution processes were unable to keep pace with sea level rise and the North Sea coastline kept on retreating.

Following the rapid sea level rise in the first millennia of the Holocene, rising groundwater tables in the still dry hinterland led to the creation of marshes and the formation of large peat bogs in the lower parts of the river valleys and coastal plains. With continuing sea level rise, the peat bogs moved further inland and marine deposits were formed on top of the flooded coastal peat lands.

As a result of decreasing rates of sea level rise over time, the coastline gradually stopped moving in southward and eastward direction. At about 6000-5000 BP (Before Present) in the present Wadden Sea region, most of the barrier island chain had been formed at close range (some 5 to 10 kilometres offshore) of their current position. At that time, sedimentation rates were still insuff-

icient to fill in the basin between the barrier islands and the mainland coasts, creating a subtidal environment with narrow zones of intertidal sand and mud flats and salt marshes. From about 5000 BP onwards, sedimentation rates started to exceed sea level rise, causing an increase in intertidal and salt marsh areas in certain parts of the Wadden Sea region, while in other parts (with higher rates of subsidence) the subtidal characteristics were maintained.

With further decelerating sea level rise, coastal soil subsidence became a more dominant factor. This is one of the reasons for the differences in development between various parts of the North Sea coasts. While the Belgian and western Netherlands coasts gradually closed, the northern Netherlands and German coasts remained open, with some of the tidal basins even becoming larger. Apart from the larger subsidence rates in the northern parts of the coastal area, this was also caused by differences in sediment availability, with larger supplies to the western coast following from both wave-driven and river related sediment transport.

Around 2600 BP the western Netherlands coastline was largely closed and extensive peat lands had formed in the coastal plains. In the Wadden Sea region, the back-barrier area never closed and remained exposed to storm surges and tidal action. By that time, extensive intertidal areas and salt marshes had formed in the tidal basin, while from the land side peat formations covering the stream valleys and coastal plains had extended in seaward direction, overlaying tidal deposits. Within this highly dynamic environment, the interplay of processes of erosion and accretion basically continued until mid-medieval times, when the influences of man started to become a major factor.

Initially, human settlements in the coastal marshes and plains were built on dwelling mounds that had a negligible influence on large-scale tidal dynamics. This situation quite drastically changed when, from about 1000 BP onwards, man started building dikes which was partly triggered by other human activities such as peat excavations and development of drainage systems (increasing the vulnerability to flooding). By about 700 BP a more



or less continuous system of winter dikes had been constructed, fixing the mainland Wadden Sea coast. These developments went along with large scale land reclamation activities, that were set back from time to time by large flooding events caused by severe storm surges. At later times, coastal defence related human activities were extended to the barrier islands (such as dike building, dune formation and fixing, and the construction of other protection works). In the last century a number of major dams were constructed involved with the closure of the 'Zuiderzee' (through the 'Afsluitdijk') and the closure of the 'Lauwersmeer'. Obviously, the increasing extent of human intervention has significantly affected the boundary conditions for the further development of the Wadden Sea region.

From the above it follows that the Wadden Sea region has been in existence as a tidal basin during some 6000 years. In this period, the conditions determining the Wadden Sea dimensions and processes have continually and significantly changed. In spite of these changes, the Wadden Sea was able to more or less maintain its basic characteristics as a highly dynamic tidal basin. When considering the future development of the Wadden Sea region, the large extent of robustness and resilience that was shown in the past may provide a certain degree of reassurance. But yet, we may now be facing a quite different situation. In the next centuries, accelerated sea level rise may exceed the values we have seen in the last 6000 years. And as the geometry and dimensions of the basin are now basically fixed (dictated by the present flood protection system), natural adaptive system responses may be severely limited. Moreover, the natural supply of river sediments to the coastal system has essentially stopped. It therefore remains highly uncertain how the Wadden Sea region will respond to the impacts of climate change that will become manifest in the next centuries.

## 4.2 Future development of Wadden Sea sediment balance

Sea level rise will lead to a sediment demand of the WS system to keep up with rising waters. The analysis of available bathymetric measurements has shown that in the last 70 years the Dutch part of the WS was able to keep up with historic sea level rise (approx. 20 cm/century). There is a certain consensus that natural sedimentation processes might be able to keep up with larger rates of sea level rise (up to 50 or 60 cm/century). Beyond these rates there is a risk that the WS might "drown".

Most experts consulted have emphasized the uncertainties surrounding the question if and when the WS system would actually enter into a 'drowning' situation. Apart from the uncertainties in climate change and sea level rise predictions proper, there still are severe limitations in our capabilities of predicting WS responses and adaptive capacity to keep up with accelerated sea level rise. Another uncertainty relates to the sediment demands following from subsidence caused by the ongoing mining of gas and (possibly) salt, extracted from deep formations within the WS area. Figure 2 provides an illustration of the main processes affecting the development of the WS sediment balance, viewed within a long timescale (of the order of a century).

Figure 2 provides an indication of the following processes over time:

- Development of sea level rise in cm/yr.
- Sediment demand (subsidence) because of mining activities (gas, salt, sand) in cm/yr.
- Total relative sea level rise (summation of the above two processes) in cm/yr.
- Sediment supply resulting from net sediment imports (cm/yr).

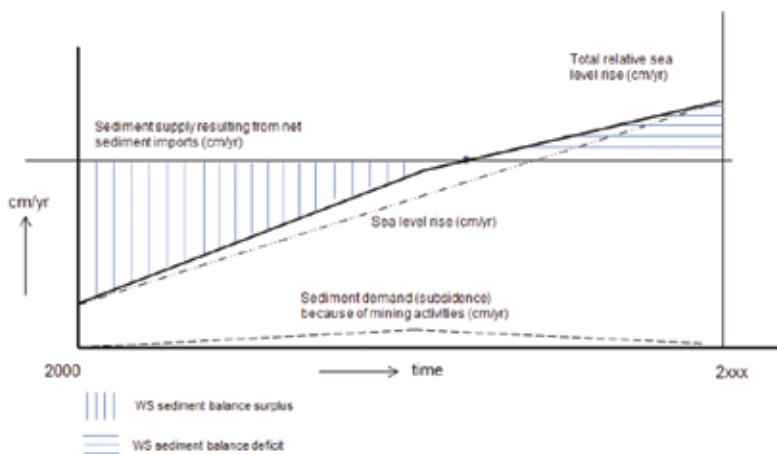
All components have been expressed in terms of cm/yr, representing changes in relative WS water depth, averaged across the entire (Dutch) Wadden Sea area. Given the surface area of the Dutch part of WS, the various components can be expressed in sediment volumes. From the viewpoint of the overall sediment balance the total relative sea level rise represents sediment demand, whereas the net sediment imports represent sediment supply. The components shown in Figure 2 merely take account of the main contributions to the total sediment balance and ignore other (smaller) contributions related to e.g. dredging activities and the effects of ecosystem engineers. The illustration in Figure 2 indicates that at present there is a sediment surplus situation. With (expected) accelerated sea level rise this surplus will be reduced over time. On longer term this may lead to a sediment deficit, marking the beginning of a 'drowning' situation.

It is noted that the development of all processes shown in Figure 2 is highly uncertain. Historic and present sea level rise is presently of the order of 0.2 cm/yr. Several scenarios for the projection of future sea level rise for a number of discrete target years have been developed (see par. 4.3) but the actual development of the rate of sea level rise (in cm/yr) over time is basically unknown. In the illustrative example of Figure 2, this development is shown as a linear curve.

Ongoing gas production from WS gas fields will lead to increasing subsidence, which may be augmented by future salt mining and the mining of sand (only limited quantities). If at a certain point in time gas (and salt) production will be reduced or stopped, the rate of subsidence (in cm/yr) will cease to accelerate and at some point start going down (presumably with some delay). The development of subsidence rates in time are presently quite uncertain. A study was recently started to determine local subsidence rates across subsidence-affected areas, based on measurements and geotechnical modelling. Further assessments would be required to provide better insights in actual sediment deficits caused by subsidence and its behaviour in time. The curve shown in Figure 2 is merely to be regarded as an illustration.

In the present WS system there is a net sediment import capacity following from the difference in sediment quantities transported with incoming and outgoing tidal flows. The extent of this capacity and its development in time is governed by many complex factors and processes (among other related to developments in sediment availability in the external sediment system, relative sea level rise, and a variety of tidal basin characteristics) and is basically unknown. For the sake of illustration, in Figure 2 this capacity is shown as a constant, which is to be regarded a very simplified representation.

Figure 2 Illustrative development of WS internal sediment balance over time





Presently there are no indications of any emerging 'drowning' problems and available measurements do not yet show an acceleration of the rate of sea level rise along the Dutch coast. Based on present knowledge and insights it is therefore rather questionable whether or not a sediment deficit would actually develop within the foreseeable future. And if so, time scales involved with emerging sediment deficits and further development of a drowning situation (becoming manifest in a gradual increase in water depths and reduction of intertidal area) would probably be very large. In this respect we need to think of time scales of a century or more.

### 4.3 Interpretation of sea level rise scenarios

In its 4<sup>th</sup> assessment report of 2007 (IPCC, 2007), the IPCC provided a range of global sea level rise projections for the year 2100 between 0.18 and 0.59 m (compared to the 1990 situation). In 2006, KNMI presented four climate scenarios for the Netherlands, covering a range of sea level rise projections for 2100 (versus 1990) between 0.35 and 0.85 m, with a medium value of 0.60 m (KNMI, 2006). Differences between IPCC and KNMI projections can be partly explained by some regional effects that were taken into account in the KNMI scenarios. In its long term assessment of vulnerability to climate change, the Dutch Delta Committee has suggested to take account of an absolute sea level rise in 2100 ranging from 0.55 to 1.20 m (Deltacommissie, 2008). So far, Dutch coastal protection policy making has been based on the KNMI scenarios.

From the illustrative example shown in Figure 2 it follows that the WS sediment demand is driven by the relative rate of sea level rise (in cm/yr) and its development in time. The comparison of this sediment demand with the net sediment import capacity at a given point in time determines whether or not a sediment balance deficit would emerge. Available sea level rise scenarios are expressed in absolute amounts of sea level rise that would be achieved in a given target year. In the examples

provided above, this is the target year 2100 versus the base year 1990. This raises the question what would be the actual development of sea level rise over time, both in terms of the absolute sea level in m and the rate of sea level rise in cm/yr. In the available scenario information, the latter information is not explicitly provided.

The figures 3a, 3b and 3c below, are based on an illustrative computation to provide some further insights in the possible development of the rate of sea level rise over time. For this purpose, it was assumed that the acceleration of the rate of sea level rise (cm/yr) over time could be represented as a linear curve. Based on this assumption, and given an estimate of the absolute sea level rise achieved in the target year (2100), the development in time of both the absolute sea level rise (in m) and the relative sea level rise (in cm/yr) were computed. The results of these computations are shown in Figures 3a, 3b and 3c for 3 different values of absolute sea level rise in 2100, inferred from the KNMI scenarios (0.35 m, 0.60 m and 0.85 m, representing the low, medium and high scenario, respectively). In figures 3a, 3b and 3c the red line represents the development of the absolute sea level rise (SLR) in m. The blue line represents the development of the relative SLR in cm/yr. Note that the vertical scale applies to both units (m and cm/yr) pertaining to these two curves.

