

Salt marshes for flood protection

Long-term adaptation by combining functions in flood defences



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Jantsje M. van Loon-Steensma

Thesis

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Contents

<i>Chapter 1</i>	Long-term adaptation by combining functions in flood defences: Context, meaning and implications	7
<i>Chapter 2</i>	Green adaptation by innovative dike concepts along the Dutch Wadden Sea coast; A systematic design and evaluation of innovative dike concepts	19
<i>Chapter 3</i>	Salt marshes to adapt the flood defences along the Dutch Wadden Sea coast; What is the potential for integrating salt marshes in the flood defence zone?	47
<i>Chapter 4</i>	Trade-offs between biodiversity and flood protection services of coastal salt marshes	67
<i>Chapter 5</i>	Development of salt marshes for coastal defence; three case studies in the Wadden region	79
<i>Chapter 6</i>	Further quantification of the ecological value of stabilized and restored salt marshes; Vegetation of two recently restored Wadden Sea salt marshes compared to established salt marshes	125
<i>Chapter 7</i>	The effect of vegetation characteristics on wave damping	139
<i>Chapter 8</i>	Synthesis	157
	References	171
	Summary	183
	Samenvatting	187
	Curriculum Vitae	193
	Dankwoord	197

1

Long-term adaptation by combining functions in flood defences: Context, meaning and implications

1.1 Evolution of flood protection in the Netherlands

In 2008, the second Delta Committee recommended that the Netherlands increase its flood protection level and seek flexible and integrated climate-change adaptation measures (Deltacommissie, 2008). This initiated a quest for new flood protection concepts that could meet these requirements. The main concerns underlying the Committee's recommendation were the effects of an accelerated sea level rise and changes in regional precipitation patterns due to global climate change (IPCC, 2007), ramifications of land subsidence, and increasing residual risk (i.e. potential damages caused by a dike breach) due to demographic (more people) and economic (increasing capital) trends.

Since the flood disaster of 1953, the Netherlands has implemented a risk-based flood protection strategy using so-called 'dike rings', based mainly on the work of Van Dantzig (1956). That approach forms the basis of Dutch flood protection, and is still being refined and extended (e.g. Speijker *et al.*, 2000; Jonkman *et al.*, 2003; Jonkman *et al.*, 2011; Brekelmans *et al.*, 2012). By law, the dike rings must protect the encircled hinterland against river floods and storm surges of a severity that could be statistically expected at a frequency varying from once in 1,250 years to once in 10,000 years, depending on the region and the related values at risk (Ministerie van Verkeer en Waterstaat, 2007a). Dutch law prescribes not only dike design requirements, but also their regular assessment and management.

When the concept of a risk-based flood protection system was conceived (Van Dantzig, 1956), anthropogenic-induced climate change and its far-reaching effects were only starting to receive attention (Revelle & Suess, 1957). In the 1990s, however, it became evident that climate change alters hydraulic boundary conditions and introduces uncertainty in extrapolations of historic patterns of sea-level rise, wind direction and strengths, rainfall and

river discharge. This was recognized as having considerable short-term impact on Dutch flood safety. Even though the basic idea of differentiated risks for different areas of the country (calculated using cost-benefit analyses) remains equally applicable under a scenario with climate change, greater safety margins and investment levels are now considered to be prudent and new dike designs are thought to be desirable. Hence, a programme on future flood safety (*Waterveiligheid 21e Eeuw*) was established in the 1990s to reconsider Dutch flood protection policy. This led to a comprehensive set of flood protection studies (e.g. Klijn *et al.*, 2004).

The second Delta Committee recommended at least a tenfold increase in the flood safety level while also emphasizing the need for development of flood protection along with climate change and ecological processes. The challenge posed by these combined requirements led to intensified research on flood protection, especially from an interdisciplinary perspective (e.g. the Knowledge for Climate Research Programme, Delta Programme). The research presented in this thesis was carried out against this backdrop. It combines hydraulic, ecological, geographical and economic aspects in a search for new discoveries and new insights on the role of salt marshes in flood protection. Central in this research is the idea to combine flood protection with other functions in the flood defence zone to increase the flood safety level and to adapt to the effects of climate change. The idea to combine the flood protection function with nature and landscape values is especially explored for the Wadden region.

1.2 Robust, multifunctional flood defences

Triggered by the recommendation of the second Delta Committee, interest in innovative flood protection techniques grew and a number of over-dimensioned dike designs were introduced. The Delta Committee introduced the ‘Delta dike’ (Deltacommissie, 2008), simultaneously with the ‘Unbreachable dike’ (Silva & Van Velzen, 2008) also called the ‘Broad dike’ (Vellinga, 2008). Table 1.1 and Figure 1.1, respectively, present details about these concepts and the relationships between them.

Table 1.1: Key dike designs and related terms (in italics) in the Netherlands (for the relations between the various concepts see Figure 1.1) (Van Loon-Steensma & Vellinga, 2014).

Traditional dike	Can withstand statistically prescribed extreme water levels, wave heights and wave overtopping. Rijkswaterstaat (2007) applies a design that anticipates foreseen changes and uncertainties with respect to subsidence and climate change over a specific planning horizon (50 years, or 100 years for dikes in built areas), and that reserves a zone to allow for dike reinforcements in the future. This is called 'robust design' as the dike is designed slightly over-dimensioned according to the actual requirements at the time of construction.
<i>prescribed extreme water levels</i>	The Dutch Water Law specifies a safety level in terms of expected flooding frequency. This varies from once in 1,250 years (0.08% annual probability) in the riverine area, to once in 10,000 years (0.01% annual probability) in the province of North Holland.
Over-dimensioned dike	Can withstand more extreme situations than prescribed (in terms of water levels, wave heights and wave overtopping).
Delta dike	Has practically zero probability of failure due to sudden or uncontrollable failure (Deltacommissie, 2008). Enhanced safety can be achieved by inner constructions (such as sheets and walls) or by heightening the dike. However, increased strength is more effectively realized by enlarging the inner berm (e.g. Klijn & Bos, 2010; Knoeff & Ellen, 2011).
Unbreachable dike (synonyms: Broad dike, by Vellinga, 2008; Climate proof dike, by Hartog <i>et al.</i> , 2009)	Owing to its increased width, has 100 times less probability of failure due to erosion by overflowing, piping, or macro-instability on the landward side than traditional dikes (Silva & Van Velzen, 2008). However, the Unbreachable dike does not exclude overflow or wave overtopping which may lead to damage.
Robust dike	Remains functioning without failure under a wide range of conditions, does not collapse during overtopping and reduces a flood disaster to a shallow flooding event. The Robust dike design includes the Unbreachable dike and Delta dike as subsets.
<i>robustness</i>	The ability of a system to continue to function despite disturbances, where the magnitude of the disturbance is variable and uncertain (e.g. De Bruijn <i>et al.</i> , 2008; Hall & Solomatine, 2008; Haasnoot <i>et al.</i> , 2011; Mens <i>et al.</i> , 2011).
Multifunctional dike	Intentionally combines other services with the primary function of flood protection. In practice, incorporation of multiple functions requires over-dimensioning and may thereby help to create a robust dike. In contrast to the 'multi-functional dike' the 'mono-functional dike', is designed considering only the flood protection function.
<i>multifunctional complementary functions secondary functions</i>	Functions that a dike can fulfil in addition to its primary flood defence function. Examples are: transport, housing, agriculture, nature and recreation. Houses with water-retaining walls, and parking garages in dunes are other examples.

The most important paradigm shift associated with the new robust dike designs is that overflow would lead to gradually increasing damage in the hinterland, while overflow of a traditionally designed dike (see Table 1.1) is likely lead to catastrophic flooding due to collapse of the dike (as occurred during the 1953 flood in the south-western delta area of the Netherlands). Traditional dikes have a sudden threshold from no damage to excessive damage, while with Broad dikes, damage escalates gradually and should never reach extremely high levels (Vellinga, 2008). Hence, Broad dikes (if applied over the whole dike ring system or at the most critical sections of the dike rings) could significantly improve the robustness of the flood defence system over a wide range of possible futures and uncertainties. Their use would thus seem to offer a feasible climate adaptation strategy (Vellinga, 2008; Mens *et al.*, 2011; Klijn *et al.*, 2012).

Of course, a Robust dike would require more material and space; but it would provide new opportunities for using the space as well (Vellinga, 2008; Hartog *et al.*, 2009). Such dikes could be designed as multifunctional areas, combining urban development, transport infrastructure, recreation, agricultural use and nature conservation or development. These other functions could even play a role in developing and financing the Robust dike. Figure 1.2 illustrates the physical differences between a Traditional dike (with reinforcement), a Delta dike and a robust Multifunctional dike by comparing cross-sections.

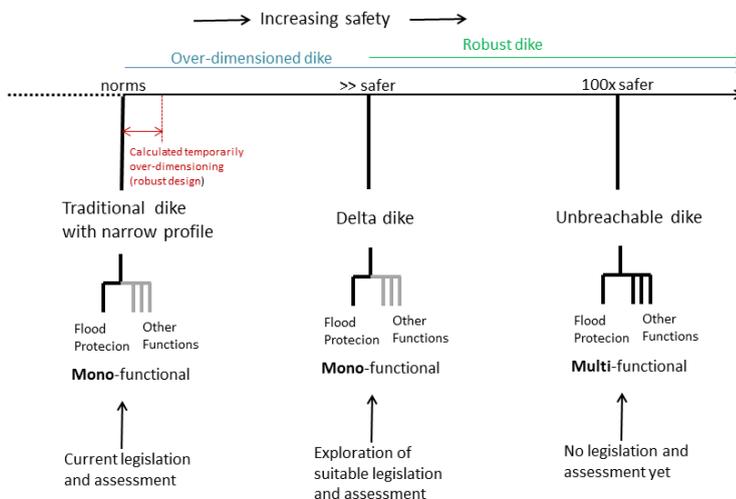


Figure 1.1: Visualization of the relation between the various dikes designs in the Netherlands; these designs are described in Table 1.1 (Van Loon-Steensma & Vellinga, 2014).

Since 2008, a number of researchers have investigated the concept of Delta dikes and Robust multifunctional flood defences (see e.g. Hartog *et al.*, 2009; Ellen *et al.*, 2011). Klijn & Bos (2010) explored the potential effects of Delta dikes on spatial quality, whereas Knoeff & Ellen (2011) examined mechanisms and probabilities of failure. De Moel *et al.* (2010) and Van Loon-Steensma (2011a) explored the potential for Robust multifunctional flood defences in rural riverine areas. De Urbanisten *et al.* (2010) and Stalenberg (2010) focused on urban areas, developing an adaptable multifunctional design.

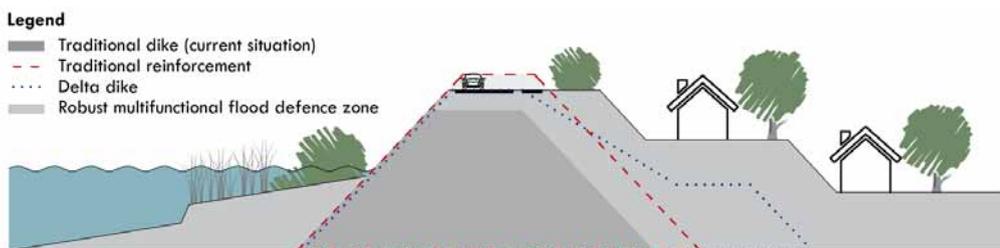


Figure 1.2: Diagram of a Traditional dike (current situation), a traditional reinforcement, a Delta dike and a Robust multifunctional flood defence zone (Van Loon-Steensma & Vellinga, 2014).

Outside the scientific community, regional water boards, local policymakers and private companies have expressed interest in robust, multifunctional approaches to flood defences (see e.g. De Moel *et al.*, 2010). One reason why is their long-term stability. Currently, regular reinforcement works are needed to maintain the dikes. This involves heightening and strengthening the revetment or enlargement of the inner berm every 10 to 20 years. Perhaps this could be avoided with the use of an over-dimensioned dike design. Other reasons for the rising interest are the opportunities that the multifunctional approach presents in terms of adding value and combining goals and plans. The Municipality of Rotterdam, for example, has initiated explorative studies (e.g. De Urbanisten *et al.*, 2010) and projects to identify opportunities for Robust, multifunctional dikes. Furthermore, studies are under way as part of various research programmes, including Knowledge for Climate, STW-NWO Perspectief and the Delta Programme.

1.3 The challenge of adapting to climate change and strengthening nature and landscape values in the Wadden region

In the context of the Delta Programme, there is growing interest in new flood protection techniques suitable for the Wadden region. The Delta Programme's aim in this region is to ensure long-term flood protection (targeting the coastal areas of both the mainland and the barrier islands) while also preserving the nature and landscape values of the Wadden Sea (Ministerie van Verkeer en Waterstaat *et al.*, 2010). Special attention is being given to adaptation strategies based on natural processes that could strengthen the ecological resilience of the area while facilitating sustainable human use.

Central in the Wadden region is the Wadden Sea, one of the world's largest tidal areas, renowned for its sandflats and mudflats (see e.g. Wolff, 1983; CWSS, 1991; De Jong *et al.*, 1999; Essink *et al.*, 2005; Reise *et al.*, 2010). The Wadden Sea has been on the UNESCO World Heritage List since 2009 in recognition of its unique tidal mudflat ecosystem (CWSS, 2008; UNESCO, 2009). Furthermore, the Wadden Sea performs a key role in protecting the Dutch mainland from flooding due to the wave damping capacity of its row of barrier islands and its tidal flats, banks and salt marshes. Some 227 km of dikes (excluding the 'Afsluitdijk') defend the islands and mainland against flooding by the Wadden Sea. On the northern side of the islands, facing the North Sea, the primary flood defence consists of dunes and sandy beaches which are actively maintained by sand nourishments and dune protection programmes.

Human inhabitants of the Wadden region have a long history of adapting their environment to their needs. The first populations settled on the natural high grounds in this tidal landscape. The salt marshes were used for grazing (by cattle and sheep) and for harvesting hay. The first artificial earth mounds for protection against flooding were raised more than 2,000 years ago (Cools, 1948). Starting in the Middle Ages, these mounds were progressively connected by dikes, leading to the formation of dike rings protecting the hinterland. When sedimentation on the seaward side of these dikes produced new salt marshes, new dikes were built to reclaim these areas for agriculture (for both grazing and arable land). Centuries of land reclamation caused the boundary between land and the Wadden Sea to gradually shift seawards, and natural salt-marsh formation became increasingly difficult. Therefore, from the 17th century onwards at locations with favourable conditions, sedimentation was actively stimulated by digging drainage systems into the mudflats, planting cordgrass (*Spartina anglica*) and, from the 1930s onwards, by placement of brushwood groynes (Dijkema *et al.*, 2001). This process of stimulating accretion and land reclamation by embanking elevated areas continued into the 20th century. Construction of fixed dikes around the elevated marsh area, together with the

closing of parts of the Wadden Sea and the rising sea level resulted in coastal ‘squeezing’ and the decrease of natural salt-marsh area along the fringes of the Wadden Sea dikes.

The interaction of nature and human activity created a unique flat and open landscape of broad horizons and dikes, yet with fields still exhibiting the characteristic patterns of the former salt marsh gullies alongside colonization and reclamation works (Frederiksen, 2012).

Agriculture had traditionally been very important in the Wadden region. However, from the 1970s, recreation and tourism rose in prominence, especially on the Wadden islands (Sijtsma & Werner, 2008; Sijtsma *et al.*, 2012). On the mainland, however, agriculture, as well as fisheries, industry and shipping, emerged as significant economic activities in the Wadden Sea coastal regions (Van Dijk *et al.*, 2009). In order to preserve the unique natural and cultural values of the Wadden Sea landscape and to improve the socio-economic situation in the Wadden Sea region, ambitions were formulated for sustainable, shared human use of the region’s resources (see e.g. Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieu, 2007).

Figure 1.3 shows the present elevation of the Wadden region (varying from 0 m +NAP to some 1.5 m +NAP). Mean high water ranges from 0.66 m +NAP in the western part of the Wadden Sea to 1.33 m +NAP in Eemshaven and 1.65 m +NAP in Nieuw Statenzijl (in the Dollard Estuary).

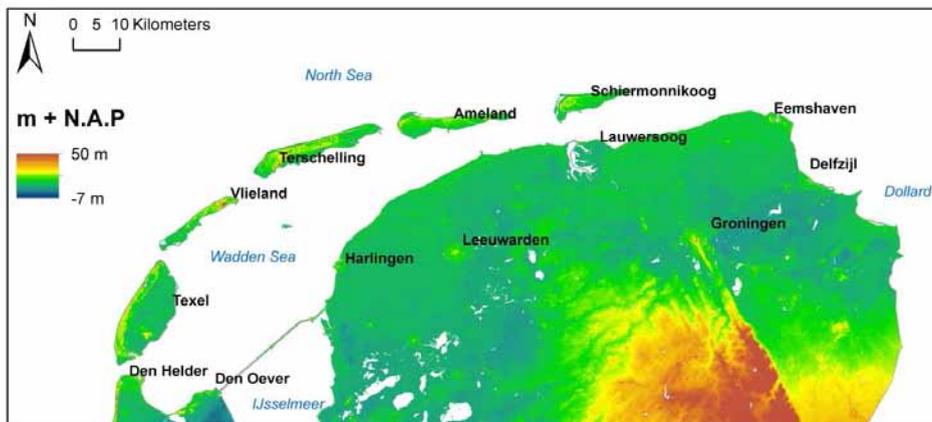


Figure 1.3: Digital Elevation Model of the Wadden region (Source: AHN 2012).

The low elevation and flat character of the Wadden Sea coastal areas make land and infrastructure susceptible to inundation by seawater. The dikes along the Wadden Sea coast

are variously dimensioned to withstand extreme situations with a probable return frequency of once in 4,000 years (mainland coast of Fryslân, Groningen, Wieringen and the coast of Texel), once in 2,000 years (Vlieland, Terschelling, Ameland and Schiermonnikoog) and once in 10,000 years (Noord Holland). Climate change, however, is altering the hydraulic conditions (e.g. surge level, wave height, wind direction) related to these extreme situations. Notwithstanding the various global and regional studies available on the impact of climate change on both sea level and storm climate (severity of storms, wind direction and frequency), there are still many uncertainties about the effects that climate change might have on the Wadden Sea system (Kabat *et al.*, 2009).

At present, nearly half of the dikes along the Wadden Sea do not meet current standards due to problems with grass cover, the stone revetment or with the inner berm (Ministerie van Infrastructuur en Milieu, 2011; Deltaprogramma Waddengebied, 2012). These problems are expected to increase if new boundary conditions are applied that include the foreseen effects of climate change. The current requirement to improve the dikes also offers an opportunity to implement new flood protection designs and ideas.

One of the new ideas that has attracted the attention of the Wadden region Delta Programme is a dike design that includes vegetated forelands (see Van Loon-Steensma *et al.*, 2012a, 2012b). Along the coasts of both the Dutch mainland and the barrier islands, salt marshes are found. These salt marshes have a natural flood-protection potential because they dissipate wave energy (see e.g. Brampton, 1992; King & Lester, 1995; Möller *et al.*, 2001; Costanza *et al.*, 2008; Gedan *et al.*, 2011; Shephard *et al.*, 2011). Reduced wave height and wave energy could have important implications for the required dike dimensions (in particular, dike slope and height) and the need for dike slope and toe protection structures (e.g. hard revetments and rocks). In addition, the presence of salt marshes may have a favourable effect on other aspects of dike design, such as dike (macro)stability and piping (Venema *et al.*, 2012). Furthermore, salt marshes provide characteristic and valuable habitats (see e.g. Adam, 1990) that are protected by national and international legislation such as the European Habitats Directive (Council of the European Communities, 1992). One of the explicit aims of the international Natura 2000 network is to conserve the areal extent of salt marshes in the Wadden region including all succession stages and salt-to-freshwater transition regimes (Ministerie van Economische Zaken Landbouw & Innovatie, 2011; Ministerie van Volkshuisvesting Ruimtelijke Ordening & Milieu, 2007). Other Natura 2000 ambitions are to increase the variety of geomorphological forms and substrates of salt marshes and to optimize management. Beyond EU-level conservation efforts, there is a trilateral agreement between Denmark, Germany and the Netherlands to increase the area of natural salt marshes, to

enhance natural morphological and dynamic processes in the Wadden Sea region, to enrich the natural vegetation structure of artificial salt marshes, and to improve conditions for wading birds (CWSS, 1998, 2010).

The existing salt marshes along the mainland coast of the northernmost Dutch provinces of Groningen and Fryslân are the result of constructed accretion works (e.g. brushwood groynes, drainage pattern by ditches, dams of clay). These works were originally designed for reclamation of agricultural land, but the goal progressively shifted to nature conservation from the 1970s onwards (Dijkema *et al.*, 2001; De Jonge & De Jong, 2002). Without these accretion works, the total area of the semi-natural salt marshes along the embanked mainland coast would be much smaller than it is today. Salt marshes on the barrier islands developed from the deposition of silt on top of sandy layers on the lee side of sand dunes (Olf *et al.*, 1997).

1.4 Objectives and research questions

To identify the best means to ensure long-term flood protection and preserve the nature and landscape qualities of the Wadden region, insights are needed into the benefits, costs and trade-offs involved in the various innovative dike designs presented in recent years. However, these benefits, costs and trade-offs also depend on site-specific physical and societal constraints as well as opportunities.

This thesis investigates if and how the same or an even higher level of safety can be achieved in the Wadden region by means of creating a flood defence zone that favours, besides flood protection, nature and landscape values, heritage, recreational, or even economic values. While several available innovative flood defences are considered, special attention is given to the role of salt marshes in this context.

Towards this general aim, five main research questions have been formulated as follows:

1. What innovative flood defence concepts hold promise for the Wadden region in the context of rising sea level?
2. What locations in the Wadden region appear promising for salt marshes?
3. How do vegetated forelands, like salt marshes, contribute to flood protection?
4. What is the potential ecological value of a restored salt-marsh foreland?
5. What are the prospects for salt-marsh protection and restoration in the Wadden region?

These questions are investigated in this thesis (see Figure 1.4 for the thesis outline and the relation between the chapters and the research questions (RQ)).

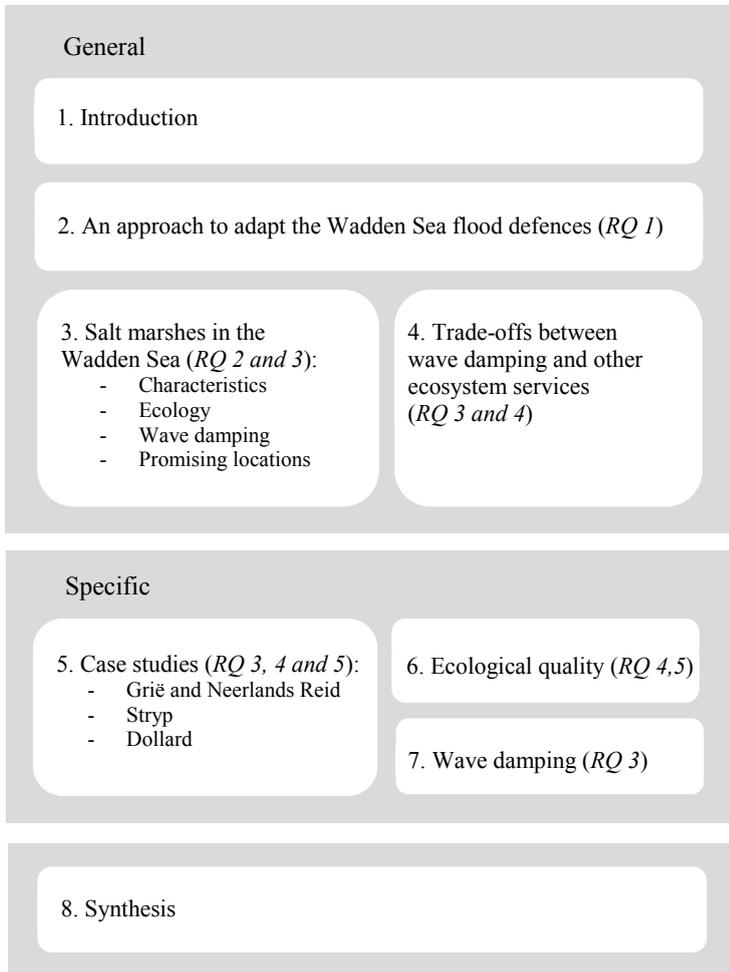


Figure 1.4: Thesis outline. Chapters 1-4 present general information on the task to find a long-term adaptation strategy for the Wadden region that preserve or even strengthen the important nature and landscape qualities of the Wadden Sea. Chapters 5-7 present more specific information based on case studies. RQ means Research Question.

Chapter 2 is based on explorative studies commissioned by the Delta Programme Wadden region and is published as an article in the journal of Environmental Science & Policy:

- Van Loon-Steensma, J.M., Schelfhout, H.A., Eernink, N.M.L. & Paulissen, M.P.C.P., 2012. Verkenning Innovatieve Dijken in het Waddengebied; Een verkenning naar mogelijkheden voor innovatieve dijken in het Waddengebied. Wageningen: Alterra (Alterra rapport 2294).
- Van Loon-Steensma, J.M. & Schelfhout, H.A., 2013. Gevoeligheidsanalyse innovatieve dijken Waddengebied; Een verkenning naar de meest kansrijke dijkconcepten voor de Waddenkust. Wageningen: Alterra (Alterra rapport 2483).
- Van Loon-Steensma, J.M., Schelfhout, H.A. & Vellinga, P., 2014. Green adaptation by innovative dike concepts along the Dutch Wadden Sea coast. Environmental Science & Policy 44: 108-125.

2

Green adaptation by innovative dike concepts along the Dutch Wadden Sea coast; A systematic design and evaluation of innovative dike concepts

This chapter describes the development and application of an approach to adapt the flood defences along the Dutch Wadden Sea coast to the foreseen effects of climate change and related uncertainties. The approach takes both nature and landscape values of the internationally protected Wadden Sea into account. It consists of the development of a dike-portfolio with traditional as well as new flood protection concepts and a subsequent evaluation of these concepts by means of a multi-criteria analysis by local experts. The objective is to identify realistic adaptation options that use or enable natural processes to strengthen ecological resilience in the area and facilitate sustainable human use. However, to identify the most appropriate concept from the suitable options, a thorough analysis is required. Such an analysis needs detailed site-specific information on many aspects, including location specific plans and ambitions.

Lessons learned:

- A carefully designed portfolio of both traditional and innovative dike concepts proves to be invaluable to find adequate adaptation options in practice.
- The ambition to integrate nature and landscape values and natural processes in a long-term flood protection strategy opened a window for innovation in flood protection along the Dutch Wadden Sea coast.
- Local characteristics determine the potential for innovative flood defences.
- Multifunctional dikes are robust and offer space for other functions and values. However, their performance in an integral assessment strongly depends on the applied functions and the weight per evaluation criterion.
- A long-term flood protection strategy that integrates nature with an engineered solution appears especially attractive at locations with salt marshes adjacent to the dike present.
- Eco-engineering concepts can potentially contribute to nature and landscape values, but implementation may lead to tension with nature legislation.

2.1 Introduction

In the last decade, concern about the effects of climate change (IPCC, 2007) triggered extensive research efforts to understand and predict the impacts of climate change and to develop methods to adapt to the foreseen effects (e.g. Thames 2100 in the UK, the Climate changes Spatial Planning Programme and the Knowledge for Climate Programme in the Netherlands, KLIMZUG in Germany, EU FP6 and FP7 programmes). With the addition of adaptation to (inter)national as well as local political agendas, a growing demand for methods and tools did arise among decision makers to help them respond to climate change impacts and to opportunities for adaptation. In the Netherlands such methods and tools are currently both explored and applied in the Delta Programme, aimed at developing a long-term flood protection strategy for the Wadden region while taking nature and landscape values into consideration (Delta Commissioner, 2010; Delta Programma Waddengebied, 2011).

At present, the northern part of the Netherlands is protected against flooding from the Wadden Sea by some 227 km of dikes (excluding the ‘*Afsluitdijk*’). In general, these sea dikes comprise a soil construction consisting of a sand core, an outer protection layer of clay and grass or stones and asphalt, a toe protection and a maintenance road. These ‘Traditional dikes’ along the Wadden Sea coast are sloped at an average gradient of approximately 1:5 at the seaward side and of approximately 1:3 at the landward side, sometimes with an additional stability berm or piping berm. They are designed to withstand extreme storm surges with probabilities of 1/2,000 up to 1/10,000 per year, with the crest of the dike well above the extreme storm surge level and expected wave run-up. Climate change, however, will result in changing boundary conditions. In view of that, the effects of accelerated sea level rise due to climate change on boundary conditions and design requirements were explored (Calderon & Smale, 2013). As a result of this study, the question arose whether reinforcing of these Traditional dikes could continue to provide adequate safety in a changing climate, or should there be a search for new innovative flood protection concepts. The governmental organisation Delta Programme Wadden region prioritized ‘Innovative dikes’ as a strategy for closer study (Delta Programma Waddengebied, 2011). Such Innovative dike concepts have an alternative design that does meet all criteria to withstand extreme conditions in the current climate (like Traditional dikes), but may in addition be more robust to extreme conditions in a future climate, may enhance nature or landscape values, may offer new opportunities for combining functions, may be cheaper than traditional reinforcements, and/or may provide new socio-economic opportunities for the Wadden region (Van Loon-Steensma *et al.*, 2012b).

Following this prioritization, several explorative studies have been conducted to examine the adaptation potential of the present dikes, and to search for new designs aimed at long-term solutions (e.g. Van Loon-Steensma *et al.*, 2012b, Van Loon-Steensma & Schelfhout, 2013a).

The search for new dike concepts and the evaluation of the suitability of these concepts is challenging due to the many relevant criteria besides flood protection, which are partially embedded into the spatial and temporal context of land-use planning and political decision making. In spite of the general (and partially quite abstract) theory that is available in support of multiple criteria analysis in landscape planning and infrastructural design (e.g. Beinart & Nijkamp, 1998; Gregory *et al.*, 2012) and the elaborated guidelines for traditional dike reinforcement in the Netherlands (e.g. Rijkswaterstaat, 2007), there is so far not much experience with the application of a template which facilitates the design and in particular the evaluation of a comprehensive set of innovative solutions in a delta with a long history of flood protection like the Netherlands. For the Dutch urban riverine area, however, a web-based decision support tool was developed by Stalenberg (2010), which contains a number of urban types of riverfronts (like a road, a quay wall and some other flood retaining structures), in order to let flood controllers and urban planners work more closely together in the conceptual design cycle.

Furthermore, there is a pending dike reinforcement task. A recent assessment showed that almost 50% of the dikes along the Wadden Sea do not fully meet current flood safety criteria, mainly due to problems with the grass cover or stone revetment (Smale & Hoonhout, 2012). On top of that, the reference hydraulic boundary conditions are being reviewed, with the likely outcome that they will be more severe than the present ones, thus requiring additional reinforcements. This offers a chance to connect the long-term flood protection strategy with the short-term reinforcement task.

This chapter describes the development and application of an approach to adapt the flood defences along the Dutch Wadden Sea coast, taking into account both nature and landscape values of the internationally protected Wadden Sea. The approach consists of a systematic design of new flood protection concepts for the Wadden Sea coast and an evaluation of these concepts by means of a multi-criteria analysis by local experts. The objective of the study is three-fold. Firstly, it identifies realistic adaptation options for the Wadden region that use or enable natural processes to strengthen ecological resilience in the Wadden Sea area and facilitate sustainable human use. Secondly, it provides a comprehensive portfolio of dike concepts. And thirdly, it describes a realistic and practical approach that may be useful for

coastal areas elsewhere in the world where flood protection schemes need to be reconsidered in view of rising seas and subsiding land.

2.1 Methods

General workflow of the approach to adapt flood defences

The general sequence of tasks for adaptation of flood defences we applied was as follows (see Figure 2.1). First a portfolio of existing and innovative dike concepts was made (*step 1*). This task was conducted by a small interdisciplinary team of experienced experts from research institutes. Next, the performance of all innovative concepts was qualitatively assessed by dike-experts from local water boards (*step 2*). This assessment comprised an integral and rapid appraisal, based on evaluation criteria for adaptation strategies provided by the national Delta Programme (Lamberigts *et al.*, 2012). The performance in an integral assessment strongly depends on the weight per evaluation criterion. In our study all criteria had the same weight. For a differentiation in weights between the criteria, it is necessary to take policy objectives into account and to involve stakeholders, activities which form a follow-up to this study. Following that, for the locations where these experts were knowledgeable, the Wadden Sea dike was divided in homogeneous dike-sections based on current local dike, land use and landscape characteristics (*step 3*). Next, the most appropriate concepts were selected based on site-specific physical and ecological boundary conditions as well as on tasks and ambitions for the region (*step 4*).

Study area

The Wadden Sea is an intertidal zone in the south-eastern part of the North Sea. It lies between the coast of north-western continental Europe and a range of barrier islands, forming a shallow body of water with tidal flats and salt marshes (Figure 2.2). These barrier islands, tidal flats and salt marshes dampen incoming waves. The northern provinces of the Netherlands are protected against flooding from the Wadden Sea by some 166 km dikes along the mainland coast and some 61 km dikes along the coast of the islands (and the ‘*Afsluitdijk*’). Their safety level is set by an anticipated extreme water level with a defined return period, which is called the safety standard (see Figure 2.2). The Wadden islands are protected against flooding from the North Sea by natural sand dunes. Similar coastal systems with similar flood protection challenges can be found elsewhere in the world.

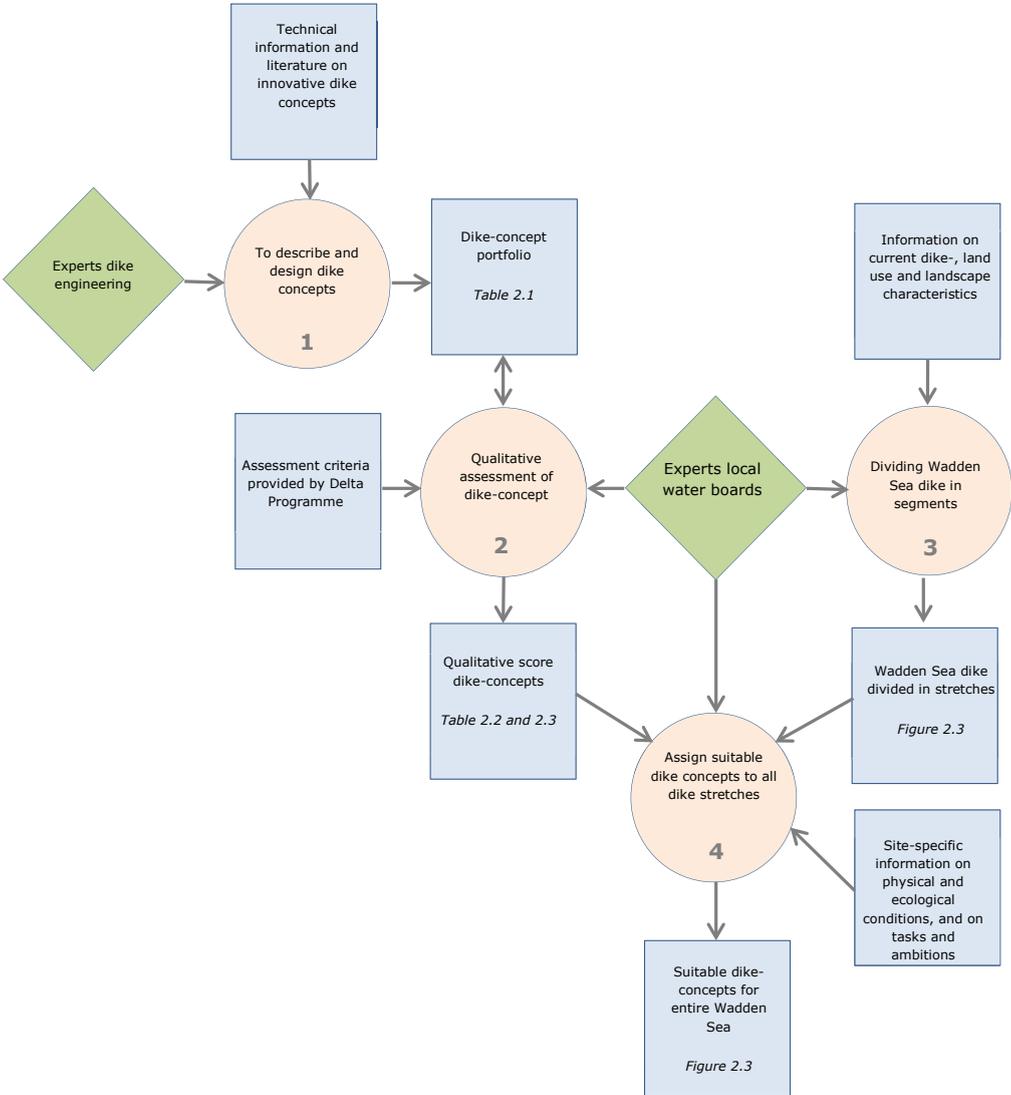


Figure 2.1: Flow chart of the four-step process to identify suitable innovative dike-concepts. Diamonds represent input from experts, squares represent available information and (intermediate) results, and circles represent activities.

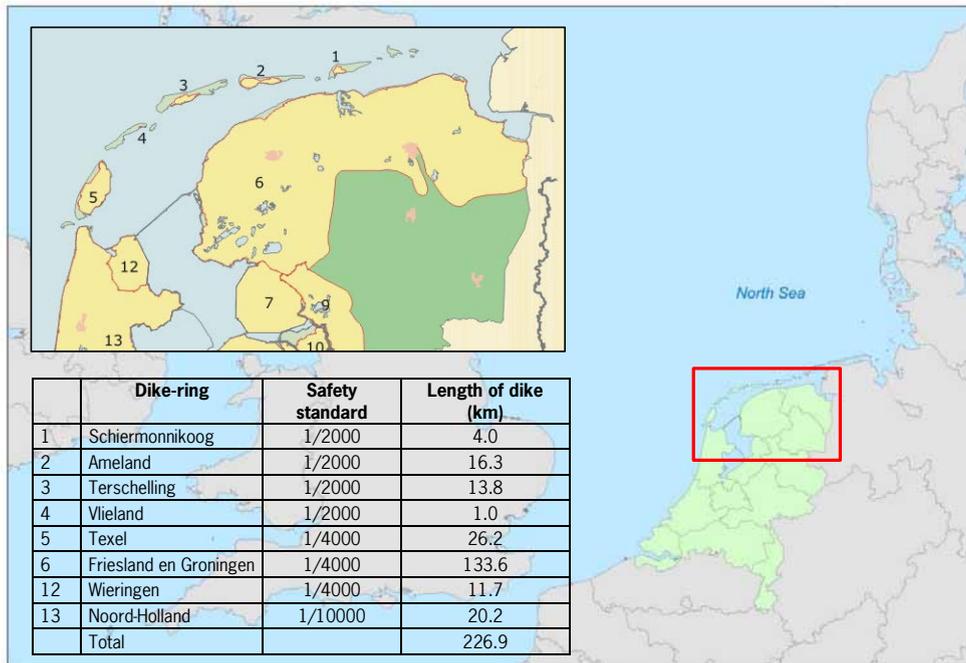


Figure 2.2: Dike-rings in the Dutch Wadden region with safety standard and dike length (km).

The dikes are maintained by four regional water boards (‘Waterschap Hunze en Aa’s’, ‘Waterschap Noorderzijlvest’, ‘Wetterskip Fryslân’ and ‘Hoogheemraadschap Hollands Noorderkwartier’). Because of land reclamation activities, several of the dikes along the mainland have shifted seaward during the past centuries. In many locations the history of land reclamation by ‘*inpoldering*’ of salt marshes by dikes is still visible in the Wadden coastal landscape. Salt marshes are present along several coastal stretches of both the Netherlands’ mainland and the Wadden Sea barrier islands. Most of these marshes are the result of accretion works. These works were originally designed for reclamation of agricultural land, but the goal progressively shifted towards nature conservation from the 1970s onward (Dijkema *et al.*, 2001; De Jonge & De Jong, 2002).

The low-lying fertile hinterland is open and mostly used for arable as well as dairy farming. Furthermore, there are some regional harbours (recreational, industrial and for the ferry boats to the Wadden islands) and industrial areas. The Wadden Sea is rich in biological diversity and subject to the EU Habitat directive and EU Wild Birds directive and formally designated as Natura 2000 area (Ministerie van Economische Zaken, Landbouw & Innovatie, 2011). In

2009, the Dutch and German parts of the Wadden Sea were appointed as a UNESCO World Heritage site.

Dike-portfolio (Step 1 in Figure 2.1)

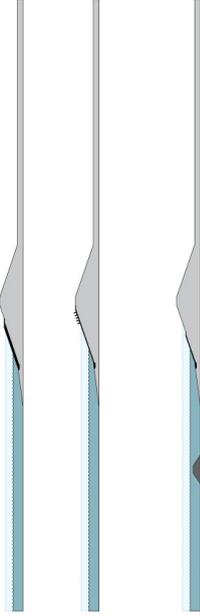
The study was started by making an overview of existing and of potentially applicable dike concepts found in scientific literature and in national research institutes' research and engineering papers (mainly grey literature). The basic function of a sea dike (also called embankment, dyke or levee) is to reduce the risk of inundation of the protected area. Therefore, the dikes must meet the requirements and criteria of a number of failure mechanisms, such as overflowing, external erosion, internal erosion and instability (TAW, 1998). Traditional dikes in the Wadden region are designed to prevent breaching and overflowing and to minimize wave overtopping (which may lead to erosion of the crest and of the landward slope) due to wave run-up and to resist wave action (which may lead to erosion of the seaward slope). Therefore, the crest height must be above the defined extreme water level and a certain amount of wave overtopping discharge (for the clay and grass covered dikes along the Wadden Sea coast defined as 0.001 m^3 per second per meter). The allowable amount of wave overtopping depends on the strength of the revetment on the crest and landside slope and on the allowable water hazard in the hinterland. Furthermore, the landward slope must be stable under overtopping, and the subsoil should provide sufficient stability (to prevent sliding at the landward or seaward side). The slope stability must meet the required stability factor, which is related to the safety standard. The resistance in the subsoil depends on the buildup of the layers of soil and is also influenced by the high water level. Furthermore, under-seepage with transport of soil particles (piping) must be prevented.

Innovative dike concepts, which have an alternative design, will have to meet these criteria as well.

All dike concepts were categorised based on their cross section profile and their flood protection principle resulting in a portfolio of possible dike concepts. The portfolio consists of a set of Traditional dike concepts, series A and a set of Innovative dike concepts, series B (Table 2.1).

Although the Wadden Sea barrier islands and the sand and mudflats in the Wadden Sea intertidal zone are very important in flood protection of the Wadden region by their wave damping capacity, we did not include them in our overview of dike concepts. Their influence on the water level and wave conditions is fully accounted for in the computation of the hydraulic boundary conditions applied for the flood safety assessment of the mainland dikes.

Table 2.1 Portfolio of all dike concepts (henceforth denoted by 'dike-portfolio') that were identified or in some cases specially developed, series A and B.

