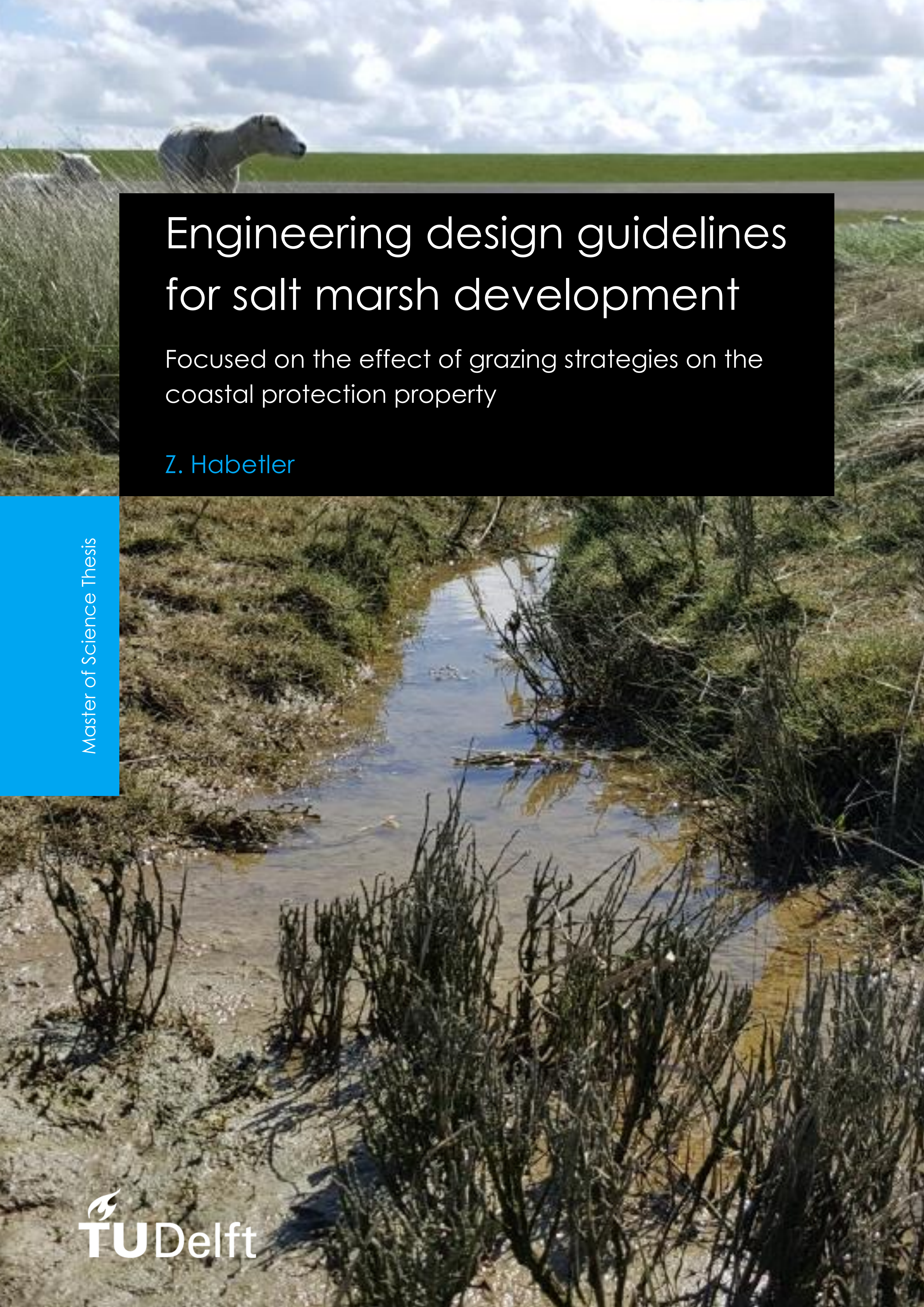

Engineering design guidelines for salt marsh development

Focused on the effect of grazing strategies on the coastal protection property

Z. Habetler

Master of Science Thesis

TU Delft

Engineering design guidelines for salt marsh development

Focused on the effect of grazing strategies on the coastal protection property

to obtain the degree of

Master of Science

in Hydraulic Engineering
at the Delft University of Technology,
to be defended publicly on Wednesday July 12, 2017 at 15:00.