Figure 3a Illustrative sea level rise development (in cm/yr and m)  
For absolute sea level rise of 0.35 m in 2100

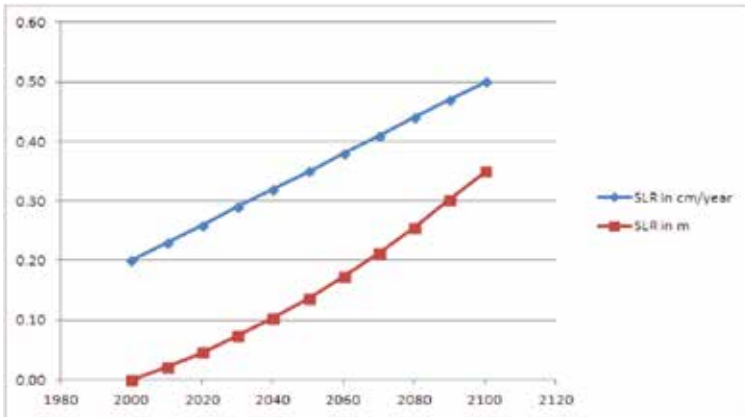


Figure 3b Illustrative sea level rise development (in cm/yr and m)  
For absolute sea level rise of 0.60 m in 2100

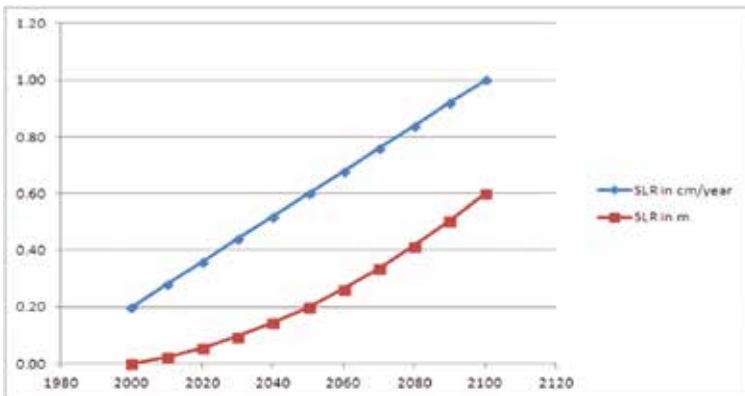
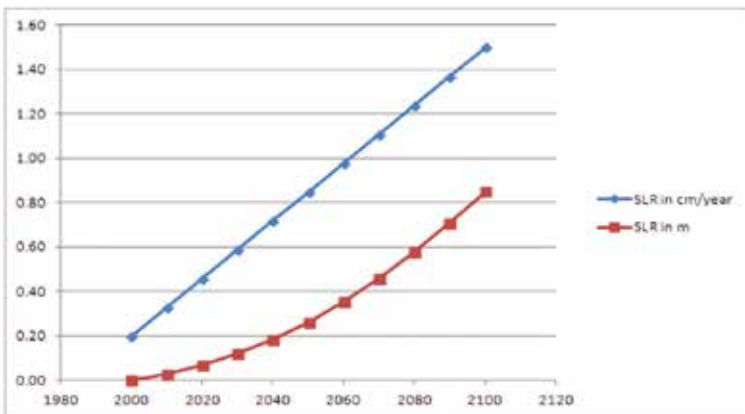


Figure 3c Illustrative sea level rise development (in cm/yr and m)  
For absolute sea level rise of 0.85 m in 2100





Under the assumption that the development of the rate of sea level rise in time would be linear, the development of absolute sea level rise would be a parabolic function, which is more or less in line with the general shape of absolute sea level rise scenarios provided. Under the low KNMI scenario in Figure 3a (sea level rise is 0.35 m in 2100) we find that the rate of sea level rise in 2100 would have to be as high as 0.5 cm/yr to achieve the assumed absolute sea level rise (2.5 times higher than the initial rate of sea level rise in 2000). Under the medium KNMI scenario in Figure 3b (sea level rise is 0.60 m in 2100) the rate of sea level rise in 2100 would be 1.0 cm/yr (5 times higher than the initial value in 2000). And under the high KNMI scenario in Figure 3c (sea level rise is 0.85 m in 2100) the rate of sea level rise in 2100 would be 1.5 cm/yr (7.5 times higher than the initial value in 2000).

These examples illustrate that, with an initial value of the rate of sea level rise of 0.2 cm/yr, very significant increases in the rate of sea level rise would have to emerge in order to achieve the absolute sea level rises projected in the various (absolute) scenarios. Such potential increases, with a factor of 5 or more, may well be beyond the natural sediment import capacity of the WS system. This suggests that, if the medium or high KNMI scenario would be realized, the beginning of a "drowning" situation may become manifest in the second half of this century.

The figures also show that, even in the highest scenario, the rate of sea level rise would still be only 0.3 cm in 2010 (and much lower in the other cases). In other words: a potentially rapid increase in the rate of sea level in the second half of this century would not be in contrast with present observations. The assumption of the development of the rate of sea level in time being a linear function is a crucial assumption in this respect. It is noted that, if the shape of the actual function would be degressive, the resulting increase in the rate of sea level rise in 2100 versus 2000 would be less, but the acceleration of sea level rise in the first half of the century, and resulting rates of sea level rise around e.g. 2050, would be much higher. In case of a progressive (exponential) function, the initial acceleration would be considerably less,

but the rate of sea level rise achieved in 2100 would be much higher. In either case, the rates of sea level rise observed in the second half of the century would be much higher than the rates presently observed.

Given the uncertainties in the present scenarios it still remains to be seen whether or not a significant increase in absolute sea level rise will actually emerge by 2100. But if this happens, there is a considerable chance that WS sediment deficits might become clearly manifest in the second half of this century. The fact that such developments have presently not yet been detected is hardly reassuring in this respect.

#### 4.4 Sediment demands of Coastal Foundation and Wadden Sea

Several studies have addressed the assessment of sediment demands following from relative sea level rise, required to maintain the Coastal Foundation sediment budget (De Ronde, J.G., 2008; Dillingh, D. et al, 2010; Mulder, J.P.M., 2011; and Nederbragt, G., 2006). In Dillingh, D. et al, 2010 explicit estimates were made of sediment amounts required (in million m<sup>3</sup>/year) to maintain the Coastal Foundation and the directly connected subsystems for a number of projections of the rate of sea level rise. An overview of these estimates, extrapolated for a number of other situations, is provided in Table 1. Sediment demands shown in Table 1 include the amounts required for maintaining the sediment budget of the Coastal Foundation proper, the Wadden Sea and the Westerschelde. Annual demands are approximated by multiplying the areas of these subsystems with the annual rate of sea level rise. The amounts required for maintaining the sand balances of the Wadden Sea and Westerschelde will essentially be taken from the Coastal Foundation as long as sufficient amounts of sediment would be available and within the limits of the natural net sediment transport capacities to these subsystems. This leads to a total requirement of the sediment-sharing system which is equal to the summation of the subsystem requirements. In addition there are a

number of demands for various other purposes and historic reasons that have been denoted as 'compensations'. These include the demands following from sand mining, harbour maintenance dredging, the influence of engineering works in the past (e.g. closure dams such as the Afsluitdijk) and historic gas mining. For the present situation, the total of these additional demands was estimated at 6.5 million m<sup>3</sup>/year. For the future, it was assumed that these demands will remain constant.

Based on the above assumptions, in the study of Deltares (Dillingh, D. et al, 2010) rough approximations of total required sediment amounts were established for various rates of sea level rise (0.2, 0.3 and 0.6 cm/yr). In Table 1 these estimates have been extrapolated for a number of other rates of sea level rise (0.5, 1.0 and 1.5 cm/yr). From the indicative numbers in Table 1 it becomes clear that present sediment demands required to maintain the (total) Coastal Foundation may increase substantially within the next century **if** a significant sea level rise, according to present sea level rise scenarios, would actually occur.

Table 1 Approximation of sediment demands (million m<sup>3</sup>/yr) to maintain CF-related sediment system under various rates of sea level rise (cm/yr)

Sediment balance component (million m <sup>3</sup> /yr)	Rate of sea level rise					
	0.2 cm/yr	0.3 cm/yr	0.5 cm/yr	0.6 cm/yr	1.0 cm/yr	1.5 cm/yr
Maintaining Coastal Foundation (CF) proper	8.4	12.6	21.0	25.0	42.0	63.0
Maintaining Wadden Sea sediment balance	5.0	7.5	12.5	15.0	25.0	37.5
Maintaining Westerschelde sediment balance	0.5	0.7	1.2	1.5	2.5	3.8
<b>Total CF-related sediment system</b>	<b>13.9</b>	<b>20.9</b>	<b>34.7</b>	<b>41.5</b>	<b>69.5</b>	<b>104.3</b>
Compensations	6.5	6.5	6.5	6.5	6.5	6.5
<b>Overall total</b>	<b>20.4</b>	<b>27.3</b>	<b>41.2</b>	<b>48.0</b>	<b>76.0</b>	<b>110.8</b>
Dillingh, D. et al (2010)	x	x		x		
Extrapolated from Dillingh (2010)			x		x	x





# 5

## Framework for adaptation strategy

## 5.1 Framework objectives and contents

The particular focus of the assessment described in this report is on exploring the possibilities of an adaptation strategy which is based on augmenting natural sediment flows into the WS system to keep up with accelerated sea level rise. From the diagram of Figure 1 it becomes clear that the WS system is to be regarded a complex system of interacting subsystems and processes, facilitating a number of important functions and values. In view of different objectives to be achieved, a variety of measures may be applied to maintain, enhance or restore these functions and values. Most or many of these measures somehow affect the WS sediment balance. Also, when considering the effects of possible measures there may be several interactions and trade-offs. In order to take account of the various measure interactions, a framework was created to support the process of adaptation strategy development. Specific objectives of this adaptation strategy framework are to provide:

- A coherent overview of WS system related measures that (may) affect the overall WS sediment balance.
- A structure for evaluating potential measures and identifying relevant trade-offs.

In Figure 1, five different categories of measures (M1 through M5) have been distinguished, applying to the various WS subsystems. These include:

- M1: Maintaining the WS external sediment system.
- M2: Preserving the WS internal sediment system.
- M3: Upgrading the hard WS flood protection system.
- M4: Enhancing natural areas and/or biotic potential.
- M5: Reducing adverse effects of economic functions.

It is noted that all or most of the above measures are covered within existing programmes. Measures within M1 are considered within the Delta (sub)Programme Coast (DP Coast) as part of the national Delta Programme. Measures within M2 and M3 are (primarily) within the domain of the Delta (sub)Programme Wadden region (DP Wad-

den). Measures M4 and M5 are included in the Programme "Rijke Waddenzee". Section 5.2 more explicitly describes the types of measures within the above categories following from various literature sources including: Deltaprogramma Waddengebied, 2013; De Vriend, H.J. and M. van Koningsveld, 2012; Ministerie EZ, 2013a en 2013b; Ministeries I&M en EZ, 2013; PRW, 2010; Van Loon-Steensma, J.M. et al, 2012b and 2013; and Witteveen en Bos, 2011.

## 5.2 Measures and trade-offs considered in adaptation strategy

### M1: Maintaining the WS external sediment system

A vision on the long term strategy for the protection of the entire Dutch sandy coast is developed within DP Coast. Based on the existing coastal protection policy, DP Coast considers a range of more and less conservative levels of nourishment for the preservation of the Basal Coast Line (BCL) and the Coastal Foundation (CF) zone, under various scenarios of sea level rise (Ministeries I&M en EZ, 2013, Bijlage A7).

The development of the WS external sediment system, as part of the national CF zone, is directly determined by the national coastal protection strategy. The WS internal sediment system is not included in the CF zone, but is to be regarded an integral part of the overall sediment-sharing system. Consequently, the net sediment imports to the WS internal sediment system, driven by projected sea level rise, will be achieved at the expense of the CF zone. From the viewpoint of the national coastal protection strategy, this net sediment import could therefore be considered as a 'loss' to the CF sediment balance.

It is assumed that any future national coastal protection strategy will minimally preserve the BCL.



The implications are twofold:

- The flood protection function of the WS soft flood protection system (the North Sea side of the barrier islands) will be ensured by the national coastal protection strategy.
- Sediment availability in the tidal inlet zones surrounding the WS is not very likely to become a limiting factor.