A. Traditional dike concepts	
A1. Standard dike	<p>Traditional dikes are designed to prevent flooding (overflow) and wave overtopping (erosion landward slope) and to resist wave action (erosion of the seaward slope). Therefore, the crest height must be above the agreed extreme water level and overtopping discharge due to wave-run-up. Furthermore, the design must moderate wave run-up. The allowable amount of wave overtopping discharge depends on the strength of the revetment on the crest and landward slope and on the allowable water hazard in the hinterland. Furthermore, the inner slope must be stable under overtopping, and the subsoil should provide sufficient stability (<i>shearing, and sliding landward and seaward slope</i>). The slope stability must meet the required stability factor, which is related to the safety standard. The resistance in the subsoil depends on the buildup of the layers of soil and is also influenced by the water level. Furthermore, waterflow underneath the dike with transport of soil particles (<i>pipng</i>) must be prevented (Ministerie van Verkeer & Waterstaat, 2007).</p> 
A2. Dike with wave reducing elements	<p>The wave attack, wave run-up and wave overtopping of a sea dike can be influenced by means of the application of wave reducing elements on the seaward slope.</p> <p>A2.a Storm surge berm Reducing wave run-up and wave overtopping up to 60% by a berm at the seaward side. The maximum effect can be realized with a berm height at the design water level and a width of 5 times the design wave height (Pullen <i>et al.</i>, 2007).</p> <p>A2.b Revetment with elevated elements Reducing wave run-up and overtopping height (up to 75%) by blocks or ribs on the slope, or by the roughness of the armour rock (Pullen <i>et al.</i>, 2007).</p> <p>A2.c Detached breakwater Detached breakwaters, groynes or jetties can reduce the wave action on the dike by reducing wave heights. This reduction depends on the height of the breakwater with respect to the design water level and the strength of the construction.</p> 
A3. Dike with screens	<p>Traditional dike with vertical elements to improve the stability or the resistance against piping. An additional possibility is to use the screen as a functional division between the water retaining and other functions.</p>

A3.a Cut-off sheetpile wall

A special water retaining construction, consisting of two separate sheetpiles, connected with horizontal anchors above the design water level. This type of construction requires less space than a traditional dike and offers more possibilities for other functions.



A3.b Diaphragm wall

A reinforced concrete screen in the landward or seaward crestline for improvement of the stability of the dike.



A3.c Stability screen

A sheetpile in or near the dike instead of a stability berm (at the landward or the seaward side) can improve the stability of the dike. This can be done with or without anchors. This solution requires less space than application of a stability berm of soil.



Piping screen

A screens of steel or bentonite to increase the seepage length. This solution requires less space than the application of a piping berm of soil.



A4. Standard dike with innovative elements

A dike with a traditional profile but with new revetment types to create better conditions for nature or landscape or with new techniques or materials to improve the stability of the dike.

A4.a Dike with nature friendly revetment

A dike with a revetment at the seaward side that aims to create variable habitats in the intertidal and subtidal zone of dikes and foreshores while maintaining safety levels by utilizing a variety of different materials, gradients and shapes to create differences in height, refuges in a variation of environments with different exposure levels to currents and waves (Borsje *et al.*, 2011).



A4.b Mixed-In-Place

Improved stability by columns of soil mixed with cement.



Dike nailing

Improved stability by reinforced soil with steel or plastic nails.



Expanding Columns

Improved stability by a rod with expanding grout anchors.



A.5 Hard engineering concepts

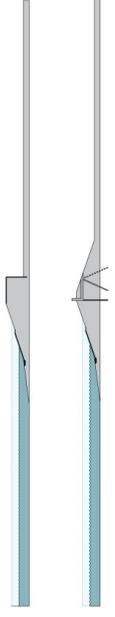
Structures that can independently fulfill the water retaining function.

A5.a Quay wall (seaward)

The quay wall can be projected at the waterside or landside, depending on other functions near the flood defence.



A5.b Wall (landward)



Compact massive or concrete structures founded in the soil or on piles (e.g. floodwalls).

A5.c Structures

B. Innovative dike concepts

B1. Overtopping resistant dike

Dike with a revetment designed to withstand a predetermined higher amount of overtopping discharge than a Traditional dike. Stone and asphalt are more overtopping resistant than grass, but do not contribute to the spatial quality. The area behind the dike has to be prepared for occasional flooding by drainage ditches, pumps, megarounds, or by a more landward second dike. Overtopping of a sea dike will lead to some damage in the hinterland, but can also turn out positive for salt-tolerant agriculture or for salty habitats (Van Loon-Steensma *et al.*, 2014a).



B2. Robust concepts

In our study robustness is defined as 10 times safer than a Traditional dike with a time horizon of 100 years for the hydraulic boundary conditions.

B2.a Delta dike

A dike with a negligible probability of failure due to sudden or uncontrollable failure (Deltacommissie, 2008). Enhanced safety can be achieved by extra heightening or broadening of the dike by enlarging the landward berm.



B2.b Multifunctional dike

Combines other functions with the primary function of flood protection. In practice, incorporation of multiple functions requires over-dimensioning (because it may hinder future adjustments) and may thereby help to create a robust dike (see e.g. Van Loon-Steensma & Vellinga, 2014). Functions like nature or buildings may fit very well in rural respectively urban area, while this is not necessarily the case for wind turbines. Other functions may not adversely affect the flood protection function, management or maintenance.

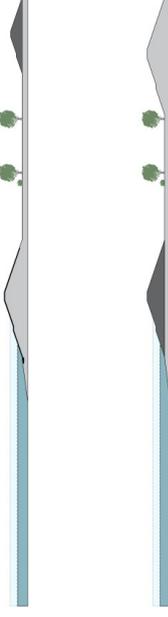


B3. Multiple lines of defence

The required safety standard of the hinterland is met by the application of multiple lines of dikes.

B3.a Parallel dike landward

A secondary dike landward of the primary dike. This extra dike reduces the probability of flooding of the hinterland. In some parts of the Wadden region historical dikes are found parallel along the coast (originating from historic land reclamation of salt marshes). The most seaward dike has to be resistant to overtopping. Overtopping can lead to some damage in the enclosed area, but can also turn out positive for salt-tolerant agriculture or salty habitats (Van Loon-Steensma *et al.*, 2014a).



B3.b Parallel dike seaward

An extra dike seaward of the primary dike. This foreland dike reduces the hydraulic loads on the primary dike.



B4. Hybrid solutions

This concept consists of a combination of a hard and soft engineering solution. For instance, a gently sloping foreshore adjacent to the dike reduces the wave attack.

B4.a Dike integrated into dunes

The dike with a hard revetment is covered with sand and looks like a dune. This solution needs less space than dunes, and may be attractive in urban areas where buildings are adjacent to dunes and the beach.



B4.b Dike integrated into boulevard

The hard flood defence is covered by sand and a boulevard, which results in a strong connection between urban area and the coast. Buildings on the boulevard may hinder future adjustments (so the flood defence has to be over-dimensioned).



B4.c Dike with an artificial foreshore (also called 'foreshore dike')

Dike with an artificial soft foreshore of clay or sand instead of a hard revetment. Such a vegetated foreshore may result in reduced requirements concerning the height and/or revetment of the dike.



B5. Eco-engineering

Dikes combined with intentional use of ecosystems and natural processes for flood protection.

B5.a Salt marshes adjacent to the dike

A dike with a foreshore of salt marshes. These salt marshes dampen incoming waves. Their wave damping capacity depends on both height and width of the salt-marsh zone. Under condition of abundant sediment they can keep pace with sea-level rise. The salt marshes harbour important nature values as well (Van Loon-Steensma *et al.*, 2012a).



B5.b Salt-marshes and berm at seaward slope

A dike with a foreshore and a berm on the seaward slope, meant to absorb potential erosion during extreme conditions (Lammers, 2009).



B5.c Wide green dike

A dike with a shallow sloped (some 1:7) grass covered seaward face that merges into the adjacent salt marshes. Normally, incoming waves are dampened by the foreland. Only during storm conditions waves will reach the dike. Sedimentation in the salt marshes may supply the clay needed for such a broad dike. The grass cover (on a thick clay cover) needs regular maintenance, and debris has to be removed after storms (see e.g. Van Loon-Steensma & Schelfhout, 2013a).



B5.d Breakwater of oyster/mussel reefs

A reef of oysters or mussels seaward of the dike that reduces the wave attack. Furthermore, such a reef can capture sediment which will contribute to stabilization of the coastal fundamnt. There are experiments to stimulate the growth of oyster reefs by placing baskets with oysters on desired locations (see Borsje *et al.*, 2011).



B6. Dynamic preservation

Preservation of the coastline by the supply of sand on the foreshore that will be transported and redistributed by natural coastal processes (currents and wind).

B6.a Sediment nourishment

Location specific (limited) sediment nourishment (sand or dredging material) to increase the dimensions of the intertidal and tidal zone to absorb future erosion in order to maintain the coastline.



B6.b Sand-engine

Coastal maintenance by mega nourishment of sand just out from the coast concentrated in space and time. The sand will be gradually redistributed by waves, currents and wind in some decades (see Fiselier, 2011).



B7. Integrated hard solutions

The integration of buildings in the dike saves space, and may have a positive effect on the spatial quality of the urban area.



Potential additional value of innovative dike concepts (Step 2 in Figure 2.1)

The performance of all Innovative dike concepts was qualitatively assessed in cooperation with 8 experts from the local water boards (all involved in the Dutch Flood Protection Programme, *Hoogwater Beschermings Programma* (HWBP)). This assessment was based on evaluation criteria for adaptation strategies provided by the national Delta Programme (Lamberigts *et al.*, 2012), which consist of five main criteria: safety against flooding, fresh water supply, effects on and opportunities for other functions and values, feasibility, and financial aspects. The five main criteria are sub-divided in 33 sub-criteria. We did not include the criterion fresh water supply in our assessment, because in practice this is not relevant for dikes along the Wadden Sea coast. Furthermore, assessing the risk of fatalities was beyond the scope of our study, because this requires an assessment on the level of the entire dike-ring. We included the sea side area directly in front of the dike in the assessment because some concepts will affect this area.

Although site specific characteristics will determine the real potential of each concept, we assessed the innovative concepts on the scale of the entire Wadden region. We compared the foreseen effects of each concept with a reference situation and qualitatively ranked the differences on a five-point scale, varying from strongly negative effects (--), via negative effects (-), no effects (0), to positive effects (+) and strongly positive effects (++) in order to find suitable dike concepts among the potential available options. The Standard dike formed the reference situation. All concepts were designed such that these met at least the legally established safety standards. However, this did result in different dimensions for each concept (both in crest height and in footprint), and subsequently in different effects on their environment.

Next, a criterion function was defined, to aid in combining the multiple criteria per dike concept. The chosen criterion function translated the ordinal scale into a linear range centered around zero.

$$T_k = \sum_j w_{j,k} \quad (1)$$

$$T = \sum_k v_k T_k \quad (2)$$

$$R = \max_k(T_k) - \min_k(T_k) \quad (3)$$

Where T_k is the total score per dike concept with regard to the assessed main criteria k ($k=1$ represents safety against flooding, $k=2$: effects on and chances for other functions and values, $k=3$: feasibility, and $k=4$: financial aspects); $w_{j,k}$ is the value for each sub-criterion j within

each main criterion k . $w_{j,k}$ can take the values $-2, -1, 0, 1$ or 2 in this study. Indices for indicating the different dike concepts are omitted for compactness.

A total score for each dike concept (T) is calculated by a weighted sum (with weights v_k) over the 4 main criteria (equation 2). Obviously, the performance of the alternatives strongly depends on the weights v_k for each criterion. In this study the weights v_k were chosen to be 1 (hence no differences for the different criteria). The range over the scores for the main criteria (R) is calculated to assess the robustness of a concept in the decision process, when the main criteria might receive different weights.

Segmentation of dikes along the Wadden Sea coast (step 3 in Figure 2.1)

With regard to the relevant current dike properties, as well as land-use and landscape features, the dikes along the entire Dutch Wadden coast have been segmented by the experts into stretches that were considered as suitable units for innovative dike concepts (quantitative and detailed information about dike segments is generally available at Dutch water authorities). The ‘*Afsluitdijk*’, a barrier dam which separated the former ‘Zuyder Zee’ from the Wadden Sea in 1932, was not included.

Suitability of innovative dike concepts along the Wadden Sea coast (step 4 in Figure 2.1)

Suitable concepts were selected based on site-specific physical and ecological boundary conditions as well as on tasks and ambitions for the region (as far as known by the experts). Additional to expert knowledge, maps on topography, population density, habitats, nature reserves, land use and soil characteristics were used in support of this activity (see Van Loon-Steensma & Schelfhout, 2013a). It was assumed that reinforcement of the present dikes in the Wadden region (the Standard dike in the rural area) forms the ‘business as usual’ solution to adapt the present dikes in the Wadden region to the required standards.

2.3 Results

The scores on the sub-criteria for all dike concepts, as generated by the experts in the appraisal, forms the central result in the evaluation process that we describe here. The Standard dike formed the Reference in the assessment. The entire set of scores is given in Table 2.2. With regard to the four main evaluation criteria, the following results become apparent in this overview.

Table 2.2: Qualitative scores of all Traditional and Innovative dike concepts on the Delta Programme assessment criteria (with the Standard dike as Reference).

A. Traditional dike concepts				B. Innovative dike concepts																								
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7																	
Reference	Dike with wave damping elements	Dike with screens	Dike with innovative elements	Hard engineering	Over-topping resistant	Robust dike concepts	Multiple lines of defences	Hybrid dike concepts	Eco-engineering concepts	Dynamic preservation	Int. hard solutions																	
	A2.c	A4.a	A4.b		B2a	B2b	B3a	B3b	B4a	B4b	B4c	B5a	B5b	B5c	B5d	B6a	B6b											
	Dike with breakwater	Dike with groyne	Dike with nature friendly revetment	Dike with new techniques/materials	Delta dike	Multifunctional dike	Extra dike landward	Extra dike seaward	Dike integrated into dunes	Dike integrated into boulevard	Dike with artificial foreshore	Dike with adjacent salt marsh	Dike with salt marsh and berm	Wide green dike	Dike with oyster/mussel reefs	Sediment nourishment	Sand engine	Integrated hard solutions										
Safety against flooding	0	0	0	0	0	+	0	0	0	0	0	0	0	0	0	0	0	0										
Probability of flooding (dike breaching/disaster)	0	0	0	0	0	+	0	0	0	0	0	0	0	0	0	0	0	0										
Casualties (in hinterland)	0	0	0	0	0	+	0	0	0	0	0	0	0	0	0	0	0	0										
Damage (in hinterland)	0	0	0	0	0	+	0	0	0	0	0	0	0	0	0	0	0	0										
Risk of casualties	0	0	0	0	0	+	0	0	0	0	0	0	0	0	0	0	0	0										
Risk of casualties	0	0	0	0	0	+	0	0	0	0	0	0	0	0	0	0	0	0										
Supply of fresh water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Effects on and opportunities for other functions and values	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
International competitiveness	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Opportunities for local businesses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Effect on livability in urban areas (including villages)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Spacial quality (additional values)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Agriculture	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Fishery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Industry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Shipping	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Maritime	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Heritors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Recreation and tourism (both on land and w/ water)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Nature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Feasibility	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Risks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Opportunities to link with other programs or ambitions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Acceptability	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Financial aspects	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Investment costs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Costs for management, maintenance and operation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Costs for management, maintenance and operation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
Possibilities for co-funding	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										

0 no effects (compared to reference situation)
 ++ Strong positive effect (compared to reference situation)
 + Positive effects (compared to reference situation)
 - Negative effects (compared to reference situation)
 -- Strong negative effects (compared to reference situation)
 +/- Potential effect depends on location specific conditions
 0+/- Location specific strong positive or negative effects

Protection against flooding

All dike concepts are obligatory dimensioned to meet the legal safety standards and thus do not differ from the reference concept with respect to this criterion. Only the Robust concepts (the Delta dike (B2.a) in the dike-portfolio and the Multifunctional dike (B2.b)) will reduce the inundation risk because they are over-dimensioned by definition (see van Loon-Steensma & Vellinga, 2014). Concepts that allow overtopping may lead to occasional damage/nuisance (B1 and B3). A breakwater in front of the dike (A1.b) or a groyne can cushion the impact of waves on the area outside the dike.

Effects on and opportunities for other functions and values

Almost all concepts will lead to additional effects on and opportunities for other functions and values. However, the effects of each dike concept depend on the characteristics of the location and may be positive or negative. For example, the integration of structures is attractive in modern urban areas but less so in sites with historical values. Furthermore, the effect of the Multifunctional dike (B2.b), which offers literally space for other functions and values, strongly depends on the performed functions. A Multifunctional dike which combines flood protection with wind energy does not contribute to the spatial quality of the Wadden area, while a dike which combines flood protection with agriculture or nature fits perfectly in the rural landscape. Implementation of over-dimensioned concepts (B2) cost more energy than tailored solutions, but when combined with wind turbines or innovative hydro-power installations these dike concepts may also produce energy. Therefore, the score of a Multifunctional dike on the criterion 'effects on and opportunities for other functions and values' varies from modest to strong positive effects. Besides the Multifunctional dike, also Eco-engineering concepts (B5) were assessed positive because of their presumed positive contribution to nature and to the spatial quality of the area, which favours recreation and tourism. On top of that, the use of natural processes makes them energy-friendly.

Feasibility

Both Robust concepts (B2) are considered to be non-risky because their over-dimensioning prevents short-term reinforcement and the landward extension of their footprint does not conflict with nature legislation. The seaward extension of the footprint of the Eco-engineering (B5), Dynamic preservation (B6) and most Hybrid solutions (B4) on the other hand, will affect the protected Wadden Sea habitats. The long lifetime of functions like housing and transport hamper the adaptability of Multifunctional dikes. This also applies for hard

engineering concepts. Sediment-based concepts, such as Eco-engineering and Dynamic preservative solutions, on the contrary, are very adaptable.

Financial aspects

Initial investment costs of most concepts are higher than the investment costs of the Standard dike. Because of their over-dimensioning, the Delta dike and the Multifunctional dike are the most expensive to construct, but they need less maintenance. Eco-engineering solutions appear attractive in view of investment costs (because of the use of natural processes), but require substantial monitoring and maintenance to guarantee their flood protective capacity during extreme events (see Van Loon-Steensma & Vellinga, 2013).

Overall summary of the additional value of innovative dike concepts

Table 2.3 shows the scores per assessed criterion (T1 to T4) as well as the overall score (T) and the range over the scores (R). It illustrates that especially the criteria ‘safety against flooding’ and ‘effects on and opportunities for other functions and values’ are distinctive. Dependent on the applied functions, a Multifunctional dike has a good performance on both criteria, and Eco-engineering concepts perform well on the criterion ‘effects on and opportunities for other functions and values’. Although both concepts were not negatively evaluated for any of the criteria, the broad range in their score indicates that in a decision process the actual weight that might be placed on different criteria will strongly determine their total score and hence the ultimate choice for a dike concept to be implemented.

Table 2.3: Scores of the innovative dike concepts on the main Delta Programme assessment criteria (highest score in bold). The scores are an aggregation of the scores on the sub-criteria by 8 local water board experts (Table 2.2) using equations 1 to 3. If the score for the main criterion (T) depends on applied functions or environmental factors, a score-range is given for that criterion. The Range (R) is the maximum summed score on the main criteria minus the minimum summed score on the main criteria (equation 3), and gives an impression of the robustness of the concerned dike concept. See section 2.2 for details of the calculations underlying the values in this table.

		Safety against flooding (T1)	Effects on and chances for other functions and values (T2)	Feasibility (T3)	Financial aspects (T4)	Total Score (T)	Range over the scores for the main criteria (R)
A. Traditional dike concepts							
Reference	A1. Standard dike	0	0	0	0	0	0
A2. Dike with wave reducing elements	A2.c With attached breakwater	1	0	0	0	1	1
	A2.c With groyne	1	1	0	0	2	1
A3. Dike with screens		0	0 to 2	-2	0	-2 to 0	4
A4. Dike with innovative elements	A4.a Nature friendly revetment	0	3	0	-1	2	4
	A4.b With new techniques/materials	0	0	0	-1	-1	1
A5. Hard engineering		0	0 to 2	-2	1	-1 to 1	5
B. Innovative dike concepts							
B1. Overtopping resistant		-1	-1	-1	0	-3	1
B2. Robust concepts	B2.a Delta dike	5	-2	1	-1	3	7
	B2.b Multifunctional dike	5	2 to 10	1	1	9 to 17	9
B3. Multiple lines of defences/ Parallel defences	B3.a Extra dike landward	-1	0	0	-1	-2	1
	B3.b Extra dike seaward	1	1	0	0	2	1
B4. Hybrid concepts	B4.a Dike integrated into dunes	0	1 to 3	0	-2	-1 to 1	5
	B4.b Dike integrated into boulevard	0	0 to 2	-2-0	-3	-5 to -1	5
	B4.c With artificial foreshore	0	2	2	0	4	2
B5. Eco-engineering	B5.a Adjacent salt marshes	0	5	2	0	7	5
	B5.b Salt marshes and berm	0	5	2	0	7	5
	B5.c Wide green dike	0	6	2	0-1	8 to 9	6
	B5.d Breakwater of oyster/mussel reefs	0	3	2	0	5	3
B6. Dynamic preservation	B6.a Sediment nourishment	0	1	0	-2	-1	3
	B6.b Sand engine	0	1 to 2	0	0	2	2
B7. Integrated hard solutions (urban area)		0	1 to 3	-1	0	0 to 2	4

Segmentation of the dike and the suitability of innovative flood protection concepts along the Wadden Sea coast

Based on current dike properties, as well as land-use and landscape features, the dikes along the Wadden Sea coast were divided by the experts in some 45 segments (Figure 2.3, see Van Loon-Steensma & Schelfhout, 2013a for a detailed description and rationale). Especially in the Wadden Sea harbour towns and villages (among others Den Helder, Den Oever,

Harlingen, Delfzijl) and industrial areas (among others Den Helder, Harlingen, Lauwersoog, Eemshaven, Delfzijl), the present Wadden Sea dikes exhibit a variety of forms and features, rooted in the current economic activities (historical, recreational and industrial harbours and ferries to the Wadden Sea islands) and constraints (among others buildings close to the dike and cultural-historical values). This resulted in relatively short dike stretches. The dike along the rural parts of the Wadden Sea is more homogenous, which resulted in long dike-stretches. Here the segmentation was also based on the differences in exposure towards the Wadden Sea, the current land-use of the hinterland, and the presence of polders or salt marshes at the seaward side of the dike.

Based on site-specific physical and ecological conditions (as shown by maps on topography, population density, habitats, nature reserves, land use and soil characteristics, see Van Loon-Steensma & Schelfhout, 2013a), as well as on tasks and ambitions for the region, we assigned (in collaboration with local experts) potential suitable dike concepts (that are interesting for further exploration) to all dike stretches (Figure 2.3).

It was assumed that traditional reinforcement of the present dikes in the Wadden region (Standard dikes in the rural area (A1), and Dikes with screens (A3) or new techniques or materials (A4) in built areas) forms the ‘business as usual’ solution to adapt the present dikes in the Wadden region to the required standards, and that the application of a more nature friendly revetment (A4.a) is possible for such traditional solutions (Figure 2.3 top).

Overtopping resistant dikes (B1) were considered potential suitable for dike-sections with a lake or salty nature on the landward side of the dike (a.o. Wieringermeer, Lauwersmeer, Polder Breebaart) (Figure 2.3 top), or with historical dikes parallel along the coast.

Robust solutions are particularly interesting for areas that require extra safety, for example in areas where flooding would result in many fatalities or in the loss of vital infrastructure (Deltacommissie, 2008; De Bruijn & Klijn, 2009). Therefore the experts considered Delta dikes (B2.a) potentially suitable for the Eems region (Figure 2.3 top), which plays a nationally important role in terms of Dutch national energy supply. In rural areas, Multifunctional dikes offer space to combine flood protection with energy production by wind-turbines (B2.b), which was considered by the local experts as worthwhile to explore for several stretches along the Wadden Sea coast (Figure 2.3 middle). Furthermore, Multifunctional dikes (B2.b) that offer space for economic activities, tourist facilities and educational purposes were considered especially interesting for further exploration in built-up areas with re-development ambitions and space constraints (among others Lauwersoog) (Figure 2.3 middle).



Figure 2.3: Potential suitable Traditional and Innovative Dike concepts (interesting for further exploration) for all dike-section along the entire Wadden Sea coast, as considered by local experts (Top: Standard dike, Overtopping resistant and Delta dike; Middle: Multifunctional dike, Parallel dike at Landward side of the dike, Breakwater at seaside of the dike; Bottom: Dike with salt marsh, Wide green dike and Dike with integrated buildings).

Dike stretches with historical dikes parallel along the coast (originating from land reclamation of salt marshes) were identified as potentially suitable for the concept with an extra landward dike (B3.a) (Figure 2.3 middle). This should be combined with an Overtopping resistant seaward dike (B1).

A breakwater, groyne or mussel or oyster reef at the seaside of the existing dike is efficient with respect to reduction of the incoming waves, so that the dike revetment is less attacked and the required crest height can be lower (B3.b, B5.c) (Figure 2.3 middle).

All dike-stretches with existing salt marshes, or developing salt marshes adjacent to the dike (Figure 2.3 bottom) were selected as interesting for further exploration of the integration of a vegetated foreshore with an engineered solution (B5.a and B5.b), or for the Wide green dike (B5.c) (Figure 2.3 bottom). This applies for example, to the dike along the Dollard which has extensive salt marshes in front of the dike, and borders the German Wide green dike.

Sand-based solutions as Dike into dune, Sand nourishment or the Sand-engine (B4.a and B6) are more suitable for the North Sea coast than for the Wadden Sea coast (because the latter is characterized by and protected for its mud-flat related nature values), and except for the *Prins Hendrikpolder* at Texel, no stretches were identified as potentially suitable for these concepts.

Finally, innovative concepts like Dike integrated into a boulevard (B4.b) and the Dike with Integrated hard solutions (B7) were considered as potentially suitable in built-up areas with space constraints, historic buildings, or specific constraints (among others Den Helder, Harlingen, Lauwersoog, Eemshaven, Delfzijl) (Figure 2.3 bottom).

2.4 Discussion

The applicability of the dike-portfolio to find adequate adaptation options

Our approach to identify suitable adaptation options for the Wadden Sea coast by 1) developing an elaborate portfolio of Traditional and Innovative dike concepts, 2) qualitative assessment of the performance of all dike-concepts by local experts, 3) dividing the Wadden Sea dike in dike-sections, and 4) selection of appropriate dike-concepts for each dike section, worked well and led to a set of potential suitable dike concepts (interesting for further exploration) for the entire Wadden Sea coast.

In general, the characteristics of the present dikes are the result of historical trends, regulatory (safety) requirements, and site characteristics. A traditional reinforcement of the present dikes

would form the ‘business as usual’ adaptation strategy. It turned out, that the systematic categorization of cross-sections of existing dike concepts and the systematic design of innovative concepts based on their flood protection principles and the targeted failure mechanism (i.e. the mechanism they should resist), was fundamental to identify potential suitable innovative solutions for the Wadden Sea coast (which has a long history of diking). The potential flood protection performance of each dike-concept is reflected by its cross-sectional shape and dimension. Our overview of dike-concepts by their cross-sections proved to be essential to explain the potential performance of innovative concepts to experts of the local water boards (who are commonly trained as engineers). The dike-portfolio was highly appreciated by these experts and turned out to be an excellent communication aid on innovative flood protection concepts and, moreover, an efficient medium to summarize knowledge and develop shared insights.

Of course, the actual implementation of innovative dike concepts will require further site specific analysis and detailed design, to be supported by modelling studies and cost-benefit analysis (which also includes different weights for the different criteria).

We may conclude that our approach is useful and practical as its results were readily adopted by the authorities in the formal process of defining concepts and setting priorities in the policies and budget allocation for reinforcing the 227 km of coastline around the Wadden Sea. Moreover, while we were still doing our research, our approach was implemented by the coastal authorities in the South-Western Delta as part of the renewal flood protections scheme in this part of the Netherlands (Tangelder *et al.*, 2013).

Multifunctional dikes

In the assessment Multifunctional dikes received a relatively high score (score of 9 to 17 in Table 2.3). They have been evaluated as offering long-term flood protection and they score, by definition, high on the criterion effects on and opportunities for other functions and values. However, the score on the latter is extremely dependent on the applied functions and their valuation (range of 9 in Table 2.3), both of which are location-specific and also subjective when based on stakeholders judgement. In general, Multifunctional dikes are especially attractive in urbanized areas, where they offer an interesting opportunity for optimized use of scarce space (see e.g. Voorendt, 2014). Although there are some towns and some industrial areas (harbours) along the Wadden Sea coast, the majority of the Wadden Sea coastal area is sparsely inhabited and characterised by its open landscape, agricultural use and historical landscape patterns.

The experts judged that infrastructure like buildings, industry or wind turbines will negatively affect the spatial quality of the protected landscape. Nevertheless, for some rural dike-stretches the integration of wind turbines in the dike is currently being explored. For the present, research efforts are mainly targeting technical aspects of integrating wind turbines in the dike (see Vergouwen *et al.*, 2011). However, it is still unclear if the obligation from international agreements to reduce the emission of greenhouse gases and to switch to ‘green’ energy will outweigh the legislation concerning spatial quality and Natura 2000. In industrial areas there will not be such a conflict, as illustrated by the wind turbine park along the dike at Eemshaven.

According to the experts additional functions such as agriculture or nature fit in the Wadden Sea landscape, and will, via their positive effect on spatial quality, also positively affect recreation and tourism. Most dikes in the Wadden region do already allow these functions (including bicycle and walking paths to accommodate recreation and tourism).

Eco-engineering concepts

Also Eco-engineering concepts were assessed as promising. Eco-engineering concepts aim at reducing the load on the dike by their wave damping capacity. For the Wadden Sea landscape, which is characterized by the presence of semi-natural salt marshes adjacent to elongated dike stretches, the application of vegetated foreshores for flood protection seems particularly attractive. This also applies to the Wide green dike concept (which integrates the adjacent salt marshes into the flood protection function).

However, the task to guarantee the legally required safety forms a constraint for their full application in the flood protection strategy. Wave damping depends on the slope of the coastal profile, water depth, width of the salt-marsh zone and vegetation (see studies cited in Anderson *et al.*, 2011). With increasing water depth (as during storm surges), wave damping may be small (e.g. Le Hir *et al.*, 2000). This implies that their role under extreme conditions will be limited, and subsequently that safety under extreme conditions must be provided merely by the dike. For the design requirements of the dike it is therefore extremely important to have more insight in the wave damping capacity of salt marshes under different (including extreme) conditions. Although some studies have been conducted recently on the value of salt marshes for coastal hazard mitigation (e.g. Costanza *et al.*, 2008; Gedan *et al.*, 2011; Shepard *et al.*, 2011), based on modelling and field observations (e.g. Brampton 1992; King & Lester 1995; Möller *et al.*, 2001), there are still many questions. Too many uncertainties in the performance of a salt-marsh zone, will ultimately result in a traditional reinforcement. Measures to enhance salt marshes with regard to the flood protection function, e.g. by

changing their dimensions and to promote beneficial characteristics for wave damping through erosion protection or sediment nourishment, may conflict with the dynamic nature and biodiversity values of salt marshes (Spencer & Harvey, 2012). Therefore, the application of nature or natural processes in order to meet the legally required safety standards does not guarantee an overall positive effect on nature and landscape values in the Wadden region. A dike with adjacent salt marshes complemented with a berm meant to absorb potential erosion during extreme conditions (B5.b), as suggested in a reinforcement strategy for the ‘*Afsluitdijk*’ (Lammers, 2009), may solve some of these conflicting interests.

Also the Wide green dike concept, that combines wave damping by salt marshes and moderation of wave run-up during extreme conditions by a shallow green seaward slope, is an interesting combination of engineered and nature based solutions for further exploration.

The potential of innovative dikes for a long-term adaptation strategy

In this study it was assumed that traditional reinforcement of the present dikes in the Wadden region forms the ‘business as usual’ solution to adapt (on the mid-term) the present dikes in the Wadden region to the required standards. The experts considered for most dike-stretches also several innovative dike concepts potentially suitable (Figure 2.3). Our assessment provides an impression of the general performance of all innovative concepts according to local experts (Table 2.2 and 2.3), and identified Multifunctional dikes and Eco-engineering concepts interesting for further exploration. The next step would be to select the best solution, which requires further site specific analysis and detailed design, to be supported by modelling studies and cost-benefit analysis (which includes a site-specific assignment of weights to the criteria). In our opinion, the long-term performance should then form an important additional selection criterion.

Facing the effects of climate change and the related uncertainties, especially robust and flexible measures are interesting for a long-term adaptation strategy. Flexible measures offer the possibility to adapt stepwise in response to new insights or changing conditions and the possibility to postpone climate adaptation investments.

Although a Multifunctional dike is very robust (because it is over-dimensioned with respect to the current safety standards), this concept is not flexible at all when functions like infrastructure, wind turbines or buildings are applied. Notwithstanding that they appear not very robust (as discussed in the previous paragraph), Eco-engineering concepts, on the other hand, are very flexible. This makes them particularly attractive from a climate adaptation perspective (Temmerman *et al.*, 2013). Under the condition of abundant sediment supply, salt

marshes can keep pace with sea level rise (Allen, 2000). After eroding by an extreme event, an accreting salt marsh may recover (Pethick, 1992), while a traditional engineering solution is static (Borsje *et al.*, 2011). By responding to changes in the system, salt marshes offer a promising opportunity to deal with the uncertainties in the future climate. This also applies for oyster or mussel reefs, although there is so far only little experimental or observational experience on deliberate stimulation of reef formation, and hardly any insight into their role for flood protection and the reliability of these living structures on the longer term. Also a Wide green dike performs better on the criterion ‘flexibility’ than Traditional dikes. The reason is that a grass covered dike will be easier and cheaper to adapt than a dike with a revetment of stones or asphalt, or a dike with structural elements.

Furthermore, Eco-engineering concepts may contribute to the nature conservation and restoration aims for the Wadden Sea, and therefore form a low or no-regret adaptation measure. This is in line with the recommendations of the Deltacommissie (2008) for development along with climate change and ecological processes.

Dike-rings

In our study we identified suitable dike concepts for each dike-section. But it is important to keep in mind that the strength of a flood defence system is determined by its weakest dike-section.

We assumed that there is basically no difference in the provided minimum safety against flooding between the concepts, because of the obligation to meet the legally established standards. When applied, the design of the profile of the innovative concept must meet the standards. However, so far, for most innovative concepts design and assessment guidelines do not yet exist. In order to get more insight into their performance and various failure mechanisms, more research and technical elaboration is needed. The Robust concepts (when applied on the whole dike-ring or on the most critical section of the dike-ring), could significantly improve the robustness of the flood defence system over a wide range of possible futures and uncertainties (Vellinga, 2008, Mens *et al.*, 2011, Klijn *et al.*, 2012). Furthermore, a Robust dike will not breach when overflowed during extreme conditions, which provides time to prepare and evacuate.

Costs and benefits

To identify the most appropriate concept, a thorough analysis of all costs and benefits of the suitable concepts is required, which needs detailed site-specific information on many aspects, including plans and ambitions for the location. The exact dimensions of each concept, which

determine the effects on their environment, are extremely site-specific. There are extensive data available on physical, morphological, ecological as well as socio-economic aspects of the Wadden Sea and the Wadden Sea system (via e.g. Waddenacademie). However, the suitability of that information for a cost-benefit analysis is unclear. Although there is some experience with valuing ecosystem services for example for salt marshes (e.g. Luisetti *et al.*, 2011), it is in general hard to weight the effects of measures on nature or on spatial quality.

Furthermore, the weight of the criteria in a decision process depends on the stakeholders involved. Weighting factors are always subjective and influence the solution. Interests of local residents are not necessarily the same as the interests of the water board (who is responsible for financing and maintenance of the flood protection) or of nature conservation organisations. Therefore a broad range of stakeholders has to be involved to elucidate all aspects. The range in our qualitative assessment (R in Table 2.3) gives an impression of the robustness of each concept in the decision process. The most attractive concepts (with the highest score for T), appear to also have high values for R and are thus also sensitive to preferences in the decision process.

2.5 Conclusion

We presented an approach to systematically define and evaluate flood defences along the Dutch Wadden Sea coast in the context of the foreseen effects of climate change and related uncertainties. The approach comprises the systematic development of a portfolio with traditional as well as new flood protection concepts and an evaluation of these concepts by means of a multi-criteria analysis in close collaboration with local experts. It has been successfully used as a first stage in planning dike reinforcements along the Wadden Sea and led to a suitable set of adaptation options. As part of the approach, the overview of dike concepts by their cross-sections proved especially essential as an explanation of the potential performance of innovative concepts to experts of the local water boards. We conclude therefore that a carefully designed portfolio of both Traditional and Innovative dike concepts proves to be invaluable to find adequate adaptation options in practice.

The ambition to integrate nature and landscape values and natural processes in a long-term flood protection strategy triggered the systematic exploration of all possibilities by designing innovative dikes based on their flood protection principle and targeted failure mechanisms. Instead of acting as a restriction it rather opened a window for innovation in flood protection along the Dutch Wadden Sea coast.

In our analyses Eco-engineering concepts (in rural areas) as well as a Multifunctional dike (in built areas) were assessed as the most optimal concepts, and are therefore interesting for further exploration. Multifunctional dikes are robust and offer space for other functions and values. However, their performance in an integral assessment strongly depends on the applied functions and the weight per evaluation criterion. They are especially attractive in built areas with limited space. Eco-engineering concepts can potentially contribute to nature and landscape values, but implementation may lead to tension with nature legislation.

For the Wadden Sea landscape, which is characterized by the presence of semi-natural salt marshes adjacent to elongated dike stretches, the application of vegetated foreshores for flood protection seems particularly attractive.

This chapter is among others based on studies commissioned by the Delta Programme Wadden region and is submitted to the journal *Mitigation and Adaptation Strategies for Global Change*:

- Van Loon-Steensma, J.M., Slim, P.A., Vroom, J., Stapel, J. & Oost, A.P., 2012. Een Dijk van een Kwelder: een verkenning naar de golfreducerende werking van kwelders. Wageningen: Alterra, (Alterra rapport 2267).
- Van Loon-Steensma, J.M., De Groot, A.V., Van Duin, W.E., Van Wesenbeeck, B.K. & Smale, A.J., 2012. Zoekkaart Kwelders en Waterveiligheid Waddengebied; Een verkenning naar locaties in het Waddengebied waar bestaande kwelders of kwelderontwikkeling mogelijk kunnen bijdragen aan de waterveiligheid. Wageningen: Alterra (Alterra rapport 2391).
- Van Loon-Steensma, J.M. Salt marshes to adapt the flood defences along the Dutch Wadden Sea coast. *Submitted* to *Mitigation and Adaptation Strategies for Global Change*.

3

Salt marshes to adapt the flood defences along the Dutch Wadden Sea coast; What is the potential for integrating salt marshes in the flood defence zone?

As a first step to explore the potential of a Dike with a foreshore of salt marshes as an adaptation strategy in the Wadden Sea region, this chapter starts with some background information about the Wadden Sea salt marshes, then describes the role of salt marshes as a natural flood defence. Next a '*Salt marsh potential map*' is presented, based on biophysical characteristics that may help in determining the future of salt marshes in the Dutch Wadden Sea and in identifying promising locations/conditions where salt marshes could possible contribute to coastal protection. Based on this, the potential to integrate salt marshes in the Wadden Sea flood defences is sketched.

Lessons learned:

- By their wave damping capacity, salt marshes in front of a dike reduce wave action and wave run-up on the dike.
- An increase in width and/or height of the salt marshes improves their effectiveness in damping waves.
- Besides elongated stretches where semi-natural salt marshes are already present (some 73 km) or developing (some 15 km), several stretches along the Wadden Sea coast have favourable abiotic conditions for salt marsh development (some 42 km).

3.1 Introduction

Salt marshes and their adjacent mudflats are a prominent feature of the Wadden Sea (e.g. Wolff, 1983; CWSS, 1991; De Jong *et al.*, 1999; Essink *et al.*, 2005; Reise *et al.*, 2010). They constitute a vegetated transition zone from land to water. This shallow zone influences incoming waves, by decreasing wave-length and velocity, by breaking shallow water waves, and ultimately by dissipating the wave energy due to friction created by the vegetation and the surface of the marsh (e.g. Anderson *et al.*, 2011). The shallow salt-marsh zone functions thus as a natural flood defence (e.g. Brampton, 1992; King & Lester, 1995; Möller *et al.*, 2001; Costanza *et al.*, 2008; Gedan *et al.*, 2011), and salt marshes in front of a dike form a natural vegetated foreland that protect these hard defences against wave action (Figure 3.1).



Figure 3.1: Illustration of a sea dike and a fronting saltmarsh (photo taken at the Wadden Sea coast of Terschelling).

Salt marshes are defined as areas vegetated by salt-tolerant plants and subject to periodic flooding due to the fluctuating water levels of the adjoining saline water body (Adam, 1990). They generally develop high in the intertidal zone in sheltered conditions, where wave action is limited so that fine sediment can settle and accumulate (Allen & Pye, 1992; Allen, 2000). Once the upper part of the intertidal zone is not continuously submerged, salt-marsh plants can colonize it and establish themselves. By trapping sediment, pioneer vegetation contributes to accretion and development of creeks, rendering the environment suitable for the establishment of species (forbs, grasses or low shrubs) that need more stable sediment and that are less tolerant against flooding (duration as well as frequency) (Adam, 1990; Allen, 2000).

In the salt-marsh zone, the boundary between land and sea shifts with the tides and water levels. However, as described in the previous chapter, most land in the Dutch Wadden region is shielded by dikes. Hence, these dikes form a very clear and rigid boundary between land and the dynamic seaward coastal zone of the Wadden Sea. The vegetated area grades seaward into mud or sand flats, from which the vegetated environment often is separated by either a ramp or cliff (Allen & Pye, 1992; Allen, 1993, 2000). Both salt marshes and the fronting mudflats are an integral part of the intertidal profile (Pethick, 1992). The marsh may experience lateral accretion and/or erosion, which depends on changes in wind-wave climate. Salt-marsh sediment which erodes during a storm may be redeposited as sand and silt banks. This helps to protect the system from further storm waves, by reducing the amount of wave energy reaching the edge of the marsh cliff (Pethick, 1992; Haslett, 2009).

Generally, a moderate sea level rise shapes conditions for marshes to build upward by accretion (Allen, 2000) and shift landward. However, the dikes along the coast prevent a landward shift. To keep pace with the sea level rise, a permanent import of sediment into the tidal system is required. If sediment import is insufficient, flats and marshes will drown as the sea level rises (Van Goor, 2003). Because of the positive feedback between salt-marsh vegetation and sedimentation, vegetation plays an important role in salt-marsh geomorphology (Allen, 2000). Salt-marsh plants are thus eco-engineers, i.e. organisms that physically change the abiotic environment and this feeds back to the biota (Jones *et al.*, 1994; Hastings *et al.*, 2007).

Salt marsh plants are often specialists and restricted to the salt marsh ecosystem (Adam, 1990). Along the north-western European coast the salt marsh vegetation grades from a seaward zone of pioneer plant species of e.g. *Salicornia* spp., *Spartina anglica* (which are well adapted to daily tidal flooding), to a more mature plant community landward of e.g.

Puccinellia maritima, *Suaeda maritima*, *Aster tripolium*, *Limonium vulgare* (Adam, 1990). These zones represent different stages of vegetation succession. The boundaries of the zones are usually determined by geomorphological variables like frequency of inundation, sedimentation and erosion, which are in turn related to geological, climatological, vegetation and land use history (Doing, 1995; Doody, 2008). The floristically most diverse part of the salt marsh is the zone which submerges regularly, but not daily. In the most elevated zones (only flooded during storm conditions) the vegetation diversity decreases with on-going succession (Dijkema *et al.*, 2001).

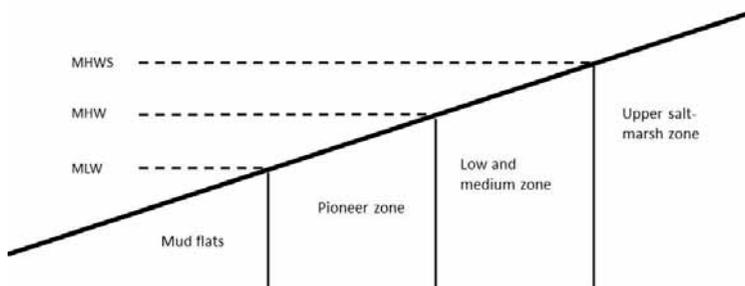


Figure 3.2: The relation between height, frequency of inundation and vegetation zones in salt marshes (MLW = mean low water level, MHW = mean high water level, MHWS = mean high water spring).

Salt marshes are important for many migrating wading birds using the Wadden Sea as stopover area (e.g. Laursen *et al.*, 2010) and by offering a flood refuge. They also serve as a spawning area and nursery for fish and are an important habitat for several invertebrate species (Bakker *et al.*, 2005). Thus salt marshes harbour important biodiversity values, and are named in the European Habitats Directive (Council of the European Communities, 1992). The various stages of salt-marsh habitats and the mudflats in the Wadden Sea are therefore protected under both national and international policy and legislation (e.g. Natura 2000, Water Framework Directive, Spatial Key Decision) (Ministerie van Volkshuisvesting, Ruimtelijke Ordening & Milieu, 2007; Ministerie van Verkeer en Waterstaat, 2009; Ministerie van Economische zaken Landbouw & Innovatie, 2011), as well as under trilateral agreements between Denmark, Germany and the Netherlands (CWSS, 1998, 2010). These habitats are characterized as (i) halophyte pioneer vegetation (H1310), (ii) *Spartina* swards (H1320) and (iii) salt marshes, including a diversity of characteristic vegetation (H1330). The adjacent mudflats are another key habitat type (H1140) (European Commission, 2007).

Like most coastal sedimentary systems, salt-marsh ecosystems are extremely sensitive to changing environmental conditions (Allen, 2000), including climate change. Elaborate studies have examined the effects of climate change on the intertidal ecosystem as a whole, on habitats and species in the intertidal zone and on particular intertidal processes (see e.g. Allen, 2000; Healy *et al.*, 2002; Schernewski *et al.*, 2011).

For the Wadden Sea, researchers have studied the effects of climate change at the level of the system in its entirety (e.g. Brinkman *et al.*, 2001; Van Goor *et al.*, 2003; Kabat, 2009), at the level of processes in salt marshes (e.g. Houwing *et al.*, 1995; Olf *et al.*, 1997; Jansen-Stelder, 2000), and in relation to species compositions (e.g. Van Dobben & Slim, 2011).

3.2 Dutch Wadden Sea salt marshes

In the Dutch part of the Wadden Sea, some 9,000 ha of salt marshes are found along the shores of both the mainland and the barrier islands (Dijkema *et al.*, 2008) (Figure 3.3). Except for the salt marsh areas at the easternmost end of the Wadden Sea islands, the salt marshes are at the landward side bounded by dikes.

Extensive parts of the salt marshes along the Frisian coast concern ‘summerpolders’ that are deliberately re-connected to the Wadden Sea by opening sluices (Noorderleeg) or accidentally re-connected to the Wadden Sea by breaching of the low seaward dike (Paezmerlannen).

Along some dike sections, the salt-marsh zone is rather narrow (a few meters, as in Wieringen and along the dike of Polder Breebaart), while the salt marshes along the Dollard and the coast of Noord Groningen and the summer polders and salt marshes in Noorderleeg are locally more than a kilometre in width.



Figure 3.3: Salt marshes along the Dutch Wadden Sea coast.

Flora and vegetation of the Dutch salt marshes have been studied intensively (e.g. Westhoff, 1947; Bakker, 1989; Westhoff & Van Oosten, 1991; Van Wijnen *et al.*, 1997) and areal extent, sedimentation, relative water levels and vegetation succession, have been monitored for more than 50 years (Dijkema *et al.*, 2013).

The lower salt-marsh zone increases from mean high water (which is 0.6 m +NAP in the western part of the Wadden Sea and 1.5 m +NAP in the Dollard region) towards the higher salt marsh zone (which varies from some 1.7 m +NAP in the western part of the Wadden Sea towards ca. 2.9 m +NAP in the Dollard region) (*source*: AHN 2012).

Until the 1970s, at locations with favourable conditions, sedimentation was actively stimulated by digging drainage systems in the mudflats, planting cordgrass (*Spartina anglica*), and (from the 1930s onwards) by constructing brushwood groynes (Dijkema *et al.*, 2001). These works were originally designed for reclamation of agricultural land. Since the 1950s however, reclamation of salt marshes became economically less feasible, and maintenance of the sedimentation works was reduced or even discontinued, which initiated a shift towards lateral erosion in various salt marsh areas (such as the Dollard, see e.g. Esselink

et al., 2011). The increased awareness of the importance of nature values of the Wadden Sea's salt marshes for nature and biodiversity since the 1970's, initiated a search for best practices to stop the steady decline of the Wadden Sea's salt marshes.

After adjustments in the size of the sedimentation fields, the observed decline has been turned into an increase of the salt-marsh area along the Frisian and Groningen coast. Recently the expansion of the Frisian salt-marsh area has stopped, while the pioneer salt marsh zone in Groningen is still expanding (Dijkema *et al.*, 2013).

Monitoring revealed that during 1960-1995 the average accretion rates were 1.8 and 1.2 cm per year for the marshes along the coast of respectively Fryslân and Groningen (Dijkema *et al.*, 2013). During the period 1992-2010 the accretion rate were respectively 1.4 and 1.0 cm per year. Accretion in the Dollard marshes was 0.8 cm per year between 1984 and 2003 (Esselink *et al.*, 2011).

The monitoring revealed furthermore, that accretion of the Wadden Sea salt marshes is strongly influenced by storms. More storms after 2000 led to ongoing accretion in the higher salt-marsh zone, while during 1960-2000 (a period with a lower storm frequency) accretion decreased (Dijkema *et al.*, 2013). Van Duin *et al.* (1997) found that in the Paezemerlannen an extreme event (with a water level of 2.30 m +NAP) imported some 125 times the average sediment load seen during a normal tide.

On the mainland coast extensive stretches of the salt marshes are still owned by farmers and used for extensive cattle grazing, while an equally substantial area is owned and managed by nature conservation organisations (e.g. Balgzand, Noorderleech, Peazemerlannen, Punt van Reide, the eastern section of the Dutch Dollard-salt marshes). On the Dutch Wadden islands the majority of the salt marshes are owned and protected by nature conservation organisations, although there are still some privately owned areas on Ameland as well as on Terschelling.

3.3 From reclamation to preservation

Conservation tasks and development goals

The increased interest in nature conservation since the 1970s led to the inclusion of the entire Wadden Sea area in the Ramsar convention. The Wadden Sea is also subject to the EU Habitat directive and EU Wild Birds directive and was in 2009 appointed as an UNESCO World Heritage site. In order to implement the EU birds and habitat directives in national

legislation, the entire Dutch Wadden Sea (including the salt marshes) is under the Dutch Nature Conservation Act and appointed as Nature 2000 area for which target species and habitats are agreed (Ministerie van Economische zaken Landbouw & Innovatie, 2011).

The present salt-marsh area along the Wadden Sea mainland coast, however, is mostly the result of man-made accretion works (Dijkema *et al.*, 2013). It still features a strong pattern of drainage ditches perpendicular on the coast and has brushwood groynes in the seaward sedimentation fields.

Already in the first nature conservation plans of the late 1980s the prioritization of natural geomorphological processes in the Wadden Sea and the minimization of human intervention has been agreed. This was formalized in the '*Planologische Kernbeslissing*' (Spatial Key Decision) (Ministerie van Volkshuisvesting Ruimtelijke Ordening & Milieu, 1993). Initially this resulted in management focusing on the preservation of existing nature and landscape values and the existing habitat areas. Accretion works were maintained to preserve the salt-marsh area (Dijkema *et al.*, 2001). However, the third Spatial Key Decision for the Wadden Sea also included developing goals for salt marshes: i) to increase the area of natural salt marshes, ii) to enhance the natural morphological and dynamic processes and iii) to enhance the structure of the vegetation (Ministerie van Volkshuisvesting Ruimtelijke Ordening & Milieu, 2007).

An explicit aim of Natura 2000 is to conserve the areal extent of salt marshes in the Wadden Sea region with all of their succession stages and salt-fresh water transitions. Other Natura 2000 ambitions are to increase the variability in geomorphological forms and substrates of salt marshes and to optimise management regimes (Ministerie van Economische zaken Landbouw & Innovatie, 2011).

In the EU Water Framework Directive salt marshes are regarded as indicators for the quality of estuarine water. Rijkswaterstaat monitors and reports the extent as well as the vegetation structure of the Dutch salt marshes to the EU. To prevent erosion of the marsh area along the coast of the Groningen and Fryslân, maintenance of the accretion works is prescribed.

Beyond EU-level conservation efforts, there is a trilateral agreement between Denmark, Germany and the Netherlands to increase the area of natural salt marshes, to enhance natural morphological and dynamic processes in the Wadden Sea region, to enrich the natural vegetation structure of artificial salt marshes, and to improve conditions for wading birds (CWSS, 1998, 2010).

Management and maintenance

Traditionally most salt marshes were used for livestock grazing or hay making. Grazing contributes to the biodiversity of the salt marshes by slowing down succession, preserving more species-rich succession stages, and (dependent on the livestock species and density) induce patchiness of vegetation and structural heterogeneity (Adler *et al.*, 2001; Nolte *et al.*, 2014). This may also affect ground-breeding birds and other animals. Without grazing, tall growing species such as *Elytrigia atherica* will on the higher elevated salt marsh zones outcompete shorter species (Olf *et al.*, 1997). However, livestock grazing on the salt marsh needs daily monitoring of the animals because of the risk associated with tidal inundations of the lower marsh zone, the risk of flooding during storm conditions, and the silted up ditches that form a continuous danger of drowning for the animals. To reduce the risk of drowning, the ditches require periodical maintenance. Therefore, livestock grazing on the salt marshes became less economically feasible and decreased on the privately owned salt-marshes since the 1970s. In the areas owned by nature and environmental organizations, the grazing intensity was also reduced, but this was due to biodiversity and landscape objectives (e.g. Esselink *et al.*, 2000). However, grazing in low stocking densities is a common tool to preserve species rich semi-natural grasslands. Recently, experiments were deployed to search for optimum grazing treatments in view of salt-marsh biodiversity (e.g. Nolte *et al.*, 2014).

Recreation and tourism

Salt marshes offer opportunities for cycling (over bicycle paths on or along the dike), walking, bird watching, nature excursions and mudflat hiking (in Dutch: *wadlopen*). Their value for recreation and tourism is strongly related to their nature and landscape value.

3.4 Wave damping by salt marshes

Salt marshes form a shallow transition zone from sea to land that affects incoming waves. When a wave encounters water depths shallower than the wave-base, the wave shape gets modified by the topography of the foreland and starts shoaling. Wavelength and wave velocity both decrease, but the energy from these reductions contributes to an increase in wave height. A shallow water wave will usually break when it encounters water depth that is less than wave height and will undergo refraction or reflection, and later dissipate due to friction created by the vegetation and the surface of the shallow zone. Wave damping strongly depends on the slope of the coastal profile, water depth above the salt marsh, width of the salt marsh zone, surface topography and vegetation characteristics (see studies cited in Anderson

et al., 2011; Le Hir *et al.*, 2000), and is the subject of numerous studies (see studies cited in Gedan *et al.*, 2011). Especially water depth has a strong effect on wave attenuation. In general waves break in shallow water. The exact point where a wave breaks is a function of wave height (H), water depth (h) and the slope of the coastal profile. A broad range of values for H/h are reported, from 0.45 for a horizontal surface, to 0.6 or even 1.59 for a sloped surface (see Holthuijsen, 2007). Under natural conditions, there may be strong spatial and temporal heterogeneity in local topography of the foreland, and with that of the inundation depth. Furthermore, cliff edges (or shallow dams, accretion works, etc.) may lead to local effects in wave heights (Möller *et al.*, 2002).

With shallow water depths vegetation dissipates wave energy by creating friction, which results in smaller wave heights. Field measurements in Norfolk (UK) pointed out that wave heights were reduced by (on average) 61% over a 180 m wide vegetated salt marsh and 15% over 197 m wide sand flats (median value of all water depths 1.1 m) (Möller *et al.*, 2001). Measurement and calculations of wave attenuation in the Yangtze Estuary (China), showed a 1-2 times higher wave attenuation per unit distance over a *Spartina alterniflora* vegetation than over the adjacent mudflat (incident wave height ranging from <0.1 to 1.5 m) (Yang *et al.*, 2012). Yang *et al.*, (2012) found that on average, waves reaching the salt marsh were eliminated over a distance of ~80 m, whereas this would be >400 m without vegetation. Not only the effects of vegetation presence has been investigated in this context, but also the effect of several vegetation properties. Zones with a higher plant-stem density of *Spartina alterniflora* for example, were more effective in wave damping than zones with a lower density (Yang *et al.*, 2012). A tall canopy of perennial *Spartina* spp. in Essex (UK), damped the waves more than a shorter canopy of the annual *Salicornia* spp. (Möller, 2006), and Bouma *et al.* (2005) found that dissipation of hydrodynamic forces from waves was roughly a factor of three higher in vegetation with stiff leaves compared to those with flexible leaves. Vegetation characteristics, however, may vary seasonally and spatially.

Because wave damping is strongly determined by the breaking of waves, a narrow zone of salt marshes may, under low surge levels, already affect wave heights. Dissipation of wave energy due to friction by vegetation or by the salt marsh surface, on the other hand, requires a substantial extent of foreland (at least some wave-lengths). Therefore, most wave damping occurs in the 10-50 m seaward zone of the salt marsh (e.g. Möller *et al.*, 2002; Koch *et al.*, 2009), and relative wave damping decreases with increasing width of the salt marsh (see Table 1 in Anderson *et al.*, 2011). However, to apply the flood-defence value of natural forelands, it is advisable to account also for the effects of erosion during extreme storm conditions. This erosion during extreme conditions may be viewed as similar, in some

respects, to the wave buffering capacity of sand dune systems. They act as an energy buffer in times of storm and are able to release sediments, stored during low-magnitude, high-frequency events, to assist in short-term morphological response of the profile to storms (Pethick, 1992).

Notwithstanding the increasing interest for the flood defence value of salt marshes, so far there has not been a great deal of quantitative work on their flood defence capacity under storm conditions, and most information comes from laboratory studies (e.g. Brampton, 1992; Suzuki *et al.*, 2009) or field measurement under moderate wave conditions (e.g. Möller *et al.*, 2001, 2002; Möller, 2006).

Modelled effect of Wadden Sea salt marshes

The dikes along the Wadden Sea coast are designed to withstand extreme storm surges (in the Wadden Sea region with probabilities of 1/2,000 up to 1/10,000 per year), with the crest of the dike well above the extreme storm surge level and expected wave run-up. This hydraulic load on the Wadden Sea dikes is determined by i) North Sea waves that during storm conditions may penetrate partially into the Wadden Sea, ii) water level and flow driven by tidal phase and wind conditions, iii) wind direction and –speed, and iv) local bathymetry and characteristics of the nearshore zone.

Salt marshes form a shallow zone (called foreland) in front of the dike that affects wave action and wave run-up. Their wave damping capacity may therefore result in lower requirements concerning crest height and revetment. In order to anticipate the effect of salt marshes in dike design, it is necessary to quantify their effect by modelling wave propagation and generation. An example of a model used for this purpose is SWAN (Simulating WAVes Nearshore model), a physically based two-dimensional model which converts wind data into near shore wave parameters (height, period and direction) for a given location (Booij *et al.*, 1999). The interplay between the various spatial (e.g. topographic) and temporal (e.g. seasonal) factors, however, introduces a significant degree of variability in the wave attenuation process that is very difficult to model (Van der Meer, 2002).

To get a first impression of the potential of salt marshes for coastal protection in the Wadden region, Venema *et al.* (2012) modelled wave attenuation over a schematic salt-marsh zone (50-200 m in width, 1.0-2.3 m +NAP in height) under extreme conditions (1/10 to 1/10,000 per year). They used information on local storm water levels and wind conditions, and assumed that water level and significant wave height are 3.6 m +NAP and 1.84 m respectively during a severe storm (1/10 per year), and 5.0 m +NAP and 2.4 m respectively during an

extreme storm event (1/10,000 per year). The dikes along the mainland coast of Fryslân and Groningen are designed for extreme events with a return period of 1/4,000 per year, and, depending on the location, the current statistically derived extreme water levels and related wave heights vary between 4.6-6.8 m +NAP and 0.9-2.8 m respectively (Ministerie van Verkeer en Waterstaat, 2007a). The height of the salt marshes in front of the dikes along the mainland coast of Fryslân and Groningen is some 1.5 m (*source*: AHN 2012). In general their elevation increases in landward direction, resulting in elevations of more than 2 m in the proximity of the dike.

The results of the modelling work by Venema *et al.* (2012) (Figure 3.4) indicate that even under extreme conditions (with a water level of 5 m +NAP) an elevated foreshore (2.3 m +NAP) of 50 m in width dampens the waves (of some 2.4 m) with some 20 % (resulting in wave heights of 1.90 m). Widening of this high foreshore up to 200 m results in a reduction of 37% with respect to the initial wave height (resulting in a wave height of 1.5 m). Under severe storm conditions (1/10 per year) such a wide and high foreshore will dampen the wave height (of some 1.84 m) even up to some 60% (resulting in a wave height of 0.75 m). However, a low foreshore (1 m +NAP) has a modest effect on wave damping under extreme conditions (Figure 3.4). Increased friction by vegetation, or erosion during extreme events, may result in a slight shift of the modelled wave heights.

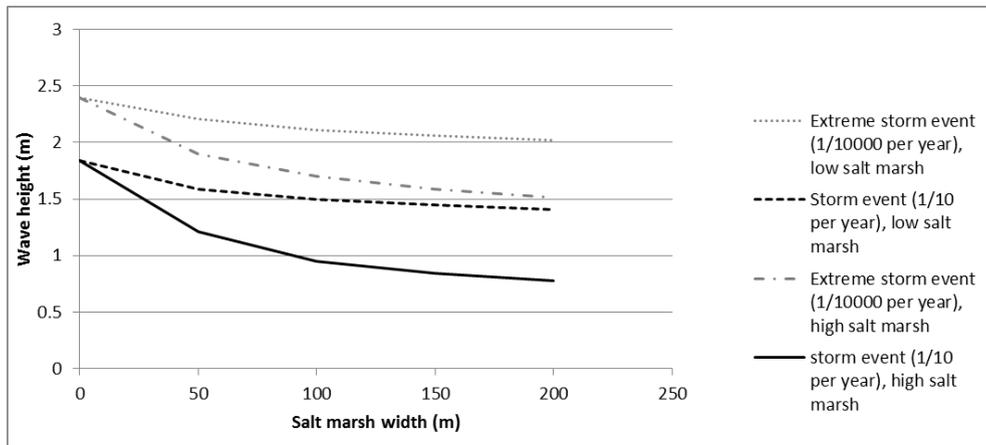


Figure 3.4: Modelled wave height over a foreshore (1 m +NAP and 2.3 m +NAP) under extreme storm conditions (1/10 and 1/10,000 per year) (based on Venema *et al.*, 2012).

Under moderate storm conditions, with lower water levels and wave heights than in Figure 3.4, salt marshes definitely prevent full wave action on the dike. Because these storms have a return time of several times per year, salt marshes will result in less wear and damage of the revetment. Furthermore, they increase the under-seepage length.

Calderon & Smale (2013) explored with SWAN the potential effect of a zone of some 600 m in width in front of all Wadden Sea dikes on the future dike reinforcement task. As reference they applied a schematized Traditional dike profile that meet in the current situation the required crest height. They found that when such a zone of 600 m in front of the dikes could keep pace with sea level rise (of 0.15 m in 2050), there would be only a modest dike reinforcement task in 2050 (some 0-0.25 m for some 50 km dike), whereas without such a salt marsh zone all dikes must be heightened (0-0.5 m). The presence of a salt-marsh zone that could keep pace with sea level rise, would result in an unchanged water depth in front of the dike despite sea level rise. Furthermore, the effect of widening of the salt-marsh zone and of the accretion pace was explored by Smale (2014). This study found that in the situation of a sea level rise of some 0.15 m in 2050, waves are damped in the first 1000 m of the salt marsh, while increasing the width further did not result in more wave damping. An increase in elevation of the marsh surface (by sedimentation) that outpaces sea level rise, results in a reduced dike reinforcement task due to the decreasing water depths in front of the dike. In reality, however, there are only salt marshes along certain dike sections, and not all salt marshes are 600 m or more in width (see section 3.2).

With regard to the promising modelling results, it is important to keep in mind that there is still little field data about the effects of natural vegetated foreshores on wave attenuation during extreme conditions. Wave models are developed and evaluated on the basis of either scaled down lab tests or field measurements under less than extreme conditions. Hence, applying these models to predict effects under extreme conditions relies on extrapolation. To further evaluate and calibrate the existing models (aiming at reducing prediction uncertainties) it is advisable to monitor the wave attenuation on a number of distinctive locations, especially during high surge events.

Furthermore, it is important to examine how salt marshes respond to the effects of a changing climate such as an accelerated sea level rise, another storm climate and a higher temperature. A reduction in the width and/or height of the salt marshes reduces their effectiveness in damping waves and increases the risk of overtopping or breaching of sea defence structures on their landward side.

3.5 Salt marsh potential map

As a step to explore the possible role of salt marshes in protecting the Wadden region against flooding, promising locations were identified and presented in a ‘*Salt marsh potential map*’ (Figure 3.5). The identification was based on the basis of a) the current situation (salt marshes already present, see Figure 3.2), b) an inventory and assessment of abiotic conditions for salt-marsh formation, and c) a biotic classification of the coastal zone along the Wadden Sea coast (island and mainland dikes) (Van Loon-Steensma *et al.*, 2012c).

The potential for salt-marsh development was expressed at an ordinal 5-point scale (see the first column in Table 3.1) and based on available information on i) bathymetry of the coastal zone (source: data Rijkswaterstaat, Open Earth), ii) concentration of fine-grained sediment in the upper sediment layer (source: data Rijkswaterstaat, Open Earth), iii) velocity of currents along the coast (Zwarts, 2004) (see columns two to four in Table 3.1). General information about salt-marsh formation concerning elevation in relation to tidal range (e.g. Allen, 2000) was used to determine bathymetry classes, i.e. the pioneer zone develops between mean low water level and mean high water, while the more mature salt-marsh zones rise from the mean high water level. Facing the extensive experience with salt-marsh formation by stimulating sedimentation through simple brushwood groynes, it is expected that salt-marsh formation in the shallow intertidal zone (above mean low water level) needs only small efforts. In contrast, salt marshes can only develop at deeper locations after raising the elevation by nourishment. This is expensive, and probably requires additional measures to prevent erosion and to cushion the unfavourable conditions that led to the local depth.

The concentration of fine-grained sediment ($< 0,063$ mm (Van Duren *et al.*, 2011), for brevity called silt) in deposited sediment reflects local hydrodynamic conditions: under dynamic conditions there is hardly any deposition of suspended small particles, while under lee conditions silt may also be deposited beside coarser sand particles. In general silt concentrations in the upper layer of the present salt marshes in the Wadden Sea are more than 5%. Therefore, hydrodynamic conditions at locations with lower silt concentrations were considered as unfavourable for salt marsh development (Van Loon-Steensma *et al.*, 2012c).

Table 3.1: Classes for the potential of salt-marsh developing and the defining abiotic parameters (MHWL=mean high water level, MLWL= mean low water level) (Van Loon-Steensma et al., 2012c).

Class	Bathymetry	Concentration fine-grained sediment	Maximum flow velocity
Salt marshes already present	> MHWL	> 5%	< 1.2 m/s
Natural developing salt marshes	around MHWL	> 5%	< 1.2 m/s
Small efforts required for salt marsh formation	around MLWL	> 5%	< 1.2 m/s
Large efforts required for salt marsh formation	between -5 m NAP – MLWL	> 5%	> 1.2 m/s
No possibilities for salt marsh formation	< -5 m NAP	< 5%	> 1.2 m/s

Modelling of the maximum flow velocity in the Wadden Sea (Zwarts, 2004) revealed that flow velocity in the shallow coastal area near salt marshes is less than 1.2 m/s, and in the tidal gullies more than 1.2 m/s. Therefore a flow velocity of 1.2 m/s was chosen as class boundary for flow conditions where salt marsh formation is relatively easy (Van Loon-Steensma *et al.*, 2012c).

Both salt marshes and the adjacent sand and mudflats provide important nature values, and are protected by (inter)national legislation (see section 3.3). Most present salt marshes along the mainland coast, however, are the result of accretion works and thus, by definition, semi-natural. As the value of salt marshes is strongly connected with natural morphological processes, especially the natural developing salt marshes represent important nature and landscape values.

A point of concern is that an extension of the salt-marsh area comes at the cost of the shallow sand and mudflats fronting it. These parts of the (sub)littoral zone are important as feeding areas for wading birds and spawning grounds for fish, and sometimes harbour mussel banks (see Wadden Sea Atlas, http://documents.plant.wur.nl/imares/ecologische_atlas.pdf). So development of salt marshes can result in the creation of valuable salt-marsh pioneer habitat (an important goal for the Wadden Sea), but at the same time seaward development of salt marshes on these locations will affect the adjacent sand and mudflats. Therefore, unique (sub)littoral habitats formed an additional class in the ‘*Salt marsh potential map*’.

Figure 3.5 presents the potential of salt marsh development for the stretches of the Wadden Sea coast based on the classes defined in Table 3.1 and the presence of unique (sub)littoral habitats along the coast. This map illustrates that, besides elongated stretches where semi-natural salt marshes are already present (some 73 Km), several stretches along the Wadden

Sea coast have favourable abiotic conditions for salt marsh development (some 15 Km). However, such development may come at the cost of valuable (sub)littoral habitats. Furthermore, there are also several stretches where salt marsh development requires small efforts (some 42 km) or large efforts (some 56 km) by raising the elevation by nourishment and possibly additional measures to prevent erosion and cushion the unfavourable conditions that led to the local depth. Along approximately 75 km of dike, abiotic conditions are considered totally unsuitable for salt-marsh development.

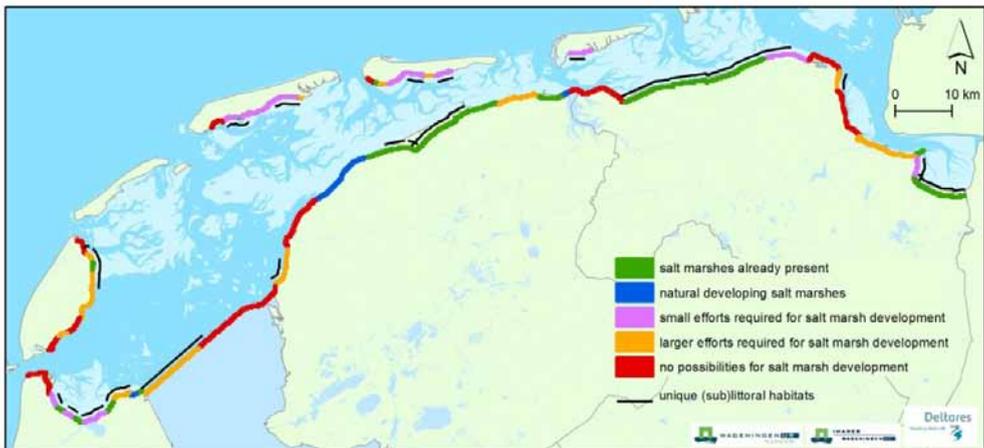


Figure 3.5: (Dutch) Wadden Sea 'Salt marsh potential map' (Van Loon-Steensma et al., 2012c).

Noteworthy is that salt marshes are already deliberately included in the design of the 12.5 km dike section along summerpolder 'Noorderleeg'. In 1992, this grass covered dike was completed after flume studies of the Waterloopkundig Laboratorium (1984) proved that a Wide green dike with adjacent polders and salt marshes was able to withstand extreme storm conditions.

3.7 Discussion: next steps for salt marsh conservation and development in view of coastal defence in the Dutch Wadden Sea

The first explorative modelling results indicate that Wadden Sea salt marshes affect wave heights, even under extreme conditions (Venema *et al.*, 2012). A salt-marsh zone of some 600 m in front of all Wadden Sea dikes that could keep pace with sea level rise, may result in a reduced dike reinforcement task in 2050 (Calderon & Smale, 2013). Especially at locations where currently no salt marshes are present, salt marshes would lead to a significant reduction

in the dike reinforcement task (Calderon & Smale, 2013). However, at these locations, conditions are not particularly favourable for salt marsh formation, because the elevation may be too low for establishment of pioneer species, or currents or wave action may be too strong for sedimentation. Here, salt marshes can only develop after raising the elevation by nourishment and after the implementation of measures to prevent erosion and to mitigate the unfavourable abiotic conditions for salt-marsh development. The benefits of salt marshes as coastal defence at these locations (reduced dike reinforcement task) will probably not outweigh the costs of salt-marsh development. Therefore, conservation or development of salt marshes for flood protection appear not feasible for all dike sections.

The '*Salt marsh potential map*' gives a rough impression (however no specific information such as salt-marsh width) of locations that are potentially interesting for salt marsh conservation and development. It is based on the current situation, on available information about abiotic conditions for salt marsh formation and the habitats present in the coastal zone.

In the further exploration of the potential role of salt marshes in the Wadden Sea flood protection strategy it is advisable to start with locations where salt marshes are already present or where their development needs only small efforts. Monitoring and modelling their effect on wave damping and experiments with management regimes will lead to more insight in their potential role in flood protection and in the best management strategy in view of flood protection.

So far, there is only a limited amount of information available about relevant abiotic parameters for salt marsh formation in the Wadden Sea coastal zone. Therefore, it is important to gain more insight into these conditions by monitoring important parameters like (changes in) elevation, currents, flow velocity, and sediment concentration.

Because the development of salt marshes will affect the adjacent sand and mudflats, it is also important to gain more insight in the effects of conservation and restoration measures on the ecological values on different spatial, as well as on different temporal scales. Restoration will, in any case, lead to short-time disturbance, but may also lead in the longer term to a seaward shift of the intertidal zone.

Measures to maintain or increase the area of present salt marshes or to stimulate the development of new salt marshes (e.g. brushwood groynes, drainage pattern by ditches, dams of stones, shells or clay) are an important concern. Most of these measures target to influence natural morphological processes: they cushion dynamic conditions in order to stimulate

sedimentation, to prevent erosion or add sediment into the system. These measures may have side-effects on the natural and landscape qualities of the salt marshes.

In the current situation, the salt marshes along the mainland coast are the result of accretion works. Without these works, most salt-marsh areas in front of the dikes would have been exposed to slow but steady erosion. The dikes have prevented a landward shift of the salt-marsh zones under rising sea levels (a phenomenon known as ‘coastal squeeze’; Pontee, 2013). The closures of the former *Zuyderzee* (1932) and the *Lauwerszee* (1969) are suspected of having increased erosion by its effect on the tidal prism (Elias, 2006).

Furthermore, it is wise to take long-term developments into account. The ‘*Salt marsh potential map*’ is based on the present situation and observations on short-term developments. However, long-term processes such as sea level rise and changes in the sediment fluxes are important for salt marsh dynamics. The Wadden Sea system is still moving towards a new balance after the closures of the *Afsluitdijk* (1931) and the *Lauwerszee* (1969), which results in the steady rising of some deeper coastal areas which may become intertidal areas in the future. Although developing salt marshes on such locations may require a large effort initially, probably less additional measures are subsequently needed because it connects to an existing trend (Van Loon-Steensma *et al.*, 2012c).

Sea level rise forms an important physical factor in the salt-marsh formation. With moderate rises in sea levels, salt marshes typically build upward (Allen, 2000). To keep pace with the sea level rise, however, a permanent import of sediment is required for the tidal system. Based on the results of more than 50 years of monitoring, Dijkema *et al.* (2013) expect that Wadden Sea salt marshes are able to keep pace with accelerated sea level rise of 1.0-2.0 cm per year and 0.5-1.0 per year for the mainland and the Wadden islands respectively. However, the availability of sufficient sediment forms an important prerequisite for their ability to keep pace with the sea level rise.

Additionally, there are still uncertainties about the effects of climate change on the storm climate in the Wadden Sea. A reduction in the width and/or height of the salt marshes due to increased erosion reduces their effectiveness in damping waves and increases the risk of overtopping or breaching of sea defence structures on their landward side. Although there are some studies on the implications of climate change for salt-marsh management (e.g. Vermaat *et al.*, 2006), there is not much experience yet with the management and maintenance of salt marshes in view of flood protection.

As already mentioned in section 3.4, it is important to keep in mind that there is still little field data about the effects of natural vegetated foreshores on wave attenuation during extreme conditions. Wave models are developed and evaluated on the basis of either scaled down lab tests or field measurements under less than extreme conditions. Hence, applying these models to predict effects under extreme conditions relies on extrapolation. To further evaluate and calibrate the existing models (aiming at reducing prediction uncertainties) it is advisable to monitor the wave attenuation on a number of distinctive locations, especially during storm conditions.

Finally, the ability of salt marshes to keep pace with sea level rise, which results in unchanged water depths in front of the dike, can never exclude future adjustments in crest height of the dike. Wadden Sea dikes are dimensioned to prevent overflow and to withstand wave action and wave run-up under extreme conditions. Salt marshes only affect the latter, but not the increasing water levels under extreme conditions in a changing climate.

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4

Trade-offs between biodiversity and flood protection services of coastal salt marshes

The interest for the natural sea defence of salt marshes did not only increase recently in the Wadden region, but in many deltaic regions in the world. For decades, however, the focus of researchers as well as policy makers was mainly on their biodiversity value. The increased interest in the role of salt marshes for flood protection fits into the increasing interest in valuing ecosystem services: valuing the benefits to human society provided by natural and semi-natural ecosystems and landscapes. Coastal salt marshes are an excellent example of a (semi) natural ecosystem that provides a broad range of important goods and services to humans. The intentional use, or the deliberate management or creation of an ecosystem for the beneficiary use of one targeted service, coastal protection in this case, may affect the other services provided. This chapter reviews salt-marsh restoration options described in the literature, and then considers trade-offs between enhancement of salt marshes' flood protection service and the ecological quality of the ecosystem.

Lessons learned:

- Restoration of salt-marshes represents an attractive no-regret climate adaptation strategy.
- Due to the pace of sea level rise, there is still time to experiment with salt-marsh restoration techniques.
- Trade-offs are involved in enhancing both the ecological and flood protection services of salt marshes.

4.1 Introduction

Coastal salt marshes and adjacent mudflats form a dynamic gradient between land and sea and are the typical habitat of salt-tolerant vegetation (Adam, 1990). They are common in many tidal-dominated temperate environments, like coastal lagoons and estuaries, and are often intensively used for human settlement and agriculture due to their location, flat surface and fertile soils (Barbier *et al.*, 2011). Human activities in marsh ecosystems include exploitation of plant production, drainage and reclamation for agriculture and building, introduction of non-native species, construction of engineering works for shipping and flood protection, and resource extraction (Gedan *et al.*, 2009). Yet such activities have led to pollution, degradation and erosion of up to half of the salt marshes worldwide (Barbier *et al.*, 2011). Furthermore, salt marshes are threatened by urbanization, economic development and the accelerated rise of sea level due to climate change (Nicholls *et al.*, 2011).

For decades, considerable attention has been given to the biodiversity value of wetlands such as salt marshes. Conservation and development goals have been formalized in international policy and legislative frameworks, most of which focus on protecting the areal extent of salt marshes and the associated habitat (vegetation species abundance and diversity) alongside other ecological parameters such as bird and invertebrate populations. In consequence, salt marshes are the subject of a range of management and restoration strategies. Since the Millennium Ecosystem Assessment, however, emphasis has shifted to their value and services in relation to food and fiber production; regulation of nutrients, carbon and water levels; and recreation (see e.g. Barbier *et al.*, 2011). Major flooding disasters like Hurricane Katrina (2005) and Hurricane Sandy (2012) brought added focus to the value of salt marshes as natural flood defences. Studies have demonstrated the buffering effect of salt marshes by calculating the damage avoided due to vegetated coastal zones; 60% of the variation in relative damages of 34 major US hurricanes could be explained by the presence of coastal wetlands (Costanza *et al.*, 2008). Research has also shown that artificial embankments have lower construction and maintenance costs when combined with a natural foreshore (e.g. Luisetti *et al.*, 2011).

Due to these new insights, several projects have been initiated worldwide to conserve, restore and (re)create salt-marsh zones. These did involve, for instance, erosion protection of salt-marsh edges; nourishment of existing salt marshes; development of new salt marshes; accretion works; management of marsh vegetation; and creation of space for salt-marsh development on formerly embanked areas (Elliot *et al.*, 2007). Sediment nourishment on the larger scale of the estuary or lagoon is a more recent topic of research.

Questions, however, have been raised about the effectiveness of the flood defence service of natural coastal ecosystems during extreme storm conditions (see e.g. Feagin, 2008), and there is growing appreciation of the biodiversity value of restored salt marshes (see e.g. Elliot *et al.*, 2007; Spencer & Harvey, 2012). This has led to several reviews and meta-analyses on the feasibility of using salt marshes to contribute to flood protection (e.g. Gedan *et al.*, 2011; Shephard *et al.*, 2011). Other studies have investigated the biodiversity value of salt marshes (e.g. Mossmann *et al.*, 2012), seeking to identify knowledge gaps and make recommendations for marsh restoration (e.g. Spencer & Harvey, 2012).

We argue that any restoration project involves trade-offs between flood protection and biodiversity conservation. Nonetheless, opportunities for synergy can be found with the use of an integrated approach and collaboration between coastal engineers, coastal morphologists

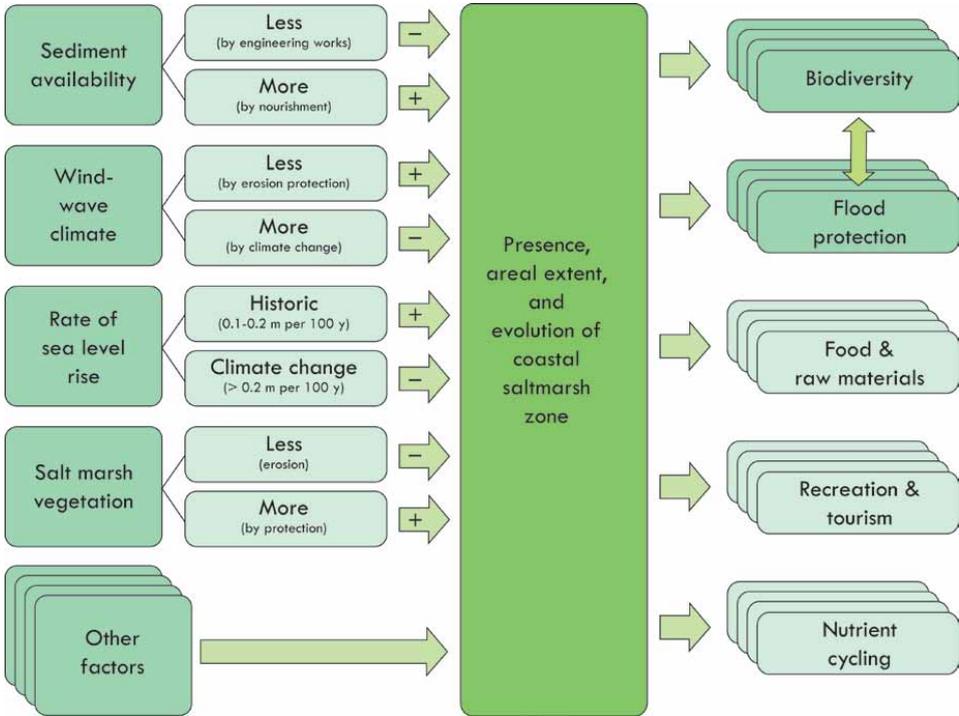


Figure 4.1: The main controlling factors of salt-marsh formation (left) and the services provided by salt marshes (right).

and ecologists with the shared ambition to utilize natural ecosystems and natural processes in a flood protection strategy. This paper describes (1) the effectiveness of salt marshes in wave damping during extreme storm conditions, (2) opportunities and constraints for improving the flood defence function of salt marshes, and (3) synergies and trade-offs between the flood protection service and biodiversity. We start by describing the salt-marsh ecosystem. Figure 4.1 illustrates processes within the salt-marsh system and the services they provide.

4.2 Salt marshes: The result of geomorphological, hydrodynamic and biological processes

Salt marshes occur high in the intertidal zone in sheltered conditions, rising up from the mean high water neap tide (MHWN) level landward, where the height, length and frequency of inundation by saline water decreases. The lower levels of the salt-marsh area support pioneer species. By trapping sediment, this vegetation contributes to accretion and development of creeks, rendering the environment suitable for the establishment of species that need more stable sediment. Because of the positive feedback between salt-marsh vegetation and sedimentation, vegetation forms an important aspect of salt-marsh geomorphology (Allen, 2000).

In addition to the tidal regime, the main physical factors that control salt-marsh dynamics (vertical and lateral accretion and erosion) are sediment supply, the wind-wave dynamics and rising sea level (Allen, 2000). Salt marshes adapt quickly to changes in their boundary conditions. With abundant sediment supply, a salt marsh can keep pace with sea level rise by accretion or moving landwards (if there is sufficient space to accommodate them). Similarly, a change in tidal currents or wave action may change the profile of the marsh, and with it, its areal extent.

The most floristically diverse part of the salt marsh is the zone that is regularly, but not daily, submerged. In zones that are only occasionally flooded, vegetation diversity decreases with ongoing succession. In a dynamic environment, the succession process is cyclic due to erosion and sedimentation. The inter-relation between physical and biological processes within marshes has long been a subject of study. With the availability of remote sensing data over the last 10-20 years, variations in vegetation and relevant physical properties have been explored as well (Townend *et al.*, 2011).

4.3 Flood protection by salt marshes

In the shallow coastal salt-marsh zone, incoming incident waves break and wave energy dissipates. This action is strongly dependent on the slope of the coastal profile, water depth, width of the salt-marsh zone and vegetation. With increasing water depth (as during storm surges), wave damping becomes smaller (e.g. Le Hir *et al.*, 2000). As several authors point out, wave reduction especially occurs in the first few meters from the salt-marsh edge, and a strip of at least 10-80 m is required for significant wave reduction (see authors cited in Gedan *et al.*, 2011 and Shephard *et al.*, 2011). Thus, a salt marsh in front of a coastal dike (an earth structure designed to resist wave action and to prevent or minimizing overtopping, also called levee or embankment, Figure 4.2), including vegetation, creeks and cliff edges, as well as the adjacent silt and sand banks on the seaward side, dampens incoming waves before they reach the dike (Callaghan *et al.*, 2010). A natural foreshore is formed that reduces wave run-up as well as wave overtopping. Furthermore, it protects the revetment against wave action and prevents piping problems (the wash-out of material by seepage under the embankment).

Most field studies of such systems have so far been rather location specific, which is almost unavoidable since wind conditions (wind speed and direction), tidal range and tidal currents are extremely site and time dependent. Although some field studies have measured wave heights of more than 1 m (Yang *et al.*, 2012), there is little experience with extreme storm conditions because they are rare and difficult to measure. Models are therefore used to predict the wave damping effect of salt marshes under extreme storm conditions. In general, such models convert measures of wind conditions and information about local bathymetry into nearshore wave parameters (height, period and direction). Such models are also used to investigate the effect of salt-marsh restoration and degradation on storm surges and waves (see e.g. Wamsley *et al.*, 2009). However, due to, for example, their heterogeneity, it remains difficult to incorporate effects of salt marshes into predictive models for wave run-up and wave overtopping. It is therefore difficult to include the effects of natural or semi-natural foreshores in calculations of dike dimensions or to incorporate them into sea defence and management schemes (Koch *et al.*, 2009).

In a natural setting, it is extremely difficult to separate effects due to topography from those due to vegetation (as they are co-linear) and consequently to determine an appropriate friction factor that can be used in a formula for calculating dissipation of wave energy. An additional concern is seasonal variation in marsh vegetation cover (vegetation density, structure and composition) (Möller, 2006). Another unknown is how the marsh surface and vegetation will respond to extreme situations. To be effective in these situations, salt marshes must be

relatively high and stable; vertical erosion during extreme storm conditions reduces wave attenuation capacity. Moreover, sediment that is eroded in a storm event may be redeposited as sand and silt banks. This helps to protect the system in subsequent storms by reducing the amount of wave energy reaching the marsh edge (Pethick, 1992).

The dynamic nature of salt marshes and their ability to adjust to rising sea level makes them particularly attractive from a flood protection perspective. In areas with subsidence and abundant sediment supply, accretion of more than 20 mm per year has been reported (see e.g. Day *et al.*, 1999) on Venice Lagoon and the Mississippi Delta and grey literature on the Dutch Wadden region). However, if a salt marsh cannot keep pace with the sea level rise, and there is no accommodation space to move landward, it will deteriorate and eventually disappear.