Besides sediment availability in the WS tidal inlet zones of the external sediment system, net sediment import to the WS is also determined by the natural sediment import capacity (the capacity to transport, distribute and retain sediment quantities within the WS). With increasing demands of the WS internal sediment system due to accelerated sea level rise, this natural import capacity may become a limiting factor.

In principle, the objective of the Dutch coastal protection policy is to preserve the entire sediment-sharing system by applying sand nourishment. So far the CF zone has not really been fully maintained, however. For example, it has been observed that available sand budgets within the ebb-tidal deltas of the WS external sediment system have been declining during a considerable period (Elias, E.P.L. et al, 2012b). This may be acceptable as long as the BCL is not affected. From the viewpoint of the sediment-sharing system the national coastal protection policy provides the boundary conditions for the development and preservation of the WS internal sediment system. In this respect, crucial questions are:

- 1) To what extent would sand buffer reductions in the CF zone be acceptable in future coastal policy specification?
- 2) What would be the implications for the quantities and time scales of future nourishment requirements in case of ongoing, long term CF sand buffer reductions?
- 3) To what extent will increasing future 'losses' to the CF sediment balance caused by net sediment imports to the WS internal sediment system be acceptable?

- 4) Is it conceivable that additional measures would be taken to increase net sediment imports to the WS internal sediment system (at the expense of the CF sediment budget) in order to prevent the WS from entering into a drowning situation?

In case of a national coastal protection strategy falling short of maintaining the entire CF sediment budget, in the long run, the amounts of sand nourishment required to preserve the BCL might increase (as surrounding sand buffers in the CF may be depleted). Trade-offs to be made within national coastal protection strategy development would be involved with required nourishment quantities and costs over time versus the possibilities and acceptability of depleting existing sediment buffers within the CF zone.

With accelerated sea level rise, net sediment imports to the WS internal sediment system will increase within the system's natural transport and distribution capacity limits. Imported sediment quantities will be taken from the CF zone, and may (eventually) have to be supplied by sediment nourishment as part of the national coastal protection strategy. If the (increasing) costs of these 'losses' to the CF zone would be deemed unacceptable, actions might be considered – if at all feasible - to reduce net sediment imports to the WS system (e.g. by changing nourishment practices in the WS external sediment system). In case the WS system would enter into a drowning situation because of limitations in sediment transport capacity, also the opposite of such actions could be considered (measures that would increase net sediment imports to the WS at the expense of the CF zone). Relevant trade-offs pertain to two different levels. From the perspective of the national coastal protection strategy, the trade-off is involved with additional nourishment cost versus the cost of measures to reduce sediment 'losses' to the WS system. Trade-offs regarding the WS adaptation strategy are involved with the cost of increasing sediment imports (and/or alternative measures to increase the WS internal sediment budget) versus the benefits of preventing the WS system to enter into a drowning situation.

The answers to these questions and the results of the national level trade-offs (in terms of the national coastal protection strategy specification) provide the boundary conditions for further steps in WS adaptation strategy development.

## M2: Preserving the WS internal sediment system

Given the natural sediment transport and distribution capacity of the WS internal sediment system, there will be certain limits to the system's capabilities to keep pace with rising sea levels. If the rate of sea level rise exceeds these limits the WS would gradually enter into a drowning situation. Drowning could only be prevented by increasing net sediment supplies to the WS. This should primarily be achieved by supplying sufficient quantities of sand. Principle options considered to enhance sediment supply to the WS system include:

- a) Options to increase the WS natural sediment import capacity.
- b) Options to provide additional sediment quantities to the internal WS channel system.
- c) Options to directly provide additional sediment quantities at specific WS locations.

Main trade-offs involved with the analysis and evaluation of these options relate to:

- Specific nourishment objectives.
- Nourishment costs.
- The ecological impacts of nourishments.
- Benefits/potential of using natural sediment transport, distribution and sorting processes.

Option a) would aim to develop alternative nourishment practices in the tidal inlet zones of the WS external sediment system (Elias, E.P.L. et al, 2012b). This could be achieved by considering alternative locations (such as the ebb-tidal deltas); different nourishment quantities and frequencies; and sediment compositions. Such options should increase net sediment flows into the WS system, while at the same time meeting the nourishment objectives of the external sediment system (maintaining the BCL and related flood protection standards). Sand nourishments in the external sediment system can be executed at relatively low costs, while ecological impacts in the highly dynamic tidal inlet zones will be rather limited. The specific challenge is to develop a nourishment

measure that will actually increase net sediment flows to the WS system, making optimal use of natural sediment transport, distribution and sorting processes. Another option is to (partly) restore the natural dynamics in dune formation processes by allowing wind driven sediment transports across the barrier islands. This would potentially create a robust and attractive dune area and provide an additional source of sediment to the WS system.

Option b) would consider the possibilities of sediment nourishment inside the WS channel system, while optimally exploiting natural mechanisms to further transport and distribute sediment quantities within the WS system. Costs (per m<sup>3</sup>) would increase as nourishment would take place at more specific locations and in smaller quantities. Ecological impacts would presumably still be limited as nourishment would take place in the dynamic parts of the WS internal channel system.

Option c) would be involved with direct sediment supplies to preserve or control specific components of the WS system, such as tidal flats, salt marsh formation areas or existing flood protection structures. While such nourishments may be effective in preserving local sediment systems they may lead to high cost and potentially large adverse ecological impacts (because of direct damages to vulnerable ecosystems and effects of turbidity).

Given these impacts and trade-offs, the above sequence from a) to c) in principle reflects an order of preference. If feasible solutions could be developed within options a) or b), these would be generally preferred above solutions within option c). For a number of specific measures within option c) the latter may not be true, however. In particular, this may pertain to measures that would increase the WS internal sediment budget while at the same time achieving other objectives, such as enhancing ecological or landscape values. In general, the use of such measures is referred to as "building with nature" (De Vriend, H.J. and M. van Koningsveld, 2012). Examples of such measures might include the possibilities of enhancing the formation of salt marshes, the nourishment of tidal flats in combination with establishing oyster



reefs, or the creation of multifunctional flood protection zones (see description of M3).

Salt marsh development provides an effective way of retaining considerable quantities of fine sediments and may serve several other functions, such as reducing hydraulic loads to existing dike systems and enhancing ecological and landscape values. A number of studies have been conducted to assess the coastal protection potential of salt marshes by dissipating wave energy and to identify promising locations for salt marsh development (Van Loon-Steensma, J.M. et al, 2012a and 2012c; Venema, J.E. et al, 2012). The process of salt marsh formation could be accelerated by improving conditions for salt marsh development, making use of natural availability of fine sediments. A promising possibility to further enhance salt marsh formation would be to use fine sediments becoming available from dredging harbour basins and navigation channels in the WS area, which could be achieved by depositing dredging material at close range of high potential salt marsh formation locations. As the development of salt marsh areas would basically be at the expense of existing areas of (inter)tidal flats, there is a trade-off involved between the values associated with salt marsh expansion and loss of (inter)tidal area. The appreciation of these values among other depends on existing ratios of salt marsh and (inter)tidal areas present, that may be different for various parts of the WS system.

Experiments with direct nourishment of tidal flats have been conducted in the Oosterschelde estuary, which has turned into a slowly 'drowning' system after construction of the Oosterschelde barrier. Experiments were based on applying a direct ring-shaped nourishment of tidal flats with sediments taken from the adjacent channel system. The ring shape aims to reduce direct damages of the nourishment to benthic life, while sediments are to be further spread from the ring across the tidal flat by natural processes (wind, waves). Preliminary results of the ongoing experiments and monitoring programs indicate that such measures may be promising. Another type of experiment to preserve tidal flats in the Oosterschelde is involved with the application of artificial reefs composed of a dead oyster shell body confined in a

steel wire box. The oyster shells provide the hard substrate for oyster larvae (that are abundantly present) to attach and grow. This will gradually turn the artificial reef into a live, self-sustaining oyster reef, offering a habitat for many other organisms (such as crabs and different types of shellfish).

It is noted that the feasibility and consequences of the above options to preserve the WS internal sediment system still suffer from major uncertainties. One of these uncertainties, for example, is whether the execution of nourishments inside the WS system would have an adverse effect on the system's natural net sediment import capacity. If this were the case, a situation could occur whereby **relatively cheap** nourishments outside the WS would be partly replaced by **relatively expensive** nourishments inside the WS. Hence, the general principle should be to try and exploit the capacities of the natural dynamic processes to the extent possible, before considering more expensive solutions. Thorough investigations, supported by field experiments and monitoring programmes would be required to further identify, assess and evaluate such possibilities.

### M3: Upgrading the hard WS flood protection system

Measures for upgrading the hard WS flood protection system would be based on:

- The need for reinforcement measures as identified in the new Flood Protection Programme (nHWBP) based on the third periodical Technical Assessment.
- The development and introduction of the new flood risk assessment methodology and possible changes in flood safety standards.
- Reinforcement requirements due to changes in hydraulic loads following from accelerated sea level rise.

Reinforcement measures identified in the nHWBP will be executed in the next decades, subject to priorities and further requirements following from assessments on desired flood safety standards according to the new methodology. On longer term, developments in hydraulic loads may lead to additional needs for dike reinforcement. As of this moment, the actual measures to be executed are

still subject to large uncertainties. The required upgrading of the 'Afsluitdijk' is an exception in this respect. For the Afsluitdijk, it has been decided that the new dike design is to be based on a 1:10000 flooding probability and should be able to withstand any possible occurrence of overtopping. For the upgrading of existing dike systems, various options could be considered, as follows:

- Traditional reinforcement solutions.
- Innovative, multifunctional solutions by seaward or landward expansion.
- Dedicated solutions.

Traditional reinforcement solutions generally include an adjustment of dike elevation and related dike profile proportions and/or a strengthening of dike revetments or other parts of the dike profile. The upgrading of the dike profile would lead to additional space requirements on the seaward or landward side of the existing dike system. In designing required solutions it should be considered to apply the principles according to the 'Rijke Dijk' (Rich Dike) concept which aims to improve the ecological values of hard coastal protection works.

Various innovative solutions could be considered, aimed at offering potential for multifunctional use and/or reductions in flood protection costs. In particular, such solutions would consider the possibilities for establishing an integrated flood protection zone, combining different functions and natural, landscape elements. A promising concept is to create a broader flood protection zone by seaward expansion of the dike profile, using existing foreland and salt marsh areas. The 'integration' of a foreshore zone within the dike profile offers the possibility of reducing hydraulic loads through wave energy dissipation. This may allow for alternative dike profile designs such as the "green dike" concept, where 'hard' revetments would no longer be required, or other designs that would create opportunities for combining different nature, landscape and land use functions (Van Loon-Steensma, J.M. et al, 2012b and 2013). It is noted that such a seaward expansion of the dike system could introduce a number of potential conflicts. As the entire WS has been designated as Natura 2000 area, any seaward extension would be at the expense of existing nature area

that must be compensated, unless it can be shown that the extension would substantially enhance existing ecological values. In case of an integration of existing salt marshes within the flood protection system, there would be certain requirements regarding the management of salt marsh dimensions, vegetation cover and stability. These are likely to be in conflict with the management requirements from an ecological perspective, where the main interest is in developing or restoring dynamic, natural salt marshes. The various technical design questions and potentially conflicting demands represent important challenges in the further development of the seaward oriented flood protection zone concept.

The establishment of a wider flood protection zone could also be achieved through changes on the landward side of the flood protection system, by expanding the landward side of the dike system and/or a setback of the existing dike (in both cases at the expense of existing land use). Such possibilities should be viewed from a long term perspective of economic development scenarios in relation to future land use pressures. Other considerations are that in the past, significant areas have been reclaimed from salt marsh development that could be part of an integrated, landward oriented flood protection zone. It is noted that landward solutions requiring the construction of a new dike system would be very expensive, unless such solutions could be combined with already existing parallel dike systems. Obviously, in considering such solutions there would be many important trade-offs between present and future land use functions and required management conditions.

The solution developed for the reinforcement of the Prins Hendrik dike on the island of Texel represents an example of a 'dedicated solution' (Witteveen en Bos, 2011). This dike, with a length of about 3 km, is located at the WS side near the southern tip of the island and was found to be non-compliant with required flood safety standards. The solution developed includes the formation of an artificial dune adjacent to the existing dike, together with an intertidal sand barrier that will create a lagoon area, as well as certain other measures to enhance the ecological potential of



the lagoon area. This solution will meet required flood protection standards and create considerable ecological potential at costs comparable to traditional measures for dike reinforcement. Additional advantages relate to the large degree of flexibility and the fact that sediment quantities to be supplied for maintenance of the artificial dune will become available to the WS internal sediment system.

The nature and costs of possible solutions considered would be dependent on the future development (possible drowning) of the WS internal sediment system and the related effects on hydraulic loads to the dike systems. This implies a certain trade-off between measures to reinforce existing WS dike systems and measures to preserve the WS internal sediment system (by increasing WS sediment imports). Conversely, as shown in the above examples, some of the innovative solutions for reinforcing the hard flood protection system considered under M3 may effectively contribute to increasing the internal WS sediment budget.

Regardless of the development of the WS internal sediment system, it would always be possible to meet required flood safety standards by strengthening the existing dike system in a more or less traditional way. This may in fact be the only (or most) feasible option in the extreme case where in the long run the drowning of the WS system would be unavoidable. In this case, another, more rigorous measure to be potentially considered could be the closure or reclamation of (parts of) the WS area according to the principle of shortening the coast line, as applied in other parts of the Dutch flood protection system (such as the Delta works).

#### M4: Enhancing natural areas and/or biotic potential

Within the boundary conditions provided by the existing or future WS internal sediment system, a variety of options can be considered for enhancing the potential of the WS ecological values and functions, some of which have been or are being implemented within the Programme 'Rijke Waddenzee' (PRW, 2010).

These options include:

- Restoration and expansion of sea grass fields.
- Restoration and expansion of mussel beds and oyster reefs (including the possibility of establishing artificial oyster reefs).
- Expansion of salt marsh areas.
- Restoring salt marsh area dynamics.
- Development of fish migration rivers.
- Development of fresh-salt transition zones.

In addition to enhancing natural values and functions, the measures related to restoring and expanding the areas and activities of the various ecosystem engineers will also provide positive contributions to the WS internal sediment balance.

#### M5: Reducing adverse effects of economic functions

Various disturbances following from human exploitation seriously affect benthic fauna, natural habits and sediment dynamics and may cause fundamental changes to the Wadden Sea ecosystem (Eriksson, B.K. et al, 2010). Within the Programme 'Rijke Waddenzee' a number of actions and projects have been defined which aim to reduce the adverse effects of economic functions. Examples are:

- A covenant for mussel sector transition; the covenant is to achieve a sustainable mussel sector by ending the harvesting of mussel seed from 2020 onwards.
- Ongoing actions to develop covenants for the transition of other (shrimp, cockle) sectors.
- Mediation between nature organizations, areal managers and recreational boating on accessibility issues.

Other ongoing or possible actions relate to mining and navigation related dredging. For the present gas mining fields, computations are made of 'effective subsidence capacity' (De Waal, J.A. et al, 2012), given expected rates of sea level rise during the production period and natural sedimentation capacity. Elevation of tidal flats are continually monitored and if actual subsidence rates exceed effective subsidence capacity, gas production will be reduced ("hand aan de kraan beleid"). Certain sources question the feasibility of this policy, however (Houtenbos, A.P.E.M, 2011). Another option that may be considered is the as-

assessment of gas mining induced sediment deficits for the WS area (based on expanded monitoring and geotechnical modelling) and the introduction of a system of compensation payments by the mining sector for these sediment deficits, based on nourishment costs.

Dredging volumes from navigation channels and harbour basins could potentially be reduced by using dredging material for salt marsh formation, decreasing the return flows of dredging material that are presently dumped in the vicinity of dredging locations. Other possibilities to limit dredging volumes might be to change existing navigation routes or ship designs. For example, a possible option might be to change the route of the ferry-service to 'Ameland' (ending up in the village of 'Nes' at the midpoint of the island) which, due to its unfavourable position, presently requires frequent dredging. Changes in ship designs might be aimed at decreasing ship draughts, reducing navigation channel design depths and dredging volumes.

Some of the measure options under M4 and M5 may also offer opportunities for increasing economic potential. Examples of such opportunities are:

- Selective increases in shellfish harvesting potential from mussel beds or oyster reefs.
- Reduction of dredging cost by using dredging material for salt marsh formation or by relocation of dredging-intensive navigation channels (as in the example of Ameland).

### 5.3 Evaluating measures and trade-offs

In strategy development, potential measures and measure combinations are to be evaluated based on an assessment and evaluation of the costs and benefits involved, taking into account the various relevant trade-offs. Table 2 presents a structure to describe and support the evaluation process. The vertical axis of Table 2 provides a concise representation of measure categories and measures. Measure categories coincide with the categories M1 through M5 described in the previous section.

Within these categories a number of specific (example) measures/strategies are considered.

#### **M1: Maintaining the WS external sediment system**

- a) Continue present policy to maintain Basal Coast Line (BCL) and Coastal Foundation (CF).
  - b) Minimize nourishment policy to maintain BCL.
  - c) Expand nourishment policy to maintain BCL.
- Strategy M1a is merely a continuation of the present coastal policy, providing a reference situation for the other strategies. Strategy M1b would aim to at least maintain the BCL while minimizing nourishment volumes to the extent possible (e.g. by trying to reduce net sediment imports to the WS internal sediment system). Strategy M1c would provide all nourishment volumes required to fully maintain the external sediment system and to accommodate the net sediment transport flows to the WS internal sediment system.

#### **M2: Preserving the WS internal sediment system**

- a) Nourishment adjustments to increase net sediment flows to the WS sediment system.
- b) Nourishment of WS internal channel system.
- c) Nourishment of WS (inter)tidal flats / local subsystems.

Strategy M2a is involved with adjustments to nourishment and management practices that will increase net sediment flows to the WS internal sediment system, which could be accomplished by affecting water or wind driven sediment transport processes. Net sediment imports by tidal flows could possibly be increased by changing external nourishment practices in tidal inlet zones. Wind driven sediment transports to the WS could be induced by restoring the natural dynamics in dune formation processes. It is noted that strategy M2a is to be regarded in close connection to strategy M1c. Strategies M2b and M2c represent the options of supplying additional sediment quantities to the WS by direct nourishment of different WS subsystems.

#### **M3: Upgrading the hard WS flood protection system**

- a) Traditional.
- b) Innovative, multifunctional and/or dedicated solutions.

Traditional options for reinforcing the hard flood





protection are considered under strategy M3a, which can be considered as a reference situation. Strategy M3b is involved with a variety of innovative, multifunctional and/or dedicated options for meeting the safety standards of the hard flood protection system by applying the principles of 'building with nature' and/or by establishing win-win combinations with other functional uses.

#### **M4: Enhancing natural areas and/or biotic potential**

- a) Ecosystem engineers (mussels, oysters, sea grass).
- b) Salt marsh development.
- c) Other nature development or restoration measures.

Strategy M4a includes a variety of options to enhance the quality of the natural system by increasing ecosystem engineer activity. Strategy M4b is concerned with the options to increase salt marsh development (potentially to be combined with the use of dredging material from WS internal navigation channels). Strategy M4c includes a number of other potential measures such as developing fish migration rivers or fresh-salt transition zones.

#### **M5: Reducing the adverse effects of economic functions**

- a) Restricting/stopping gas/salt/sand mining.
- b) Restricting/stopping benthic fisheries.
- c) Reducing dredging volumes navigation channels.
- d) Restricting recreational boating.

Under M5, various options (strategies) are considered to restrict or adjust the various economic activities in order to reduce their adverse effects on ecological functions and values or (the costs of) flood protection.

The horizontal axis of Table 2 describes a number of relevant measure impacts, considered within three main groups:

- **Costs of measures** with a distinction in 'nourishment costs'; 'hard flood protection costs'; and 'other measure costs'.
- **Ecological functions and values**, distinguishing between various WS subsystems, i.e. the 'WS internal sediment system'; 'natural areas and biotic activities'; '(shell)fish/mammals, birds,

vegetation and landscape' ; and the 'soft' and 'hard flood protection system'.

- **Costs and (production) values of economic functions**, separately considering the functions 'gas, salt and sand mining'; 'navigation'; 'fisheries'; and 'recreation and tourism'.

The following provides a brief description of the illustrative effects in Table 2. In this respect, strategies M1a (continue present nourishment policy) and M3a (traditional hard flood protection measures) serve as reference situations. For these situations (by definition), no impacts are shown. Positive impacts involved with M1 and M2 on the WS internal sediment budget reflect a situation in which deficits to the internal WS sediment budget would actually occur. If these deficits would not occur, there would be no need to implement additional measures to increase the sediment budget and these impacts would not be relevant.

### Costs of measures

In this case, a positive effect (+) is to be interpreted as a reduction in cost, whereas a negative effect (-) corresponds with a cost increase (compared to the reference policy). Strategy M1b would decrease nourishment costs, whereas all other nourishment options (M1c, M2a, M2b and M2c) would increase nourishment costs. Certain innovative, multifunctional and/or dedicated solutions to the hard flood protection system (M3b) that increase the WS internal sediment budget may reduce nourishment requirements. Restricting/stopping gas/salt mining (M5a) would also reduce nourishment requirements.

The various nourishment options (M1b, M1c, M2a, M2b and M2c) may indirectly affect **hard flood protection costs** by changing the WS internal sediment budget and hydraulic loads to the hard flood protection system. The indirect effect is negative if the internal sediment budget is decreased and positive if it is increased. The effect of innovative, multifunctional and/or dedicated solutions to hard flood protection costs (M3b) may be positive or negative, depending on specif-

ic measures considered. Enhancing ecosystem engineer activity (M4a) positively affects the internal sediment balance and may indirectly reduce hard flood protection costs. Other cost reductions to the hard flood protection system may result from salt marsh development (M4b) and restricting or stopping gas/salt/sand mining (M5a).

**Other measure costs** are involved with the measures/strategies: enhancing ecosystem engineer activity (M4a); salt marsh development (M4b); other nature development or restoration measures (M4c); and reducing dredging volumes of navigation channels (M5c) (in case the latter measures would be involved with changing existing navigation routes).