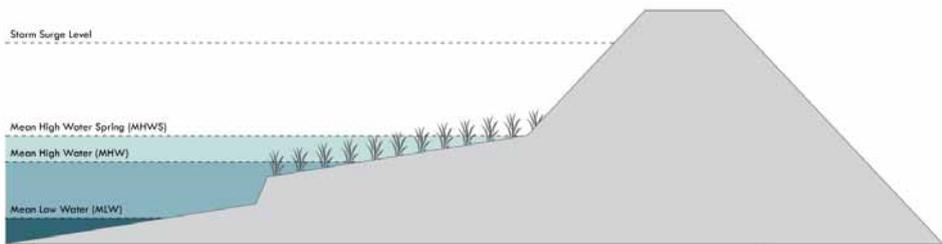


Figure 4.2: *Vegetated foreshore in front of the dike; the lower level (between MLW and MHW) is inundated daily and supports pioneer species.*

4.4 Techniques and measures to restore and create salt marshes

Considerable experience has been gained in small-scale salt-marsh restoration projects. The aim of many of these projects is to conserve and enhance biodiversity values by returning a system to a previous state after it has been degraded or disrupted (Elliott *et al.*, 2007). Alternatively they might attempt to replicate conditions at a nearby undisturbed marsh site to compensate for habitat loss due to industrial expansion or engineering works. Ideally, management that targets habitat restoration or enhancement would allow natural processes, leading to variation along the coastline. However, as discussed in the previous section, to be effective for flood protection, a salt marsh has to be relatively high, broad and stable even under extreme storm conditions.

Numerous studies have examined the effects of hydrodynamic forces (e.g. Callaghan *et al.*, 2010), rising sea level (e.g. Yang *et al.*, 2008; Day *et al.*, 2011; De Groot *et al.*, 2011) and vegetation (e.g. Van Dobben & Slim, 2012; Temmerman *et al.*, 2012) on sedimentation. Research on prevention of wave-induced erosion, furthermore, suggests that soil type is an important factor in salt-marsh erosion rates (Feagin *et al.*, 2009). This implies that restoration by nourishment with dredged material would affect erosion. A study in the Baltic Sea on wave height attenuation by reed beds pointed to the possibility of physiological adaptation (stem diameter) to water depth and wave exposure (Möller *et al.*, 2011). Studies on feedback between vegetation, hydrodynamics and landform (Van de Koppel *et al.*, 2005; Van Wesenbeeck *et al.*, 2008a,b; Silva *et al.*, 2009; Bouma *et al.*, 2010) in salt-marsh landscape development found interactions between vegetation and hydrodynamics to be scale-dependent.

The conditions that enable a salt marsh to persist are not by definition the same as those that make the development of a new marsh possible (Van Wesenbeeck *et al.*, 2008a). For example, an old marsh with mature vegetative growth can resist a higher wave impact than a marsh where young seedlings have just settled (Day *et al.*, 1999; Balke *et al.*, 2012). In addition, factors that determine the potential for salt-marsh development take place on different scales. On the scale of an estuary in its entirety, tidal prism and sediment availability are of great importance, while on a local scale, elevation relative to the mean high water level and hydrodynamics are main factors of interest. Wave and current dynamics and the erosivity of the soil (estimated by the sand-silt ratio) determine whether pioneer plants will grow (Balke *et al.*, 2012).

Currently, most measures to preserve or develop salt-marsh areas aim to influence local processes of marsh formation: controlling or reducing wave action; preventing erosion and promoting accretion to increase height and allow marsh plants to develop; increasing inundation to impounded marshes by deliberate breaching or replacing existing sea defences (managed realignment), opening sluices and increasing channel and culvert size; excavating to lower the topography to aid water retention; and ecological engineering and use of dredged material to stabilize shorelines (Elliott *et al.*, 2007). A distinction can be made between soft engineering techniques which are flexible and basically temporary in nature, and hard engineering techniques which are rigid. Numerous soft interventions can be listed: accretion works made of brushwood groynes or clay; oyster or mussel reefs to protect the foreshore (Borsje *et al.*, 2011); dams built of clay or shells; local sediment nourishment; creek system improvement for both drainage and sediment capture; and planting or managing vegetation to

improve sedimentation. Hard measures are, for example, stone or rubber dams and geotextile, asphalt and concrete revetments on a salt-marsh edge (Table 4.1).

Table 4.1: Overview of salt-marsh preservation and development techniques (soft measures in italics).

	Salt-marsh preservation	Salt-marsh development
Sediment availability	<i>nourishment</i> - <i>local</i> - <i>large scale (estuary or lagoon)</i> <i>restoration of creeks and gullies (or connection with tidal system by sluices or culverts)</i>	<i>nourishment</i> - <i>local</i> - <i>large scale (estuary or lagoon)</i> <i>creation of creeks and gullies</i>
wind-wave climate	erosion protection - <i>brushwood groynes (along salt-marsh edge or perpendicular on the edge)</i> - dams of stone - <i>dams of clay or shells</i> - <i>oyster or mussel reefs</i> - dams of geo-textile - asphalt or concrete revetment on the salt-marsh edge	accretion works - <i>brushwood groynes (along coast or perpendicular on the edge)</i> - dams of stone - <i>dams of clay or shells</i> - <i>oyster or mussel reefs</i> - dams of geo-textile
rate of sea level rise	-	-
salt marsh vegetation	<i>optimised grazing regime</i>	<i>planting of salt-marsh vegetation</i>
else	creation of accomodation space for salt marshes to migrate landward <i>excavating</i> influencing of tidal prism	managed realignment <i>raising of coastal area</i> influencing of tidal prism

If tidal flats are not high enough to enable establishment of pioneer vegetation, they may be elevated by local nourishment. Obviously, this is useful only if there is no net erosion.

Nourishment, therefore, often has to be supplemented with some kind of erosion protection.

Any action that influences the advection of fine sediment from the estuarine source is likely to influence marsh development (see Figure 4.1) (French, 2006; Townend *et al.*, 2011). Typical interventions are the closure of parts of the estuary by dams for flood protection or navigation, extraction of oil and gas, dredging of navigation channels, and construction of dams or

embankments along the coast or in the watershed of sediment-supplying rivers. Any of these will affect the tidal prism, bathymetry and, in particular, the influx of sediment into the estuary or accommodation space. They will consequently affect accretion and erosion (Townend *et al.*, 2011). Supply of sediment from outside the system can rapidly produce considerable change in the sedimentation rate (Costanza *et al.*, 2008; Détriché *et al.*, 2011). This insight has led to the novel idea of stimulating salt-marsh formation by deliberate sediment nourishment on the scale of the estuary or lagoon, for example, by feeding the tidal inflow at the mouth of the estuary with sediment. The aim of such efforts is to use natural dynamics to transport externally supplied sediment into the system, comparable to the idea of the ‘sand engine’, in which mega-sand nourishment is applied to maintain the sand volume of the coastal foundation in the face of rising sea level (Mulder & Tonnon, 2010). After distribution by the tidal flows, sediment is expected to be available for (natural) salt-marsh accretion.

4.5 Trade-offs between flood protection and ecological quality of salt marshes

In salt-marsh restoration, the goals of flood protection and habitat conservation and enhancement can be mutually reinforcing. However, trade-offs between these services are also encountered, mainly arising from the fact that flood protection is mostly required during extreme events, which impose rather different requirements on the extent and features of salt marshes compared to biodiversity conservation.

One trade-off relates to the elevation of the salt marsh. The flood protection service increases with higher elevation of the salt-marsh surface. Thus, to be effective during extreme storm conditions (with surges far above mean high water levels and with exceptional waves), the salt-marsh surface needs to be relatively high. Unfortunately, raising the salt marsh conflicts with the requirements for biodiversity where a relatively low-lying and dynamic salt marsh is best. In the highest zones that are seldom flooded, vegetation diversity diminishes with ongoing succession.

Other trade-offs are also involved in measures to prevent erosion or enhance salt-marsh formation by reducing wave action or increasing accommodation space. The flood protection service is better assured by a stable salt marsh. In general, hard engineering techniques are more reliable than soft techniques and are also applicable under less favorable wind-wave conditions. However, the naturalness of salt marshes decreases if geomorphological processes are hindered. Furthermore, erosion protection may limit opportunities for seaward extension

of the salt marsh. In general it is preferable to stimulate natural processes to augment biodiversity. On the other hand, using the technique of ‘building with nature’ does not automatically lead to enhanced biodiversity values (Spencer & Harvey, 2012).

Pioneer habitat often develops quickly following measures like erosion protection, accretion works and managed realignment (see e.g. Kadiri *et al.*, 2011; Mossman *et al.*, 2012; Van Loon-Steensma & Slim, 2013), but these sites are often considered immature in terms of the functioning of the wider ecosystem (Kadiri *et al.*, 2011; Mossman *et al.*, 2012). Fully functioning ecosystems require effective rehabilitation and long-term sustainability of inextricably linked ecological, biogeochemical and physical processes (Townend *et al.*, 2011).

Another category of trade-offs involves the effects of sediment nourishment to compensate for structurally reduced sediment supply. Sediment can be reintroduced in the system at the local level. This has been done in numerous cases, sometimes with dredged material, though this has a different biochemical makeup than natural silt and leads to immature salt marshes (Feagin, 2008). Sediment nourishment on the scale of the estuary or lagoon, however, is new, and only limited monitoring data of the impact are available. An important question is where to find the sediment to be nourished, and whether the required amount of sediment can be dredged elsewhere without causing ecological damage. Furthermore, nourishment may increase the turbidity of the water, leading to disturbances in primary production in the estuary. This happened, for instance, after the large-scale dumping of dredged material in the Ems-Dollard Estuary (Essink *et al.*, 2005). It may also influence the prey capture success of plunge-diving seabirds (Baptist & Leopold, 2010). Thus, the effects in the estuary or lagoon and the quality of the newly formed salt marsh may depend on the nourishment technique applied and the quality of the sediment introduced (Mossman *et al.*, 2012; Spencer & Harvey, 2012). To what extent can the sediment introduced into the system be matched to the properties of the sediment naturally present in the estuary or lagoon?

The potential trade-offs can be summarized as follows: the more sediment that is introduced into the system, the greater the potential impact in terms of the flood protection service. However, the effect on ecosystem functioning will be equally great. Furthermore, an element of uncertainty is inevitable, because these techniques aim to use natural dynamics, which are inherently unpredictable and variable in space and time (Van den Hoek *et al.*, 2012). On the other hand, this technique can be easily modified to accommodate new insights and developments. It is therefore an attractive strategy for adaptation to climate change (so-called ‘adaptive management’).

4.6 Concluding remarks

Under favourable conditions salt marshes form self-maintaining ‘horizontal levees’ that attenuate wave energy and thus contribute to coastal protection. In addition, they host valuable ecosystem services, like biodiversity. Restoration and conservation of salt-marsh zones thus constitute an attractive flood protection strategy.

The role of vegetation and other biota to stabilize existing salt-marsh zones and to stimulate foreshore formation is still under research.

Climate change influences salt-marsh formation processes through its effect on sea level, wave conditions and vegetation. These factors must therefore be taken into account in policy development concerning the suitability of salt marshes as climate adaptation measure.

Protection and restoration of salt marshes by soft engineering techniques represents an interesting no-regret adaptation strategy. Moreover, due to the time scale of climate change (long term) and salt-marsh dynamics (short term) we still have some time to experiment with techniques to protect, develop and effectively manage salt marshes. However, encouraging experimentation in a financially constrained climate is a problem.

An interesting idea to further explore is active creation of natural foreshores – for example, by trapping sediment via ecological engineering and sediment nourishment on the scale of the estuary. This requires integrated, interdisciplinary studies over a range of spatial and temporal scales, and collaboration among engineers, ecologists and geomorphologists.

Chapter 5 includes the summarized versions of two articles and is based on two reports:

- Van Loon-Steensma, J.M. & Slim, P.A., 2013. The Impact of Erosion Protection by Stone Dams on Salt-Marsh Vegetation on Two Wadden Sea Barrier Islands. *Journal of Coastal Research* 29(4): 783-796.
- Van Loon-Steensma, J.M., Slim, P.A., Decuyper, M. & Hu, Z., 2014. Salt-marsh erosion and restoration in relation to flood protection on the Wadden Sea barrier island Terschelling. *Journal of Coastal Conservation* 18: 415-430.
- Van Loon-Steensma, J.M. & Schelfhout, H.A., 2013. Pilotstudie Groene Dollard Dijk; Verkenning naar de haalbaarheid van een brede groene dijk met flauw talud en een voorland van kwelders. Wageningen: Alterra (Alterra rapport 2437).
- Van Loon-Steensma, J.M., Schelfhout, H.A., Broekmeyer, M.E.A., Paulissen, M.P.C.P., Oostenbrink, W.T., Smit, C., Cornelius, E.-J., & Jolink, E., 2014. Nadere verkenning Groene Dollard Dijk; Een civieltechnische, juridische en maatschappelijke verkenning naar de haalbaarheid van een brede groene dijk. Wageningen: Alterra (Alterra rapport 2522).

5

Development of salt marshes for coastal defence; Three case studies in the Wadden region

This chapter illustrates the potential of salt-marsh development and preservation for coastal defence by describing three case studies in the Wadden region. The first study explores and quantifies the effects of low stone dams on the development of salt marshes on the Wadden barrier islands Terschelling and Ameland. These dams were constructed to prevent erosion of the marsh edge. Within decades, sedimentation raised the mudflats between the dam and the former cliff, creating a broader foreshore and new marsh area with typical salt-marsh vegetation. The second case explores the impact of erosion and restoration measures on habitat development and the flood protection value of a small salt marsh along the Wadden Sea dike of Terschelling. The third case focuses on the application of salt marshes in combination with a Wide green dike along the Dollard. The objective of this chapter is to contribute to knowledge about preservation and development of foreland for flood protection while considering the effects on nature.

Lessons learned:

- under favourable abiotic conditions, erosion protection by low stone dams brings about strong reduction in retreat of the salt-marsh edge, while also helping to restore an ecologically attractive foreshore zone.
- areal extent as well as vegetation of restored salt marsh affect wave height.
- salt marshes combined with a Wide green dike offer various advantages.

5.1 Introduction

There is a long history of stimulating salt-marsh development as well as managing and maintaining the salt-marsh area in the Wadden Sea region by various types of accretion and erosion protection works (Dijkema *et al.*, 2001). Until the 1970s the protection and development of salt marshes in the Wadden Sea was focused on agriculture, and since then more on nature conservation (De Jonge & De Jong, 2002). However, from the perspective of adaptation to the impacts of climate change it becomes relevant to explore the potential of salt-marshes for coastal defence, and to connect this with their value for nature and landscape. Chances for mutual enhancement of all these functions would strengthen their potential as a climate adaptation strategy. However, as highlighted in the previous chapter, restoration and protection of salt marshes for coastal defence may have side-effects on the ecological quality of the ecosystem. Therefore, it is important to gain more insight in the effectiveness of conservation and restoration measures on the salt-marsh area and related flood protection capacity, and to analyse the value of restored salt marshes in view of biodiversity. Eventually, quantitative information about the performance of restored salt marshes on wave damping and about their effect on nature and landscape values will be needed for a balanced decision regarding the best adaptation strategy. The case studies in this chapter provide such information. The first case study explores and quantifies the effects of low stone dams on the development of salt marshes on the Wadden Sea barrier islands Terschelling (Grië) and Ameland (Neerlands Reid) (Figure 5.1). The second case explores the impact of erosion and of restoration measures on habitat development and on the flood protection value of a small salt marsh (Stryp) on the Wadden Sea barrier island Terschelling (Figure 5.1). The third case focuses on the application of salt marshes in combination with a Wide green dike along the Dollard (Figure 5.1). The presence of extensive salt-marsh area in front of the Dollard dike, together with the satisfactory performance of the Wide green dikes along the German Dollard coast, triggered the interest for a Wide green dike along the Dutch side of the Dollard. A wide green dike has a shallow sloped seaward face (with a slope of some 1:7) covered by a thick layer of clay and grass, and merges into the adjacent salt marshes. Normally, incoming waves are damped by the salt-marsh foreland. Salt marshes form an indispensable part of the Wide green dike concept. Additionally, these salt marshes could potentially form a source for the clay needed for the Wide green dike.



Figure 5.1: The study sites Grië and Stryp (Terschelling), Neerlands Reid (Ameland) and Dollard.

5.2 Case study 1: Salt marsh Grië (Terschelling) and Neerlands Reid (Ameland)

Case description

The aim of this case study was to contribute to knowledge about foreland restoration and development as well as habitat diversity by quantifying the effects of low stone dams on the extent and composition of salt-marsh habitat. Both study sites are located on the east end of the islands where no flood defence was constructed to protect the hinterland. Likewise, the salt marshes are not artificially bounded on the landward side. Rather, the landscape grades gradually into dunes. A distinct erosion cliff had developed along the salt-marsh front at both sites (Figure 5.2 a,b), and measures (a low stone dam) had been taken to prevent further erosion of the cliff. Both locations are protected under the European Habitats Directive as ‘Waddenzee’ Natura 2000 sites, in particular for three habitat types: (i) halophyte pioneer vegetation (H1310), (ii) *Spartina* swards (H1320) and (iii) salt marshes, including a diversity of typical vegetation (H1330). The adjacent seaward habitat is designated as mudflats and sandflats not covered by seawater at low tide (H1140) (Ministerie van Economische Zaken, Landbouw & Innovatie, 2011).



Figure 5.2: Illustrations of marsh cliff edges and vegetation. Unprotected cliffs at A) Grië during low tide (photo 15 August 2011), B) Neerlands Reid during a relatively low high tide (1 September 2011), and protected area C) area behind the dam at Grië, Habitat 1310 (photo 16 August 2011), and D) area behind dam at Neerlands Reid, Habitat 1310 & 1330 (photo 1 September 2011).

Grië

The dam at Grië is some 60 m seaward of the marsh cliff. It was built in 1991 of loosely stacked boulders approximately 0.3 m in diameter. The dam is some 1.3 m in height, 2 m in width and some 2,500 m in length. It has five openings and is at the east side not connected with the coast, allowing seawater to enter and exit during high and low tide. In the sheltered area behind the dam, sedimentation has raised the elevation of the former mudflats, which have become overgrown with typical salt-marsh vegetation. The new salt-marsh zone is lower lying than the original salt marsh, and the area is subjected to daily tidal flooding. The openings in the dam have resulted in gully and creek formation between the dam and the former cliff edge (Figure 5.2 c).

Neerlands Reid

The salt marsh at Neerlands Reid, like all salt marshes in the Wadden Sea, has been subjected to rising sea levels, but it is influenced by subsidence as well due to extraction of natural gas (Dijkema *et al.*, 2011). For more than half a century, the salt marsh eroded, forming a cliff edge. In 1998–1999, a stone dam was constructed some 5–15 m seaward of the marsh cliff, on the remains of a low coastal defence made out of asphalt and bricks (this older construction stems from 1962). After covering the old defence by geotextile the edge was reinforced and elevated using loosely stacked boulders. The fortified structure is some 0.8 m in height, 8 m in width, and 1,800 m in length. Shortly after the construction of the dam a new salt-marsh vegetation developed (Figure 5.2 d).

Analysis of salt-marsh edge retreat*Method*

Based on aerial photographs taken between 1949 and 2010 at intervals of some 10 years, we analysed for both sites the effect of the dams on the marsh areas. The use of chronological sequences of aerial photographs to map and quantify changes in an inter-tidal area and vegetation is well documented (see e.g. Cox *et al.*, 2003; Sanders *et al.*, 2005; Slim *et al.*, 2011). We divided the coast into a section without a dam (A) and a section with a dam (B). Comparing the digital geo-referenced photographs, we then quantified the rates of marsh retreat and extension before and after construction of the dam for the different sections.

The studied sections without a dam were 250 m and 168 m (A), and with a dam were 950 m and 150 m (B), respectively for Grië and Neerlands Reid.

Before construction of the dams, and in the areas without a dam, the cliff (clearly evident as the boundary of continuously vegetated area) forms the seaward marsh edge. After construction of the dam, the former cliff forms a seaward edge only at high water and remains visible in the landscape and on the aerial photographs due to relief as well as differences in vegetation. The changes in the position of the cliff were quantified.

We compared our findings for Grië with measurements conducted by the Dutch Directorate General for Public Works and Water Management (*‘Rijkswaterstaat’*). This government agency monitored the position of the salt-marsh edge from 1941 to 2000 along 12 transects perpendicular to the coast of Grië. Furthermore, Public Works also estimated sedimentation at Grië by comparing elevations in 1992 and 2000 at regular 15 m intervals parallel to the dam (see De Boer, 2002). For Neerlands Reid such information was not available.

Results

Analysis of the aerial photographs indicates considerable retreat of the salt-marsh cliff edge at Grië during 1949–2010 (Figure 5.3 and Table 5.1). Construction of the low stone dam considerably reduced this erosion. The rate of marsh edge retreat declined from 1.3 m per year on average during 1949–1990 to just 0.2 m per year during 1990–2010 (section B). The unprotected marsh edge adjacent to the protected stretch continued to retreat, with the average rate of 1.6 m per year during 1949–1990 to 1.9 m per year during 1990–2010 (section A). In all situations, the rate of erosion varied from decade to decade. As shown in Figure 5.3, some spatial variation was also measured in rates of erosion, especially near the creek outlets.



Figure 5.3: Aerial view of Grië with the position of the marsh edge in 1949, 1959, 1969, 1980, 1990, 2000 and 2010, and the erosion protection works (dashed lines).

Monitoring data from Public Works show an average retreat over the whole length of the salt marsh of 1.04 m per year before the construction of the dam and 0.45 m per year during 1991–2000 after dam construction (De Boer, 2002; see also Figure 5.4). The regression results show edge retreat to be significantly higher before than after dam construction. Moreover, prior to dam construction, edge retreat appears to be significantly greater towards the east, while after dam construction edge retreat was constant along the length of the dam. As Figure 5.4 shows, the retreat measured using the aerial photographs during 1949–1990 (section B divided into 3 subsections, matching the eastern 950 m of the section monitored by Public Works) corresponds with the spatial gradient found in the Public Works monitoring data. In the section without a dam, retreat after 1991 continued in line with this spatial gradient.

Table 5.1: Average and standard deviation of cliff retreat (-) and growth (+) of the coastal zone at Grië (Terschelling) and Neerlands Reid (Ameland). Sections A are without erosion protection (reference situation). Sections B are with erosion protection. The dam at Grië dates from 1991. The coast protection structure at Neerlands Reid stems from 1962 and was fortified in 1998–1999. Grey-shaded cells represent the periods and areas affected by the erosion protection.

Location	Period	Average rate of erosion (m per year)		
		Section		Difference
Grië		Section A (250 m)	Section B (950 m) with erosion protection after 1991	
	1949-1959	-1.2	-1.0	0.1
	1959-1969	-2.0	-1.7	0.3
	1969-1980	-1.3	-0.9	0.4
	1980-1990	-1.9	-1.7	0.2
	Average (st.dev.)	-1.6 (0.39)	-1.3 (0.38)	0.3 (0.10)
	1990-2000	-1.9	-0.3	1.6
	Average (st.dev.)	-1.9 (0.02)	-0.2 (0.12)	1.7 (0.14)
Neerlands Reid		Section A (168 m)	Section B (150 m) with erosion protection after 1962 and 1998/1999	Difference
	1949-1959	-0.5	-1.2	-0.7
	1959-1969	0.3	-0.6	-0.9
	1969-1979	0.2	0.3	0.0
	1979-1990	-0.7	-0.2	0.5
	1990-2000	-1.3	-2.4	-1.1
	Average (st.dev.)	-0.3 (0.62)	-0.7 (1.15)	-0.4 (0.68)
	2000-2009	-0.5	0.7	1.2

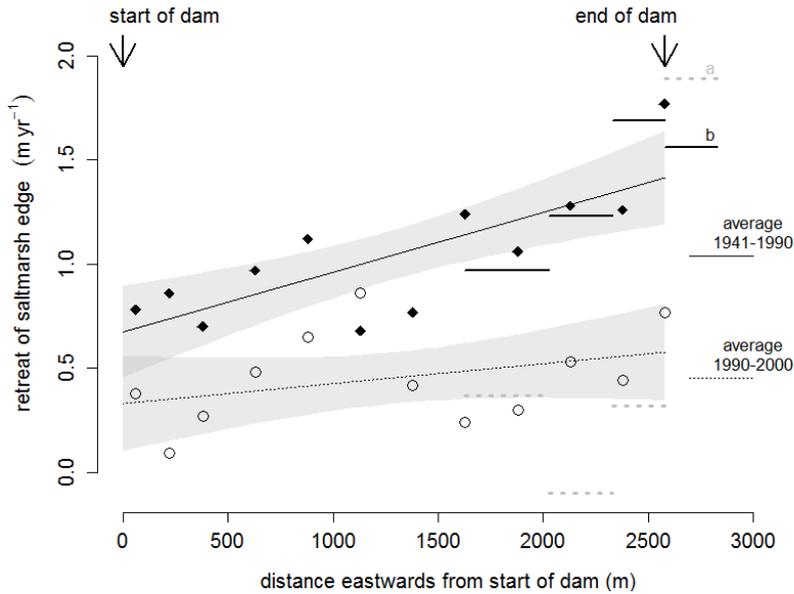


Figure 5.4: The average edge retreat over the distance from the westernmost part of the dam at Grië. The black diamonds and the solid regression line represent the period 1941–1990 ($\text{retreat} = 0.68 + 0.00029 \cdot \text{distance}$; $R^2\text{-adjusted} = 0.56$, $p = 0.003$), while the circles and the dashed line represent the period 1990–2010 ($\text{retreat} = 0.33 + 0.000095 \cdot \text{distance}$; $R^2\text{-adjusted} = 0.05$, $p = 0.243$). The shaded areas represent 0.95 prediction intervals for the two models. At the right side of the graph, the average edge retreats for the distance range of 0 to 2580 m are shown. The horizontal line segments in the graph (from a distance of 1630 up to 2830 m) show the retreat measured on aerial photographs. Black solid line segments refer to the period of 1949–1990 and grey dashed segments refer to the period 1990–2010. The rightmost line segments (marked with a and b) show that, eastward of the dam, the edge retreat rate continues at its original rate, while behind the dam it has been strongly reduced (source for symbols: Rijkswaterstaat directie Noord-Nederland, cited in De Boer, 2002; source for line segments: own analysis on aerial photographs).

Figure 5.5 shows the changes in elevation at Grië for the 1990–2000 period in 15 m-wide zones parallel to the dam. Changes in elevation are strongly related to distance from the dam. Elevation increases are largest in the zone just landward of the dam, and are less pronounced at some distance of the dam. Both in the zone 60–75 m inland from the dam (this is the zone immediately beyond the former cliff) and in the seaward side directly in front of the dam there are reductions in elevation.

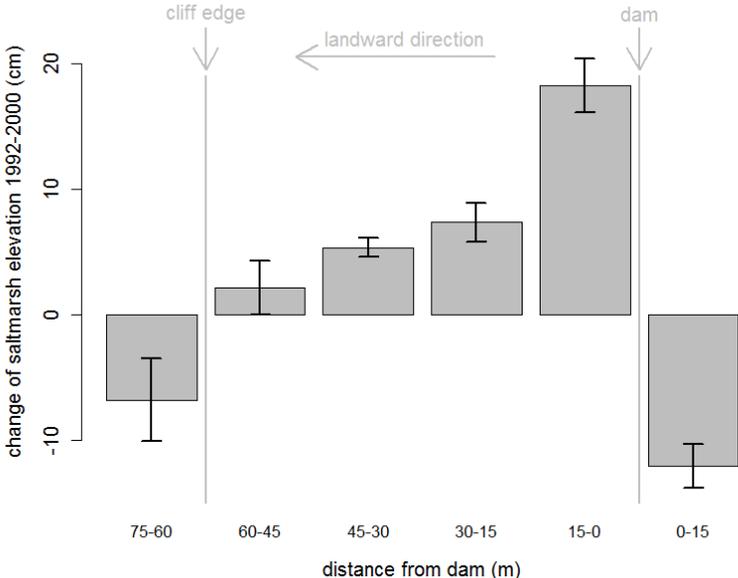


Figure 5.5: Elevation changes for the 1990–2000 period for zones of 15 m wide, parallel to the dam. The height of the bars represents the average elevation change for each 15 m strip along the entire length of the dam. The hinges give the standard error of the mean (source: Rijkswaterstaat directie Noord-Nederland, cited in De Boer, 2002).

Figure 5.6 shows the retreat of the salt-marsh cliff edge at Neerlands Reid. The retreat of the marsh edge before construction of the original low brick dam in 1962 was 1.2 m per year (Table 5.1). The low brick dam functioned as a revetment against and along the top of the cliff edge (Figure 5.7). Reduced retreat of the salt marsh was observed during 1959–1990. Ongoing erosion after 1990 led to an increased retreat of the salt-marsh zone behind the low brick wall, which prompted reinforcement of the dam in 1998–1999. The cliff behind the dam is difficult to distinguish on the aerial photograph of 2009, indicating that the zone behind the dam had become overgrown with vegetation in the intervening years. At the unprotected part of Neerlands Reid, on the other hand, the salt-marsh edge eroded further, though with fluctuations in retreat and expansion between 1949 and 2009 (Figure 5.6 and Table 5.1).

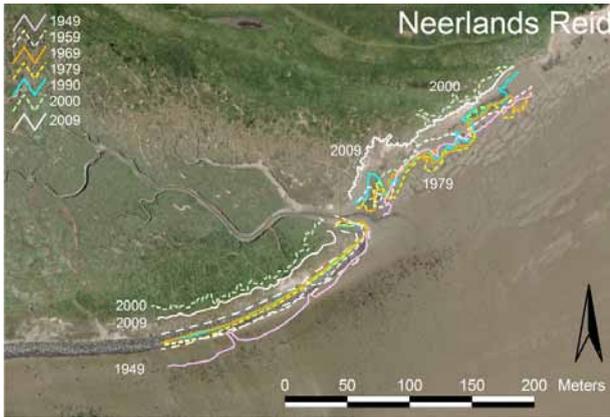


Figure 5.6: Aerial view of Neerlands Reid with the position of the marsh edge in 1949, 1959, 1969, 1979, 1990, 2000 and 2009, and the erosion protection works (dashed line).

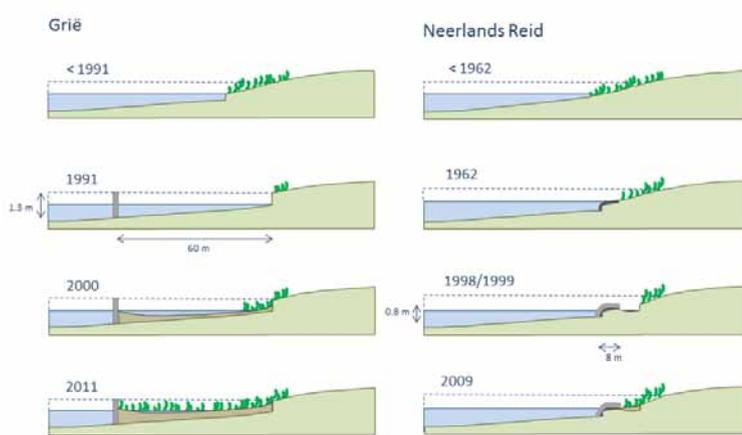


Figure 5.7: Outline of marsh development behind the erosion protection works at Grië (left) and Neerlands Reid (right).

Figure 5.7 shows the retreat of the salt marsh due to erosion before the protection works were constructed and development of the salt marsh after construction. At Grië, some 15 ha of salt marsh developed in 20 years' time between the marsh cliff and the dam (some 60 m in width along the dam's 2,500 m length). The dam at Neerlands Reid was constructed just seawards of the cliff, so only a small strip of salt marsh was restored. At the time of dam construction (1991 at Grië and 1998–1999 at Neerlands Reid) the soil level inland of the dam was lower at Grië than at Neerlands Reid.

Vegetation surveys

Methods

To explore the effects of the erosion protection measures on species composition and habitats, we surveyed the vegetation at both study sites. Along 10 transects perpendicular to the coastline 56 circular plots, measuring 4 m² (r = 1.13m), were chosen inland of the dam and at nearby locations without a dam. This involved 6 plots in section A and 23 plots in section B, and 16 plots in section A and 11 plots in section B, respectively for Grië and Neerlands Reid. Plot spacing was such that key transitions between vegetation zones in the salt marsh were included. The zone inland of the former marsh cliff edge was also sampled (Figure 5.8). Selecting the transects in close proximity to one another minimized differences in exposure to tides, wind and waves and in suspended sediment concentration. We considered the transects without a dam to be the reference situation. Here, mudflats were situated directly against the cliff edge of the eroding upper marsh zone (Figure 5.2 a,b). This sampling design is known as an impact-reference sampling design (Morrison *et al.*, 2008) and is applicable to situations in which the effect of an intervention is being evaluated and no reference observations are available prior to the intervention.

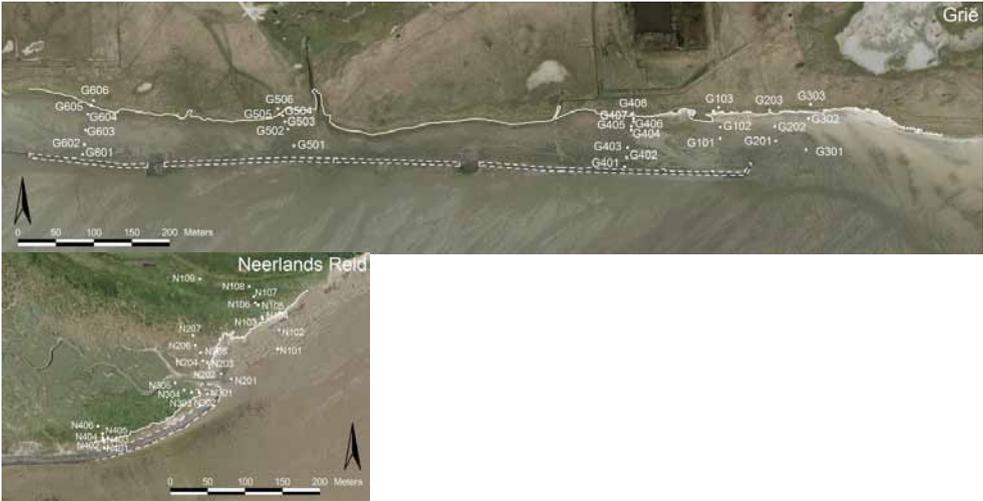


Figure 5.8: The plots with their numbers along transects perpendicular on the coastline at Grië (2010, top) and Neerlands Reid (2009, bottom). Contours of the erosion protection works are indicated by dashed white lines. The solid white line indicates the salt-marsh edge (Grië 2010 and Neerlands Reid 2009).

The fieldwork was carried out in August and September 2011. At this time of year, salt-marsh vegetation is at its most vigorous. We investigated the vegetation by making 4 m² relevés ($r=1.13$ m) estimating the abundance of the plant species found (Braun-Blanquet, 1928). An ordinal scale with ten classes was used for these estimates (Dirkse, 1998). Species were identified according to nomenclature following Van der Meijden (2005). Handheld GPS devices served for plot localization. Photographs were taken of each plot. Storage and handling of the vegetation relevés was one using TURBOVEG data management system (Hennekens & Schaminée, 2001; www.synbiosys.alterra.nl/turboveg/). Based on the species found, the plots were classified in plant communities as defined by Schaminée *et al.* (1998), with ASSOCIA (Van Tongeren *et al.*, 2008) and in habitats (European Commission, 2007; Janssen & Schaminée, 2003).

Results

Table 5.2 lists the plant species found in each transect. Table 5.3 presents the plant communities (syntaxa) based on the vegetation relevés. In total 44 plant species (taxa) were found on the plots (35 at Grië and 30 at Neerlands Reid). The top part of Table 5.2 shows the presence of typical salt-marsh plant species. Some species are restricted to Grië, others to Neerlands Reid (bottom part Table 5.2). For Grië these species represent the dominant *Elytrigia atherica* vegetation at the cliff edge (i.e., the climax stage of salt-marsh succession). Species restricted to Neerlands Reid are upper salt-marsh zone vegetation types (Figure 5.3, transect N1 and N2).

Table 5.2: Plant species and reference numbers recorded in the transects at Grië (G) and Neerlands Reid (N). Nomenclature follows Van der Meijden (2005).

Species	G1	G2	G3	G4	G5	G6	N1	N2	N3	N4
<i>Fucus species</i>							+	+		
<i>Ulva lactuca</i>	+	+	+	+	+	+	+		+	+
<i>Vaucheria species</i>	+	+	+	+	+	+	+		+	+
<i>Salicornia europaea</i>	+	+		+	+	+	+	+	+	+
<i>Spartina anglica</i>	+			+	+	+	+	+		+
<i>Suaeda maritima</i>	+			+	+	+	+		+	+
<i>Puccinellia maritima</i>	+			+	+	+	+		+	+
<i>Agrostis stolonifera</i>	+	+	+				+	+		
<i>Festuca rubra</i>	+	+	+		+		+	+	+	+
<i>Atriplex prostrata</i>	+			+			+	+	+	+
<i>Plantago maritima</i>	+	+		+	+	+	+	+		+
<i>Aster tripolium</i>				+	+	+	+	+	+	+
<i>Atriplex portulacoides</i>				+	+	+	+	+	+	+
<i>Spergularia media</i>				+	+	+	+	+	+	+
<i>Limonium vulgare</i>				+	+	+				+
<i>Artemisia maritima</i>					+			+	+	+
<i>Triglochin maritima</i>					+		+	+		+

<i>Glaux maritima</i>						+		+	+		+
<i>Potentilla anserina</i>		+				+		+	+		
<i>Armeria maritima</i>			+					+			+
<i>Elytrigia atherica</i>	+	+	+		+	+		+	+	+	+
<i>Atriplex littoralis</i>	+		+	+							
<i>Cochlearia officinalis</i> subsp. <i>anglica</i>				+	+	+					
<i>Odontites vernus</i> subsp. <i>serotinus</i>					+						
<i>Henediella heimii</i>						+					
<i>Juncus gerardi</i>								+	+		
<i>Bolboschoenus maritimus</i> s. <i>compactus</i>								+			
<i>Parapholis strigosa</i>								+			
<i>Carex distans</i>									+		
<i>Carex arenaria</i>	+										
<i>Sonchus arvensis</i> var. <i>maritimus</i>	+	+									
<i>Trifolium repens</i>	+	+	+		+						
<i>Poa pratensis</i>		+	+								
<i>Polygonum aviculare</i>		+	+								
<i>Ammophila arenaria</i>			+								
<i>Leontodon saxatilis</i>			+								
<i>Lolium perenne</i>			+								
<i>Vicia cracca</i>			+								
<i>Lotus species</i>			+								
<i>Rumex crispus</i>								+			
<i>Vicia lathyroides</i>								+			
<i>Cirsium arvense</i>									+		
<i>Phragmites australis</i>									+		
<i>Stellaria media</i>									+		
Total species per transect	15	12	15	14	20	14		25	20	12	18

Table 5.3: Plant communities (syntaxa) and reference numbers recorded in transects at Grië (G) and Neerlands Reid (N). Syntaxa and syntax codes follow Schaminée et al. (1998). Habitat codes follow Janssen & Schaminée (2003). RG = rompgemeenschap (impoverished vegetation).

Syntaxa	Syntaxa code	Habitat code	G1	G2	G3	G4	G5	G6	N1	N2	N3	N4
Spartinetum townsendii	24AA02	1320	+			+		+	+	+		+
Salicornietum dolichostachyae	25AA01	1310		+	+				+	+		
Salicornietum brachystachyae	25AA02	1310	+	+		+	+	+		+	+	+
Suaedetum maritimae	25AA03	1310								+		
Puccinellietum maritimae	26AA01	1330							+			+
Plantagini-Limonietum	26AA02	1330						+				
Halimionetum portulacoidis	26AA03	1330				+	+				+	+
Juncetum gerardi	26AC01	1330							+			
Artimisietum maritimae	26AC05	1330							+	+	+	
Atriplici-Elytrigietum pungentis	26AC06	1330	+	+	+	+	+	+	+	+	+	+
RG Scirpus maritimus (Asteretea tripolii)	26RG01	1330							+			

We encountered 11 salt-marsh plant communities ranging from those representing the early pioneer phase with *Salicornietum dolichostachyae* to those of the upper salt-marsh zone with the climax *Atriplici-Elytrigietum pungentis* vegetation. The following four habitats were encountered: ‘mudflats and sandflats not covered by seawater at low tide’ (H1140), ‘*Salicornia* and other annuals colonising mud and sand’ (H1310), ‘*Spartina* sward (*Spartinion*)’ (H1320) and ‘Atlantic salt meadows (*Glauco-Puccinellietalia*)’ (H1330). All relevant salt-marsh habitats were thus present. These last three habitat types enclose the ‘Atlantic and continental salt marshes and salt meadows’ (European Commission, 2007). Pooling the data from the two sites, the plant species found were categorized into four classes. Class boundaries were set such that the four groups formed quartiles: 25% of the plots had 0–4 species, 50% of the plots had 5–8 species, and 25% of the plots had more than 8 species. Figure 5.9 shows the spatial distribution of the EU-protected habitats (Habitats Directive, 1992) and the number of plant species found per plot.



Figure 5.9: Spatial presentation of habitats and number of species per plot at Grië (top) and Neerlands Reid (bottom). The meaning of the habitats codes is: H1310- halophyte pioneer vegetation, H1320- *Spartina* swards, H1330- salt marshes, including a diversity of typical vegetation, and H1140- mudflats and sandflats not covered by seawater at low tide (European Commission DG Environment).

The newly formed marsh areas between the dams and the former marsh cliffs were already well-established, representing the pioneer salt-marsh zone with *Salicornia* and *Spartina* (H1310 and H1320) (Figure 5.9). Habitat 1330, which is the vegetation of the upper marsh zone, was found behind the marsh cliff edges at both sites, but at some locations it was also

developing just in front of the former salt-marsh cliff. Species richness was greatest behind the cliff (the old salt marsh) and in the dam-protected area just in front of the cliff. Habitat 1140, ‘mudflats and sandflats’, was found not only in front of the marsh cliff without a dam (the reference situation), but also on the seaward side of the dams (visual registration, but not included in the vegetation survey).

5.3 Case study 2: Salt marsh Stryp (Terschelling)

Case description

The aim of this case study was to advance knowledge about the benefits on both biodiversity and flood protection and on possible side-effects of salt-marsh restoration.

Salt marsh Stryp is located in a sheltered corner alongside the dike that protects Stryp Polder (Figure 5.1, 5.10 and 5.11). The current Salt marsh Stryp measures some 4 ha and is covered with characteristic salt-marsh vegetation (Figure 5.10). The western part is accessible to sheep grazing the dike, while the eastern part is inaccessible due to a tidal gully resulting from a former pumping station outlet. The salt marsh forms a refuge for the abundant breeding and wading birds.



Figure 5.10: Vegetation in the salt marsh adjacent to the flood defence at Stryp (August 2011). Just in front of the dike is a strip of salt marsh dominated by *Puccinellia maritima* (H1330), flanked by vegetation dominated by *Spartina anglica* (H1320).

A precursor of Stryp Polder was created in the early 16th century when the salt-marsh area was first embanked. The current Wadden Sea dike (which also protects Polder Stryp) was constructed in 1858, since which time no breaches have occurred. Historical maps (e.g. Bonnebladen, 1920) show development of a small salt-marsh zone east of the polder between the dike and the drainage gully of a pumping station outlet. In the 1930s, local residents tried to stimulate sedimentation at this location by planting common cord grass (*Spartina anglica*), by digging ditches to improve drainage and by placing wooden groynes (Donkersloot-De Vrij 2002), enclosing an area of some 35 ha (Figure 5.11). The drainage gully of the pumping station (which was closed in 1948) developed into a tidal gully (Figure 5.11).

Maintenance of these reclamation works was discontinued in the 1950s. Their remnants, in the form of wooden groynes and ditches, are still visible in the field and on aerial photographs.



Figure 5.11: Pattern of ditches and wooden groynes constructed to enhance sedimentation and reclamation of new agricultural land on the east side of Stryp Polder, viewed on an aerial photograph taken by the Royal Air Force (UK) on 4 August 1944 (source: Land Registry Office or 'Kadaster'). The pumping station is marked by a white star. A white line indicates a stretch of dike that was outwardly extended in the 1960s; a stretch that is straightened later, is marked by a white triangle.

Stryp Polder, including the dike, was privately owned until 1955. In response to the flooding disaster of 1953, which caused more than 1,835 fatalities in the southwest delta area of The Netherlands, the dike was transferred to the local public water board and reinforcement plans were drawn up. By law, the Wadden Sea dike of Terschelling must protect the hinterland against extreme storm surges, as could statistically be expected once in 2,000 years.

Calculated hydraulic conditions of such an extreme storm surge for the dike east of Stryp are 4.2 m +NAP, wave setup 0.9 m, and wind direction of 30° (Ministerie van Verkeer en Waterstaat, 2007a). To meet this standard, the Wadden Sea dike of Terschelling (including the embankment around Stryp Polder) was reinforced during 1962-1968 to a height of 5.5-5.6 m +NAP (Gorter & Muiser, 1994). Along the outer berm, a maintenance path was constructed. East of Stryp Polder, this was done at the expense of a strip of some 17 m in width of salt marsh (Figure 5.11). Furthermore, a small area of land was transformed into sea by straightening a stretch of the dike (Figure 5.11). In the 1970s, the stone revetment at the toe of the dike was heightened to improve its resistance to wave action (Gorter & Muiser, 1994). In 1997, the revetment was again improved. In order to replace the stones, the toe of the dike east of Stryp Polder was excavated. Since then, the slightly lowered zone adjacent to the dike has tended to develop towards a gully in Salt marsh Stryp. The corner was smoothed in 2009 (compare Figure 5.11 and Figure 5.12).

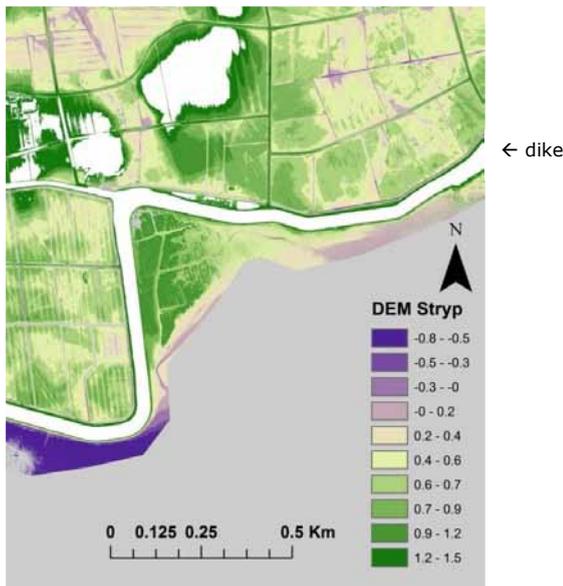


Figure 5.12: Map of Digital Elevation Model (DEM) in m NAP (Dutch reference height) of the salt marsh east of Stryp Polder. The white areas are the dike or small ponds (source: AHN 2012).

Currently, the remaining salt marsh at Stryp is some 0.90-1.20 m +NAP, with some lower-lying areas 0.60-0.90 m +NAP (Figure 5.12). Mean high-tide level is 0.83 m +NAP; spring neap tide is 0.95 m +NAP (Rijkswaterstaat). When storm surges come from the northwest, the water level in the Wadden Sea sets up. On the Wadden Sea side of Terschelling, a water level of 3.12 m +NAP was observed during the storm surge of 1953 (Gorter & Muiser 1994); a

water level of 3.24 m +NAP was observed during a storm surge in January 1976 (Rijkswaterstaat). During ‘normal’ storm surges from a north-easterly direction (occurring with a frequency of some 5 times per year) the water level along the Wadden coast is some 1.95 m +NAP. Southeast storms lead to a water level lower than normal, because the water of the Wadden Sea is blown towards the North Sea. As a consequence, the waves are already damped before reaching the Wadden Sea coast of Terschelling (A. Kiers pers. comm.).

Analysis of the salt-marsh area

Methods

We analysed erosion over the last 50 years by comparing the vegetated area on a time series of aerial photographs taken between 1944 and 2010, at intervals of about 10 years (see also section 5.2).

This study quantified changes in the position of the vegetated area. Only the main gullies and trenches were excluded from the areal calculation, because delineation of small trenches would decrease the degree of confidence between the years and the calculated erosion. The edge where cliff erosion occurred was very distinct.

Results

Analysis of the aerial photographs indicates an increase of the salt-marsh area of some 6 ha (7 ha if the strip used for dike reinforcement is included) between 1944 and 1959. The marsh expanded from approximately 3.2 ha to 9.2 ha (10.2 ha including the strip used for dike

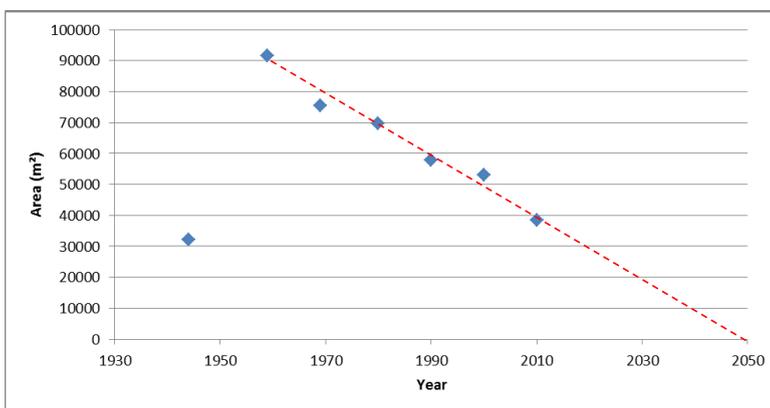


Figure 5.13: Development of the salt-marsh area of Salt marsh Stryp (Terschelling). Symbols represent the area measured on aerial photographs, and the dashed line represents the extrapolated decrease.

reinforcement). After 1959, a steady decrease is observed of some 0.1 ha/year, to reach 3.8 ha in 2010 (Figure 5.13). Besides diminishment due to erosion on the seaward side, the area also decreased due to a widening of the gullies and creeks and the onset of low-lying, unvegetated areas within the marsh zone (Figure 5.14). Extrapolation of the observed decrease indicates that the salt marsh at Stryp will disappear around 2050.



Figure 5.14: Salt-marsh area in 1959 (dashed line) and 2010 (solid line) (source: Kadaster). The star marks the groyne placed in 2010 to prevent erosion of the dike by the gully.

Vegetation surveys

Methods

To gain insight into the species composition, vegetation types and habitats, we applied the same method as described for case study 1 (see section 5.2). Eleven plots were chosen along 2 transects in the accessible part of the salt marsh. Plot spacing was chosen so as to include key transitions between vegetation zones in the salt marsh. The fieldwork was carried out in August 2011.

Additional vegetation relevés (measuring 4-25 m²) and charts were provided by the Data ICT Rijkswaterstaat (Department of the Dutch Department of Public Works and Water

Management) for the years 1996 (n=5), 2000 (n=5) and 2007 (n=7) (in July or September). These data were also stored and handled in TURBOVEG.

The study site was revisited at the end of the growing season of 2012 to sample *Atriplex portulacoides* L. (syn. *Halimione portulacoides* (L.) Aell.) and in June 2013. Although vegetation was not systematically surveyed, the visits provided an impression of the vegetation present during the winter and spring periods. In total, 20 samples of *A. portulacoides* were taken for age determination from randomized locations (see Decuyper *et al.*, 2014).

Results

In this relatively low-lying salt marsh, we observed a difference in vegetation species composition, height of vegetation and vegetation cover between the grazed and the ungrazed part (Figure 5.15). In the western part, which is accessible to sheep, the vegetation is short (5-15 cm) and dominated by *Salicornia europaea* and *Spartina anglica*, with *Puccinellia maritima* and low *Atriplex portulacoides* plants. In the most intensively grazed parts (Figure 5.15, in the foreground to the right), vegetation (here comprising solely *Salicornia*) was very scarce. Subsequently most of the sandy substrate was bare and not covered by plants.

The eastern part of the salt-marsh area is not accessible to the grazing sheep because of the gully. It is fully covered by dense patches of the shrubby perennial *A. portulacoides* and with *S. anglica*. The vegetation is taller here (15-25 cm) than in the grazed part (Figure 5.15).

Our vegetation surveys were mainly taken in the grazed part of the salt marsh (Figure 5.16). Table 5.4 lists the plant species found in each transect in August 2011. Table 5.5 and Figure 5.16 present the plant communities (syntaxa) and EU protected habitats found by us and by the Department of Public Works. In total, our vegetation survey found 11 plant species, of which 2 are macro-algae. We encountered 5 salt-marsh plant communities.



Figure 5.15: Photograph of the salt marsh at Stryp. In the foreground is the grazed area dominated by *Salicornia europaea*. Visible beyond the creek is the ungrazed area dominated by *Atriplex portulacoides* and *Spartina anglica* (28 June 2013).

Table 5.4: Occurrence of species on the different relevés in 2011.

Species	1a	1b	1c	1d	1f	2a	2b	2c	2d	2e	2f
<i>Ulva lactuca</i>	+										
<i>Vaucheria species</i>	+	+	+	+	+	+	+	+	+	+	+
<i>Salicornia europaea</i>		+	+	+	+	+	+	+	+	+	+
<i>Spartina anglica</i>		+	+	+	+	+	+	+	+	+	+
<i>Suaeda maritima</i>		+			+	+	+	+	+	+	+
<i>Puccinellia maritima</i>	+	+	+	+	+	+	+	+	+	+	+
<i>Aster tripolium</i>				+							+
<i>Atriplex portulacoides</i>		+			+	+	+	+	+	+	
<i>Spergularia media</i>	+						+	+			
<i>Limonium vulgare</i>			+	+	+		+	+	+	+	
<i>Triglochin maritima</i>				+	+		+	+			+
Total species per relevé	4	6	5	7	8	6	9	9	7	9	5

Table 5.5: Plant communities (syntaxa) at Salt marsh Stryp (n =number of vegetation relevés). Syntaxa and syntaxa codes follow Schaminée et al. (1998). Habitat codes follow Janssen and Schaminée (2003). The + symbols indicate how many relevés contained the plant community.

Year			1996	2000	2007	2011
Syntaxa	Syntaxa code	Habitat code	n=5	n=5	n=7	n=11
Spartinetum townsendii	24AA02	1320	+++	+++	+++	++
Salicornietum dolichostachyae	25AA01	1310			+	
Salicornietum brachystachyae	25AA02	1310	+	+	+++	+++
Puccinellietum maritimae	26AA01	1330		+		+
Halimionetum portulacoidis	26AA03	1330	+			+++++

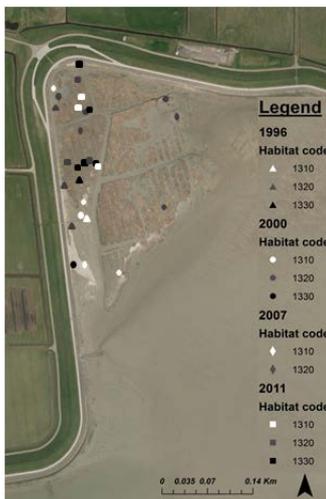


Figure 5.16: Spatial presentation of the habitats of the relevés. The meaning of the habitats codes is: H1310- halophyte pioneer vegetation, H1320- *Spartina* swards, H1330- salt marshes, including a diversity of typical vegetation, and H1140- mudflats and sandflats not covered by seawater at low tide (European Commission DG Environment).

Wave damping

Methods

Using the SWAN wave model (Booij *et al.*, 1999) we predicted the wave damping effect of Salt marsh Stryp under different conditions. SWAN explicitly considers the effect of varying wave/wind conditions and local bathymetry on near-shore wave parameters (height, period and direction). In this study, a detailed computation domain with different salt-marsh states was nested into an overall domain in order to obtain suitable boundary conditions. The overall domain is a square, which is 4000 m from east to west and 4000 m from north to south. Its origin is 53°21'N, 5°17'E. The detailed domain is a 1200 m by 1200 m square located inside the overall domain. Its origin is 2000 m north and 1000 m east to that of the overall domain. Both domains used a rectangular 20 m by 20 m grid.

The model was forced by given incident wave conditions while the effect of wind was not included for simplicity. The incident wave came from the southeast of the overall domain, which is about 3000 m seaward of the dike. Because a southeast wind leads to a low water level and low wave heights (because the water of the Wadden Sea is blown towards the North Sea), we applied a water level of 0.95 m instead of the extreme water levels associated with storms from the northeast (4.2 m). We tested incident significant wave heights of 0.5 m and 0.15 m, while the peak wave period was fixed to be 2.5 second. A JONSWAP spectrum (Hasselmann *et al.*, 1973) was selected to be the incident wave spectrum. Other parameters that describe wave shoaling, breaking and bed friction were set to default values.

To gain insight into the effect of salt-marsh degradation and restoration, we compared the situation with a salt marsh present to a situation without a salt marsh (as a result of ongoing erosion) and to a situation with a broader salt marsh (as a result of salt-marsh restoration) (Table 5.6). The salt marsh was characterised by the present bathymetry of Salt marsh Stryp, which constitutes an elevated area near the dike with a triangular shape (see Figure 5.12). In the situation without the salt marsh, the elevation from dike towards the sea was set at 0 m +NAP, while for the situation of the restored salt marsh the elevated area (at 0.5 m +NAP) was extended by some 350 m in the seaward direction). Furthermore, for the restored salt marsh, the mudflat in front of the saltmarsh (up to ~1000 m in front of the dike) was elevated to allow for a natural gradient between salt marsh and mudflat. To illustrate the bathymetry in these three scenarios, one-dimensional profiles along a north-south transect (vertical white lines in Figures 5.17a-g) are shown separately in Figure 5.17h. Several detailed results on wave-damping are shown for this transect (see Figures 5.18 and 5.19).

To obtain an impression of the potential effect of the vegetation we compared the situation with an unvegetated salt marsh, to a situation with a salt marsh densely vegetated by short grasses and salt-marsh plants (such as *Puccinellia maritima* and *Salicornia europaea*), to a situation with a salt marsh sparsely vegetated by short grasses, and to a situation with a salt marsh vegetated by a shrubby, branched plant (such as *Atriplex portulacoides*). We used the averaged plant height (as observed at Salt marsh Stryp in August 2011). For the class 'salt marsh with high density of low plants' we used plant density (stems/m²) and stem diameter comparable to these found on a low/middle salt-marsh zone on a nearby salt-marsh location. At that location all stems in sub-samples of 60 surveyed relevés were counted and the diameter of the encountered species were estimated (see Chapter 7). We applied estimations of the density of the sparsely vegetated salt marsh zone and of the shrubby *Atriplex portulacoides* (which has a vertical layered structure because of branching of the main stem). We used the averaged stem diameter of a subsample of *Atriplex portulacoides*.

Also the drag coefficient is important to the modelling outcome, but cannot be obtained easily by field surveys as it depends on both plant traits as well as on hydrodynamic conditions (Nepf, 2011). Accurately determining drag coefficients requires a large number of flume experiment data (Hu *et al.*, 2014). Therefore, for simplicity a drag coefficient of 1.0 and 1.2 was used in our study, as commonly found in previous studies (Nepf, 2011; Suzuki *et al.*, 2012).

Furthermore, we analyzed the effect on wave propagation of a higher water level, which might become the situation if the elevation of the salt marsh is unable to keep pace with rising sea level (Table 5.7). We used information from the Department of Public Works on the bathymetry (with a grid of 20-20 m) of the Wadden Sea.

Table 5.6: The different situations for wave height 0.5 and 0.15 m, wind from the southeast, wave period 2.5 s and water depth 0.95 m +NAP (spring tide level) for which SWAN calculations were made. The values refer specifically to conditions along the transect indicated in Figure 5.17.

Situation	Salt marsh	Salt marsh vegetation	Plant height (m)	Plant density (stems/m ²)	Stem diameter (m)	drag coefficient
a. Salt marsh without vegetation	current situation	no	-	-	-	-
b. Salt marsh with high density of low plants	current situation	plants	0.04	21800	0.0005	1
c. Salt marsh with low density of low plants	current situation	plants	0.04	1000	0.0005	1
d. Salt marsh with high plants	current situation	plants	0.25	385	0.0021	1
e. Salt marsh with high plants with high drag coeff.	current situation	plants	0.25	385	0.0021	1.2
f. No salt marsh	eroded marsh	no	-	-	-	-
g. Broadened salt marsh	restored	plants	0.25	385	0.0021	1.2

Table 5.7: The different situations for wave height 0.5 m, wind from the southeast, wave period 2.5 s with a high sea level rise (SLR) scenario (85 cm), a medium SLR scenario (35 cm) and a low SLR scenario (10 cm) for which SWAN calculations were made. The values refer specifically to conditions along the transect indicated in Figure 5.17.

Situation	Salt marsh	Water depth	Salt marsh vegetation	Plant height (m)	Plant density (stems/m ²)	Stem diameter (m)	drag coefficient
a. High SLR	eroded	1.8	no	-	-	-	-
b. Medium SLR	eroded	1.3	no	-	-	-	-
c. Low SLR	eroded	1.05	no	-	-	-	-
d. High SLR and broadened marsh	restored	1.8	plants	0.25	385	0.0021	1.2
e. Medium SLR and broadened marsh	restored	1.3	plants	0.25	385	0.0021	1.2
f. Low SLR and broadened marsh	restored	1.05	plants	0.25	385	0.0021	1.2

Results

Figure 5.17 presents the modelled significant wave height distribution for the different situations (see Table 5.6). We see from the figure that at this location the salt marsh dampens the waves. In a situation without a salt marsh (Figure 5.17f) there is hardly any wave damping compared to a situation with an area of salt marsh present (Figure 5.17a-e). Broadening the salt-marsh zone in front of the dike (Figure 5.17g) increases wave attenuation. Figure 5.17 shows a clear effect of vegetation. A dense vegetation of short plants (Figure 5.17b) and a vegetation of tall plants (Figure 5.17d and e) affect the height of the waves, whereas a sparse vegetation of short plants (Figure 5.17c) shows a wave damping pattern similar to an unvegetated salt marsh (Figure 5.17a). Figure 5.18 presents the wave propagation along the transect indicated in Figure 5.17 by a white vertical line.

The model boundary is 2000 m seaward from the rightmost values at x-axes in Figures 5.18 and 5.19. Because of wave breaking and friction over this distance, the wave heights at the right in these figures are considerably less than the imposed wave heights of 0.5 m and 0.15 m. In fact, the modelled wave damping in this environment is some 0.08% per m (for the situation with an initial wave height of 0.5 m), while wave damping by 350 m of unvegetated marsh or sparsely vegetated marsh is some 0.13% m per m and 0.14% m per m respectively. The modelled wave damping by the densely vegetated marsh is some 0.22% per m, and by a salt marsh vegetated with the shrubby plant is some 0.20% per m. This is strikingly similar to reported wave damping by salt marshes of the same length and comparable dominant plant species (Anderson *et al.*, 2011, see Table 1 in that study).

Figure 5.19 presents the modelled significant wave height for different sea level rise scenarios. This figure shows that under sea level rise, a broadening of the salt-marsh zone significantly influences the height of the waves.

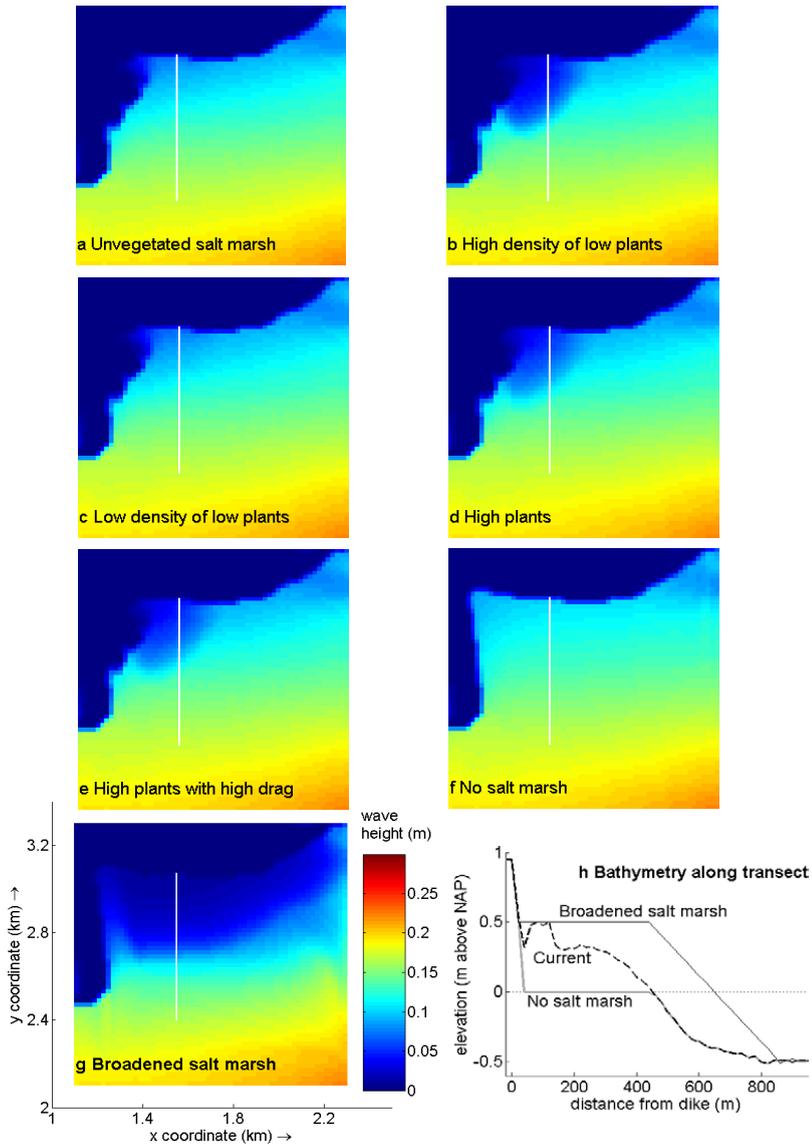


Figure 5.17: Modelled significant wave height distribution for the different situations. The white vertical line indicates the transect to which the parameters in Table 5.6 refer and for which results are also shown in Figure 5.18 top. The bathymetry for this transect (for the three different scenarios) is shown in 6.17h. The 0,0 coordinate of the graph is situated at 53°21'N, 5°17'E.

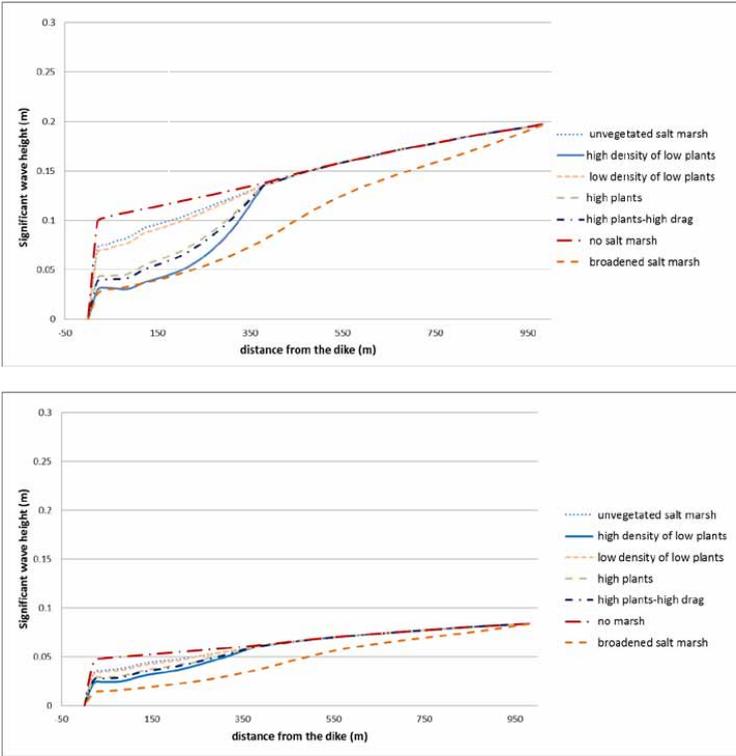


Figure 5.18: Modelled significant wave height (top=wave height of 0.5 m; bottom=wave height of 0.15 m, both at 3,000 m) along a transect perpendicular to the coast near the Stryp Polder under different situations (see Table 5.6).

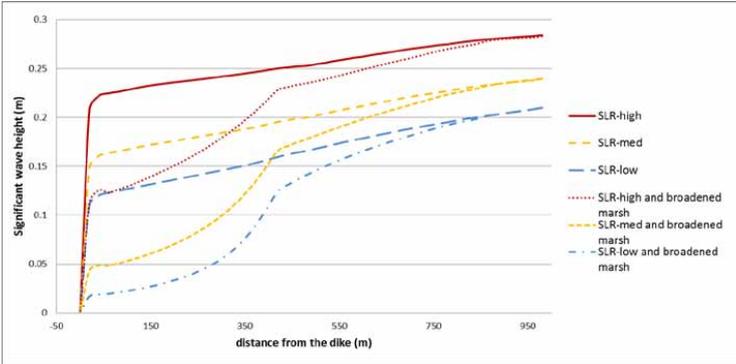


Figure 5.19: Modelled significant wave height for different sea level rise (SLR) scenarios (wave height of 0.5 m at 3,000 m). See Table 5.7.

5.4 Case study 3: Dollard salt marshes

Case description

This case focuses on the application of salt marshes in combination with a Wide green dike along the Dollard (Figure 5.1). The presence of extensive salt-marsh area in front of the Dollard dike, together with the satisfactory performance of the Wide green dikes along the German Dollard coast, triggered the interest for a Wide green dike along the Dutch side of the Dollard. A wide green dike has a shallow sloped seaward face (with a slope of some 1:7) covered by a thick layer of clay and grass, and merges into the adjacent salt marshes. Normally, incoming waves are damped by the salt-marsh foreland. Therefore, salt marshes form an indispensable part of the Wide green dike concept. Additional to this, salt marshes could potentially form a source for the clay needed for the construction of the dike, as they traditionally did.

The impact of the Wide green dike on salt marshes is explored by comparing the potential differences between a Wide green dike and a Traditional dike reinforcement in impact on the Dollard salt-marsh area as well as on nature values.

The Dollard is an embayment of some 10 x 10 km with extensive salt marshes along the south and eastern coasts (on some locations more than 2 km in width, see Figure 5.20). It is located on the northeast border between the Netherlands and Germany and is part of the Ems-Dollard estuary (Figure 5.1 and 5.20). The first inhabitants used the Dollard salt marshes mainly as pasture for their cattle. Over time, they protected their agricultural land against flooding by building dikes (Cools, 1948). After some disastrous dike breaches, the Dollard reached at the beginning of the 16th century its maximum size (Cools, 1948; Esselink, 2000). Thereafter a period of fairly intensive salt marsh reclamation started. Since the 18th century, sedimentation was stimulated by land reclamation works. After the reclamation of some 670 ha land in 1924, a comparable salt marsh extent was created in front of the new polder within 30 years (Esselink *et al.*, 2011). The applied reclamation works comprised dams of clay complemented with drainage ditches. Since the late 1950s the maintenance of these dams stopped, which led to a slow lateral erosion of the Dollard salt marsh with an average of 1.4 ha/year in 1981 to about 0.3 ha/year in 2008 (Esselink *et al.*, 2011), while the height of the marsh increased with an average of 8.4 mm /year (including the effects of subsidence caused by gas extraction in the eastern part) (Esselink *et al.*, 2011).

Currently there are some 1000 ha of salt marshes seaward of the dike, of which 760 ha is situated in the Dutch part of the Dollard (Esselink *et al.*, 2011). The western part of these salt

marshes along the southern coast is privately owned (some 263 ha), and the eastern part (some 450 ha) is owned by the nature conservation organization *Stichting Groninger Landschap* (SGL) (Figure 5.20).



Figure 5.20: Dike (red in the Netherlands and white in Germany) with salt marshes along the southern and eastern coast of the Dollard.

The area seaward of the dike, is both in Germany and the Netherlands designated as Natura 2000 site Wadden Sea and protected by (inter)national legislation (Ministerie van Landbouw, Natuurbeheer en Visserij, 2011). Due to the brackish character, the Dollard salt marshes harbour some typical plant species compared to other Wadden Sea salt marshes. Furthermore, the Dollard is a bird region of global significance.

Interventions like deepening and streamlining of navigation channels, affected the tidal range and flow and did lead to increased turbidity (Esselink *et al.*, 2011; De Jonge *et al.*, 2014), which is a major concern in view of water quality standards and ecological quality. The Dollard itself is not dredged, but modelling revealed that a large part of the sludge that is

deposited near the Dollard is dispersed into the Dollard (Cleveringa, 2008). Objectives and measures to improve the water quality are part of the Ems river basin management plan.

The dikes along the Dutch part of the Dollard are designed to withstand extreme events with a return period of 1/4,000 per year. These dikes comprise an earth structure (height 7.7-9.3 +NAP; width 53-67 m along the south section of the Dollard) covered with clay and grass completed by a stone revetment at the toe, an berm at the landward side, maintenance roads (on the berm at the landward as well as on the seaward face) and a ditch which borders the salt marshes in front of the dike (Figure 5.21). The upper part of the present seaward slope has a gradient of 1:7, while the lower part has a gradient of 1:4.

Some 80% of the present dike along the Dutch part of the Dollard does not meet the current standards, mainly due to problems with the grass cover in the wave impact zone (Waterschap Hunze en Aa's, 2010). Including the expected impact of climate change in the evaluation criteria for flood safety will likely result in additional reinforcement tasks. A Traditional dike-reinforcement would result in an improved revetment of asphalt and stones. The presence of extensive salt-marsh area in front of the dike, together with the satisfactory performance of the Wide green dikes along the German Dollard coast, triggered the interest for a Wide green dike along the Dutch side of the Dollard. This grass covered dike merges into the adjacent salt marshes. Normally, incoming waves are damped by the salt-marsh foreland. Only during storm conditions waves will reach the dike. The shallow seaward slope reduces wave action and wave run-up, and therefore a cover of grass (on a thick clay cover) is sufficient to protect the dike against erosion during extreme conditions, and no stones or asphalt revetment is required (Waterloopkundig Laboratorium, 1984). Such a Wide green dike fits much better in the Wadden Sea landscape than a reinforced traditional dike. However, such a wide dike needs more space than a traditional dike reinforcement, and more clay as well.

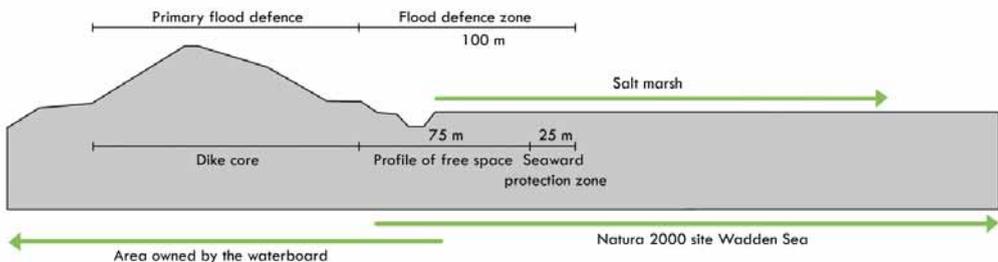


Figure 5.21: Cross section of the profile of the Dollard dike.

A seaward zone of some 100 m adjacent to the dike is subjected to planning restrictions and is reserved for future dike reinforcements. Part of this zone (till the seaward side of the drainage canal) is owned by the water board, which is also responsible for the maintenance of this zone. However, all area seaward of the toe of the dike is appointed as Natura 2000 area (Figure 5.21).

To gain insight into the spatial impact of a Wide green dike on the present salt-marsh area, we compared the footprint (i.a. the space needed) of the Wide green dike with the footprint of a Traditional dike. In our analyses the Traditional dike is characterized by a grass cover on the upper part of the seaward slope (1:7) and an asphalt cover on the lower part of the seaward slope (1:4), while the Wide green dike is covered by grass on the entire seaward face (1:7). We designed both dike-concept for different climate change scenarios.

Furthermore, the difference in clay demand between both dike-concepts was calculated.

The nature value of a Wide green dike was explored by a survey of the vegetation on the seaward slope. Such quantitative information (besides information about e.g. construction and maintenance costs, and benefits for the landscape quality) will be needed in the decision process on the best reinforcement strategy.

Spatial impact of the Wide green dike

Methods

In order to gain insight into the differences in footprint of both dike-concepts, firstly the southern part of the Dollard (which is 10.75 km) was divided in four more or less homogeneous dike sections (see Figure 5.22).



Figure 5.22: Dike section along the southern part of the Dollard (left) and the cross sections of the profiles of these four sections (right) (Van Loon-Steensma & Schelfhout, 2013b).

Thereafter, the footprint of both dike-concepts for the 4 dike-sections was calculated based on the required crest height under updated hydraulic boundary conditions (Smale & Hoonhout, 2012) and three scenarios out of a range in sea level rise scenarios explored by the Delta program (see Bruggemans *et al.*, 2013). These scenarios comprised a sea level rise of i) 0.35 m in 2050 (moderate sea level rise), ii) 0.60 m in 2100 (moderate sea level rise on the long term), iii) 0.60 m in 2050 (severe sea level rise on the short term), and iv) 0.85 m in 2100 (and for the latter 10% higher wind speeds) (severe sea level rise) with respect to the sea level in 2015. Furthermore, we analyzed the impact of enhancing the safety 10 times for the scenario of 0.6 m sea level rise in 2100, by building a Delta dike (see Deltacommissie, 2008) that can withstand overtopping during extreme conditions which statistically occur 1/40,000 year (instead of the current standard of 1/4,000 year). We included 0.6 m in the crest height to account for foreseen changes and uncertainties with respect to subsidence and hydraulic conditions in the planning period. The software used for the crest height calculations was 'PC-overslag'¹. The expected extreme water levels and wave heights for the different climate change scenarios were calculated with the software Hydra-K².

Information of Rijkswaterstaat on salt-marsh habitats in the Dollard was used to estimate how much of the present salt marsh would be affected by the extra space needed for the Wide Green dike.

Results

Table 5.8 presents the calculated required crest heights for both dike-concepts (for all four sections) under different climate change scenarios and for different time horizons. Sea level rise will impose a severe task to increase the crest heights of most dike sections along the Dollard as illustrated by these results. But updating the hydraulic boundary conditions (from an extreme water level of 6.5-6.7 m +NAP and wave heights of 0.9-1.15 m for the four dike sections, into 6.3-6.6 m +NAP and 1.0-2.2 m respectively) also results in a task for dike reinforcement. Dike section 4 is in the present situation overdimensioned, which results in a postponed reinforcement task for this section. Table 5.9 and Figure 5.23 present the extra space needed for both dike concepts under different climate change scenarios and for different time horizons with respect to the present situation. Only a Traditional dike designed for a planning horizon till 2050 under moderate sea level rise (0.35 m in 2050) does not require salt-marsh area seaward of the present drainage canal. In all other scenarios (when

¹ The model PC-Overslag can calculate wave run up and overtopping for all possible situations, and is based on technical publications about wave run up and overtopping by e.g. Van de Meer (2002).

² With the model Hydra-K coastal defences can be tested probabilistically on the failure mechanisms wave run-up, overtopping and instability. The model can also generate combinations of wave conditions and water levels in order to define hydraulic boundary conditions for hard defences.

anticipating on higher sea level rise or designing for a longer term), the footprint of the reinforced dike will exceed the area owned by the water board (which is bounded by the ditch).

Table 5.8: Calculated required crest height of a Traditional dike and a Wide green dike for 4 sections along the Dollard under different climate change scenarios (Van Loon-Steensma & Schelfhout, 2013b).

Present situation		Updated hydraulic boundary conditions		Traditional dike				Wide green Dollard dike				
Dike section	length (km)	Min-Max crest height (m +NAP)	Mean crest height (m +NAP)	Crest height (m +NAP)	0.85 m SLR in 2100 + 10% higher wind speeds				0.85 m SLR in 2100 + 10% higher wind speeds			
					0.35 m SLR in 2050	0.60 m SLR in 2050 or 2100	Delta dike (10 x safer; 0.6 m SLR in 2100)	Crest height (m +NAP)	0.35 m SLR in 2050	0.60 m SLR in 2050 or 2100	Delta dike (10 x safer; 0.6 m SLR in 2100)	Crest height (m +NAP)
1	5.05	7.89-9.29	8.8	9.3	9.8	10.4	11.1	11.3	9.3	10.3	10.5	11
2	2.5	7.95-8.52	8.2	8.5	9	9.5	10.3	10.3	8.9	9.8	9.9	10.5
3	1.65	7.86-8.49	8.2	8.4	9	9.6	10.3	10.5	8.7	9.5	9.8	10.3
4	1.55	7.75-8.01	7.9	7.3	7.8	8.6	9.1	9.3	7.9	8.8	8.9	9.3

Table 5.9: Calculated extra space needed for a Traditional dike and a Wide green dike for 4 sections along the Dollard under different climate change scenarios (Van Loon-Steensma & Schelfhout, 2013b).

Present situation			Traditional dike				Wide green Dollard dike			
Dike section	length (km)	Width (m)	0.85 m SLR in 2100 + 10% higher wind speeds				0.85 m SLR in 2100 + 10% higher wind speeds			
			0.35 m SLR in 2050	0.6 m SLR in 2100	Delta dike (10 x safer; 0.6 m SLR in 2100)	Extra space (m)	0.35 m SLR in 2050	0.6 m SLR in 2100	Delta dike (10 x safer; 0.6 m SLR in 2100)	Extra space (m)
1	5.05	ca. 53	6	10	14	15	16	19	20	29
2	2.5	ca. 65	4	6	11	12	15	18	20	23
3	1.65	ca. 67	5	9	12	15	15	17	19	23
4	1.55	ca. 59	4	6	8	10	14	16	18	20

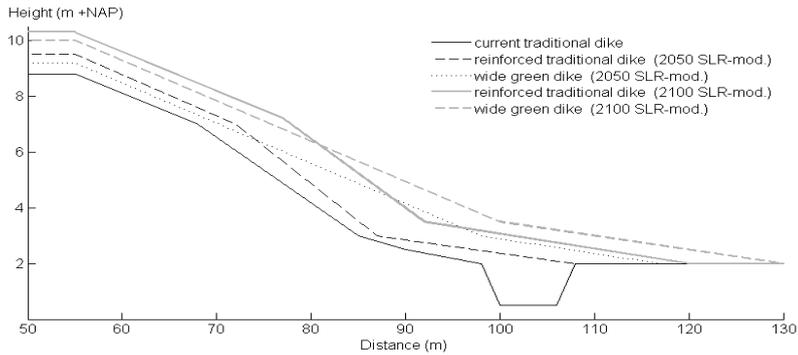


Figure 5.23: Required dike profile for the Traditional dike and Wide green dike (for 2050 and 2100 under moderate sea level rise) for dike section 1 compared with current situation.

A Wide green dike (designed for a planning period till 2050 under a moderate climate change scenario) needs at the seaward side some 10 m additional space compared to a Traditional dike. This implies that that some 11 ha salt marshes (with different salt marsh types, see Figure 5.24) seaward of the ditch is needed for implementing the Green Dollard Diike. Concerning the area between the toe of the current dike and the seaward side of the ditch there is no difference between both dike concepts (as it will be used for dike reinforcement in any case).

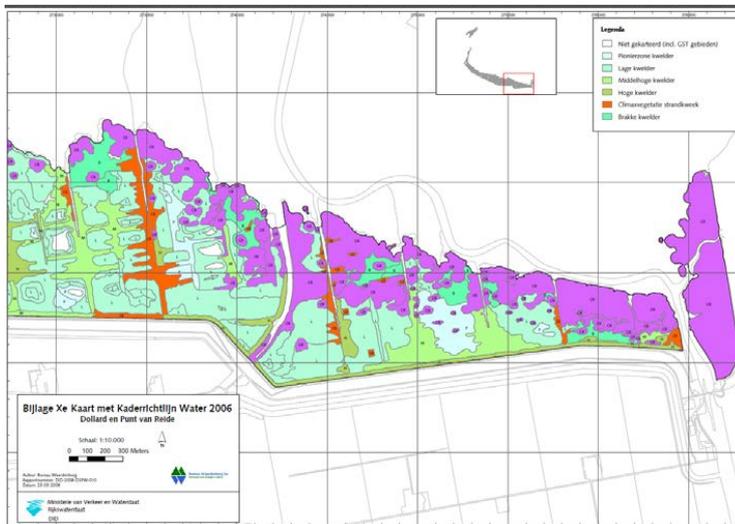


Figure 5.24: Habitats along section of Dollard dike. The green, aquamarine, red and purple patches represent respectively high salt-marshes, low salt-marshes, climax vegetation and reed (source: Rijkswaterstaat).

Clay demand

Methods

To get an impression of the difference in clay demand between both dike concepts, the amount of clay needed was estimated for designs with a planning period till 2050 under a scenario of moderate sea level rise (0.35 m in 2050 with respect to 2015).

It was assumed that the landward face of both concepts is covered with a layer of 0.8 m clay, that the crest and the upper part (wave run-up zone) of the seaward face of the Traditional dike is covered with a layer of 1.2 m clay and the lower part (wave action zone) is covered with asphalt on a sand layer, whilst the lower part of the wide green dike is covered by a thick clay layer of 2.0 m (Figure 5.25).

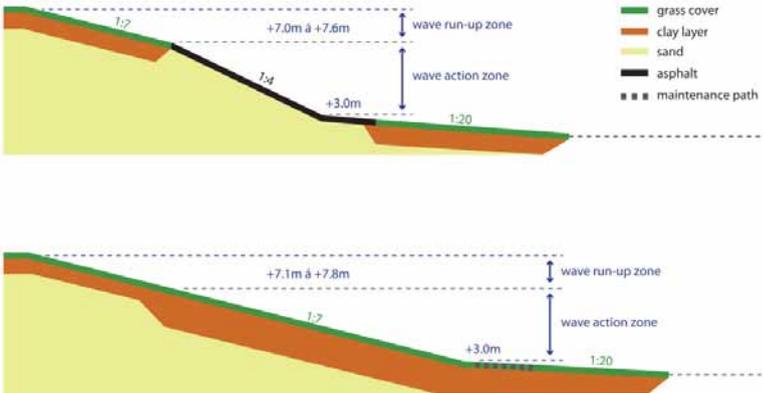


Figure 5.25: Schematized cross-sections of Traditional dike (top) and Wide green dike (bottom).

Results

Table 5.10 presents the clay demand for both the Traditional dike and the Wide green dike concept designed for a planning period till 2050 under a scenario of moderate sea level rise (0.35 m in 2050 in respect with 2015). Additional to the difference in clay and sand demand, an important difference between the Traditional and the Wide green dike is that no asphalt is needed in the wave action zone of the Wide green dike.

Table 5.10: Estimated volume of sand and clay required for the seaward layer of a Traditional dike and a Wide green dike (see Figure 5.25) along the southern part of the Dollard designed for a planning period till 2050 under a scenario of moderate sea level rise (0.35 m in 2050 with respect to 2015).

Dike section	length (km)	Traditional dike		Wide green dike
		Sand	Clay	Clay
		(x 1000) m ³	(x 1000) m ³	(x 1000) m ³
1	5.05	188.673	242.304	496.982
2	2.5	82.668	96.137	215.118
3	1.65	54.153	65.131	139.155
4	1.55	49.848	48.426	120.448
		375.342	451.998	971.703

Dike Vegetation

Methods

In order to get an impression of the potential floristic value of a Wide green dike with respect to the Traditional dike, which is sown with a robust and dense sod-forming grass-mixture, we surveyed in July 2013 the vegetation on two plots (16 m²) at the seaward slope of the present Traditional dike and on two plots on the nearby German Wide green dike (Fig 5.26).



Figure 5.26: Locations of the survey plots.