### Measure impacts to ecological functions and values

The various nourishment options (M1b, M1c, M2a, M2b and M2c) all affect the **WS internal sediment system**. Except for the first (M1b), which reduces the internal sediment budget, the effects to the sediment budget and related ecological functions

Table 2 Overview of measures/strategies and potential impacts

Measures	Measure impacts											
	Costs of measures			Ecological functions and values					Costs and (production) values of economic functions			
	Nourishment cost	Hard flood protection costs	Other measure costs	Wadden Sea internal sediment system	Natural areas and biotic activities	Shellfish and mammals, birds, vegetation, landscape	Soft flood protection system	Hard flood protection system	Gas, salt and sand mining	Navigation	Fisheries	Recreation and tourism
<b>M1: Maintaining the WS external sediment system</b>												
a) Continue present policy to maintain BCL/CF												
b) Minimize nourishment policy to maintain BCL	+	(-)		-	-	-					(-)	(-)
c) Expand nourishment policy to maintain BCL/CF	-	(+)		+	+	+	+				(+)	(+)
<b>M2: Preserving the WS internal sediment system</b>												
a) Nourishment adjustments to increase net flows to WS	-	(+)		+	+	+	+				(+)	(+)
b) Nourishment of WS internal channel system	-	(+)		+	+/(-)	+/(-)					(+)	(+)
c) Nourishment of WS (intertidal flats / local subsystems)	-	(+)		+	+/-	+/-					(+)	(+)
<b>M3: Upgrading the hard WS flood protection system</b>												
a) Traditional												
b) Innovative, multifunctional and/or dedicated solutions	(+)	+/-?		(+)	+	+		+			(+)	(+)
<b>M4: Enhancing natural areas and/or biotic potential</b>												
a) Ecosystem engineers (mussels, oysters, sea grass)		(+)	-	(+)	+	+					(+)	(+)
b) Salt marsh development		+	-	+	+/-	+/-				(+)	(-)	(+/-)
c) Other nature development or restoration measures			-	+	+	+					(+)	(+)
<b>M5: Reducing adverse effects of economic functions</b>												
a) Restricting/stopping gas/salt/sand mining	+	+		+	+	+			-		(+)	(+)
b) Restricting/stopping benthic fisheries											-	
c) Reducing dredging volumes of navigation channels				-	+	+				+/-		
d) Restricting recreational boating												-
<b>Legend:</b>												
+ direct positive effect												
- direct negative effect												
+/- both positive and negative effects												
+/-? positive or negative effect												
(±), (-), (+/-) indirect or possible effects												



and values are positive. Certain innovative, multi-functional and/or dedicated solutions to the hard flood protection system (M3b) may enhance the WS internal sediment budget. Positive contributions to the WS internal sediment balance also follow from strategies M4a, M4b and M5a.

For both the impact categories **WS natural areas and biotic activities and (shell)fish, mammals, birds, vegetation and landscape** there will be positive effects following from improving the internal sediment balance (strategies M1c, M2a, M2b, M2c and M5a) and negative effects if the sediment balance is reduced (M1b). However, in case of nourishments applied to the WS internal sediment system, both impact categories will be adversely affected. The negative effects may be limited in case of nourishment to the internal WS channel system (M2b), but may be quite substantial if nourishments would be directly applied to (inter)tidal flats or other local subsystems (M2c). A number of strategies (including M3b, M4a, M4c, M5b and M5c) would have a direct positive effect on both impact categories. The impacts of salt marsh development (M4b) would both be positive (increase in salt marsh area) and negative (decrease in (inter)tidal flats), for both impact categories. A specific positive effect applying to fish, mammals and birds relates to restricting recreational boating.

Ecological functions and values of the **soft flood protection system** (in particular the dune area) will be positively affected by restoring the natural dynamics in dune formation processes that may be included in strategies M1c/M2a (which are to be regarded in combination). Ecological functions and values related to the **hard flood protection system** are positively affected by innovative, multi-functional and/or dedicated solutions (M3b).

### Costs and (production) values of economic functions

Restricting or stopping gas/salt/sand mining will lead to a negative impact on mining production values. **Navigation** may benefit from salt marsh development (M4b) in case dredging material from WS navigation channels would be used (which would reduce 'return flows' of dredging material to navigation channels and thereby

dredging costs). Specific measures to reduce dredging volumes of navigation channels (M5c) might have positive or negative effects to the navigation sector. Effects would be positive in case of changes to navigation routes that would structurally reduce dredging volumes and costs. Effects to the sector might be negative in case of required changes in ship designs (decreasing ship draughts) if design depths of navigation channels would be reduced. The economic functions **fisheries and recreation and tourism** both are expected to (indirectly) benefit from a situation whereby the WS internal sediment system and related ecological functions and values are preserved or improved. In this respect, negative impacts may follow from applying a minimum nourishment strategy to maintain the BCL (M1b). Salt marsh development (M4b) could be negative to fisheries (reducing (inter)tidal area) and might have both positive and negative effects on recreation and tourism (increasing salt marsh areas while reducing (inter)tidal areas). Restricting/stopping benthic fisheries (M5b) would have an obvious adverse impact on fisheries production values, whereas restricting recreational boating would adversely affect recreation and tourism.

Table 2 provides a basis to support the evaluation of measures and strategies taking into account the various trade-offs (and possible conflicts) within and across functions and interests as well as the potential for win-win situations. The main societal interests associated with the WS system region relate to:

- Flood protection of barrier islands and mainland areas surrounding the WS.
- WS ecological functions and values.
- WS economic functions.

Examples of trade-offs to be considered within and across these societal interests are:

- Increasing net sediment transport to the WS system raising costs to meet required flood protection standards of the soft coastal protection system.
- Nourishment measures to augment the WS internal sediment balance adversely affecting ecological functions and values within the WS system.

- Salt marsh development providing opportunities for ecological functions and values at the expense of intertidal areas facilitating other ecological functions and values.
- Ecological benefits and reductions in flood protection costs achieved by restricting WS economic functions at the expense of economic production losses.

Examples of possible win-win situations include:

- The ecological benefits associated with preserving the internal WS sediment system and the potential benefits associated with reductions in hydraulic loads to various parts of the hard flood protection system.
- The potential of innovative and multifunctional solutions for dike reinforcement to strengthen the WS sediment balance, to enhance natural and recreational values, and to reduce flood protection cost.
- The potential of improving the ecological system by restoring and expanding the areas and activities of ecosystem engineers while strengthening the WS sediment balance.
- Enhancing ecological values and reducing navigation channel maintenance costs by making available the sediments from dredging activities for salt marsh development.

A framework such as the example provided in Table 2 could be used as a vehicle to support the evaluation and decision making process regarding the future management of the WS region. The key question to be addressed is whether the WS sediment system could and should be preserved by applying a soft adaptation strategy (based on sediment nourishment), in view of the long term effects of accelerated sea level rise. Alternatively, if such measures would not be feasible, or would become too costly, other solutions might have to be developed in the long run.



# 6

## Adaptation strategy development

## 6.1 Time aspects and phasing

The objective of the present assessment is to identify the need and possibilities of developing an adaptation strategy for preserving the WS sediment system based on natural solutions. Given the large uncertainties and time scales involved, the adaptation strategy is to be framed within a long term development path of the WS sediment system as part of the sediment-sharing system of the North Sea Coastal Foundation zone. The question if and when the WS system might actually enter into a 'drowning' situation is subject to major uncertainty. As of yet, there are no indications of any emerging 'drowning' problems. And in view of the large time scales of the processes involved there would in principle be ample time to respond if observed future trends would provide such indications. The conclusion is that, besides measures following from coastal protection policies in force, there is no need to apply specific, additional measures to preserve the WS sediment system in the foreseeable future. However, it is important to timely anticipate and prepare for future action, should the need arise. An obvious requirement therefore is to closely monitor actual system behaviour and to take careful notice of large scale development trends. In addition, specific monitoring efforts, supported by ongoing modelling development and execution of pilot projects, should be aimed at improving the understanding of WS system processes and identifying promising measures that may prevent or reduce future drowning problems.

While the focus is on the possibilities of preserving the WS sediment system with (soft) nourishment measures, a variety of other measures may be required to ensure specific functions and values of the WS system, related to flood protection, ecological and landscape values, and economic functions. In the long run, it remains to be seen whether a soft adaptation strategy would actually be capable of preserving the present features of the WS system. Therefore, the soft adaptation strategy will be considered within a broader context of possible options to meet the various objectives related to the long term development and functioning of the WS system.

The crucial driver for strategy development is the behaviour of the WS internal sediment system under different scenarios of accelerated sea level rise. Within potential development paths over time, important milestones may arise which are governed by a number of critical questions. The key question is: "Can the WS internal sediment system keep pace with emerging sea level rise within its natural sedimentation transport and distribution capacity?"

If (or as long as) the answer to this question is 'yes', there is no need for applying other measures, than the measures following from the continuation of present policies. If the answer would be 'no', further questions are:

- a) What additional measures would be most appropriate in sustaining the WS internal sediment balance?
- b) Will these measures be effective in preventing the WS system from entering into a drowning situation?

It is noted that, in view of the uncertainties and long term processes involved, it might take a considerable amount of time before a definitive answer can be given to these questions.

The answer to question a) follows from an assessment of (soft) adaptation strategy measure options (indicated as M2 in the previous chapter) within the boundary conditions provided by the national coastal protection policy and the underlying measures and trade-offs (indicated as M1 in the previous chapter). This assessment should lead to the identification and selection of feasible measure options to be included in the soft adaptation strategy, as well as an indication of strategy potential. Based on the results of the assessment, a decision is to be taken whether to actually start the implementation of the soft adaptation strategy.

The answer to question b) is conditional to the implementation of the (soft) adaptation strategy. If (or as long as) the answer to this question is 'yes', in principle no further actions to preserve the WS sediment system would be required. If the answer would be 'no', the soft adaptation strategy will not (or no longer) be able to adequately ensure the preservation of the WS sediment system. The conclusion then is that in the long run a soft adaptation strategy would either fall short of preserving



sediment budgets, would become too costly, or would eventually have too many adverse effects. Following this conclusion, the question arises what other feasible options would remain.

From the above it follows that three main phases could be considered in the long term time path of developing and implementing the WS adaptation strategy:

- Phase 1: time period needed to assess if the WS system will be entering into a drowning situation.
- Phase 2: time period needed to assess if a soft adaptation strategy would be adequate in the foreseeable future (conditional to the conclusion that without additional measures a drowning situation would emerge).
- Phase 3: transition period from a soft adaptation strategy to an alternative strategy (conditional to the conclusion that merely a soft adaptation strategy to prevent the WS system from drowning would not be adequate or feasible in the long run).

The time periods involved with each of these phases, if they become at all relevant, may be very substantial (from decades to centuries). And potentially, within foreseeable time scales, either Phases 1 and 2 may in fact not come to an end. Obviously, at the present stage, further steps to prepare for a long term adaptation strategy should concentrate on Phase 1.

## 6.2 Activities and measures by phase

Within different phases, various activities and potential measures could be considered related to the WS subsystems as defined in the previous chapters. The present section provides a brief elaboration of the contents of these phases. The focus is clearly on Phase 1. In addition, an illustration is given of the contents of the (potentially) following phases.

In identifying the more detailed activities and measures required in adaptation strategy development, a distinction is made into:

- Subsystem related measure and trade-off levels (M1 through M5).
- Different stages and types of analysis and measure implementation.

Subsystem related measure and trade-off levels as defined earlier include:

- M1: Maintaining the WS external sediment system.
- M2: Preserving the WS internal sediment system.
- M3: Upgrading the hard WS flood protection system.
- M4: Enhancing natural areas and/or biotic potential.
- M5: Reducing the adverse effects of economic functions.

Stages and types of analysis and measure implementation considered are:

1. Analysis of WS system processes and development:
  - a. Research questions.
  - b. Monitoring requirements & early warning.
2. Measure preparation and pilot execution:
  - a. Research questions and identification of pilots.
  - b. Monitoring effects of pilots.
3. Measure implementation (building/execution).

According to the above structure and based on the adaptation strategy framework developed in Chapter 5, Tables 3a, 3b and 3c provide an overview of the activities and measures to be potentially considered in Phases 1, 2 and 3, respectively.

### Phase 1: time period needed to assess if WS system will enter into drowning situation

In Phase 1 (Table 3a), the main activities can be summarised as follows:

1. Analysis of WS system processes and development: improvement of understanding of relevant WS system processes and monitoring of system developments aimed at identifying the need for further action.

2. Measure preparation: identification of feasible measure options based on additional research and/or pilot execution. These include:
  - M1: options for more efficient nourishment levels and schemes in national policy.
  - M2: options for increasing net sediment imports to WS system and/or supplementing WS internal sediment balances by nourishment measures on different scales and locations.
  - M3: potential for innovative and multifunctional dike (reinforcement) concepts.
  - M4: options to enhance WS ecological functions and values.
  - M5: options to reduce adverse effects of economic functions.
3. Measure implementation: potential and required measures, including:
  - M1: feasible and desired adjustments to national coastal protection policy options.
  - M3: high priority (required) nHWBP measures.
  - M4: feasible and attractive projects to enhance WS ecological functions and values.
  - M5: feasible and attractive options to reduce adverse effects of economic functions.