Results

Table 5.11 gives the species found on two plots on the present Traditional dike on the Dutch side, and in two plots on the Wide green dike on the German side. According to Frissel *et al.*

(2006) and VTV 2006 (Ministerie van Verkeer en Waterstaat, 2007b) the vegetation in both Dutch plots can be classified as ‘species poor Lolio-Cynosuretum grassland’, and the vegetation on the German plots as ‘Poo-Lolietum grassland’ and ‘species poor Arrhenatheretum grassland’. According to VTV 2006 (Ministerie van Verkeer en Waterstaat, 2007b) the ‘species poor Lolio-Cynosuretum grassland’ is moderately to fairly erosion resistant and represents a moderate ecological value, whilst the ‘Poo-Lolietum grassland’ is poorly to moderately erosion resistant and represents a poor ecological value and the ‘species poor Arrhenatheretum grassland’ is poorly erosion resistant and represents a poor ecological value.

Table 5.11: Species (grasses and forbs) found on 23 July 2013 on two plots on the Dutch dike along the Dollard (NL1 and NL2) and on two plots on the German dike along the Dollard (D1 and D2). + = a few ind. plants, r = one or very few individual plants coverage < 5% of the plot area, 1 = some plants (1-50 ind.) < 5% coverage of the plot area, 2m = some plants (>50 ind.) < 5% coverage of the plot area, 2a = 5-12.5% coverage, 2b = 12.5-25% coverage, 3 = 25-50% coverage, 4 = 50-75% coverage. Nomenclature follows Van der Meijden (2005).

	NL1	NL2	D1	D2
Grasses				
<i>Arrhenatherum elatius</i>				2a
<i>Agrostis stolonifera</i>	2a	2a	2b	1
<i>Bromus hordeaceus</i>	1	1	2a	
<i>Cynosurus cristatus</i>	1	2a	1	
<i>Dactylis glomerata</i>	1		2a	2b
<i>Elytrigia repens</i>	2b	1	1	1
<i>Festuca rubra</i>	4	5	1	2m
<i>Hordeum murinum</i>	1			
<i>Lolium perenne</i>	2b	2a	4	3
<i>Phleum pratense</i>			1	
<i>Poa trivialis</i>				1
<i>Poa pratensis</i>	1			
Forbs				
<i>Achillea millefolium</i>		+		
<i>Bellis perennis</i>	1	1		
<i>Cerastium fontanum</i>			2a	
<i>Leontodon autumnalis</i>			1	
<i>Rumex acetosella</i>			+	
<i>Rumex crispus</i>				+
<i>Stellaria media</i>			2a	
<i>Taraxacum officinale</i>			+	
<i>Trifolium dubium</i>	+		1	
<i>Trifolium repens</i>	1			+
<i>Veronica arvensis</i>	+			
Number of species	12	8	15	9

5.5 Discussion

Impact of erosion protection measures and cessation of maintenance of accretion works on salt-marsh extent and vegetation

Analysis of the areal extent of the salt marshes at Grië and Neerlands Reid (case 1) and Stryp (case 2) revealed that the implementation of erosion protection measures, as well as the implementation and the cessation of maintenance of accretion works affected the salt marsh area within decades. This also applies to the Dollard salt marshes (case 3) (Esselink *et al.*, 2011).

At Grië, the dam at 60 m in front of the marsh cliff effectively diminished the retreat of the marsh edge (from 1.3 m per year before construction of the dam to 0.2 m per year after construction of the dam), and reclaimed in 20 years an expanse of salt marsh (some 15 ha) that had been eroded in the preceding 45 years.

At Neerlands Reid the reinforcement of the dam in the late 1990s, resulted within 10 years to the restoration of 4.3 ha salt marsh behind the dam (which was eroded since the early 1990's).

The aim of the measures taken at Stryp in the 1930s was to reclaim land. The expansion of salt marsh by some 7 ha between 1944 and 1959 demonstrates that the accretion works stimulated sedimentation and subsequently formation of the salt marsh east of Stryp Polder. Nevertheless, the salt-marsh area present in 1959 (10.2 ha including the strip used for dike reinforcement) related to the area enclosed by accretion works (34 ha) indicates that the abiotic conditions east of Stryp are not particularly favourable for salt-marsh development.

Since the cessation of maintenance of the accretion works, the marsh area at Stryp has steadily diminished. Lateral erosion (at the outer salt marsh edge and the creek edges) and medial erosion (of the salt marsh interior) have both been at work. Although a small area of salt marsh might remain in the most sheltered corner, our analysis indicates that under unchanged conditions the salt marsh will probably disappear around 2050.

In the Dollard, some 670 ha salt marsh developed within 30 years after implementation of reclamation works, while after cessation of the maintenance of these works in 1954, the salt marsh area decreased with an average of 1.4 ha/year in 1981 to about 0.3 ha/year in 2008 due to lateral erosion (Esselink *et al.*, 2011). However, at the same time the height of the Dollard marshes increased with an average of 8.4 mm /year (including the effects of subsidence caused by gas extraction in the eastern part) (Esselink *et al.*, 2011).

At both Grië and Neerlands Reid, characteristic pioneer salt-marsh vegetation (H1310 and H1320) developed in the raised area between the erosion protection works and the former marsh edge. These habitats were not found in the transects without erosion protection, which was the reference situation. In addition to preventing the retreat of the salt-marsh cliff, the low dam in front of the eroding marsh edge thus appears to have created favourable boundary conditions for sedimentation. This effectively meant the restoration of pioneer marsh vegetation (H1310 and H1320 and at some places already H1330) in salt-marsh areas that were changed into mudflats and sandflats (H1140) by erosion.

The salt-marsh species and habitats found at Salt marsh Stryp are in accordance with what can be expected on a salt marsh of this height (0.9-1.2 m +NAP, which is up to 0.4 m above the local mean high water) and age (some 70 years). The grazed and lowest-lying parts of the salt marsh are dominated by the pioneer species *Salicornia europaea* and *Spartina anglica*, with on the middle section, also *Puccinellia maritima*, which is a fast-growing and prostrate small species that is tolerant to trampling and damage caused by grazing sheep.

The part of Salt marsh Stryp that is not accessible to sheep is dominated by the shrubby perennial *Atriplex portulacoides* and *Spartina anglica*. *Atriplex* is a late successional species found at sites some 20 cm above mean high water (Olf *et al.*, 1997). *A. portulacoides* at this site has a well-developed root system, being relatively wide and densely branched (Decuyper *et al.*, 2014). Due to its relatively high and wide stems this species is vulnerable to mechanical damage, as well as to grazing. As a result, trampling and grazing by livestock excludes this plant species from most of the salt marshes in Europe, restricting its occurrence to creek banks (Kiehl *et al.*, 1996; Dormann *et al.*, 2000). The age of the *A. portulacoides* sampled at Stryp was between 3 and 15 years (average 7-8 years) (Decuyper *et al.*, 2014). Obviously, in the ungrazed area of Stryp, *A. portulacoides* is able to survive for a longer period despite the unfavourable abiotic boundary conditions (ongoing erosion). *A. portulacoides* is also found along the creek banks in the grazed part of the salt marsh.

Like the salt marsh vegetation of Salt marsh Stryp, the vegetation of the Dollard salt marshes is influenced by grazing. Initially the vegetation of the marsh edge was dominated by *Pragmites australis* and *Bolboschoenus maritimus* (Esselink, 2000). However, the abundance of the latter species decreased, presumably by grazing by geese (Esselink *et al.*, 2011). Since the management of the eastern part of the salt marshes in 1984 shifted towards a more nature oriented management style (through a lower stock density and discontinuation of the maintenance of the drainage ditches), density of *P. australis* increased (Esselink *et al.*, 2011).

Effect of area and vegetation on wave height

The modelling work in case study 2 indicates that wave height (of low waves) is significantly affected by the areal extent of the salt marsh as well as by the vegetation at Stryp. Tall vegetation (such as *A. portulacoides*) and dense short vegetation (such as *Puccinellia maritima*) are in our models nearly as effective in wave attenuation as a widening of the salt-marsh area by 350 m. A low density of short plants, as observed in the grazed part of the marsh, had almost no wave damping effect. Therefore, if improved wave damping capacity of a salt marsh is desired, intensive grazing by sheep is not advisable.

In the modelling work a drag coefficient of 1.0 and 1.2 was applied, as commonly found in previous studies (Nepf, 2011; Suzuki *et al.*, 2012). However, in order to get more insight in actual wave damping by natural salt-marsh vegetation it is advisable to explore the differences in drag coefficient between a dense vegetation of short and thin leaves and a vegetation of shrubby plants in depth by both flume experiments and field observations of wave damping.

The effect of sea level rise was analyzed by applying a greater water depth in the model study. A water depth of 1.05 m corresponds with an expected autonomous sea level rise of 0.10 m by 2050 (based on the observed sea level rise during the past century). A water depth of 1.30 m corresponds with the ‘moderate’ Dutch delta scenario with a sea level rise of 0.35 m in 2100 and the ‘severe’ delta scenario in 2050, whereas a water depth of 1.8 m corresponds with the ‘severe’ Dutch delta scenario of 0.85 m in 2100 (Bruggeman *et al.*, 2013). A broader salt marsh, vegetated with shrubby and stiff plants such as *A. portulacoides*, significantly affects the wave height under conditions of a rising sea level. Elevation change of the marsh surface by sedimentation was not taken into account. If the salt marsh can keep pace with rising sea level (resulting in less water depth) it will dampen the waves more effectively (Figure 5.19). However, in the current situation Salt marsh Stryp is diminishing. Without measures, it will probably disappear around 2050 (Figure 5.13).

The model was parameterized with great care and with the best information available. Nonetheless, it remains difficult to realistically and meaningfully estimate wave height, water level and wind direction for Salt marsh Stryp, because it is nestled along the dike, in a lee corner. Hydraulic boundary conditions for this dike section given by the Ministry of Transport, Public Works and Water Management *et al.* (2007a) (i.e., 4.2 m +NAP and H_{m0} 0.9 m) are for a situation with northwest wind, meaning that the south side of the island is in the lee of the wind. With a southwest wind, the water level will be lower, but waves might be higher.

Sensitivity studies show that wave conditions in the Wadden Sea interior are predominantly locally generated by wind, and are strongly determined by the limited water depths above the tidal flats in the Wadden Sea (Van der Westhuysen & De Waal, 2008). Therefore, under southwest winds, the highest waves can be expected during spring tide (as in our model).

Accurate and reliable information about wave damping by vegetated foreshores under different hydraulic conditions is a prerequisite for the implementation of vegetated foreshores in dike dimensions. To this end both field and laboratory experiments will be indispensable. Field experiments will be required to understand the influence of complex terrain geometry as well as effects of subtle soil-vegetation characteristics such as soil layering, plant densities, plant rooting characteristics and plant phenology on terrain roughness and stability. Laboratory experiments (e.g. in experimental flumes) will remain important due to the possibility to control many more variables effectively than in the field, to collect more replicates and less noisy measurements.

Specific to study location Salt marsh Stryp, it is at this stage (after initial model parameterization and first model results) advisable to measure the development of wave height in the field under different weather conditions to obtain observational data with which the modelled wave attenuation capacity of the current salt marsh can be evaluated and (if necessary) calibrated. While providing more reliable wave-height predictions, such measurements would also advance the understanding of the influence of the vegetation structure (properties like stem density, stem diameter, height, drag) on wave attenuation.

Values of salt marshes applied for flood protection

Wave height reduction by salt marshes is strongly dependent on the slope of the salt-marsh profile, water depth, width of the salt-marsh zone and vegetation (e.g. Anderson *et al.*, 2011). To be effective in extreme situations, salt marshes must be relatively high and stable. Therefore the application of salt marshes for flood protection requires preconditions to optimize and guarantee their spatial configuration. Most measures to stimulate and ensure their existence, however, have side-effects on the nature value of the marshes (Chapter 4).

The restored salt marshes at Grië and Stryp (case 1) provide information on the nature value of salt marshes restored by hard erosion protection works in the Wadden region.

At both Grië and Neerlands Reid, characteristic pioneer salt-marsh vegetation (H1310 and H1320) developed in the raised area between the erosion protection works and the former marsh edge. These habitats were not found in the transects without erosion protection. In addition to preventing the retreat of the salt-marsh cliff, the low dam in front of the eroding

marsh edge thus appears to have created favourable boundary conditions for sedimentation. This effectively meant the restoration of pioneer marsh vegetation (H1310 and H1320 and at some places already H1330) in areas that were transformed by erosion into mudflats and sandflats (H1140).

Although the stone structure led to establishment of a natural salt-marsh vegetation behind the dam, the dam itself is an unnatural element in the Wadden Sea landscape. It is a fixed and straight line, while a natural cliff edge forms a meandering and dynamic coastline. Furthermore, stone is a non-local material. Nonetheless, a low stone dam is a relative simple management measure. Unlike wooden groynes, no regular maintenance is required. Since the construction of the dams at Grië and Neerlands Reid, no damage to the dams has been observed (Overdiep, pers. com.; Van der Valk, pers. com.).

The initiative launched by the inhabitants of Terschelling to restore the eroding marsh at Stryp (case 2) illustrates the public interest for the values of a restored marsh at this location. The marsh provides a refuge for wading birds and forms a characteristic landscape feature along the Wadden Sea coast of Terschelling (Van Loon-Steensma, 2011b). It forms a smoother transition zone from the dry coastal area to the marine environment than solely the stone-covered dike. Without measures, the present human-induced salt-marsh habitats at Stryp will revert within a few decades to sandflats and mudflats (Figure 5.13). Furthermore, salt-marsh areas covered with *Atriplex portulacoides* are scarce in Europe (Dormann *et al.*, 2000), forming an additional argument for its preservation.

Broadening of the salt marsh would impinge upon sandflat and mudflat habitat, and would probably have some negative effect on the abundant breeding and wading birds that feed on the benthic invertebrates on the tidal flats in front of Salt marsh Stryp. On the other hand, extensive flats would remain adjacent to a broadened salt marsh, and restoration of the salt marsh would probably lead to a seaward shifts of these habitats.

Local stakeholders identified cultural-heritage and landscape quality among the important services of the salt marsh (Van Loon-Steensma, 2011b). Restoration of the eroding salt marsh would reinforce these services. Furthermore, restoration of the salt marsh could form an interesting pilot location, to experiment with techniques for protecting, developing and effectively managing salt marshes as an climate adaptation strategy.

The restored marsh at Stryp could also fulfil an educational purpose. Salt-marsh development and dynamics are very visible at Stryp, because the marsh lies alongside a bicycle path that follows the Wadden Sea flood defence. Using information panels and observation facilities,

tourists and residents could be informed about the ongoing unique natural processes and the characteristics of the salt-marsh habitat, increasing appreciation of the Wadden Sea dynamics.

The analysis of the impact of the implementation of a Wide green dike along the Dollard (case 3) showed that such a Wide green dike has a larger footprint (some 11 ha), and will overlap more Natura 2000 area than a Traditional dike reinforcement (Table 5.9). Although the grass cover on the middle and upper zone of a Wide green dike represents no special ecological values (Table 5.11), the lower zone of the dike (which merges into the adjacent salt marshes) will probably be settled by species of the higher salt marsh zones within a few years, whilst this zone is covered by asphalt for the Traditional dike.

An assessment of the costs and benefits of the Wide green dike along the Dollard revealed that the advantages of this dike are primarily formed by its lower initial investment costs (based on standard prices per unit), the easiness to repair, its adaptability, and its spatial quality with respect to a Traditional dike reinforcement (Van Loon-Steensma *et al.*, 2014a,b).

On the other hand, the maintenance costs of a Wide green dike will probably outpace these of a Traditional dike. After every storm the deposited debris must be removed within a few days to prevent damage of the grass cover by the decaying organic layer. In Germany the removal of the extensive loads of reeds and other debris originating from the adjacent salt marshes, costs a lot of effort (Van Loon-Steensma & Schelfhout, 2013b).

Analysis revealed that the difference in costs between the concepts is mainly determined by the costs of clay and the asphalt revetment (Van Loon-Steensma *et al.*, 2014b) In view of cost-efficiency and sustainability, winning of dike-construction resources from nearby locations is preferable (as it saves transport time and energy). This initiated thinking about potential suitable mining locations, such as the stored clay that was released by previous infrastructural project, applying dredging material (from the Dollard or from local salt-marsh creeks and silted up recreational harbours), extracting clay from the adjacent salt marshes, or the 'harvesting' of accreted clay in a polder that is connected by culverts with the Dollard (and is under influence of the tidal regime) (Van Loon-Steensma & Schelfhout, 2013b).

Although there has been in the Wadden region a long tradition of using salt marsh sediment as a resource for dike construction (H. Kingma, pers. comm.), this was abandoned since the Wadden Sea was appointed as a nature conservation site and protected by (inter)national legislation.

Because of the expected increasing demand for resources for dike construction facing the effects of sea level rise, in the Jade Bay (Germany) in 1999 a pilot project was initiated to

monitor the effects of clay extraction (Bartholomä *et al.*, 2013). After the extraction of 150,000 m³ clay, the clay pit of 10 ha was connected to the tidal drainage system of the Jade Bay, and the infilling process and ecological developments were monitored for 10 years (Bartholomä *et al.*, 2013). Karle & Bartholomä (2008) observed that very soon after having connected the clay pit to the tidal drainage system, a meandering channel system developed. Therefore, with an increasing degree of filling, a self-organized morphology developed within the clay pit, in contrast to the topography of the adjacent salt marsh dominated by linear drainage channels. They found that especially in the first years accretion was very high (15 cm per year during the first two years) and decreased with increasing elevation of the clay-pit surface (less than 4 cm per year in 2007) (Karle & Bartholomä, 2008).

In view of this, it is recommendable to explore the potential of clay pits for recycling sediment as natural resource for construction of a Wide green dike along the Dollard, and to monitor the effects on the Dollard salt marshes.

5.6 Conclusions

Based on the findings at Grië and Neerlands Reid (case 1) can be concluded that under favourable conditions for sedimentation, the development of an ecologically attractive foreshore zone is feasible using relatively simple measures.

Species composition in the newly formed marshlands is comparable with that in natural pioneer salt-marsh zones. Placement of the low stone dam seems to have enabled the restoration of pioneer salt-marsh habitat within 10 to 20 years at Grië and Neerlands Reid.

Salt-marsh restoration, however, is a multifaceted endeavour, and one in which a large array of effect types must be considered. Care has to be taken to ensure that undesirable side effects of restoration do not outweigh benefits. An *ex ante* assessment of impacts and side effects is therefore a precondition for any decision to restore the salt marsh. Stakeholders, too, should be involved in such assessment, as they play a role in both valuation of the impacts and in defining the objectives of restoration measures.

Furthermore, long-term monitoring of sedimentation processes and vegetation development is key to advance knowledge about the effectiveness of measures taken and to indicate any necessary adjustments of management or additional measures required.

Modelling wave damping indicates that a vegetated foreland in front of the dike leads to reduced wave attack on the dike. This may result in changed requirements for both height and

revetment of the dike while maintaining the required safety level. However, to account for the effect of salt marshes on dike dimensions, more information about wave damping under different hydraulic conditions is needed. Therefore, it is advisable to measure the development of wave height in the field under different weather conditions to obtain observational data to further evaluate and calibrate the model. Such measurements would also advance the understanding of the influence of vegetation characteristics.

Interestingly, the modelling work indicates that the spatial distribution of the different vegetation types typically found on natural salt marshes can have a considerable impact on wave damping. There was a strong difference between wave attenuation by vegetation found on ungrazed salt marshes (covered with tall, stiff and branched plants such as *A. portulacoides*), and intensive grazed salt marshes (where vegetation was scarce).

Therefore, if improved wave damping capacity of a salt marsh is desired, very intensive grazing by livestock appears to be not advisable. Moreover, in view of the flood protection value of vegetated forelands, it is recommendable to pay more attention to salt-marsh vegetation management.

The implementation of a Wide green dike along the Dollard will cost an area of some 11 ha salt marshes, but offers a more natural transition of the salt marshes towards the grass covered dike than a traditional reinforced dike (which is covered by asphalt and/or a stone revetment).

Because of the expected increasing demand for resources for dike construction during the coming decades, it would be wise to explore the potential of clay pits for harvesting sediment in a sustainable, yet cost-efficient way. De Dollard salt marshes would form an excellent pilot location for such explorative research.

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6

Further quantification of the ecological value of stabilized and restored salt marshes

Vegetation of two recently restored Wadden Sea salt marshes compared to established salt marshes

Although there is in general broad support for the idea to simultaneously strengthen the flood defence service of salt marshes and their value for biodiversity, the ecological value of developed or preserved salt marshes is questioned by some ecologists (e.g. Mossman *et al.*, 2012). The restored salt marshes Grië (Terschelling) and Neerlands Reid (Ameland) provide an excellent opportunity to explore the ecological value of such restored salt marshes. The previous chapter presented already a first impression of their floristic value. In this chapter the ecological value of stabilized and restored salt marshes is further quantified by comparing vegetation relevés made in the two sites, with a reference set consisting of some 6000 relevés made in salt marshes all over the Dutch Wadden Sea. This quantification concerned i) simple species-by-species analysis based on frequencies in both data sets, and by ii) ordination, where relevés of the restored sites were projected into a multivariate space defined by the species' abundances in the reference relevés.

Lessons learned:

- Salt marsh succession behind low dams is not different from normal succession starting in unprotected mudflats.
- Measures targeting salt-marsh development in view of flood protection do not frustrate nature conservation ambitions.

6.1 Introduction

Although there is in general broad support for the idea to simultaneously strengthen the flood defence service of salt marshes and their value for biodiversity, occasionally questions about the ecological value of restored or preserved salt marshes are raised. According to Garbutt & Wolters (2008) restoration efforts may never fully replace natural wetland functions. Mossman *et al.* (2012) even conclude that marshes reactivated by managed realignment do not provide habitats and species in comparable proportions to natural marshes and do not have equivalent biological characteristics. According to these authors such salt marshes do not satisfy the requirements of the EU Habitats Directive.

The restored salt marshes Grië (Terschelling) and Neerlands Reid (Ameland) provide an excellent opportunity to explore the ecological value of such restored Wadden Sea salt marshes. The previous chapter presented already a first impression of their floristic value. In this chapter the ecological value of stabilized and restored salt marshes is further quantified by comparing vegetation relevés made in the two sites, with a reference set consisting of some 6000 relevés made in salt marshes all over the Dutch Wadden Sea. The aim is to explore if coastal protection by the construction of low stone dams to promote salt-marsh development also lead to an increase of natural values.

6.2 Methods

Vegetation description at the study sites

This study uses data from Grië (Terschelling) and Neerlands Reid (NLR, Ameland), which are described in section 5.2. Both are eroding salt marshes where attempts were made to prevent further erosion and loss of typical salt marsh vegetation by the construction of low (i.e. some 1 m above mean sea level) stone dams some 60 m (Grië) or some 10 m (NLR) seaward of the eroding salt marsh edge, in 1991 and 1998, respectively. To describe the vegetation of these sites we made vegetation relevés in 2011 and 2013. The relevés are circles with a radius of 1.13 m (surface area = 4 m²) where vegetation was recorded in terms of species quantities estimated as ground cover percentage. In total, 90 relevés were made in Grië and 80 in NLR; of these, 84 and 64, respectively, were made in the area between the stone dams and the original salt marsh edge. The other relevés were made just outside the area protected by the dams and were used as a local reference. The relevés are arranged in transects, their location is shown in Figure 6.1.

In the relevés we recorded the soil type (clay or sand) and the approximate location as X and Y coordinates determined by a handheld GPS. We used the X and Y coordinates to estimate the elevation (Z-coordinate) using the digital elevation map of the Netherlands (source: AHN 2012). In such a digital map the elevation of a given location is based on bilinear interpolation of the measured heights of the neighbouring four points of the grid, which may lead to levelling of local elevation differences in the data. In total 86 species were found in our relevés. In the statistical analysis we treat the data from Grië and NLR as a single data set that we refer to as ‘Grië NLR’.

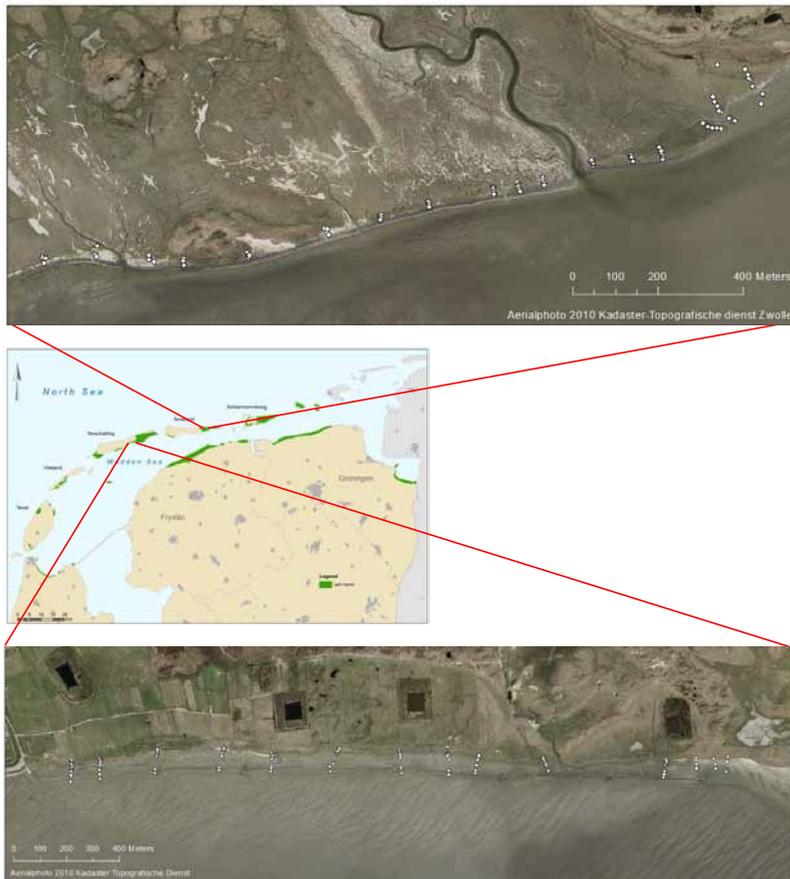


Figure 6.1: The plots along transects perpendicular on the coastline ‘Grië’ at Wadden island Terschelling (bottom, $53^{\circ}24'12''$ N, $5^{\circ}23'50''$ E; $53^{\circ}24'16''$ N, $5^{\circ}26'13''$ E) and ‘Neerlands Reid’ at Wadden island Ameland (top, $53^{\circ}26'94''$ N, $5^{\circ}52'15''$ E; $53^{\circ}17'11''$ N, $5^{\circ}53'44''$ E). The figure shows also the unvegetated plots on the mudflats (which are not included in the analysis). The black squares at Grië are duck decoys.

Reference data set

As a reference, we extracted vegetation relevés from the Dutch Global Index of Vegetation-Plot Database (Hennekens & Schaminée, 2001). We used all relevés made after 1979 in the Dutch Wadden Sea, and selected saltmarsh relevés using syntaxonomic identifications by the program ASSOCIA (Van Tongeren *et al.*, 2008). Our selection consisted of relevés identified as one of the associations (or their subassociations) listed in Table 6.1. Some of the relevés had been manually identified by their authors, and if such identifications existed we used these instead of the automatic identifications. We translated the associations to Habitat types as defined by the European Commission DG Environment, Nature and biodiversity (2007) using the translation table for The Netherlands given by e.g. Van Dobben *et al.* (2014) with two additions indicated in Table 6.1. This selection resulted in a set of 6198 relevés. The location of the relevés in the ‘reference set’ is presented in Figure 6.2.

Table 6.1: Associations used in the reference set, and their translation to Habitat types. Explanation of Habitat type codes: 1210, Annual vegetation of drift lines; 1310, Salicornia and other annuals colonizing mud and sand; 1320, *Spartina swards* (*Spartinion maritimae*); 1330, Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*). Habitat type 1310 was split into two subtypes based on the presence of either *Salicornia* (subtype A) or other species e.g. *Sagina maritima*, *S. nodosa* or *Centaureum litorale* (subtype B). The translations are according to Van Dobben *et al.* (2014) except for those marked with (*). RG = community of impoverished vegetation.

Association	Habitat
<i>Atriplicetum littoralis</i> (*)	1210
<i>Salicornietum dolichostachyae</i>	1310A
<i>Salicornietum brachystachyae</i>	1310A
<i>Suaedetum maritimae</i>	1310A
<i>Sagino maritimae</i> - <i>Cochlearietum danicae</i>	1310B
<i>Centaureo-Saginetum</i>	1310B
<i>Spartinetum maritimae</i> (*)	1320
<i>Spartinetum townsendii</i>	1320
<i>Puccinellietum maritimae</i>	1330
<i>Plantagini-Limonietum</i>	1330
<i>Halimionetum portulacoides</i>	1330
<i>Puccinellietum distantis</i>	1330
<i>Puccinellietum fasciculatae</i>	1330
<i>Puccinellietum capillaris</i>	1330
<i>Parapholido strigosae</i> - <i>Hordeetum marini</i>	1330
<i>Juncetum gerardi</i>	1330
<i>Armerio-Festucetum litoralis</i>	1330
<i>Junco-Caricetum extensae</i>	1330
<i>Blysmetum rufi</i>	1330

Artemisietum maritimae	1330
Atriplici-Elytrigietum pungentis	1330
Oenantho lachenalii-Juncetum maritimi	1330
RG Scirpus maritimus-[Asteretea tripolii]	1330
RG Agrostis stolonifera-Glaux maritima-[Asteretea tripolii]	1330
RG Triglochin maritima-[Asteretea tripolii]	1330
RG Aster tripolium-[Puccinellion maritimae]	1330

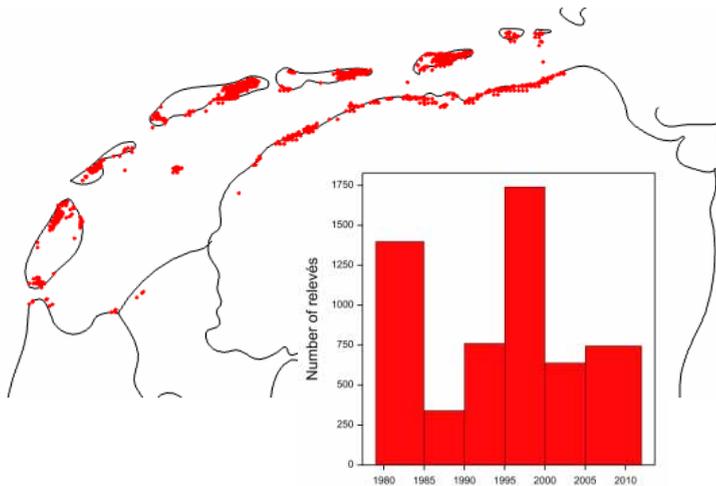


Figure 6.2: Location of the relevés in the reference set in space and time (1980-2012).

Data analysis

We used two methods to compare our relevés and the reference relevés. The first is a simple species-by-species analysis based on frequencies in both data sets; and the second is an ordination where our relevés were projected into a multivariate space defined by the species' abundances in the reference relevés. To this end we first performed a Correspondence Analysis (CA; Jongman *et al.*, 1995) on the reference data set, and subsequently added our relevés as 'passive samples', i.e. without affecting the species weights. We used the program package CANOCO (Ter Braak & Smilauer, 2002) to carry out the multivariate analysis. We limited the analysis of the reference data set to the 155 species with 10 or more occurrences in order to reduce its heterogeneity. We considered (1) comparable frequencies per species in

both data sets, and (2) placement of our relevés in the ordination diagram in or near the centre of the Habitat types as defined by the reference set, as indications of similarity in both data sets and hence, of the absence of a strong effect of the dams on the floristic composition of the salt marsh vegetation. To get an idea of the ecological interpretation of the ordination axes, we determined the correlation between the reference relevés scores on the first three axes and mean indicator values per relevé. We used the indicator values for groundwater level, soil pH, and nitrate and chloride concentration given by Wamelink *et al.* (2005, 2012). These values are based on measured data instead of expert judgement.

6.3 Results

Out of a total of 175 species, 90 exclusively occur in the reference set, whereas 20 exclusively occur in the Grië NLR set. However, most of these 'exclusive' species in the Grië NLR set are rare in our data i.e. they have frequencies below 2%. There are a few exceptions: *Cochlearia danica*, *Sagina nodosa* and *Centaurium litorale* have frequencies of ca. 5% in the reference set and are absent from the Grië NLR set. On the other hand, *Vaucheria* spp. and *Ulva lactuca* have frequencies of > 20% in the Grië NLR set and are absent from the reference set. However, this is most probably an artefact as these marine algae are not usually included in vegetation relevés.

Table 6.2 gives a comparison between the frequencies of the most common species in both data sets. Out of a total of 37 species that are common in either, or both data sets, 31 have frequencies that differ by less than a factor five, and 23 differ by less than a factor two. Only two typical salt-marsh species are rather common (ca. 5%) in the reference set and rare or absent in the Grië NLR set: *Cochlearia danica* and *Juncus maritimus*. It is concluded that the floristic difference between both data sets is rather small and this is the justification behind 'passive' treatment of the Grië NLR data in the ordination.

Table 6.2: Comparison of frequencies per species in both data sets (N reference set = 6198 and N Grië NLR set = 170) for the species with a frequency of >5% in either data set. For species given in bold the frequencies differ by more than a factor five.

Species name	Reference	Grië NLR	Ratio Grië NLR/Ref.
<i>Cochlearia danica</i>	5.10%	0.00%	0
<i>Phragmites australis</i>	7.70%	0.60%	0.08
<i>Juncus maritimus</i>	6.80%	0.60%	0.09
<i>Centaurium pulchellum</i>	6.20%	1.20%	0.19
<i>Atriplex prostrata</i>	37.90%	13.50%	0.36

<i>Carex extensa</i>	5.80%	2.40%	0.41
<i>Odontites vernus</i>	10.80%	4.70%	0.43
<i>Bolboschoenus maritimus</i>	8.60%	4.10%	0.48
<i>Atriplex littoralis</i>	5.60%	2.90%	0.53
<i>Limonium vulgare</i>	27.40%	16.50%	0.6
<i>Triglochin maritima</i>	22.50%	14.70%	0.65
<i>Aster tripolium</i>	54.70%	41.20%	0.75
<i>Juncus gerardi</i>	28.00%	21.20%	0.76
<i>Agrostis stolonifera</i>	36.30%	27.70%	0.76
<i>Seriphidium maritimum</i>	27.90%	22.40%	0.8
<i>Festuca rubra</i> agg.	44.30%	38.20%	0.86
<i>Glaux maritima</i>	39.80%	35.30%	0.89
<i>Plantago maritima</i>	36.60%	32.90%	0.9
<i>Suaeda maritima</i>	61.90%	57.10%	0.92
<i>Potentilla anserina</i>	13.40%	12.40%	0.92
<i>Atriplex portulacoides</i>	39.90%	40.00%	1
<i>Puccinellia maritima</i>	58.60%	62.90%	1.07
<i>Spergularia media</i> subsp. <i>angustata</i>	38.00%	42.40%	1.11
<i>Salicornia europaea</i>	58.60%	65.90%	1.12
<i>Spartina anglica</i>	35.30%	40.60%	1.15
<i>Armeria maritima</i>	9.30%	12.40%	1.33
<i>Elytrigia atherica</i>	24.10%	33.50%	1.39
<i>Cochlearia officinalis</i> subsp. <i>anglica</i>	8.10%	11.80%	1.46
<i>Spergularia marina</i>	8.50%	12.40%	1.46
<i>Plantago coronopus</i>	6.70%	11.20%	1.66
<i>Parapholis strigosa</i>	5.30%	9.40%	1.78
<i>Cirsium arvense</i>	2.90%	6.50%	2.27
<i>Trifolium repens</i>	6.30%	15.90%	2.53
<i>Lolium perenne</i>	2.40%	7.10%	2.98
<i>Cerastium fontanum</i>	2.00%	6.50%	3.23
<i>Vaucheria</i> spp.	0.00%	41.80%	
<i>Ulva lactuca</i>	0.00%	21.80%	

A second comparison of the Reference and the Grië NLR data sets was carried out by making ordination diagrams. First CA was applied to the reference set, resulting in the ordination diagrams given in Figure 6.3; the correlation between the sample scores and indicator values is given in Table 6.3. The Habitat types are rather well separated by CA, with the exception of the most common type 1330 (Atlantic salt meadows) that overlaps with all other types. However, this type is rather well separated from the other types along the fourth axis (not shown).

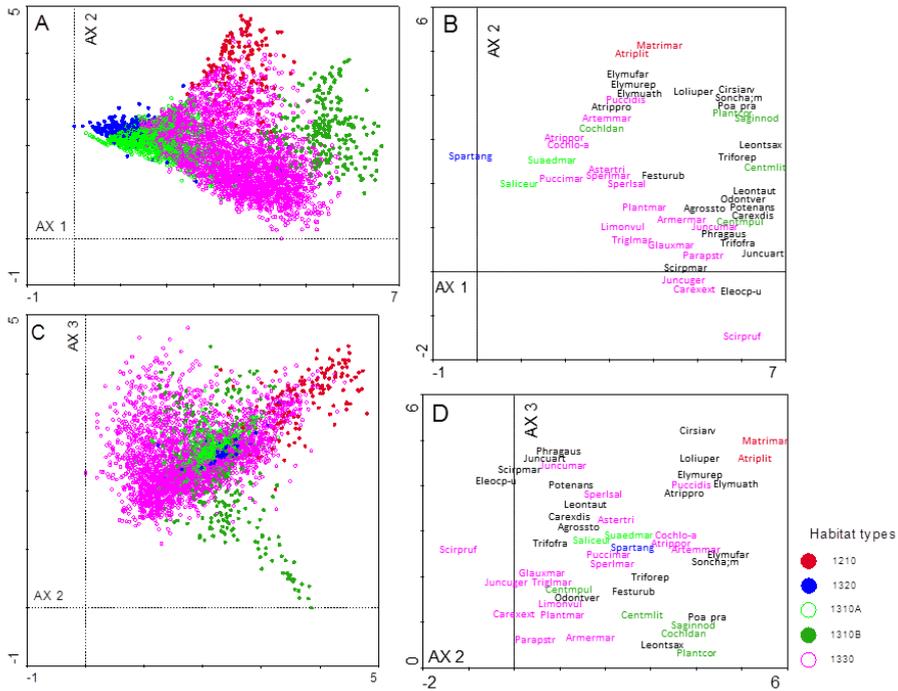


Figure 6.3: Ordination of the reference set using CA. A, samples, first and second axis; B, species, first and second axis; C, samples, second and third axis; D, species, second and third axis. Colours in A and C indicate Habitat types; their codes are explained in Table 6.1. The colours of the species names in B and D indicate their status as typical species (in the sense of the EU Habitats Directive) of Habitat types, coded as in A and C; black = no typical species of these Habitat types. Detrending by segments, no weighting of species or samples, species abundances are entered into the analysis as LOG (cover percentage + 1). Eigenvalues are 0.67, 0.36, 0.30 and 0.23, respectively, for the first four axes, sum of all eigenvalues: 11.07 i.e. these plots together explain 12% of the variance in the species data. Gradient length of the first axis is 6.6 which justifies CA instead of PCA. The plots have a distance interpretation i.e. if the sample and species plots are projected over each other in equal scaling, the expected abundance of a given species in a given sample increases as their distance decreases. Only species are displayed that have a minimum weight of 2% in CA, explanation of species codes: *Agrossto*, *Agrostis stolonifera*; *Armermar*, *Armeria maritima*; *Artemmar*, *Seriphidium maritimum*; *Astertri*, *Aster tripolium*; *Atripplit*, *Atriplex littoralis*; *Atrippor*, *Atriplex portulacoides*; *Atrippro*, *Atriplex prostrata*; *Carexdis*, *Carex distans*; *Carexext*, *Carex extensa*; *Centmlit*, *Centaurium littorale*; *Centmpul*, *Centaurium pulchellum*; *Cirsiarv*, *Cirsium arvense*; *Cochldan*, *Cochlearia danica*; *Cochlo-a*, *Cochlearia officinalis subsp. anglica*; *Eleocp-u*, *Eleocharis uniglumis*; *Elymuath*, *Elytrigia atherica*; *Elymufar*, *Elytrigia juncea subsp. boreoatlantica*; *Elymurep*, *Elytrigia repens*; *Festurub*, *Festuca rubra agg.*; *Glauxmar*, *Glaux maritima*; *Juncuar*, *Juncus articulatus*; *Juncuger*, *Juncus gerardi*; *Juncumar*, *Juncus maritimus*; *Leontaut*, *Leontodon autumnalis*; *Leontisax*, *Leontodon saxatilis*; *Limonvul*, *Limonium vulgare*; *Loliuper*, *Lolium perenne*; *Matrimar*, *Tripleurospermum maritimum*; *Odontver*, *Odontites vernus*; *Parapstr*, *Parapholis strigosa*; *Phragaus*, *Phragmites australis*; *Plantcor*, *Plantago coronopus*; *Plantmar*, *Plantago maritima*; *Poa pra*, *Poa pratensis*; *Potenans*, *Potentilla anserina*; *Puccidis*, *Puccinellia distans*; *Puccimar*, *Puccinellia maritima*; *Saginnod*, *Sagina nodosa*; *Saliceur*, *Salicornia europaea*; *Scirpella*, *Bolboschoenus maritimus*; *Scirpruf*, *Blysmus rufus*; *Soncha;m*, *Sonchus arvensis var. maritimus*; *Spartang*, *Spartina anglica*; *Sperlmar*, *Spergularia media subsp. angustata*; *Sperlsal*, *Spergularia marina*; *Suaedmar*, *Suaeda maritima*; *Trifofra*, *Trifolium fragiferum*; *Triforep*, *Trifolium repens*; *Triglmar*, *Triglochin maritima*.

The first axis clearly represents the gradient from pioneer to late successional stages, exemplified by the pioneer species *Spartina anglica* and *Salicornia europaea* on the left side of Figure 6.3B, while species of wet or even dry grassland (e.g. *Leontodon* spp., *Trifolium repens*, *Centaureum litorale*) occur on the right side of Figure 6.3B. This interpretation is confirmed by the correlation with the indicator values, where higher pH and chloride values occur at low values of the first axis, i.e. the influence of seawater increases from right to left on this axis.

Table 6.3: Pearson correlation coefficients between the sample scores on the first three axes and mean indicator

	AX 1	AX 2	AX 3
pH	-0.94	0.23	-0.13
groundwater level	-0.15	0.8	0
NO ₃	-0.66	0.11	0.32
Cl	-0.81	-0.16	-0.34

The second axis is strongly positively correlated with the groundwater level indicator, where the driest situations occur at high values of this axis i.e. in the upper part of Figure 6.3A and the right part of Figure 6.3B. Here type 1210 (Annual vegetation of drift lines) is found. This is understandable as drift lines are in places that flooded only once or a few times per year i.e. in the highest and consequently, driest parts of salt marshes. However, the species plots (Figure 6.3B and 6.3D) show that there is probably another difference, namely the contrast between sandy soil at high values of the second axis, with e.g. *Elytrigia juncea* subsp. *boreoatlantica* and *Sonchus arvensis* var. *maritimus* and clayey soil at low values, with e.g. *Blysmus rufus* and *Juncus gerardi*.

The third axis is most strongly correlated with the nitrate and chloride indicators. This axis most probably mainly represents a trophic gradient, with eutrophic situations on the high side, represented by species like *Cirsium arvense* and *Lolium perenne*, and species like *Leontodon saxatilis* and *Sagina nodosa* on the low side. The trophic gradient apparently partly coincides with a chloride gradient where the most eutrophic situations are least influenced by seawater. This is probably because these eutrophic situations are mostly drift lines that are only incidentally flooded (cf. the position of type 1210 in Figure 3C).

Surprisingly, the two subtypes of type 1310 are completely separated in the diagrams, with low values on the first axis and high values on the third axis for subtype A, and vice-versa for subtype B. This is probably because type 1310 combines pioneer situations of mudflats (subtype A) with those of sandy banks (subtype B), that are ecologically very different

situations. In the diagrams, subtype A for a large part overlaps with type 1320 while subtype B partly occupies a space where no other types are found (Figure 6.3A and 6.3C). This is understandable as mudflats can be colonised by both *Salicornia europaea* (subtype 1310A) and *Spartina anglica* (type 1320). Figure 6.3C suggests that subtype 1310B mainly occurs in sandy, dry and oligotrophic situations (the 'tail' in the lower right of the diagram) although it is not strictly confined to such situations.

Apart from the overlap of types 1310A and 1320, there is also a big overlap between type 1330 (Atlantic salt meadows) and all other types. This is probably because 1330 is the most heterogeneous of all types, consisting of 14 associations and 4 communities of impoverished vegetation, while the other types are made up of between one and three associations (cf. Table 6.1). However, when inspecting the fourth axis (not shown) it becomes clear that type 1330 has a number of characteristic species, although ones with a broad ecology e.g. *Festuca rubra*, *Seriphidium maritimum*, *Potentilla anserina* and *Elytrigia atherica*.

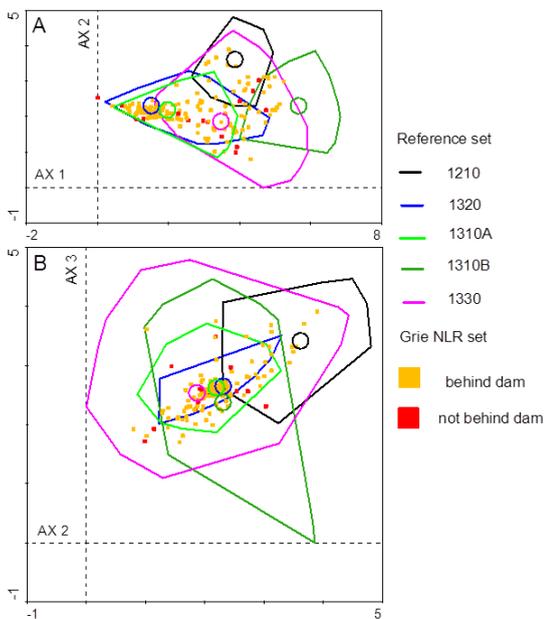


Figure 6.4: Grië NLR data (squares) projected into the ordination diagram of Figure 6.3: A, first and second axis; B, second and third axis. The colour coding is identical to Figure 3, however the sample points of the reference set have been replaced by their convex hull (lines) and their centroid (circles). Note that the corresponding species plots are identical to those in Figures 6.3B and D, respectively.

In Figure 6.4 the Grië NLR data are projected into the ordination space defined by the reference data. The Grië NLR data mostly occupy a space that is well in the centre of the space defined by the reference data. Only a single sample point of the Grië NLR data falls outside the reference space, with an extreme value on the first axis. On the second and third axis the Grië NLR data never have extreme values compared to the reference data. Also, the local reference samples (i.e. those of Grië NLR that are not behind the dams) do not take positions that are clearly different from either the other Grië NLR data or the reference set. It can therefore be concluded that the vegetation behind the dams fall well in the centre of the variation of all Habitat types present in salt marshes in The Netherlands.

The estimates that are available for the elevation (Z-coordinates) of the Grië NLR data can be used as an indirect check of the interpretation of the ordination diagram of the reference set. If the first axis mainly reflects the influence of seawater (increasing from right to left) the elevation of the Grië NLR data projected on this axis should increase from left to right. This is indeed the case as the elevation and the score on the first axis of the Grië NLR data have a correlation coefficient of 0.89. Also the interpretation of the second axis as a wet - dry gradient is confirmed by this analysis as the elevation and the second axis have a correlation coefficient of 0.31.

6.4 Discussion and conclusions

The vegetation behind the dams at Grië (Terschelling) and Neerlands Reid (Ameland) falls well in the centre of the variation of all Habitat types present in salt marshes in The Netherlands. Therefore, it can be concluded that salt marsh succession behind low dams is not different from normal succession starting in unprotected mudflats. In comparing the two data sets it should be borne in mind that the Grië NLR data only represent young stages of the succession, which started some 20 (Grië) or some 15 (NLR) years ago. This may explain the absence or rarity of *Cochlearia danica*, *Sagina nodosa* and *Juncus maritimus* in the Grië NLR data and in general, the absence of samples with high values on the first axis or with extreme values on the second and third axis.

Fast colonisation and salt marsh succession in restored salt marshes were also observed by Mossman *et al.* (2012), who compared plant communities of realignment sites (where the existing sea defences were deliberately or accidentally breached or replaced) with natural saltmarshes in the UK. However, they found differences in community composition. In the realignment sites, early-successional species remained dominant, even on the high marsh.

Even after many decades differences in vegetation between natural and realignment sites were still present (Garbutt & Wolters, 2008). In contrast, the vegetation of the Grië and Neerlands Reid sites is quite comparable with the reference set. Obviously, the low dams allowed natural salt marsh forming processes. One should also be aware that most salt marshes along the Wadden Sea mainland coast are the result of man-made reclamation works. Nevertheless, these salt marshes are appointed as Natura 2000 habitats.

The findings agree with those of Bilkovic & Mitchell (2013) who studied the effects of erosion prevention by creating a marsh in combination with a stabilizing structure such as a low-profile stone sill (like the low stone dam at our study sites). Such stabilized salt marshes are currently being implemented in many US coastal states, not only to control erosion but also to restore coastal habitats. They found that that the vegetation of low and high marsh and marsh sills was similar to natural marshes.

Because of the presence of dikes along the majority of the Dutch Wadden Sea coast, there is hardly any accommodation space for salt marshes to migrate landwards under sea level rise (Nicholls *et al.*, 2013). It is therefore likely that in a changing environment more measures are needed to conserve and stabilize the present salt marshes. To combine salt-marsh restoration from a nature conservation viewpoint and salt-marsh development from a coastal protection viewpoint is a challenging ambition. The analysis of the restored salt marshes Grië and Neerlands Reid shows that salt marsh vegetation behind low dams is comparable with the vegetation at other locations in the Wadden Sea. Therefore, it can be concluded that measures targeting salt marsh development as a means of shoreline protection do not frustrate nature conservation ambitions as far as Natura 2000 habitats types are concerned.

7

The effect of vegetation characteristics on wave damping

This chapter explores the effect of realistic salt-marsh vegetation characteristics on wave damping by modelling wave height for different salt marsh scenarios. Detailed information on species composition, as well as on height, number of stems and diameter of the plant species observed on study site Grië (Terschelling) was used to parameterize and apply the Simulating WAVes Nearshore wave model (SWAN) to a – schematized but realistic – restored salt-marsh zone in front of a section of the Wadden Sea dike of Terschelling. The modelling results confirm that additional to the width and the height of the foreland, also vegetation characteristics like stem density, stem diameter and height of the plants affect the wave-damping capacity of forelands. In this study no attention was given to the drag coefficient, which forms another determining characteristic for wave damping.

Lessons learned:

- Modelled wave height reduction by a schematized restored salt marsh covered with a dense and rigid vegetation of relatively tall and thin plants is in this study estimated to lay between 0.7% and 0.35% per m salt marsh, whereas a reduction of 0.08% is estimated in the situation of an unvegetated restored salt marsh.
- Although there are still many questions concerning dimensions and management, developing a vegetated foreland seems an alternative strategy to adapt existing flood protection works to the effects of climate change.
- The spatial distribution and structural characteristics of the different vegetation types typically found on natural salt marshes can have a considerable impact on wave damping.

7.1 Introduction

This chapter further elaborates on wave damping by a vegetated foreshore in front of the dike. Wave damping by vegetation has been studied in the field as well in the laboratory by various authors (see Table 1 and Table 2 in Anderson & Smith, 2014). Such field measurements pointed out that wave heights were significantly more reduced by salt marsh covered with vegetation, than by bare sand flats (e.g. Möller *et al.*, 2001; Yang *et al.*, 2012). Not only the effects of vegetation presence has been investigated in this context, but also the effect of several vegetation properties. Zones with a higher plant-stem density of *Spartina alterniflora*, for example, were more effective in wave damping than zones with a lower density (Yang *et al.*, 2012). A tall canopy of perennial *Spartina* spp. in Essex (UK), damped the waves more than a shorter canopy of the annual *Salicornia* spp. (Möller 2006). Dissipation of hydrodynamic forces from waves was found to be roughly a factor three higher in vegetation with stiff leaves compared to those with flexible leaves (Bouma *et al.*, 2005). In laboratory studies the interaction of waves and plants can be studied under controlled conditions. In such laboratory studies often artificial plants are utilized that are placed in a regular grid (e.g. Suzuki *et al.*, 2009; Anderson & Smith, 2014; Hu *et al.*, 2014).

Even though field studies as well as flume experiments have shown that wave damping by salt marshes is strongly affected by vegetation characteristics, the treatment of vegetation in concrete case studies to evaluate the flood defence function of salt marshes is rather elementary. In this study the effect of salt-marsh vegetation characteristics in relation to its flood defence function is explored with specific reference to study site Terschelling (Figure 7.1). Field observations of vegetation characteristics (for location Grië) were translated into relevant parameters and boundary conditions for the Simulating WAVes Nearshore (SWAN) hydrodynamic wave model (Booij *et al.*, 1999) and subsequently this model was applied to a fictional restored salt-marsh zone in front of the dike along Wadden Sea barrier island Terschelling. In this way a template is presented for the incorporation of vegetation heterogeneity in wave impact studies, as well as a case study that evaluates realistic scenarios specifically for study site Terschelling.

7.2 Methods

Characteristics of salt-marsh vegetation

In order to obtain realistic input parameters for SWAN, relevant characteristics of the salt-marsh vegetation at study site Grië (Figure 7.1) were investigated. The salt marsh at Grië

developed in 20 years between the edge of a formerly eroding salt marsh and a low stone dam built in 1991 ca. 60 m in front of the salt marsh cliff to prevent on-going erosion.

Sedimentation raised the mudflats between the dam and the former cliff, creating a broader foreshore with typical salt-marsh vegetation of the pioneer, low and middle zone, while behind the edge of the former cliff climax salt-marsh vegetation of the upper marsh zone was found (Chapter 5).



Figure 7.1: Location of the restored salt marsh at Grië on the Wadden Sea barrier island of Terschelling (The Netherlands) and the surveyed 90 plots along the 14 transects. Source aerial photograph: 'Netherlands Land Registry Office' (Kadaster), 2010.

The vegetation along 14 transects perpendicular on the coast (Figure 7.1) was surveyed. The 6 eastern transects were surveyed in August 2011, when salt-marsh vegetation was at its most vigorous, and the 8 western transects were surveyed in June 2013, at the start of the growing season. The applied method to examine the 90 relevés is described in section 5.2.

All stems in sub-samples (10x10 cm) of the 60 surveyed relevés in the 8 western transects were counted and the diameter of the stems of the encountered species was estimated as well as their height (Figure 7.2). As it was at the beginning of the growing season, *Salicornia europaea* plants were just establishing and not yet branched. Therefore every *Salicornia* plant was counted as one stem. Because the grasses had multiple stems per plant, the number of stems per area were taken (instead of the number of plants per area), but there was not accounted for the thin leaves that came from the stems. For short plants like *Suaeda maritima* the stems per area were taken, and there was not accounted for their tiny leaves.

Based on the plant composition in the sub-samples, the mean number of stems per m² was calculated, as well as the weighted mean diameter per stem (in which was accounted for the plant composition) and the weighted mean height of each sample (in which was accounted for the species composition). Then the mean vegetation characteristics (June 2013) for each of the salt-marsh vegetation zones in the restored salt marsh was calculated.



Figure 7.2: Series of sub-samples of the vegetation relevés along one of the transects in the restored salt marsh at Grië on the Wadden Sea barrier island Terschelling (June 2013) with a) densely vegetated pioneer zone behind the dam, b) sparsely vegetated pioneer zone, c) vegetation with dominance of *Spartina anglica*, d) low salt marsh zone, e) middle salt marsh zone, f) zone around flood mark, and g) vegetation with dominance of *Elytrigia atherica* on the upper salt marsh zone. Note the layered soil profile of the upper marsh zone (g) caused by sand deposition during extreme conditions on top of the organic layer in contrast to the clay dominated profile of the restored salt marsh (a-f).

Based on the observed vegetation characteristics in the field were distinguished i) unvegetated sand and mudflats in front of the dam, ii) a densely vegetated pioneer zone behind the dam, iii) *Spartina* swards, iv) a sparsely vegetated pioneer zone along the gully in the salt marsh, v) a low and middle salt-marsh zone dominated by *Puccinellia maritima*, vi) a zone around the flood mark, vii) an upper salt-marsh zone in front of former cliff, and viii) an upper salt-marsh zone behind the former cliff with a thick layer of some cm of dead stems of the former year and dominated by *Elytrigia atherica* (Figure 7.3). Furthermore, a small area with dead *Salicornia* spp. of the previous year was found, as well as a patch of *Bolboschoenus maritimus*, and atypical vegetation on a narrow walking path. However, these vegetation characteristics nor the characteristics of 8 unclear sub-samples, were used as SWAN input.

The height of the soil surface of each relevé in m above mean sea level (NAP) was determined with the 0.5 m resolution Dutch elevation model (ANH 2012) (Figure 7.4).

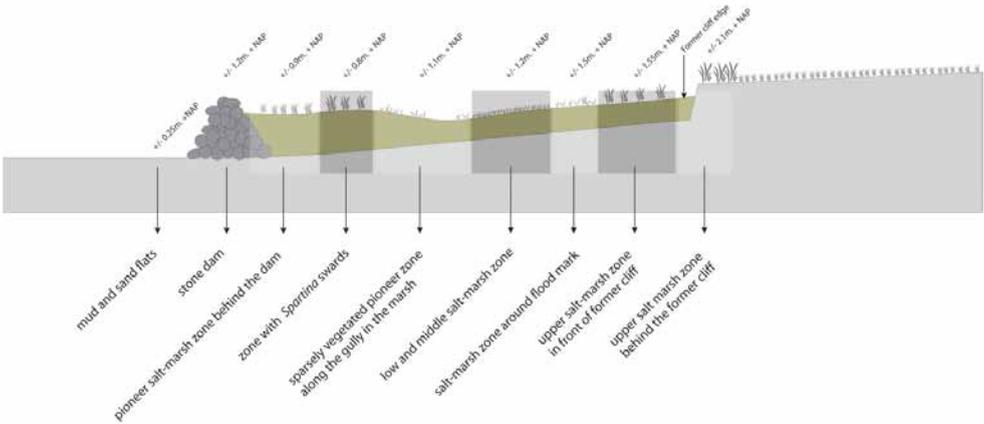


Figure 7.3: Cross section of the restored salt marsh between the dam and the former cliff edge with the different salt-marsh zones and mean height at Grië (Terschelling).

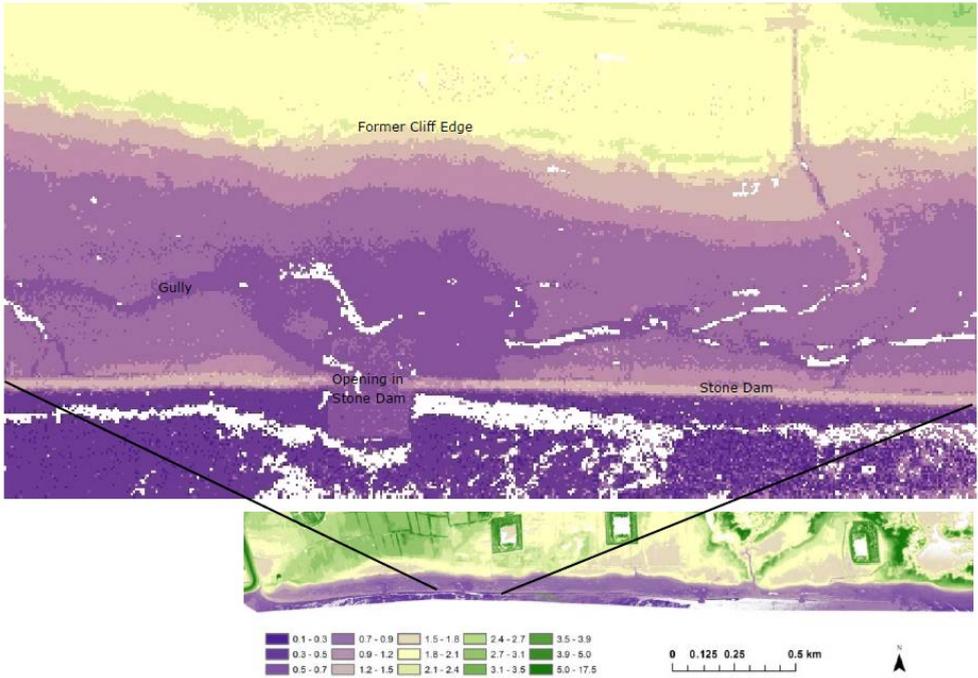


Figure 7.4: Map of Digital Elevation Model (DEM) in m above mean sea level (NAP, Dutch reference height) of the salt marsh at Grië (Terschelling) (source: AHN 2012).

Parameterisation and inputs for the Simulating WAVes Nearshore (SWAN) wave model

To explore the effect of salt-marsh restoration and of salt-marsh vegetation types and characteristics on wave damping, wave heights were modelled with SWAN for 12 different scenarios (Table 7.1). The scenarios differed with respect to the presence or absence of a salt marsh in front of the dike (150 m in width, and 0.9 m +NAP at the seaward side and 1.5 m +NAP at the landward side), and the type of vegetation on the salt marsh. Information from the Department of Public Works on the Wadden Sea's bathymetry (with a grid of 20-20 m) was used.

Table 7.1: The different scenarios applied in the Simulating WAVes Nearshore (SWAN) wave model. The width of the restored salt marsh is 150 m (in front of the dike), and the height at seaward side is 0.9 m +NAP and at landward side 1.5 m +NAP.

Scenario	Salt marsh
Current situation	no
Dam/groynes (0.9 m in height) in front of dike (150 m)	no
Unvegetated salt marsh	restored
Densely vegetated pioneer salt marsh (as found behind dam)	restored
Salt-marsh zone with <i>Spartina</i> spp.	restored
Sparsely vegetated pioneer zone (as found along the gully)	restored
Low/middle salt-marsh zone	restored
Salt-marsh zone around flood mark	restored
Upper salt-marsh zone in front of former cliff	restored
Upper salt-marsh zone (including layer of dead veg.)	restored
Upper salt-marsh zone with only <i>Elytrigia atherica</i>	restored
Zonation of pioneer, low/middle, and upper salt marsh vegetation	restored

Wave propagation along two transects (indicated by black lines in Figure 7.5) on the schematized (fictional) restored salt-marsh zone (Figure 7.5) was evaluated. SWAN converts measures of wind conditions, local bathymetry and vegetation properties into near-shore wave parameters (height, period and direction). Wave damping by vegetation in SWAN is induced by drag force acting on the plant stems (Suzuki *et al.*, 2012), which results in less wave energy behind the vegetation field and thus a lower wave height. For each of the scenarios that involved vegetation on the salt marsh, the observed vegetation characteristics (height, diameter and stems per m²) was applied for the entire transects. We did not account for flexibility of stems, and therefore the results will be somewhat exaggerated. Including these effects, however, is non-trivial and requires complex modelling (see e.g. Dijkstra & Uittenbogaard, 2010). For simplicity a drag coefficient of 1.0 was used, as commonly found in previous studies (Nepf, 2011; Suzuki *et al.*, 2012).

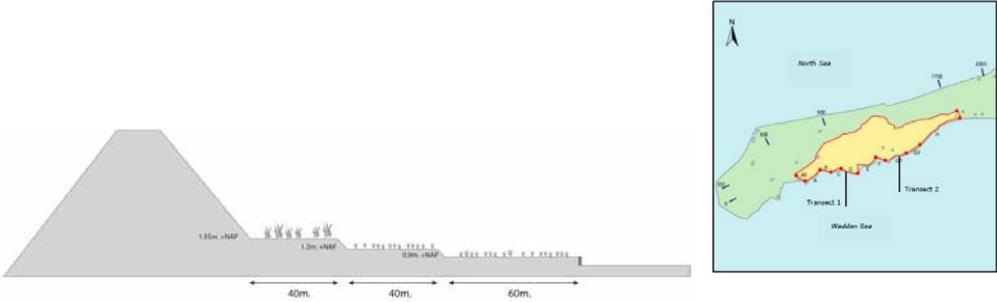


Figure 7.5: Hypothetical restored salt marsh and vegetation in front of dike (left). Dike ring at Terschelling consisting of the dike (dike stretches AO-I) along the Wadden Sea and dunes along the North Sea (right). The two analysed transects are indicated by a black line.

By law, the Wadden dike of Terschelling must protect the hinterland against extreme storm surges, as could statistically be expected once in 2,000 years. Table 7.2 gives the hydraulic boundary conditions (extreme water level, wave height, wave period and wave direction) of such an extreme storm surge for the various dike sections.

Throughout the simulations waves were applied from southwest with a wave height of 2.0 m on top of 4.2 m +NAP water levels at 3,000 m from the dike. This resulted in wave heights at the seaward marsh edge of around 1.0 m on top of a water level of 3.3 m (i.e. 4.2 m +NAP minus terrain surface of 0.9 m +NAP), a peak wave period of around 3.4 s and β of about 50°. Hence this corresponds to a situation which would be comparable to a one in 2,000 year event (viz. Table 7.2).

Table 7.2: Boundary conditions for the Wadden dike along Terschelling (Ministry of Transport, Public Works and Water Management et al. 2007). See Figure 5 for the location of the various dike sections.

Section	assessment level [m +NAP]	Hs [m]	Tm [s]	β^* [°]
A0	4.1	0.60	2.9	10
A	4.2	0.60	2.9	70
B	4.2	0.85	3.3	20
C	4.2	1.00	3.5	70
D	4.2	1.30	4.0	30
E	4.2	0.90	3.7	30
F	4.2	1.30	4.0	30
G1	4.2	0.85	3.5	30
G2	4.2	0.95	3.6	60
H	4.2	0.70	3.0	50
I	4.2	0.70	3.0	

β^* is the angle between the direction of incident wave and normal of the dike

7.3 Results

Characteristics of salt-marsh vegetation types

In the area between the stone dam and the former salt-marsh cliff edge, and behind the former salt-marsh cliff edge a range of typical salt-marsh plant species (Table 7.3), plant communities and habitats was found (Table 7.4). In total, 78 plant species were observed (including 2 algae and 11 mosses), 14 syntaxa and 3 habitat types, within the 90 vegetation relevés along the 14 transects.

Table 7.3: Most frequent plant species (phanerogams; algae* - marked with asterisk) found at Grië in 14 transects with 90 vegetation relevés. All these species are halophytes. Nomenclature follows Stace (2010).

Scientific name	Vernacular name	Nr of relevés where found out of 90
<i>Salicornia europaea</i>	Common Glasswort	66
<i>Puccinellia maritima</i>	Common Saltmarsh-grass	61
<i>Spartina anglica</i>	Common Cordgrass	53
<i>Suaeda maritima</i>	Annual Sea-blite	52
<i>Vaucheria</i> spec.*	-	49
<i>Aster tripolium</i>	Sea Aster	42
<i>Atriplex portulacoides</i>	Sea-purslane	36
<i>Spergularia media</i>	Greater Sea-spurrey	29
<i>Festuca rubra</i>	Red Fescue	26
<i>Plantago maritima</i>	Sea Plantain	24
<i>Limonium vulgare</i>	Common Sea-lavender	23
<i>Cochlearia anglica</i>	English Scurvygrass	21
<i>Elytrigia atherica</i>	Sea Couch	21
<i>Ulva lactuca</i> *	Sea Lettuce	19
<i>Glaux maritima</i>	Sea-milkwort	18
<i>Agrostis stolonifera</i>	Creeping bent	15
<i>Triglochin maritima</i>	Sea Arrowgrass	14

27 of the 90 plot are of the *Salicornietum brachystachyae* plant community. These plots of the *Salicornietum brachystachyae* type are located on the relatively low lying zone in the lee of the dam and along the gully in the middle (parallel to the dam). Besides *Salicornia europaea*, in the pioneer zone some *Spartina anglica* swards were encountered. In the zone just behind the dam, abundant low *Suaeda maritima* plants were present. In contrast, in the low-lying marsh along the gully, no *S. maritima* was present.

Landward of the central gully, relatively many plots were dominated by *Puccinellia maritima*, characteristic for the low and middle salt-marsh zone. In this zone also typical salt-marsh

species as *Atriplex portulacoides*, *Plantago maritima*, and *Limonium vulgare* were growing. On the more elevated areas towards the former cliff, also species like *Juncus gerardii*, *Agrostis stolonifera* and *Festuca rubra* were present. The upper salt marsh zone behind the former cliff (which is the old salt marsh that was eroding before the stone dam was build) is dominated by *Elytrigia atherica*.

Table 7.4: Plant communities (syntaxa) and habitats recorded at Grië in 14 transects with 90 vegetation relevés. Syntaxa and syntaxa codes follow Schaminée et al. (1998). Habitat codes follow Janssen & Schaminée (2003).

Syntaxon	Syntaxon code	Habitat code	Nr of relevés where found out of 90
<i>Pioneer salt-marsh zone</i>			
Salicornietum dolichostachyae	25AA01	1310	5
Salicornietum brachystachyae	25AA02	1310	27
Spartinetum townsendii	24AA02	1320	9
Suaedetum maritimae	25AA03	1310	2
<i>Low and middle salt-marsh zone</i>			
Puccinellietum maritimae	26AA01	1330	13
Plantagini-Limonietum	26AA02	1330	4
Halimionetum portulacoidis	26AA03	1330	8
Juncetum gerardi	26AC01	1330	2
RG* Scirpus maritimus (Asteretea tripolii)	26RG01	1330	1
<i>Zone in front of former cliff edge</i>			
Armerio-Festucetum littoralis	26AC02	1330	6
<i>Upper salt-marsh zone</i>			
Atriplici-Elytrigietum pungentis	26AC06	1330	9
Sagino maritimae-Cochlearietum danicae	27AA01	1310	1
Centauro-Saginetum	27AA02	1310	1
Trifolio fragiferi-Agrostietum stoloniferae	12BA03	-	2

*RG = abbreviation for 'Rompgemeenschap' (community of impoverished vegetation)

Stem density per m², weighted stem diameter, weighted height of the plants (June 2013) and the elevation of the relevés in the observed salt marsh zones are presented in Figure 7.6. Stem density is highest in the low and middle marsh zone (ca. 70,000 stems/m²), which is dominated by short and thin grasses like *Puccinellia maritima*. However, the variability of stem density within this zone is considerable (zone v in Figure 7.6 top left; Figure 7.7). These typical salt marsh grasses and plants were also found in the zone around the flood mark, and here also a relative high stem density was found. In the other zones, stem density was in the same order of magnitude (ca. 8000-9000 stems/m²) when in the upper salt marsh zone dead stems were included. In the salt-marsh pioneer zone, mean stem diameter is higher than in the

low and middle zone. Especially *Spartina* spp. has relatively thick stems (0.0035 m in June 2013).

Stem density in the small area dominated by the tall (mean height 0.9 m in June 2013) and robust (mean stem diameter 0.0045 m) *Bolboschoenus maritimus* was 890 stem/m². However, *Bolboschoenus maritimus* [RG* *Scirpus maritimus* (*Asteretea tripolii*)] is atypical for the Wadden Sea coast because *B. maritimus* is not a typical halophytic specie.

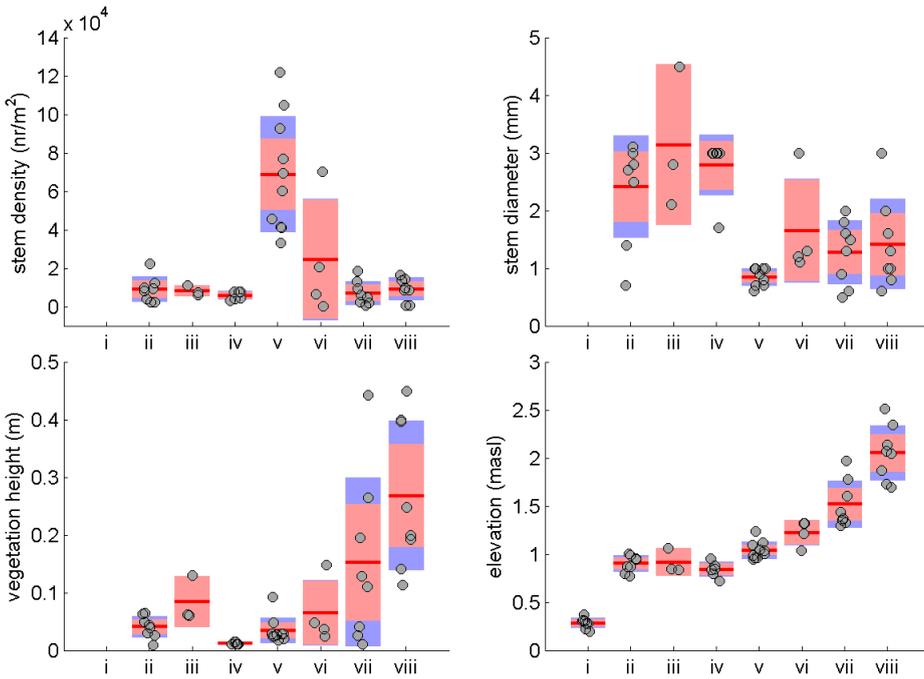


Figure 7.6: Stem density per m² (top left), stem diameter (top right), height of the plants (bottom left) and the elevation in m above sea level (bottom right) of the samples (June 2013) in the observed salt-marsh zones at Grië (Terschelling), whereby i) unvegetated mud flats in front of dam ii) densely vegetated pioneer zone behind the dam, iii) *Spartina* swards, iv) sparsely vegetated pioneer zone along gully in the marsh, v) low and middle salt marsh zone dominated by *Puccinellia maritima*, vi) zone around the flood mark, vii) upper marsh zone in front of former cliff, and viii) upper marsh zone behind the former cliff with a thick layer of some cm of dead stems of the former year and dominated by *Elytrigia atherica*. The red line represents the mean value; the pink area the 95% confidence bound around the mean, and the blue area the standard deviation of the data (added to or subtracted from the mean).



Figure 7.7: Sub-samples of densely vegetated low salt-marsh zone (left) and sparsely vegetated middle salt-marsh zone (right).

Wave damping

Figure 7.8 presents the modelled wave propagation along the two transects for the different scenarios (Table 7.5). For both locations a vegetated foreshore would result in considerably lower modelled wave heights. Although wave decay is somewhat non-linear, a linear approximation seems reasonable (Figure 7.8) and is in line with the results reported in literature (see Anderson *et al.*, 2011). In the hypothetical (and unrealistic) situation of a salt marsh covered with a dense and rigid vegetation of relatively tall and thin plants, the modelled wave height decreases along transect 1 with 0.84 m over ca. 120 m of salt marsh, and along transect 2 with 0.57 m over ca. 160 m salt marsh. This equals a wave height reduction of 0.70 % and respectively 0.35% per m salt marsh, whereas only a wave height reduction of 0.08% is found in the situation of a unvegetated restored salt marsh. A densely vegetated pioneer zone of short plants results in a reduction of 0.27% per m (averaged over the two transects), whereas a sparsely vegetated pioneer zone results in a reduction of 0.13% per m (averaged over the two transects). Furthermore, our modelling work indicates that a dense layer of short and thin grasses, as found in the low and middle salt marsh zone, is very effective in damping the waves (0.40% per m averaged over the two transects). In the situation with only a low dam at 150 m in front of the dike (which might be needed to induce salt marsh development), there is hardly any wave damping.

Table 7.5: The different situations with observed salt-marsh plant characteristics (see also Figure 7.6) at Terschelling (June 2013), for all vegetation type a drag coefficient of 1 was applied.

Scenarios	Salt marsh	Plant height (m)	Plant density (stems/m ²)	Stem diameter (m)
i Current situation	no	-*	-*	-*
Dam/groyne (0.9 m in height) in front of dike (150 m)	no	-*	-*	-*
Unvegetated salt marsh	restored	-*	-*	-*
ii Densely vegetated pioneer salt marsh (as found behind dam)	restored	0.0407	8799	0.0024
iii Salt-marsh zone with <i>Spartina</i> spp.	restored	0.0845	8120	0.0031
iv Sparsely vegetated pioneer zone (as found along the gully)	restored	0.012	5767	0.0028
v Low/middle salt-marsh zone	restored	0.0339	68742	0.0009
vi Salt-marsh zone around flood mark	restored	0.064	24407	0.0017
vii Upper salt-marsh zone in front of former cliff	restored	0.1524	7052	0.0013
viii Upper salt-marsh zone (including layer of dead vegetation)	restored	0.2677	9122	0.0014
Upper salt-marsh zone with only <i>Elytrigia atherica</i>	restored	0.3857	4644	0.0023
Zonation of pioneer, low/middle, and upper salt marsh vegetation	restored	ii-v-vii	ii-v-vii	ii-v-vii

* = salt-marsh vegetation absent

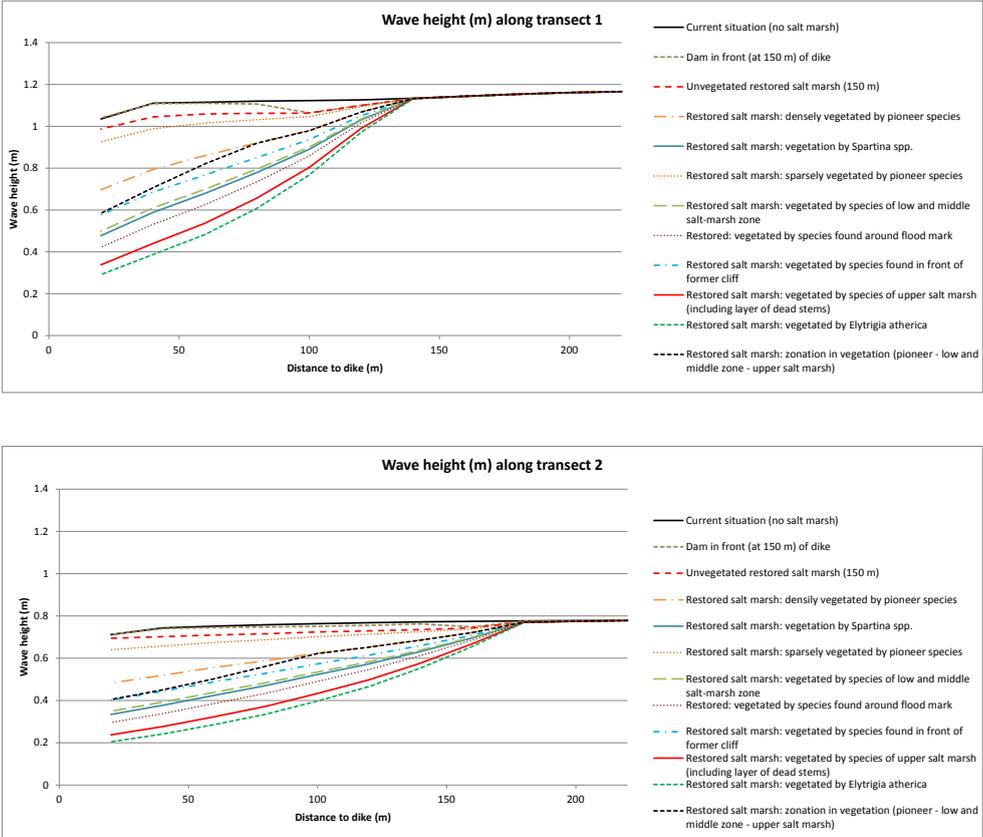


Figure 7.8: Modelled significant wave height along two transects perpendicular to the coast of Wadden barrier island Terschelling for different (fictional) scenarios (see Table 7.5). Note that the water level at the seaward marsh edge is 3.3 m and 2.7 m just in front of the dike.

7.4 Discussion, conclusions and recommendations

Wave attenuation by salt marsh vegetation

The modelling work touches on confirmatory, exploratory as well as predictive aspects. It is confirmatory in the sense that the effect of vegetation on salt marshes on wave damping have been described in various studies that were based on experiments in flumes (e.g. Bouma *et al.*, 2005; Augustin *et al.*, 2009; Koftis *et al.*, 2013; Anderson & Smith, 2014), model work (e.g. Mendez & Losada, 2004; Suzuki *et al.*, 2012; Maza *et al.*, 2013) or observational evidence (e.g. Cooper, 2005; Möller *et al.*, 2001, 2002, 2006; Ysebaert *et al.*, 2011; Yang *et*

al., 2012). The modelling work confirms much of these results: the wave-damping capacity of vegetated forelands is strongly related to stem density (Anderson & Smith, 2014), stem diameter and height of the plants. Furthermore, our wave-damping results are comparable with field measurements at other natural coastal wetlands of comparable width and with comparable plant species in NW-Europe (see e.g. Möller *et al.*, 1999, 2002; Cooper, 2005). A new result is that the vegetation of the different salt marsh zones, and thus the spatial distribution of the different vegetation types typically found on natural salt marshes, can have a considerable impact as well. Hence over-simplified experiments or simulations that do not take the zonation of different plant morphologies into account may lead to biased (or at least imprecise) conclusions.

The research is exploratory because it evaluates the effect of a relatively small sample of scenarios in a specific case study. However, to obtain results that can be generalized and treated as evidence, these scenarios (as well as other relevant scenarios) would need to be replicated at different locations, with different models and preferably also with experimental work. In addition, it would be desirable to conduct an independent validation of the vegetation effects in the SWAN 2D model to encertain that the model used in this study is indeed adequate for these purposes.

The research also provides predictive results in the sense that for a number of realistic scenarios important variables are being estimated, which provides standard output (such as wave height reduction) that can be used in the search for alternative flood defence options (as is currently explored in the Dutch Wadden region Delta Program).

Although realistic vegetation characteristics were applied, there are still a number of simplifications that may lead to biased results and need to be considered in future work.

First of all there is under natural conditions on salt marshes a considerable spatial heterogeneity (patchiness) of vegetation properties as well as surface topography at fine scales (Van de Koppel *et al.*, 2005; Balke *et al.*, 2012). In the model application such fine heterogeneity was not implemented.

In addition to the spatial variability, there is also a temporal variability in salt marsh vegetation characteristics due to seasonal vegetation growth and decay. In temperate climates, where our study is situated, the height of the salt-marsh vegetation, as well as the diameter of the stems will increase during the growing season. But even these regular cycles will show considerable inter-year variability. In June 2013 (which was the start of the growing season after a relatively cold winter and spring) the height of e.g. for *Salicornia europaea* varied

between 0.025-0.04 m, while a maximum height for *Salicornia europaea* of 0.30 m is reported (Van der Meijden, 2005). Also the mean heights of the other encountered species in June 2013 were considerably smaller than reported in literature (Van der Meijden, 2005; Feagin *et al.*, 2011). During the growing season, species like *Salicornia europaea* will develop branches. The change in shape will affect the wave-damping capacity, and there may be a difference in characteristics between the stem and the canopy of branches and leaves. It is also very likely that stem density will change during the growing season because of competition or because of grazing. In winter annual salt-marsh species will mostly disappear and the above-ground vegetative parts of some perennial species like *Elytrigia atherica* will wither. Therefore, during winter and early spring, the wave-damping capacity of the restored salt marsh will differ considerably from the capacity during summer and autumn.

Finally, the parameterisation of plant characteristics into the model may need further attention. As an example one could consider tall and thin grasses, like *Elytrigia atherica*. These will bend when exposed to severe waves during storm conditions. This leads to a much lower effective height of the vegetation during flooding and subsequently to a reduced wave damping capacity of the vegetation. Interesting in this regard is that Bouma *et al.* (2010) found that, on a biomass basis, dissipation of hydrodynamic energy from waves is very similar between the stiff grass *Spartina anglica* and the flexible grass *Puccinellia maritima*.

In the modelling work flexibility of stems was not accounted for, and for all vegetation types a drag coefficient of 1 was applied (which is in general used for rigid plants). The drag coefficient for tall and thin plants may be less than 1 (see literature cited in Anderson *et al.*, 2011). Whereas including the vertical characteristics of the vegetation layer is possible in SWAN (Suzuki *et al.*, 2012), it is still difficult to take the detailed morphology for the plants and their flexibility into account. Furthermore, the degree of wave damping may be influenced by the direction of local currents (Hu *et al.*, 2014). Nevertheless, it seems worthwhile to investigate both morphology and flexibility of natural salt marsh vegetation (including the possible seasonal variability) and to incorporate these properties in the calculation of the drag coefficient, if possible taking variable local currents into account.

Potential of salt marsh restoration as a climate adaptation measure

To incorporate natural vegetated forelands in an adaptation strategy for the Wadden Sea region, they have to be integrated in design and assessment criteria for flood defences and in management schemes. This requires profound insight in their wave attenuation performance during extreme storm events. There is still little field data about their effects during extreme conditions. It is important to keep in mind that models like SWAN are developed and

evaluated on the basis of either scaled-down lab tests or field measurements under less-than-extreme conditions. Hence, applying these models to predict effects under extreme conditions relies on extrapolation. To verify whether SWAN is able to quantify wave attenuation by vegetation under extreme situations, monitoring of wave height during storm conditions is required to further calibrate and validate the model.

The spatial and seasonal variability of vegetation characteristics makes it difficult to model the wave attenuation process by vegetation (Van der Meer, 2002) and to incorporate salt marsh vegetation in a flood protection strategy. On the other hand, salt marsh vegetation succession, species compositions and effects on these by management and restoration measures have been well-studied and monitored (e.g. Bakker, 1989; Olf *et al.*, 1997; Adam, 1990; Wolters, 2006). Therefore, it might be feasible to model the seasonal as well as the spatial variability of the vegetation characteristics and incorporate this in SWAN (or other models). This can e.g. be achieved by a piece-wise linear relation, similar to the way in which crop factors are specified to estimate potential evapo-transpiration of agricultural crops over a growing season. Monitoring the spatio-temporal variability of vegetation characteristics together with measuring *in situ* wave damping will contribute to knowledge development on this topic.

The next step would be the coupling of the seasonal variability in vegetation characteristics with the seasonal variability in storm characteristics. This would provide information about the reliability of the contribution of a vegetated salt marsh to flood protection.

Management implications

Restoring salt marshes is a dynamic and flexible adaptation strategy. Under conditions of abundant sediment supply, salt marshes can keep pace with sea level rise (Allen 2000; Dijkema *et al.*, 2013), and after eroding by an extreme event, an accreting salt marsh may recover (Pethick, 1992), while a traditional engineering solution is static (Borsje *et al.*, 2011). However, a reduction in width and/or height reduces their effectiveness in damping waves (Brampton, 1992). Therefore, in addition to the measures to prevent erosion and to stimulate accretion (Chapter 4 and 5), also monitoring of the salt-marsh extent, of the accretion rate in relation to sea level rise as well as of monitoring sediment concentration of the sea water and of the condition of the adjacent sand and mudflats form important aspects of this strategy. By responding to changes in the salt-marsh system, restoring salt marshes fits very well in an adaptive management strategy, which is based on the idea that our knowledge of ecosystems is incomplete and management should be seen as an iterative process. Thus, stepwise creating

a better understanding of the system by using the results of the experimental designs, to adapt management to the latest knowledge available (Dessai & Van der Sluijs, 2007).

To apply vegetated forelands in the water safety strategy, it is important to develop criteria for weighting the pro's and con's of traditional flood defence reinforcement against developing vegetated forelands as buffer zones. The benefits are formed by flood protection, which can be measured by avoided costs of dike reinforcement (see e.g. King & Lester, 1995; Dixon *et al.*, 1998) or avoided damage (e.g. Costanza *et al.*, 2008). The costs concern the costs for preservation, developing and maintenance of salt marshes. They furthermore include changes in estuarine habitats (see chapter 4), which are difficult to monetize.

Furthermore, it is important to develop an integrated approach to balance between flood protection and nature conservation objectives. Ideally, management that targets habitat restoration or enhancement would allow natural processes, leading to variation along the coastline. However, to be effective for flood protection, a salt marsh has to be relatively high, broad and stable even under extreme conditions. The challenge is to apply techniques that are mutually beneficial for both nature and flood protection (Van Loon-Steensma & Vellinga, 2013).

Finally, attention should be paid to salt-marsh vegetation management. The analyses underpins the importance of salt-marsh vegetation on wave damping. Thus in view of flood protection, management should favour salt-marsh plant communities with the most effective characteristics, including spatial and temporal aspects. Little information is available on this particular topic in the literature. This lack is interesting, given the extensive research on succession in salt marsh vegetation and the often acknowledged important interactions between salt-marsh vegetation, sedimentation and geomorphology.