The identification and implementation of additional or alternative measures on level M1 are not within the direct scope of the WS adaptation strategy but provide important boundary conditions to WS adaptation strategy development, in particular on level M2. For WS strategy development within Phase 1 it will preliminary be assumed that:

- The preservation of the BCL will be ensured at all times.
- No measures will be applied to effectively reduce net sediment imports to the WS internal sediment system beyond WS natural sediment transport and distribution capacity.

Measures within M3 will have to be implemented as needed to warrant flood safety within developments of flood safety standards and hydraulic conditions. These measures are to be designed and implemented in a way that best serves ecological and landscape values and other functions (including the possibilities to contribute to the WS internal sediment balance).

Measures within M4 and M5 are mainly aimed at restoring and enhancing natural values and may provide contributions to preserving the WS internal sediment balance in a number of ways. From the viewpoint of the WS adaptation strategy, these measures are to be regarded as 'win-win' or 'no regret'.

### Phase 2: time period needed to assess if soft adaptation strategy would be adequate

In Phase 2 (Table 3b) main activities and measures include:

1. Analysis of WS system processes and development: continuation of activities Phase 1.
2. Measure preparation: identification of feasible measure options based on additional research and/or pilot execution. These include:
  - M1: anticipating the possibility that the soft adaptation strategy may not be adequate or may become inadequate in the long run, potential measures should be considered to reduce net sediment inflows from the Coastal Foundation zone to the WS system.
  - M3: anticipating the possibility that the soft adaptation strategy may not be adequate or may become inadequate in the long run, alternative, and potentially more rigorous, measures should be considered to warrant flood safety of the hard WS flood protection system.
3. Measure implementation: potential and required measures, including:
  - M2: feasible measures to be included in the soft adaptation strategy up to the level required to preserve the WS internal sediment system.
  - M3: all measures required to comply with (future) flood safety standards taking into account future developments in hydraulic loads.
  - M4: feasible and attractive projects to enhance WS ecological and landscape values.
  - M5: feasible and attractive options to reduce adverse effects of economic functions.





The soft adaptation strategy is to be 'composed' from the feasible measures under M2, starting from the most attractive (cost-effective) measures. If sediment requirements increase over time the strategy could be expanded by adding other feasible measures, up to the point where the internal sediment budget could no longer be augmented within acceptable limits of costs or adverse effects to other values or functions of the WS system. If these limits are reached, the application of (merely) a soft adaptation strategy would no longer be adequate.

### Phase 3: transition period from soft adaptation strategy to alternative strategy

Main activities and measures in Phase 3 (Table 3c):

1. Analysis of WS system processes and development: continuation of activities as Phase 1 and Phase 2.
2. Measure preparation: no specific actions
3. Measure implementation: potential and required measures, including:
  - M1: feasible measures to reduce net sediment inflows to (parts of) WS system.
  - M2: selective continuation of measures included in soft adaptation strategy.
  - M3: alternative measures required to warrant long term flood safety.
  - M4/M5: selective application of feasible and attractive projects to enhance WS ecological functions/values and to reduce adverse effects of economic functions.

If the WS internal sediment system could not be maintained under the sea level rise scenario, net sediment inflows driven by natural processes will continue and may even increase. These sediment flows take place at the expense of the sediment balance of the CF zone. Under the circumstances of Phase 3, it should then be considered to implement measures that will reduce net inflows to save on national coastal protection policy cost.

Measures under M3 would be aimed at ensuring flood safety standards in a situation where the WS internal sediment system could not be maintained. Flood safety requirements can always be met with traditional reinforcement measures, but costs could potentially become very high. Given a

situation where the WS system would be 'drowning' and associated values would largely be lost, other, more rigorous measures could be considered, such as the closure or reclamation of (parts) of the WS system. In addition to possible savings in the costs of reinforcing the hard flood protection system, this would reduce or eliminate the costs of sustaining the sediment inflows to the WS (at the expense of the CF sediment balance), which may become quite substantial in a drowning situation.

Depending on solutions developed under M3, during (transition) Phase 3 it is conceivable that different WS compartments would be created, where sediment budgets would be maintained in certain part of the WS system, while other parts would gradually 'drown'. In this situation, a selective continuation of the soft adaptation strategy (M2) and application of projects within M4 and M5 could still occur.

Table 3a Components of adaptation strategy - Phase 1: time period needed to assess if WS system will be entering into a drowning situation

WS subsystems	Analysis of WS system processes and development		Measure preparation and pilot execution		Measure implementation
	Research questions	Monitoring/early warning	Research questions/pilots	Monitoring effects of pilots	
M1 WS external sediment system	Coastal foundation (CF) zone and sediment balance under different coastal protection policy options and sea level rise scenarios	Rate of accelerated sea level rise Sediment buffers in CF zones (such as ebb-tidal deltas) Basal coast line (BCL) development and nourishment requirements	Options for more efficient nourishment levels/schemes and effects on CF-zone sediment buffer development and BCL nourishment requirements Options and effects of dynamic dune management measures	Sediment buffers in CF zones (such as ebb-tidal deltas) Basal coast line development and nourishment requirements Dune area sediment balances and ecological values	Feasible and desired adjustment nourishment practices (related to CF- and BCL-zones) Feasible and desired adjustments in dune management
M2 WS internal sediment system	WS internal sediment balance and development of net sediment import capacity Quantitative insights in and development of WS geometries	Sediment transport flows into and out of WS system WS system configuration, areas and water depths (channel network, shallow waters, (inter)tidal area) Elevation/volumes of (inter)tidal flats and salt marsh areas Possible other (early warning) indicators to be developed	Options for CF/BCL-zone nourishment that will enhance sediment flows to WS system Options for nourishment of WS channel network and effects on WS net sediment balance Options for nourishment of specific WS components/locations (such as (inter)tidal flats) and effects on WS net sediment balance	WS net sediment import flows and internal sediment balance Configuration and dimensions of WS internal channel network WS internal sediment balance Elevation and volumes of (inter)tidal flats WS internal sediment balance	
M3 Hard WS flood protection system	Development of hydraulic conditions, driven by SLR and responses of WS internal sediment system	As in M2 above	Potential of innovative and multifunctional dike concepts to reduce hydraulic loads, dike failure probabilities and investment costs		High priority nHWBP measures in a way that best serves ecological and other functions (incl. the internal WS sediment balance)
M4 Potential of WS ecological values and functions	Potential of ecosystem engineers to enhance natural values and to augment the WS sediment balance	Level and quality of natural areas and biotic activity Wadden Sea bed elevation development, retained sediment volumes and grain size distribution in relation to ecosystem engineer activity	Ecosystem engineer related restoration options (sea grass; mussel beds, oyster reefs) Salt marsh development and other nature development options	Natural values, areas/elevations and volumes of retained sediments at pilot locations Natural values, areas/elevations and volumes of retained sediments at salt marsh development pilot locations	Feasible and desired ecosystem engineer restoration projects Feasible and desired salt marsh development projects and other nature development options
M5 Effects of Economic functions	Spatial and temporal patterns of subsidence and sediment demands resulting from mining	Local developments in elevation of surface areas and (inter)tidal flats			Feasible options to reduce adverse effects of economic functions (e.g. related to mining, fisheries, navigation or recreation)



Table 3b Components of adaptation strategy - Phase 2: time period needed to assess if soft adaptation strategy will be adequate

WS subsystems	Analysis of WS system processes and development		Measure preparation and pilot execution		Measure implementation
	Research questions	Monitoring/early warning	Research questions/pilots	Monitoring effects of pilots	
M1 WS external sediment system	As in Phase 1	As in Phase 1	Options and effects of potential measures to reduce net sediment inflows to WS system (in case soft adaptation strategy would turn out to be inadequate)	Sediment balance of and sediment losses from Coastal Foundation (ebb-tidal deltas)	
M2 WS internal sediment system	As in Phase 1	As in Phase 1			Feasible options for CF/BCL-zone nourishment that will enhance sediment flows to WS system
M3 Hard WS flood protection system	As in Phase 1	As in Phase 1	Options and effects of alternative measures to warrant long term flood safety at acceptable cost (in case soft adaptation strategy would turn out to be inadequate), e.g.: <ul style="list-style-type: none"> <li>• (Expanding) traditional dike reinforcement measures</li> <li>• Closure of (parts) of WS system</li> <li>• Reclamation of parts of WS system</li> </ul>		All measures required to comply with (future) flood safety standards taking into account future developments in hydraulic loads. Measures to be designed in a way that best serves ecological and landscape values and other functions (incl. internal WS sediment balance)
M4 Potential of WS values and functions					As in Phase 1
M5 Effects of Economic functions					As in Phase 1

Table 3c Components of adaptation strategy - Phase 3: transition from soft adaptation strategy to alternative strategy

WS subsystems	Analysis of WS system processes and development		Measure preparation and pilot execution		Measure implementation
	Research questions	Monitoring/early warning	Research questions/pilots	Monitoring effects of pilots	
M1 WS external sediment system	As in Phases 1 and 2	As in Phases 1 and 2			Feasible measures to reduce net sediment inflows to (parts of) WS system
M2 WS internal sediment system	As in Phases 1 and 2	As in Phases 1 and 2			Possible, selective continuation of measures included in soft adaptation strategy (to parts of WS system) Phasing out of soft adaptation strategy in other parts
M3 Hard WS flood protection system	As in Phases 1 and 2	As in Phases 1 and 2			Feasible alternative measures to warrant long term flood safety, e.g.: <ul style="list-style-type: none"> <li>• (Expanding) traditional reinforcement measures</li> <li>• Closure of (parts) of WS system</li> <li>• Reclamation of (parts of) WS system</li> </ul>
M4 Potential of					Possible, selective application
M5 Effects of Economic functions					parts of WS system Possible, selective application of feasible options to reduce adverse effects of economic functions



## 6.3 Specification of research and monitoring requirements

Research and monitoring requirements have been identified within the subsystems:

- 1) WS external and internal sediment system.
- 2) Hard WS flood protection system.
- 3) Natural areas and biotic potential.
- 4) Effects of economic functions.

As to the nature of the research requirements, a distinction is made into:

- General research requirements related to WS system processes.
- Measure and pilot related research requirements.

The following provides a further description of the main research questions and related monitoring requirements with respect to the above categories.

### 1) Research and monitoring requirements WS external and internal sediment system

#### General research requirements WS external sediment system

The WS external sediment system has been defined as the part of the coastal foundation (CF) alongside the barrier islands of the WS system in which the interactions with the WS internal sediment system take place. The particularly active parts of this system consist of the tidal inlet zones around the inlet channels in between the barrier islands, including the ebb-tidal deltas, island tips and adjacent sandy beaches and foreshores

Main research questions relate to the detailed understanding of the sediment transport processes and resulting sediment balance of the WS external sediment system in connection with accelerated sea level rise and coastal protection strategy decisions. In particular, these questions pertain to the development of:

- Sediment budgets in specific parts of the system (such as ebb-tidal deltas).
- Future nourishment requirements to maintain the barrier islands' basal coast line (BCL).

- The net sediment import volumes to the WS internal sediment system.

Specific topics for further investigation may include a number of detailed sediment processes such as: the roles of the bed flow and suspended sediment components in the dynamic sediment interactions around the inlet systems; the impact of waves; and the behaviour of different grain size fractions. In addition, there should be a particular focus on further developing the possibilities for 3D morphodynamic modelling of the relevant processes.

#### General research requirements WS internal sediment system

Research efforts with respect to the WS internal sediment systems should be involved with the understanding of various detailed transport phenomena aimed at an integrated consideration of the WS system sediment balance, including its wet and dry components and the interactions with other parts of the sediment-sharing system. Key questions in this respect relate to the development of:

- Net sediment import flows and the ability of the WS system to keep up with rising sea levels, within the boundary conditions as determined by the rate of accelerated sea level rise and available sediment budgets in the external sediment system as determined by national coastal nourishment policy decisions.
- The geometry of the WS internal sediment system in terms of channel network configuration, elevation and volumes of (inter)tidal flats and salt marshes in relation to changes in tidal characteristics (e.g. tidal asymmetry) and detailed morphological processes (such as shoal-channel interactions).