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8

Synthesis

8.1 Introduction

This thesis has presented an exploration of long-term flood protection options for the Wadden region. Several dike concepts were considered, but the goal was to find options that, in addition to flood protection, also favour nature, landscape, heritage, recreation or economic values. At present, some 227 km of dikes defend the northern part of the Netherlands against flooding by the Wadden Sea. In rural areas, these dikes are generally built with a sand core, an outer protection layer of either clay and grass or stones and asphalt, toe protection and a maintenance road. They are designed to withstand extreme storm surges with a probability of occurrence ranging from once in 2,000 years to once in 10,000 years. The crest of traditional dikes are well above the expected extreme storm surge level and wave run-up. Climate change, however, will result in changing boundary conditions. Therefore, the question arises of whether by reinforcing these ‘Traditional dikes’ adequate safety can be provided in a changing climate, or whether innovative flood protection ideas and designs should be developed instead. ‘Innovative dikes’ must meet the same standards for withstanding extreme conditions as Traditional dikes, but they may in addition be more robust under the most extreme conditions examined. Furthermore, alternative designs should ideally enhance nature or landscape qualities, while perhaps offering new opportunities for combining functions; they should be cheaper to construct and maintain than traditional reinforcements, and provide new socio-economic opportunities for the Wadden region (Van Loon-Steensma *et al.*, 2012b).

The current study considered several available innovative flood defences in its broad screening of alternatives (chapter 2). However, special attention was given to the incorporation of salt marshes in a long-term climate-change adaptation strategy for the Wadden region. There were four reasons for this emphasis: (i) salt marshes are already present along extended stretches of the dikes in the Wadden region (chapter 3), (ii) they have considerable wave damping capacity (chapters 3, 4, 5 and 7), (iii) salt marshes are adaptable

and capable of keeping pace with a rising sea level (chapters 3 and 4) and (iv) they are a prominent feature of the Wadden Sea region and represent important nature and landscape values (see e.g. Wolff, 1983; CWSS, 1991; De Jong *et al.*, 1999; Essink *et al.*, 2005; Reise *et al.*, 2010).

In the introduction of this thesis, five research questions were formulated:

1. What innovative flood defence concepts hold promise for the Wadden region in the context of rising sea level?
2. What locations in the Wadden region appear promising for salt marshes?
3. How do vegetated forelands, like salt marshes, contribute to flood protection?
4. What is the potential ecological value of a restored salt-marsh foreland?
5. What are the prospects for salt-marsh protection and restoration in the Wadden region?

These questions were investigated in the individual chapters, the findings of which are reviewed below.

8.2 Promising innovative flood defences for the Wadden region

To identify adequate new flood protection ideas and designs, a ‘portfolio’ was developed introducing existing and innovative dike designs with potential applicability to the Wadden region (chapter 2). Although most dike stretches require tailor-made solutions based on site-specific boundary conditions and characteristics, in particular the ‘Multifunctional dike’ design and the concept of ‘Eco-engineering’ were identified as promising ideas for further study for the Wadden region.

Multifunctional dikes are robust and offer space for various functions and values (Van Loon-Steensma & Vellinga, 2014). However, their performance in an integral assessment is strongly dependent on the applied functions and the weights assigned to the various evaluation criteria. Multifunctional dikes that offer space for housing, economic activities, tourist facilities and educational purposes were considered especially promising for further exploration in built areas with re-development ambitions and space constraints. In rural areas, they may offer space to combine robust flood protection with energy production by wind turbines. However, this would not necessarily contribute to the perceived spatial quality of the Wadden area, and is probably not feasible for most locations. Such a combination may well be appropriate for locations where industry or other major infrastructure is present. An

important asset of the Multifunctional dike is the high level of safety it offers, as a Multifunctional dike is over-dimensioned by definition (Van Loon-Steensma & Vellinga, 2014). This is particularly relevant for the Eems region, which is home to nationally crucial energy infrastructure.

The design that this study termed ‘Salt marshes adjacent to the dike’ was considered an attractive eco-engineering alternative for the Wadden region. In short, a salt marsh forms a vegetated foreshore in front of the dike, offering a challenging opportunity to integrate nature with an engineered solution. An advantage of this approach is the contribution of salt marshes to the spatial quality of the Wadden Sea coast, as salt marshes are appreciated by inhabitants and tourists (Van Loon-Steensma, 2011b; Van Loon-Steensma *et al.*, 2014a,b). Moreover, the vegetated elevated zone, including the adjacent mudflats, breaks waves, absorbs wave energy and, subsequently, affects wave action and wave run-up. This may have important implications for the required dike dimensions (in particular, dike slope and height) and the need for dike slope and toe protection structures (e.g. hard revetments and rocks). In addition, the presence of salt-marsh areas may have favourable effects on other design aspects, such as dike (macro)stability and piping.

The ‘Wide green dike’ concept, which combines wave damping by salt marshes and moderation of wave run-up during extreme conditions by a shallow green seaward slope, is another interesting combination of engineered and nature-based solutions. It is considered to be worthy of further exploration too. Such a grass-covered dike is more attuned with the Wadden Sea coastal landscape than the other dike designs (including these with a salt-marsh foreland adjacent to a traditional revetment).

The ‘Multiple lines of defences’ concept received somewhat lower scores in the overall assessment (chapter 2) compared with the ‘Traditional dike’, but it was nevertheless identified as potentially suitable for dike stretches with parallel historical dikes along the primary flood defence present, or where salty nature reserves or lakes are present behind the dike. This solution implies that the most seaward dike must be overtopping-resistant, as occasional wave overtopping would be allowed, and that the landward area of the most seaward dike is resistant to occasional overflow. Such occasional wave overtopping may favour salty nature, but will impede arable agriculture and dairy farming in the hinterland, unless damage or nuisance could be prevented by drainage ditches and pumps. An attractive aspect of this concept is that it builds on the unique landscape features of the Wadden region, such as the historical dikes, former salt-marsh gullies and reclamation systems, dwelling mounds, canals and ditches, and former clay-mining pits (which are now often salty nature areas landward of the dike) (Frederiksen, 2012).

8.3 Promising locations for salt marshes in the Wadden region

All dike trajectories where salt marshes are already present (some 73 km, including the 12.5 km wide green dike alongside the 'Noorderleeg' summer polder), or where they develop naturally (some 15 km) (see Figure 3.5), are considered to be suitable locations for a strategy that combines a naturally vegetated foreshore with an engineered solution (chapters 2 and 3). These appear to be areas where hydrodynamic conditions are favourable for development and maintenance of salt marshes. Furthermore, where salt marshes are already present, the application of salt marshes in a flood protection strategy would not be at the expense of sandflat and mudflat habitats.

Nevertheless, it is important to keep in mind that the existing salt marshes along the mainland coast are the result of constructed accretion works. Without these accretion works, the total area of these semi-natural salt marshes along the embanked mainland coast would steadily diminish due to erosion. Therefore, integration of these salt marshes into a flood protection strategy would require management and maintenance to enhance their width, elevation and vegetation cover, as well as their capacity to keep pace with a rising sea level (chapter 4). For decades, the marshes have been subject to a range of management and restoration strategies focusing on their biodiversity value. Nature-oriented conservation and development goals have been formalized in international policy and legislative frameworks (e.g. Natura 2000). Most of these focus on protecting the areal extent of salt marshes and the associated habitat (vegetation species abundance and diversity) alongside conservation of other ecological parameters such as bird and invertebrate populations. The challenge is to find a regime of management and maintenance that mutually enhances both the ecological and flood protection services of the salt marshes (chapter 4). Such an approach must be formalized in agreements involving those responsible for flood protection and those responsible for nature conservation.

Of course, a shift towards the inclusion of salt marshes in a flood protection strategy is especially relevant when the current flood defences are in need of reinforcement works. At present, nearly half of the dikes along the Wadden Sea do not meet current standards due to problems with the grass cover, stone revetment or inner berm (Smale & Hoonhout, 2012). There is a legal obligation to solve these problems by 2015. But including the expected effects of climate change in new boundary conditions will likely result in the need for additional reinforcement works (Figure 8.1). The future task to improve the dikes offers an opportunity to implement new flood protection designs which have been shown applicable to almost the entire Wadden Sea coast.



Figure 8.1: Future dike reinforcement task for a scenario of 0.35 m sea level rise in 2050 (compared to 2015). (source data: Deltares; Van Loon-Steensma et al., 2012c)

As previously emphasised, the dike trajectories where salt marshes are already present or where they have a natural tendency to develop are particularly promising for further exploration. Along some 42 km dike, minimal effort would be required to develop new salt marshes. Here a combination of a stimulated vegetated foreshore development and engineered design is possible, but in addition to maintenance and construction costs (e.g. for dams, groynes and sediment), the value of the sandflat and mudflat habitats that would have to be forfeited would need to be taken into consideration.

Interestingly, Smale (2014) implicitly suggested that for dike sections without salt marshes the effect of salt marshes would be substantial. However, in general, the absence of salt marshes at these locations is largely due to site-specific unfavourable abiotic conditions for their formation (i.e. adverse currents, detrimental wind-wave orientation, low elevation or low sediment concentration). Creation and subsequent preservation of salt marshes here would therefore require substantial management effort. Hence, the integration of a vegetated foreshore for these dike sections is not cost-effective and seems unfeasible.

8.4 Flood defence value of salt-marsh forelands

Salt marshes form a shallow transition zone from sea to land that affects incoming waves. The current dikes in the Wadden region are designed (depending on site-specific conditions and standards) to withstand extreme water levels between 4.1 m and 6.8 m +NAP and wave heights of 0.65-2.8 m (Ministerie van Verkeer en Waterstaat, 2007a). However, salt marshes in the Wadden Sea have at the seaward side an elevation of some 0.6-1.5 m +NAP (mean high water depends on the location in the Wadden Sea) and at the landward side a maximum elevation of some 1.7-2.9 m +NAP. Notwithstanding the significant water depth of the marsh during extreme conditions, the explorative modelling in SWAN indicates that even under extreme conditions, the presence of salt marshes would considerably lessen the heights of waves reaching the Wadden Sea dikes (chapter 3 and 7).

Climate change will increase the frequency of extreme water levels as well as raise maximum wave heights. Salt marshes have no effect on water levels in the Wadden Sea during extreme events, but they would result in reduced water depths near the dikes. This reduces wave heights near the dike during extreme events, due to the salt marshes' wave damping influence (chapters 5 and 7). Vegetation increases salt marshes' wave damping capacity further (chapters 5 and 7).

Under conditions of abundant sediment supply, salt marshes can keep pace with a rising sea level, which may result in more or less unchanged water depth near the dike, even though sea level may rise. Subsequently, wave action and wave run-up would remain more or less unchanged. In addition, after an extreme event accreting salt marshes might recover, while a traditional engineering solution is static, requiring repair by human action (Borsje *et al.*, 2011).

Modelling work by Calderon & Smale (2013) suggests that the integration of a salt-marsh foreland 600 m wide adjacent to a dike could substantially reduce, or postpone, the need for reinforcement works along several stretches of Wadden Sea dikes. They found that if such a zone could keep pace with a rising sea level (up to 0.15 m in 2050), only modest dike reinforcements would be needed in 2050 (heightening some 50 km dike by 0-0.25 m). Without a salt-marsh zone, all dikes will need to be heightened (by 0-0.5 m). The presence of a salt-marsh zone that can keep pace with a rising sea level would result in an unchanged water depth in front of the dike, even though sea levels might rise. Furthermore, Smale (2014) explored the effect of widening the salt-marsh zone and the effect of accretion pace. In a situation where sea level has risen by some 0.15 m in 2050, waves are dampened over 1,000 m of salt marsh. Additional width of the salt-marsh zone did not result in more wave damping

(Smale, 2014). An increase in elevation of the marsh surface (by sedimentation) that outpaces the rising sea level reduces the need for dike reinforcement, again, due to reduced water depth adjacent to the dike. However, salt marshes are present only along certain dike sections in the Wadden Sea, and some are rather narrow.

So far, the wave damping effect of these existing or developing salt marshes has not explicitly been taken into account in determining the design crest height of Wadden Sea dikes. Implicitly, however, their effect is included in the boundary conditions, which are specified 50-100 m from the toe of the dike. Because wave reduction particularly occurs in the first few meters from the salt-marsh edge (due to the breaking of the waves), dike heights might be over-dimensioned when a salt-marsh zone is present within 50-100 m. For such dike stretches, the integration of salt marshes in the flood defence would result in a combined, or even additional climate-change adaptation strategy. This increases flexibility and allows time to experiment with management and maintenance and to monitor the impact of salt marshes on wave height and wave action during storm conditions. Moreover, it presents an opportunity to explore an adaptive approach.

Measures to preserve the present areal extent of salt marshes and to enhance their ability to keep pace with a rising sea level are, furthermore, likely to be very effective in reducing the need for future reinforcement works. Under moderate storm conditions, with lower water levels and wave heights than extreme conditions, salt marshes certainly prevent full wave action on the dike. Because moderate storms occur several times each year, the presence of salt marshes would ensure less wear and damage to the revetment. Furthermore, they would increase the under-seepage length.

8.5 Ecological value of a restored salt-marsh foreland

The study of salt-marsh ecology presented in this thesis is limited to vegetation only. The diversity and unicity of salt-marsh vegetation is, however, considered to be indicative of other salt-marsh ecosystem components (see e.g. Doody, 2008). The restored salt marshes at the study sites exhibit vegetation comparable to that found in other Wadden Sea salt marshes, and are thus considered to harbour comparable ecological qualities (chapter 6).

At the study sites, restoration of salt-marsh habitats was a positive side effect of measures targeting erosion protection (chapter 5). The measures (low stone dams) effectively led to the restoration of pioneer marsh vegetation (H1310 and H1320 and at some places H1330) in areas that had been diminished by erosion and subsequently transformed into mudflats and

sandflats (H1140). Yet the fixed nature of the seaward boundary due to this measure remains a point of concern: the dam fixes the transition from mudflats to salt marsh and prevents the natural retreat of the salt-marsh edge in response to extreme events. This impacts the geomorphologic value of the restored salt marshes.

An intriguing idea is that the biodiversity value of salt marshes may increase in the future, because of the expected ongoing worldwide decline of this ecosystem due to rising sea levels and intensive human usage of coastal areas (Barbier *et al.*, 2011). Flood protection goals may thus form a very welcome additional incentive to preserve and restore salt marshes.

8.6 Prospects for salt-marsh protection and restoration as a long-term adaptation measure in the Wadden region

The explorative modelling work indicates that salt-marsh forelands adjacent to Wadden Sea dikes could reduce or postpone the need for reinforcement works along several stretches of Wadden Sea dikes. Therefore, integration of salt marshes in a long-term adaptation strategy is very promising, especially in view of their capacity to keep pace with a rising sea level. In a changing climate, however, incorporation of salt marshes into the flood defence zone will never eliminate the need to raise the crest of the dikes in the future. Salt marshes that can keep pace with rising sea level result in unchanged water depths in the zone fronting the dike, but they do not affect the rising level of seawater. While they reduce wave action and wave run-up, they will not prevent overflow under conditions of a rising sea level.

Whether salt marshes are able to keep pace with a rising sea level largely depends on the availability of sediment. Sediment supply is among others dependent on the morphology of channels and tidal flats seaward of the sedimentation fields (Janssen-Stelder, 2000). Whether the sediment is deposited (when the net supply is positive), however, depends on the wave conditions within the sedimentation fields. Wave heights in these sedimentation fields are greatly influenced by the height, maintenance and spatial orientation of groynes and dams.

Because wave damping is determined largely by the breaking of waves (which occurs in the first meters of the salt marsh), a narrow zone of salt marsh may already be effective for flood protection. However, salt marshes are dynamic by nature. There is still little experience in quantifying and assessing their dynamics and in integrating them dike designs. Therefore, to guarantee wave damping during extreme events, it is wise to include some over-dimensioning in the required width of the foreshore. Such over-dimensioning would also present opportunities to combine functions in the foreshore, because over-dimensioning of the

vegetated foreshore allows flexibility for natural processes, as well as spaces for recreation or agricultural uses. This would then result in a robust, multifunctional flood defence zone (see Figure 1.2).

The application of salt marshes for flood protection represents a combined approach to coastal climate-change adaptation, which is considered to allow for prudent preparation in a highly uncertain environment (e.g. Moser *et al.*, 2012; Cheong, *et al.*, 2013). This applies equally to other ecosystem engineering species, like reef-building oysters, mussel beds and eelgrass. These species can play an important role in influencing the wave climate and stabilizing sediment. Their introduction may be beneficial for protecting the salt-marsh edge from erosion and for stimulating salt-marsh formation.

Furthermore, while traditional engineering solutions are static (Borsje *et al.*, 2011), salt marshes offer a dynamic form of flood protection and a flexible adaptation strategy. This is well aligned with an adaptive management strategy, which is based on the idea that our knowledge of ecosystems is incomplete and management should be seen as an iterative process. This implies a stepwise process of improving our understanding of the system using the results of experimental designs, and continual adaptation of management to the latest knowledge (Dessai & Van der Sluijs, 2007). An important aspect of such a strategy is monitoring of the salt-marsh extent, the accretion rate in relation to sea level, the sediment concentration of seawater, and the condition of the adjacent sandflats and mudflats (Nicholls *et al.*, 2013).

In the end, however, the prospects for salt-marsh preservation and restoration for flood protection in the Wadden region depend also on aspects other than the main physical factors governing salt-marsh dynamics (such as sediment supply, wind-wave dynamics and sea level, see Figure 4.1). Prospects also hinge on the foreseen costs and benefits of salt marsh development relative to traditional reinforcements. Although ecosystem creation and restoration are advocated as cost-effective (see e.g. Temmerman *et al.*, 2013) there is still little quantitative information about these aspects.

Reasonably well understood are the benefits related to flood protection, which can be measured by the avoided costs of dike reinforcement (see e.g. King & Lester, 1995; Dixon *et al.*, 1998) or avoided damage (e.g. Costanza *et al.*, 2008). But there is not much known yet about risk quantification due to the dynamic behaviour of salt marshes. Furthermore, ecological and landscape qualities that may subsequently influence recreation and tourism, are not well understood and difficult to quantify. Costs concern those for preservation,

development and maintenance of salt marshes, as well as changes in estuarine habitats (see chapter 4), which are difficult to monetize.

8.7 Further research

As illustrated by this thesis, the integration of salt marshes into a flood protection strategy is a multifaceted endeavour, and one in which a large array of effect types must be considered. There are still many questions that need further investigation.

The ability of salt marshes to keep pace with a rising sea level under conditions of abundant sediment and to recover after erosion due to an extreme storm event suggest that salt-marsh development for flood protection is a dynamic and flexible adaptation strategy. Long-term monitoring of sedimentation processes and vegetation development is key to advance knowledge about the effectiveness of measures taken and to indicate any necessary adjustments of management or additional measures required.

The challenge is to apply techniques that are mutually beneficial for both nature and flood protection. Ideally, management that targets habitat restoration or enhancement would give natural processes free rein, leading to variation along the coastline. However, to be effective for flood protection, a salt marsh has to be relatively high, broad and stable and remain so during an extreme event. Future research should focus on best practice for management, including spatial and temporal aspects, and ways to favour salt-marsh plant communities with the most effective characteristics.

Managed realignment – the deliberate breaching of existing sea defences resulting in the creation of salt marshes in the flooded lands behind the opened dikes – is increasingly seen as a key element in sustainable flood and coast management (Ledoux *et al.*, 2005). Salt-marsh restoration by realignment will not come at the expense of protected Wadden Sea habitats, and will effectively result in increased salt-marsh area. Yet this measure may diminish agricultural land. The former summer polders ‘Noorderleeg’ and ‘Paezmerlannen’ are current realignment sites. It would be worthwhile to explore further possibilities for realignment in the Wadden Sea region.

To incorporate salt marshes in a climate-change adaptation strategy for the Wadden Sea region, they must be integrated into design and assessment criteria for flood defences and into management schemes. This requires profound insight into their wave attenuation performance during extreme storm events. Although the results for wave damping under extreme

conditions in the Wadden Sea by salt marshes from the model study in chapter 7 (Figure 7.8) are consistent with the results found by Venema *et al.* (2012) (Figure 3.4); these studies used the same model (SWAN) and results are therefore not strengthening each other. There is still little field data available about the effects of salt marshes under extreme conditions. It is important to keep in mind that models like SWAN have been developed and evaluated on the basis of either scaled-down laboratory tests or field measurements conducted under less-than-extreme conditions. Hence, applying these models to predict effects under extreme conditions relies on extrapolation. To verify whether SWAN accurately quantifies wave attenuation by vegetation under extreme situations, monitoring of wave height during storm conditions is required to further calibrate and validate the model.

Whereas including the vertical characteristics of the vegetation layer is possible in SWAN (Suzuki *et al.*, 2012), it is still difficult to take into account the detailed morphology of plants and their flexibility. Furthermore, the degree of wave damping may be influenced by the direction of local currents (Hu *et al.*, 2014). Nevertheless, it seems worthwhile to investigate more in depth both morphology and flexibility of natural salt-marsh vegetation (including possible seasonal variability) and to incorporate these properties into calculations of the drag coefficient, if possible taking variable local currents into account.

Vegetation characteristics are a major factor in the wave damping capacity of salt marshes (chapter 7). However, the spatial and seasonal variability of vegetation characteristics makes it difficult to model the wave attenuation by vegetation (Van der Meer, 2002) and to incorporate salt-marsh vegetation into a flood protection strategy. On the other hand, salt marsh vegetation succession, species compositions and effects of management and restoration measures on these have been well studied and monitored. Therefore, it might be feasible to model the seasonal variability of the vegetation characteristics and incorporate this into SWAN (or other models). Monitoring the seasonal variability of vegetation characteristics together with measuring *in situ* wave damping will contribute to knowledge development on this topic. The next step would be to couple the seasonal variability of vegetation characteristics with the seasonal variability in storm characteristics.

Finally, to underpin decision-making in environmental land use planning and nature conservation a more precise valuation of the different services (especially with regard to ecology and landscape) is an important topic for further research (De Groot, 2006; De Groot *et al.*, 2010; Luisetti *et al.*, 2011).

8.8 Final conclusions

The overall objective of this dissertation was to explore the potential for adapting the environment of the Wadden region to the rising sea level by combining functions such as nature and landscape in flood defences. Special attention was given to the role of salt marshes in this context.

The Wadden Sea's salt marshes form a shallow foreland that affects incoming waves. The explorative modelling indicates that integration of a salt-marsh foreland adjacent to the Wadden Sea dikes could reduce, or postpone, the need for reinforcement works along several stretches of Wadden Sea dikes. Therefore, integration of salt marshes in a long-term adaptation strategy appears promising, especially for dike sections where salt marshes are already present or developing. Under conditions of changing climate, however, the integration of salt marshes into the flood defence zone will not eliminate the need to raise the crest of the dikes in the future. Salt marshes that can keep pace with rising sea levels result in unchanged water depths adjacent to the dike, but they do not affect seawater levels. Salt marshes attenuate wave action and wave run-up, but they will not prevent overflow and wave overtopping as sea level rises.

This thesis has confirmed that vegetation characteristics are a major factor in the wave damping capacity of salt-marsh forelands. The analyses also reveal that the vegetation in the different salt-marsh zones, and thus the spatial distribution of the different vegetation types typically found on natural salt marshes, can have a considerable impact as well. Hence over-simplified experiments or simulations that do not take the zonation of different plant morphologies into account may lead to biased (or at least imprecise) conclusions. Furthermore, in an adaptation strategy that includes vegetated foreshores, it is advisable that attention be paid to salt-marsh vegetation management. Management should favour salt-marsh plant communities with the most effective characteristics for purposes of flood protection, including spatial and temporal aspects.

Finally, this thesis has revealed that in salt-marsh restoration, the goals of flood protection and nature and habitat conservation and enhancement can be mutually reinforcing.

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Summary

Concerns about the effects of climate change have set in motion a quest for flexible and integrated flood protection concepts that could be applied to adapt our environment to the foreseen accelerated sea level rise. The current thesis, focusing on the Dutch Wadden region, explores a number of innovative concepts that combine functions such as nature and landscape conservation with flood defence systems. Special attention is given to the role of salt marshes. Salt marshes form vegetated transition zones from land to water. Their shallow waters break incoming waves, reducing wave length and velocity, ultimately dissipating wave energy via friction with vegetation and the marsh surface. Salt marshes thus function as a natural flood defence. Salt marshes outside dikes can, to some extent, protect these hard defences against wave action and wave run-up.

Chapter 1 of this thesis introduces the Wadden region and the concepts and definitions that underlie this study. The Wadden Sea is one of the world's largest tidal areas. In recognition of its unique tidal ecosystem, it has been designated a World Heritage site. Its nature values are therefore the focus of national and international conservation efforts. The Wadden Sea also performs a key role in protecting the coast of the Netherlands' mainland by its wave-damping capacity, via its barrier islands, tidal flats, banks and salt marshes. The Dutch have a tradition of erecting dikes to defend the barrier islands and mainland against flooding by the Wadden Sea. Inhabitants of the Wadden region have a long history of adapting their environment to their needs, by building dikes and reclamation of salt marshes for agricultural uses. This interaction of human activity and nature has produced a unique flat, open landscape of broad horizons and flood defences. However, the construction of fixed dikes (now measuring some 227 km in length), together with the closing of parts of the Wadden Sea and a rising sea level, has also resulted in coastal squeezing and diminishment of natural salt-marsh area along the fringes of the Wadden Sea.

Chapter 2 of this thesis describes the development and application of an approach to adapt the existing flood defences along the Wadden Sea coast to the expected sea level rise in the context of other uncertainties and developments. It starts by developing a dike 'portfolio' introducing both traditional and innovative flood protection concepts. Next, these concepts are evaluated with the input of local experts and using multi-criteria analysis. For application in rural areas, eco-engineering techniques received the highest scores. The construction or conservation of salt marshes for flood protection emerged as a particularly attractive option for the Wadden region, because such marshes could also increase the natural quality of the Wadden Sea landscape. In built areas, multifunctional dikes were perceived as attractive.

However, their performance in an integral assessment is strongly dependent on the functions considered and the weights assigned to the different evaluation criteria.

Chapter 3 provides background information on the Wadden Sea's salt marshes and their potential contribution in terms of wave damping. The chapter furthermore screens opportunities to integrate salt marshes into flood defences. The current salt marshes along the coast of the Dutch mainland are the result of constructed accretion works. These works were originally designed for reclamation of agricultural lands, but the goal progressively shifted towards nature conservation from the 1970s onward. Along some dike sections, the salt-marsh zone is rather narrow (a few metres), while at other locations it is more than a kilometre in width. Promising locations for integrating salt marshes into flood defences (based on the current abiotic and biotic conditions) are presented in a '*Salt marsh potential map*'. Besides elongated stretches where semi-natural salt marshes are already present (some 73 km), several stretches along the Wadden Sea coast have favourable abiotic conditions for salt-marsh development (some 15 km). However, such development may come at the cost of valuable littoral and sublittoral habitats. At some stretches salt-marsh development would require minimal effort (some 42 km) or considerable effort (some 56 km), in the form of raising the elevation via nourishment and possibly additional measures to prevent erosion and to cushion the unfavourable conditions that led to increased local water depth. Along some 75 km of dike, abiotic conditions are found to be entirely unsuitable for salt-marsh development.

Chapter 4 sketches the trade-offs between the intentional use – or deliberate creation and management – of salt marshes for flood protection, and other services provided by the salt marshes in the Wadden Sea. Under favourable conditions, salt marshes form self-maintaining 'horizontal levees' that attenuate wave energy, thus contributing to coastal protection. In addition, they host valuable ecosystem services, like biodiversity. Restoration and conservation of salt-marsh zones thus constitutes an attractive flood protection strategy. Climate change influences salt-marsh formation processes through its effect on sea level, wave conditions and vegetation. These factors must therefore be taken into account in developing policy concerning the suitability of salt marshes for use as a climate-change adaptation measure. Protecting and restoring salt marshes using soft engineering techniques represents an interesting 'no regret' adaptation strategy. Moreover, due to the time scale of climate change (long term) and salt-marsh dynamics (short term) there still is some time to experiment with techniques to protect, develop and effectively manage salt marshes.

Chapter 5 presents three case studies to illustrate the potential of salt-marsh development and preservation for coastal defence. The first case study explores and quantifies the effects of low

stone dams on salt-marsh development on the barrier islands of Terschelling and Ameland. The dams were constructed to prevent erosion of the marsh edge. Within decades, sedimentation had raised the mudflats between the dam and the former cliff, creating a broader foreshore and a new marsh area with characteristic salt-marsh vegetation. The second case study examines the impact of erosion and restoration measures on habitat development and on the flood protection value of a small salt marsh along the Wadden Sea dike of Terschelling. The third case study focuses on a location where salt marshes are combined with a 'wide green dike' along the Dollard Estuary. The case studies reveal that under favourable abiotic conditions, erosion protection by low stone dams greatly reduces retreat of the salt-marsh edge, while also helping to restore an ecologically attractive foreshore zone. Both the areal extent and vegetation of the restored salt marsh affect wave height. Findings from the Dollard case study indicate that implementation of a wide green dike comes at the expense of salt marsh area, yet it offers a more natural transition from the marsh area to the grass-covered dike, especially in comparison with a traditional reinforced dike (which is covered by asphalt or a stone revetment).

In chapter 6, the ecological value of stabilized and restored salt marshes is further quantified by comparing vegetation relevés made at two study sites with a reference set consisting of some 6,000 relevés of salt marshes throughout the Dutch Wadden region. Both simple species-by-species analysis and ordination analysis reveal that salt-marsh succession alongside low dams is no different from normal succession starting on unprotected mudflats. Therefore, measures targeting salt-marsh development for flood protection objectives do not necessarily frustrate nature conservation ambitions.

Chapter 7 explores the effect of salt-marsh vegetation on wave damping by modelling wave height for different salt-marsh scenarios. Data on species composition, vegetation height, number of stems and diameter of the plant species observed at study site Grië were used to parameterize and apply the Simulating WAVes Nearshore (SWAN) model to investigate a –schematized but realistic – restored salt-marsh zone in front of the dike. The modelling results confirm that in addition to the width and height of the foreland, vegetation characteristics like stem density, stem diameter and height of plants also affect the wave-damping capacity of forelands.

Chapter 8 brings together the most important findings. On the whole, this thesis shows that integration of salt marshes into long-term adaptation strategies is very promising for the Wadden region, especially for dike sections where salt marshes are already present or developing. The salt marshes of the Wadden Sea form a shallow foreland that dampens

incoming waves. Explorative modelling indicates that integration of salt-marsh forelands into Wadden Sea flood defences could reduce, or postpone, the need for reinforcement works along several Wadden Sea dike stretches. In a changing climate, however, integration of salt marshes into flood defence systems cannot entirely replace future reinforcement works whereby the crest of the dikes is raised. Salt marshes affect wave action and wave run-up, but they do not prevent overflow under conditions of a rising sea level.

This thesis confirms that vegetation is a major factor in the wave damping capacity of salt-marsh forelands. The analyses also reveal the considerable potential impact of vegetation in the different salt-marsh zones, and thus the importance of the spatial distribution of the various vegetation types typically found in natural salt marshes. Hence, over-simplified experiments or simulations that do not take into account the zonation of different plant morphologies may lead to biased (or at least imprecise) conclusions. Furthermore, when considering adaptation strategies that include vegetated foreshores, it is advisable to pay attention to salt-marsh vegetation management. For more optimal flood protection, management should favour salt-marsh plant communities with the greatest wave-damping characteristics and include spatial and temporal aspects.

Finally, this thesis reveals that in salt-marsh restoration, the goals of flood protection and nature and habitat conservation and enhancement can be mutually reinforcing.

Samenvatting

Aandacht voor en bezorgdheid om de effecten van klimaatverandering hebben een zoektocht geïnitieerd naar flexibele en integrale waterkeringsconcepten om onze omgeving aan de verwachte zeespiegelstijging aan te passen. In deze dissertatie, die zich vooral richt op het Waddengebied, worden een aantal innovatieve concepten verkend die functies zoals natuur en landschap combineren met het beschermen tegen overstroming. Er wordt met name gefocust op de rol van kwelders. Kwelders vormen een met zouttolerante planten begroeide overgangszone tussen zee en land. In deze ondiepe zone (voorlanden) breken de inkomende golven, worden de golfenlengte en golfenergie gereduceerd, en wordt uiteindelijk de golfenergie door wrijving met de vegetatie en het kwelderoppervlak gedissipeerd. Kwelders vormen daardoor een natuurlijke waterkering. Kwelders voor een dijk kunnen, tot op zekere hoogte, deze harde keringen beschermen tegen golfaanval en golfoploop.

Hoofdstuk 1 van deze thesis introduceert het Waddengebied en de concepten en definities die in de studie worden gehanteerd. De Waddenzee is één van de grootste getijdengebieden ter wereld en is vanwege haar belangrijke natuurwaarden aangewezen als Werelderfgoed. Deze natuurwaarden worden zowel op nationaal als internationaal niveau beschermd. Het Waddengebied speelt een belangrijk rol in de kustverdediging van Noord-Nederland. De eilanden, de zand- en wadplaten en de kwelders vormen een natuurlijk buffer tegen golfaanval. Het Waddengebied kent een lange historie van het inpolderen van vruchtbare kwelders voor agrarisch gebruik en het zich beschermen tegen hoogwater door de aanleg van dijken. In het Waddengebied heeft de interactie tussen mens en natuur geleid tot een uniek vlak en open landschap waarin dijken een prominente rol spelen. Deze Waddenzeedijken (in totaal zo'n 227 km langs de vastelandskust en de eilanden), verhinderen echter wel dat kwelders met een stijgende zeespiegelstijging landwaarts kunnen opschuiven.

Hoofdstuk 2 beschrijft de ontwikkeling en de toepassing van een aanpak om de bestaande dijken langs de Waddenzee aan te passen aan de verwachte zeespiegelstijging in het licht van andere ontwikkelingen en onzekerheden. Als eerste stap is een dijk-portfolio ontwikkeld met zowel traditionele als innovatieve dijkconcepten (die een ander ontwerpprofiel of waterkeringsprincipe hebben dan traditionele dijken). Vervolgens zijn alle dijkconcepten samen met experts van de Noordelijke waterschappen beoordeeld aan de hand van criteria uit de vergelijkingssystematiek van het Deltaprogramma. Daaruit kwam naar voren dat in het landelijk gebied vooral eco-engineering concepten interessant zijn. Met name de aanleg of het behoud van kwelders is aantrekkelijk omdat deze bijdragen aan de natuur en landschappelijke kwaliteiten van het Waddengebied. In bebouwd gebied kwamen multifunctionele dijken in de

evaluatie gunstig naar voren. Wel hangt de eindscore van multifunctionele dijken in een integrale beoordeling sterk af van de beoogde functies en de gewichten die de beoordelingscriteria krijgen.

Hoofdstuk 3 geeft achtergrondinformatie over de kwelders in de Waddenzee en hun mogelijke rol voor waterveiligheid via hun golfdempende werking, en schetst de mogelijkheden om kwelders in de waterkering te integreren. De huidige kwelders langs de vastelandskust zijn vooral het resultaat van het stimuleren van sedimentatie door aanleg van kwelderwerken. Oorspronkelijk waren deze werken bedoeld om land aan te winnen voor agrarisch gebruik, maar vanaf de jaren 70 van de vorige eeuw verschoof de doelstelling richting natuurbehoud. Niet overal langs de Waddenzeekust komen kwelders voor. Op sommige dijktrajecten bevindt zich slechts een smalle strook kwelders van enkele meters voor de dijk, terwijl langs andere trajecten de kwelders meer dan een kilometer breed zijn. De ‘Zoekkaart Kwelders en Waterveiligheid’ presenteert op basis van de huidige abiotische en biotische omstandigheden locaties waar de integratie van kwelders in de waterkering veelbelovend lijkt. Naast locaties waar al semi-natuurlijke kwelders aanwezig zijn (zo’n 73 km), zijn er ook locaties waar zich nieuwe kwelders ontwikkelen (z’n 15 km). Kwelderontwikkeling kan echter ten koste gaan van waardevolle (sub)litorale habitats. Langs zo’n 42 km dijk lijkt kwelderontwikkeling met geringe inspanning mogelijk, en langs zo’n 56 km dijk met forse inspanningen. Hierbij moet gedacht worden aan het ophogen van de bodem alsmede maatregelen om erosie te beperken en gunstige condities voor kweldervorming te creëren. Langs zo’n 75 km dijk lijken de abiotische omstandigheden volstrekt ongunstig voor het ontwikkelen van kwelders.

Hoofdstuk 4 schetst de uitruil tussen het doelbewuste gebruik of ontwikkeling van kwelders voor waterveiligheid en andere diensten die door de kwelders worden geleverd. Naast voorlanden die onder gunstige omstandigheden door afzetting van slib en zand in hoogte toenemen en de golven dempen alvorens ze de dijk bereiken, vormen kwelders ook een waardevolle habitat, en zijn belangrijk voor de biodiversiteit. Bescherming, herstel en ontwikkeling van kweldervoorlanden vormt daarom een aantrekkelijke waterveiligheidsstrategie. Wel is het belangrijk om rekening te houden met de invloed van klimaatverandering op kweldervormende processen. Klimaatverandering heeft namelijk effect op de zeespiegelstijging, op het golf-wind klimaat en op de vegetatie. Vooral zogenaamde zachte technieken om kwelders te beschermen of te ontwikkelen, vormen een interessante ‘no regret’ klimaatadaptatie strategie. Omdat kwelderontwikkeling relatief snel gaat ten opzichte van de tijdshorizon van klimaatverandering, is er tijd om te experimenteren met maatregelen en technieken om kwelders zo efficiënt mogelijk te beschermen, te ontwikkelen en te beheren.

Hoofdstuk 5 presenteert drie case studies om de mogelijkheden voor kwelderontwikkeling en bescherming voor waterveiligheid te illustreren. In de eerste case studie worden de effecten verkend van lage stenen dammen op kwelderontwikkeling op de Waddeneilanden Terschelling en Ameland. Deze dammen zijn aangelegd om de bestaande kwelders te beschermen tegen erosie. Binnen enkele decennia was het gebied tussen de dammen en de voormalige kwelderklifrand door sedimentatie opgehoogd en begroeid met karakteristieke kweldervegetatie. In de tweede case studie wordt gekeken naar het effect van erosie en van herstelmaatregelen op de ontwikkeling van kwelderhabitat en op de golfdempende werking van een klein kweldergebiedje voor de dijk van Terschelling. De derde case studie betreft de dijk langs de Dollard, waar gekeken wordt naar de effecten van het meenemen van kwelders in een 'brede groene dijk'. Uit de case studies komt naar voren dat, onder gunstige omstandigheden, lage stenen dammen niet alleen erosie van de kwelderrand sterk verminderen maar ook helpen om een ecologisch aantrekkelijk voorland te creëren. Zowel het oppervlak en de hoogte van de nieuw ontstane kwelder als de daarop ontwikkelde vegetatie beïnvloeden de golfhoogte. Uit de Dollard-case komt naar voren dat de ontwikkeling van een brede groene dijk ten koste zal gaan van een strook kwelders. Wel vormt zo'n brede groene dijk een meer geleidelijke, en daardoor aantrekkelijker, overgang van de kwelder naar de dijk dan een traditionele dijk (die is bekleed met asfalt of stenen).

In hoofdstuk 6 wordt de ecologische waarde van tegen erosie beschermde kwelders en herstelde kwelders verder gekwantificeerd door de vegetatie die werd gevonden in opnamen in de onderzochte gebieden (Terschelling en Ameland), te vergelijken met een referentie set bestaande uit de vegetatie die werd gevonden in zo'n 6000 vegetatieopnamen in het Waddengebied. Zowel uit een 'species-by-species' analyse als uit ordinarie komt naar voren dat de ontwikkeling van kweldervegetatie in de herstelde kwelders niet verschilt van die op andere plaatsen in het Waddengebied. Daaruit kan worden afgeleid dat kwelderontwikkeling voor waterveiligheid niet onverenigbaar is met natuurdoelstellingen.

Hoofdstuk 7 verkent het effect van kweldervegetatie via het modelleren van golfhoogte voor verschillende kwelder-scenarios. Informatie verzameld in het studiegebied Grië (te Terschelling) rond soortensamenstelling, vegetatiehoogte, aantal stengels per oppervlak en de doorsnede van de aanwezige planten is in het model SWAN (Simulating WAVes Nearshore) gebruikt om het effect van een geschematiseerd (maar realistisch) kweldervoorland te onderzoeken. De modelresultaten bevestigen dat naast de breedte en de hoogte van het kweldervoorland, ook vegetatiekarakteristieken als de plantdichtheid, de doorsnede van de stengels en de hoogte van de planten van invloed zijn op de golfdempende werking.

In hoofdstuk 8 worden de belangrijkste bevindingen samengevat. Over het geheel genomen komt uit deze thesis naar voren dat voor het Waddengebied het integreren van kwelders in een lange-termijn adaptatiestrategie veelbelovend is, vooral voor die dijktrajecten waar zich al kwelders voor de dijk bevinden of zich spontaan ontwikkelen. De kwelders in de Waddenzee vormen lage voorlanden die de inkomende golven dempen. Verkennende modelstudies wijzen er op dat het integreren van kweldervoorlanden in de waterkeringen langs diverse dijktrajecten langs de Waddenzee er voor kunnen zorgen dat de keringen minder hoeven te worden verhoogd, of dat dijkversterking kan worden uitgesteld. Echter, in een veranderend klimaat kan het integreren van kweldervoorlanden in de waterkeringszone nooit toekomstige dijkverhogingen voorkomen. Kwelders beïnvloeden de golfaanval en golfploop tegen de dijken, maar kunnen niet het overstromen van de dijk door toenemende extreme waterstanden bij een stijgende zeespiegel voorkomen.

Deze dissertatie bevestigt dat vegetatie een belangrijke factor is voor de golfdempende werking van kweldervoorlanden. Uit de analyse komt naar voren dat de vegetatiesamenstelling in de verschillende kwelderzones potentieel veel invloed kan hebben, en dat daardoor de natuurlijke ruimtelijke verdeling van de verschillende vegetatietypen van belang is. Hierdoor kunnen experimenten of modelstudies die geen rekening houden met de zonatie van de vegetatie dus tot vertekende conclusies leiden. Ook volgt hieruit dat het belangrijk is rekening te houden met beheeraspecten van de kweldervegetatie wanneer kweldervoorlanden daadwerkelijk in een klimaatadaptatiestrategie wordt meegenomen. Voor een zo goed mogelijke bijdrage aan de waterveiligheid, zou het beheer gericht moeten zijn op de ontwikkeling van kweldervegetatie die de golven het effectiefst dempt, en die rekening houdt met ruimtelijke en temporele aspecten van een begroeide kwelder.

Ten slot toont deze dissertatie aan dat via kwelderherstel de doelstellingen van zowel waterveiligheid als natuurontwikkeling en behoud elkaar kunnen versterken.

Curriculum vitae

Jantsje M. van Loon-Steensma was born in Ysbrechtum, along the historical ‘*Hemdijk*’ in Fryslân and was raised in the Wadden Sea coastal area. After finishing secondary school at the Lauwerscollege, Bûtenpost, and Arts at ABK Minerva, Groningen, she studied Environmental Sciences at Wageningen University and specialised in water quality and aquatic ecology. Then she worked as a researcher and consultant in water management, and was involved in the first integrated water management plan for the provinces Groningen and Drenthe. After a one year period in Costa Rica, she conducted a project on the protection of transboundary rivers for Wetlands International. Then she started to work for Wageningen University’s Science Shop as a project coordinator, and switched to the research and education strategy department of the Environmental Science Group (Wageningen University and Research centre). In 2008 she was involved in the coordination of the ‘Knowledge for Climate’ programme and of Wageningen UR’s strategic knowledge programme on climate change. In 2009 she started to study the potential of robust multifunctional flood defences. From 2011 onwards she has been involved in several studies on innovative flood protection concepts for the Deltaprogramme Wadden region.

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