It is noted that there is no such thing as a common or average behaviour of a Wadden Sea tidal basin. Within the entire international WS region, a total of 39 individual tidal basins have been distinguished, most of which have quite different characteristics or are in different development stages. Consequently, a lot can be learned from studying and comparing the behaviour of different tidal basins within the international context of the Common Wadden Sea Secretariat (CWSS). In this re-

spect it is noted that the CWSS is presently embarking on a study that is to consider the behaviour of four different tidal basins within the international WS region.

#### General monitoring requirements

Monitoring requirements regarding the WS external and internal sediment system are connected to developments in:

- Accelerated sea level rise (in particular the rate of sea level rise).
- Sediment buffers in specific zones of the external sediment system (such as ebb-tidal deltas).
- Sediment transport flows into and out of the WS system.
- WS system configuration (channel network, shallow waters and (inter)tidal area) and characteristics of specific system components (such as areas, water depths, elevations and volumes).

Establishing the rate of sea level rise represents a critical factor in monitoring system development. Particular difficulties encountered in assessing the extent of sea level rise relate to eliminating the effects of natural variability. In fact, the only way to obtain reliable estimates is by combining and analysing the results of local, regional and global measurements.

Within and in addition to the above monitoring requirements there should be a specific focus on the possibilities of developing 'early warning' indicators for detecting the early stages of a possible drowning process. Promising options for developing such indicators may be based on monitoring the size, shape and elevation of tidal flats by means of LIDAR (Light Detecting And Ranging). This is an airborne and laser based technique that can be applied to tidal flats (from above water level up to approx. 0.5 m minus NAP). Such techniques are presently applied by NAM (Nederlandse Aardolie Maatschappij) to monitor tidal flats around Ameland and Schiermonnikoog. So far, the use of radar altimetry measurements from satellite observation has been inadequate for this purpose. But with the recent launching of the Sentinel-1A radar imaging satellite in the beginning of 2014 (being the first Sentinel 1 satellite as part of

the European Space Agency's Copernicus programme) more advanced techniques are becoming available. A major breakthrough might be achieved if in the near future satellite observation could be employed for the detailed monitoring of tidal flat development.

Other options for 'early warning' may be found in monitoring the level of biotic activity within (inter)tidal areas. Typically, in case of changes in morphological conditions, effects on the development of (inter)tidal flats may go unnoticed for quite some time, until a tipping point is reached. In many cases, such events are preceded by certain responses in biotic activity levels which may therefore provide effective candidates for early warning indicators.

#### Measure and pilot related research requirements and monitoring

Possible measures regarding the WS external and internal sediment systems include the following options:

- Changing nourishment levels and schemes in the WS external sediment system.
- Dynamic dune management.
- Nourishments in the WS internal channel network.
- Nourishment at specific internal WS locations.

The Dutch coastal protection policy of the sandy coast is based on the principle of 'dynamic preservation' of the basal coastline and the adjacent coastal foundation by applying sand nourishment where needed. With respect to the nourishment practices applied in the dynamic tidal inlet zones of the WS external sediment system, various alternatives might be considered. Such alternatives may be aimed at increasing net sediment imports to the WS system within primary nourishment objectives (maintaining the BCL), which could be a cost-efficient and nature-friendly way of enhancing the WS internal sediment budget. Another option is to enhance the natural dynamics and resilience of the barrier islands' dune systems by allowing wind driven transport processes. This would create potential nature benefits in the dune area and would induce an additional sediment flow into the WS system, at the expense of the external sediment system. Other possibilities



to increase the WS sediment budget are involved with direct nourishments within the WS internal sediment system, either within the main WS channel network or at specific WS locations, such as (inter)tidal flats or at locations in the vicinity of flood protection works.

Detailed research questions should be involved with the impacts of alternative nourishment practices (in terms of e.g. locations, quantities, frequencies and sediment composition) on sediment transport processes and sediment budgets in specific parts of the WS external and internal sediment systems. A critical question in this respect relates to the potential effects of nourishments in different parts of the WS system on the system's natural net sediment import capacity. For example, if a nourishment applied within the WS internal sediment system would significantly reduce the natural sediment import capacity, 'cheap' nourishments could effectively be partly replaced by 'expensive' nourishments, which is obviously not a desirable situation.

In view of the complexity of the subsystems and processes involved, the execution of large scale field experiments (pilots) seems the most appropriate way to deal with these questions (according to the principle of 'learning by doing'). Various parties have emphasized the need for conducting such pilots as a promising vehicle for obtaining the required knowledge on WS system behaviour and measure potential.

Important requirements for pilot execution include a clear definition of pilot objectives in terms of processes to be investigated, hypotheses to be tested and effects to be evaluated. The specification of adequate monitoring programmes should be an explicit part of pilot formulation, design and execution. Monitoring requirements basically include the developments in local sediment balances, transport flows and geometric dimensions in the vicinity of pilot areas. Critical factors in such a monitoring programme are the (sufficient) extent of the area and time span to be monitored (5-10 years); the spatial resolution, accuracy and frequency of measurements; and the use of appropriate measurement methods and equipment (such as the use of LIDAR; jet ski's (for operation

in shallow waters); and the application of multi beam techniques).

A potential dilemma in pilot execution pertains to the physical scale of the pilot. This particularly applies to potential nourishment pilots to be executed in the dynamic tidal inlet zones of the WS external sediment system. While some experts have emphasized the potential risks of disturbing effects in the complex WS environment (e.g. on ecological functions and biotic systems), others have expressed the need for a large scale experiment (of the order of 20 million m<sup>3</sup> or more) to ensure sufficient impact and signal detection.

Another dilemma may arise in the timing of possible pilots. On the one hand, there should be clear indications of potential problems (in terms of the WS internal sediment system not being able to keep up with rising water levels) in order to embark on relatively costly and large scale experiments. But in view of expected duration times with regard to system responses, observations, analysis and decision making processes, a timely start would be essential to allow for adequate strategy preparation.

## 2) Research and monitoring requirements hard WS flood protection system

### General research and monitoring requirements

Required flood safety standards of the hard flood protection system are to be maintained within present and future hydraulic conditions, as affected by accelerated sea level rise. In this respect, the development of the WS internal sediment budget provides an important boundary condition, where increases in hydraulic loads resulting from changes in water depths and related wave attack could have significant consequences for future dike profile and dike revetment requirements. General research questions should be aimed at the assessment of changes in hydraulic loads following from changes in morphological and geometric characteristics of the WS sediment system and the consequences in terms of dike reinforcements and related costs. Particular attention should be given in this respect to possible changes in the dimensions and position of the various transportation channels that may be

threatening the stability of dikes or other flood protection structures.

Monitoring requirements relate to various developments in the physical characteristics of the WS system configuration (as mentioned under item 1). In addition, information on historical developments could be obtained by consulting local people that really know the area (such as inhabitants, farmers, fishermen).

#### **Measure and pilot related research requirements**

Measure related research requirements are primarily involved with the potential of innovative and multifunctional dike concepts. More specifically, these include:

- The potential of salt marsh and foreland areas to reduce hydraulic loads.
- The effects of salt marsh or foreland areas on different failure mechanisms (such as dike overtopping, strength of dike revetments, piping, (macro)stability) and related dike design criteria.
- The impacts on (potential savings of) dike investment costs.

A particular research challenge relates to the possibly conflicting conditions regarding the management of the salt marsh or foreshore area from the perspective of flood protection and ecological objectives. If such areas would be explicitly considered as part of the flood protection system, the actual presence and minimum required dimensions of these areas are to be ensured in order to warrant flood safety standards. These requirements could be in conflict with ecological objectives regarding the natural dynamics of salt marsh development.

A promising concept in this respect might be to distinguish between different parts of a salt marsh area to be integrated in a flood protection zone. While the landward part would be subject to a management regime following from flood protection requirements, the management of the seaward part could be aimed at serving the ecological objectives. The 'boundary' between the management zones would then represent a sort of 'basal salt marsh line' to be maintained from the viewpoint of coastal protection (analogous to the concept of the basal coastline applied to the

sandy coastal protection system). From an overall system's view such solutions could potentially accommodate and enhance both objectives.

### **3) Research and monitoring requirements natural areas and biotic potential**

#### **General research and monitoring requirements**

Research requirements should focus at exploring the potential of enhancing and restoring ecological values through ecosystem engineer activity while at the same time augmenting the WS internal sediment balance. Specific research questions are involved with:

- The ecological potential of various ecosystem engineer related development and restoration options (such as sea grass fields; mussel beds; oyster reefs and salt marsh areas).
- Potential contributions of different types of ecosystem engineers to sediment retention capacity in relation to spatial features (extent, location) and temporal (seasonal) aspects.
- Impacts of increasing ecosystem engineer activity on the WS (fine) sediment balance and possible limitations in (fine) sediment availability.

Monitoring requirements relate to the level and quality of biotic activity at specific locations; developments in ecosystem engineer areas and local sea bed elevations; retained sediment quantities; and composition of retained sediments.

From an overall ecological perspective, an important question to be addressed is about the optimal 'balance' of the extent and locations of the various types of areas and habitats. For example, with respect to salt marshes, the main interest is in developing or restoring dynamic, natural salt marsh areas which would specifically be welcomed at certain places, such as the western part of the WS, or at selective other places to provide refuge for birds. On the other hand, the presence of (inter)tidal flats is extremely important for supporting the bird foraging function of the WS. This implies the need of making trade-offs, as further development of salt marsh areas is likely to be at the expense of (inter)tidal flat area. There is also an institutional aspect to this question. Since the entire WS area has been designated as 'Natura





2000' area, any areal change implies the loss of an existing area type that, according to Natura 2000 conventions, should be compensated for. By definition, such compensations cannot be achieved within the WS. Consequently, any areal change would only be acceptable from a nature point of view if it can be shown that a nature 'surplus value' would be achieved.

#### **Measure and pilot related research requirements and monitoring**

Measure related research would mainly be involved with the execution of pilot projects on the restoration and expansion of different types of ecosystem engineer activity. In this respect it is noted that many projects and experiments are already taking place. A promising option to be further investigated is the use of fine sediments becoming available from dredging harbour basins and navigation channels in the WS area to enhance salt marsh formation. This could be achieved by depositing dredging material at close range of high potential salt marsh formation locations. Another important topic to be further explored is the potential for salt marsh formation and restoration as part of the development of multifunctional flood protection zones. Research questions in this respect should focus on required management conditions to ensure desired ecological objectives, as part of the 'basal salt marsh line concept' (as discussed under item 2). Monitoring requirements to specific pilot areas are more or less equal to the (general) monitoring requirements mentioned above.

#### **4) Research and monitoring requirements on effects of economic functions**

In addition to climate change, an important factor contributing to relative sea level rise is the subsidence caused by salt and gas mining. Gas mining has started in the eighties at several locations in the western part of the WS and around 'Ameland'. From 2007 onwards production has started from a number of new locations in the 'Lauwersmeer' area. A permit for salt mining below an intertidal flat located Northwest of Harlingen has been applied for in 2013. According to present policies, the elevations of tidal flats and other relevant surfaces in the vicinity of gas mining locations are continually monitored and if observed subsidence

rates exceed admissible amounts, gas production will be reduced.

It is noted that both sea level rise and subsidence induced by mining activities contribute to the demand of sediments required to preserve the WS internal sediment system. Up till now, natural sedimentation has been able to compensate for this demand. Future demands from accelerated sea level rise may significantly increase in proportion to the rate of sea level rise. Present or possibly increased rates of subsidence due to mining activities will keep on adding to total demand. Total demand may eventually reach a critical level that exceeds natural sedimentation capacity. It is concluded that the contribution of mining induced subsidence increases the risk of reaching this critical level and brings forward the moment in time when this would happen. For this reason, it is quite essential to improve the quantitative knowledge and modelling capabilities in assessing mining induced subsidence rates and related quantities of sediment demands. More specifically, relevant research questions would be involved with:

- Expected developments in the spatial and temporal patterns of subsidence rates as a function of the level of mining activities.
- Expected developments in annual sediment quantities required to compensate for mining induced subsidence rates.
- The consequences for developments in the time patterns of subsidence rates and sediment demands in case of stopping or reducing mining activities (e.g. if critical levels of sediment demands would be reached).

Recently, a Long Term Subsidence Study was started to determine actual subsidence rates based on available measurements and geotechnical modelling. Further research would be required for the assessment of sediment demand caused by subsidence. Monitoring activities as presently taking place in the vicinity of NAM gas mining areas should be continued and expanded to all present and future mining locations. In the assessment of admissible subsidence rates and related sediment demands it is essential to synchronize the time scales of the cause-effect relationships.





# 7

## Conclusions and recommendations

## 7.1 Conclusions

The present report is involved with exploring the need and potential of an adaptation strategy based on natural solutions, in case the Wadden Sea sediment system would not be able to keep up with accelerated sea level rise. Critical questions in this assessment relate to:

- The long term development of the WS sediment balance.
- Measure options to increase the WS sediment balance.
- The time aspects and phasing of a possible strategy.

The following summarizes the main conclusions with respect to these questions

Long term development of WS sediment balance

- Relative sea level rise (including subsidence) represents the most important sediment demand to the WS system. Net sediment imports resulting from the difference in sediment quantities transported with incoming and outgoing tidal flows represent the main source of supply.
- Developments during the last 70 years have shown that the Dutch part of the WS was able to keep up with historic sea level rise and in fact a significant net sedimentation has taken place. There is a certain consensus that natural sedimentation processes might be able to keep up with larger rates of sea level rise (up to 0.5 or 0.6 cm/yr). Beyond these rates there is a risk that the WS might "drown".
- Given the present state of available knowledge and data it is basically uncertain **if** and **when** the WS system would actually enter into a 'drowning' situation. Available measurements do not yet show an acceleration of sea level rise along the Dutch coast and there are no indications of any emerging drowning problems.
- Changes in future (annual) sediment demand will be driven by changes in the **rate** of relative sea level rise (in cm/yr). Present scenarios for sea level rise have been expressed in terms of absolute amounts of sea level rise to be achieved in a given target year (such as 2100) and do not provide explicit information on the development of the rate of sea level rise over time.

- The absolute amounts of sea level rise to be achieved in 2100 according to present scenarios would imply a quite drastic increase in the rate of sea level rise over time. If the scenarios underlying Dutch policymaking would actually materialize, WS sediment demands would increase very significantly in the second half of this century. Under these circumstances, it is quite conceivable that the WS sediment system would enter into a 'drowning' situation.

### Measure options to increase the WS sediment balance

- WS sediment imports are taken from the Coastal Foundation (CF) zone. Within anticipated coastal protection policies it is expected that the CF sediment balance will be largely maintained.
- The net sediment import capacity of the WS system depends on a number of complex processes and is surrounded by large uncertainties regarding the influence and development of tidal basin characteristics.
- Options to increase the WS natural sediment import capacity may be found in changing CF nourishment schemes in the WS external sediment system (e.g. by changing quantities, frequencies, locations and sediment composition of nourishments).
- Additional options could be to directly apply nourishment measures to the WS internal sediment system. One possibility would be to provide a sediment nourishment to the main channels of the internal distribution system; other possibilities might be to apply nourishments to more specific locations within the WS (to intertidal flats or as part of a dedicated flood protection measure).
- Trade-offs regarding the execution of alternative nourishment options are involved with nourishment cost and (adverse) ecological effects. Moreover there is a risk of disturbing natural sediment transport processes. From the perspective of the WS system, going from outside to more inside nourishment locations would generally lead to a decrease in nourishment quantities and an increase in costs, as well as an increase in adverse ecological effects and risks of disturbing natural processes. The consideration of nourishment options



'from outside to inside' the WS system therefore represents a logical preference order.

- From the viewpoint of other objectives (related to ecological and landscape values or economic functions) other measures may be considered that positively affect the WS sediment balance. This particularly relates to a category of measures that have been referred to as 'building with nature'. The execution of such measures offers an important win-win potential.

### Time aspects and phasing of a possible strategy

- There are no indications of emerging 'drowning' problems within the next decades. Moreover, in view of the time scales involved with the relevant processes there would be ample time to respond if observed future trends would provide such indications.
- Present and anticipated policies within ongoing programmes in the Netherlands are generally very much in line with the concept of applying natural solutions to preserve coastal systems. Therefore, in the foreseeable future, there is no need to consider additional measures to preserve the WS sediment system.
- On longer term, additional measures may be required to support the WS sediment system beyond the measures that logically follow from ongoing policies and programmes.
- Available time is to be used to anticipate further measures. This triggers further action in terms of research and monitoring and measure preparation. The phasing of these actions should be viewed within a long term perspective and is subject to large uncertainties.
- The phasing of future actions is governed by the following sequence of questions:  
Will the WS sediment system be able to keep pace with accelerated sea level rise within existing and anticipated policies?  
If not, what additional measures would be most appropriate in sustaining the WS sediment balance?  
Will a 'soft' adaptation strategy be effective in preserving the WS sediment system in the long run?  
If not, what other feasible options would remain?

- Resulting phases to be considered in strategy development are:

Phase 1: period to assess if the WS system will be entering into a drowning situation.

Phase 2: period to assess if a soft adaptation strategy will be adequate.

Phase 3: transition period from a soft adaptation strategy to an alternative strategy

- For the time being, the focus of adaptation strategy development would merely be on the first phase. Key actions to be considered are:
  1. Improving the understanding of WS system sediment balance and transport processes through execution of general research and monitoring programmes.
  2. Identifying feasible measure options through specific research activities and/or pilot execution with a focus on nourishment options of the WS sediment system. Additional measures to augment the WS sediment system are to be considered in connection with other objectives, such as reinforcing the hard flood protection system and enhancing ecological values and functions.
  3. Selective implementation of measures. These include required (high priority) measures for flood protection from the nHWBP; other attractive measures such as measures that combine different objectives (win-win); or measures of which the beneficial effects are beyond doubt (no regret).

## 7.2 Recommendations

In view of present and ongoing policies there is no need for immediate action with regard to preserving the WS sediment system. On longer term, the need for additional measures cannot be excluded. Available time is to be used for preparing further steps, if so required. Actions for adaptation strategy preparation are distinguished within the following categories:

- Research and monitoring programmes.
- Development of evaluation framework.
- Institutional arrangements for WS policy development and implementation.

### Research and monitoring programmes

Research and monitoring programmes to be developed should be aimed at:

- General research requirements related to WS system processes.
- Measure and pilot related research requirements.

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 specification of adequate monitoring programmes is an explicit part of research execution. Within the specification of general monitoring requirements, particular attention should be given to the possibilities of developing 'early warning' indicators for detecting the early stages of a possible drowning process.

Extensive research programmes and agendas have been formulated by key technological institutes, coordinating bodies such as the Wadden Academy (Waddenacademie, 2009c), and within an international context (Trilateral Wadden Sea Cooperation). It is essential that additional research requirements following from adaptation strategy development needs will be embedded in the existing national and international research agendas.

### Development of evaluation framework

In support of adaptation strategy development, an evaluation framework is to be created that may be based on the initial setup provided in this report. The evaluation framework should provide an integrated view on the effects of a wide variety of measures on WS sediment transport processes and balances. Moreover, the framework should provide a vehicle for making trade-offs across different objectives. Framework development would include an explicit formulation of different policy objectives and targets (to be expressed in operational criteria and indicators) and elaborate on

methods for impact assessment in terms of costs and benefits (related to ecological and economic effects). This will facilitate the identification and analysis of measure trade-offs, win-win situations and potential conflicts.

### Institutional arrangements for WS policy development and implementation

With respect to the management of the WS system, various parties, institutions and programmes have been involved with the identification and implementation of measures and policies, operating within different government layers, from the perspective of different objectives and within different time frames. From the initial setup of the evaluation framework in this report it becomes clear that there may be many physical interactions and trade-offs in considering the impacts of different measures and policies. More specific institutional arrangements are to be developed to ensure the coherence and continuity of future policy making. In particular, such arrangements should provide a clear organizational structure for the execution of policy development and implementation related tasks, such as: analysis and evaluation; decision-making; financing; measure execution and enforcement; management; and maintenance.



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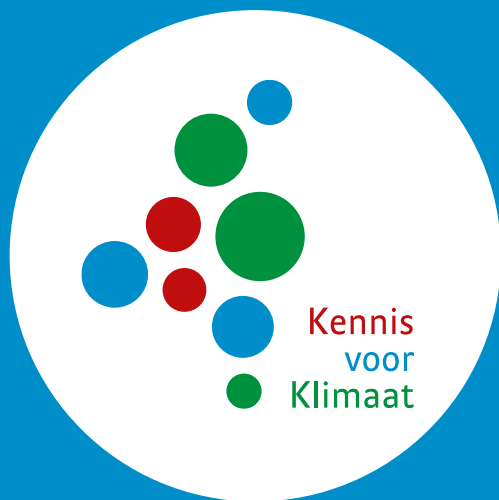


# Appendix 1

## Overview of experts consulted

1. **Han Oiff**, Professor of Community and Conservation Ecology, University of Groningen on 23 April 2013.
2. **Marcel Stive**, professor of Coastal Engineering Delft University of Technology on 24 April 2013.
3. **Jantsje van Loon**, researcher at Earth System Science Group of Wageningen University Environmental Sciences on 25 April 2013.
4. **Herman Ridderinkhof**, deputy director at the Royal Netherlands Institute for Sea Research (NIOZ) and professor at the faculty of Geosciences, University of Utrecht on 3 May 2013.
5. **Pieter den Besten**, coördinator rijksinbreng ruimtelijke belangen i.r.t. deltabeslissingen, beleidsadviseur Waddengebied en leider van Nederlandse delegatie trilaterale Task Group Climate, Ministerie van I&M op 6 mei 2013 (Nederlands).
6. **Martin Baptist**, marine ecologist at IMARES and lector "marine ecosystems management" at Van Hall Larenstein, Leeuwarden on 14 May 2013.
7. **Piet Hoekstra**, professor in coastal morphodynamics at the faculty of Geosciences, University of Utrecht on 6 June 2013.
8. **Luca van Duren**, senior researcher at Deltares in the field of marine ecology and fluid dynamics on 13 June 2013.
9. **Bert van der Valk**, senior advisor - geologist at Deltares and geologist at Dutch Palynological Society on 14 June 2013.
10. **Hessel Speelman**, member and vice president management board Wadden Academy (Theme Geosciences) on 26 June 2013.
11. **Bert Bulsink**, policy advisor at Ministry of Infrastructure and Environment and staff member of Delta Programme Coast on 2 July 2013.
12. **Kees van Es**, Programme Director of 'Rijke Waddenzee' (nature recovery programme "Rich Wadden Sea") at the Ministry of Economic Affairs on 3 July 2013.
13. **Jantsje van Loon**, researcher at Earth System Science Group of Wageningen University Environmental Sciences on 9 July 2013 (2<sup>nd</sup> interview).
14. **Bas Jonkman**, professor of Hydraulic Engineering at Delft University of Technology on 18 July 2013.
15. **Zheng Bing Wang**, professor of Hydraulic Engineering (morphodynamics of lagoons and estuaries) at Delft University of Technology and senior specialist at Deltares on 24 September 2013.





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