Z. Habetler

July 4, 2017

An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

This work is part of the research programme BE SAFE, financed primarily by the Netherlands Organisation for Scientific Research (NWO).

Cover image
Salicornia spp. at a salt marsh at Groningen, grazed by sheep. The sea dike can be seen on the background.

Author
Z. (Zsófia) Habetler
Student number: 4086023
zhabetler@gmail.com

University
Delft University of Technology
Faculty of Civil Engineering and Geosciences
Master of Hydraulic Engineering, Coastal Engineering

Thesis committee

Dr. J.J. de Vries,	Van Oord, *Supervisor*
Prof. dr. ir. S. G. J. Aarninkhof,	TU Delft, *Chair*
Dr. ir. B. C. van Prooijen,	TU Delft
Dr. ir. M. van Koningsveld,	TU Delft, Van Oord
Ir. V. Vuik	TU Delft, HKV

TU Delft Delft University of Technology

Van Oord Marine ingenuity

Preface

You are looking at the final report of my graduation research, which I conducted to complete my master in Hydraulic Engineering, at Delft University of Technology. The research concerns the development of engineering guidelines to include salt marshes in hydraulic infrastructure projects, subject to the Building with Nature philosophy. Within this research the effect of different grazing strategies is analysed on the coastal protection value of salt marshes. Within this section I would like to thank several people that supported me during the research.

First of all I would like to thank my thesis committee for giving me guidance and support throughout this research. I would like to thank Stefan Aarninkhof for being the chair of my committee. Thereby, I would like to thank him for introducing me to Van Oord and to this research topic. I have to admit that I was picky in finding the right topic, just as Stefan said. However, this topic was worth the waiting and I actually really enjoyed this research, except the couple of times that problem-solving overruled my dreams. I am grateful to Jurre de Vries, who was my supervisor at Van Oord, for attending our almost weekly brainstorm-sessions. He helped me to see possibilities for Building with Nature from an engineer's perspective. I would also like to thank Bram van Prooijen, especially for assisting me in finding an interpretation for the in-depth research, when I was stuck on the conceptual thinking of Building with Nature. I would also like to thank Mark van Koningsveld for being part of my thesis committee, as he is a great contributor to Building with Nature and helped me to specify my research objectives. Moreover, I would like to thank Van Oord and its employees for providing me this workspace for the past eight months. I met interesting people who taught me about project development and helped me with the practical view on my research. Moreover I would like to thank Ecoshape and its employees for providing me a workspace once a week at the 'headquarters' of Building with Nature and inviting me for interesting Building with Nature meetings.

I would specially thank Marcel Zijlema, who was not part of my committee, but helped me with adapting the source code of SWAN. Moreover I am grateful to Vincent Vuik, the final member of my committee, to make me contribute to this BE SAFE project and helping me with problem solving of Matlab and SWAN computations. Furthermore, I would like to thank Zhenchang Zhu for providing me the required knowledge on ecology, as it was sometimes difficult to just 'accept' the behaviour of nature, without being able to explain the physics by formulas. I would like to thank my fellow students at the university and at Van Oord. They were great as sparring partners and sometimes a nice distraction from the research. Furthermore, I am grateful to my friends and family for their support, understanding and motivating me throughout my graduation. Thank you for making my time in Delft a memorable place. Lastly, thanks reader, for reading at least this page and enjoy reading the rest of my thesis.

Z. Habetler
Rotterdam, June 2017

Summary

The inclusion of Building with Nature (BwN) solutions is increasingly mentioned as a supplemental solution to traditional coastal protection measures. This design approach utilises natural processes to generate benefits for nature, society and economy. An example is the ecosystem of salt marshes, which can reduce the impact of waves and storm surges on flood defence structures. From previous studies, it follows that certain BwN solutions can lead to a wave load reduction up to 60% compared to the bare foreshore. Although the interest in these solutions is increasing, a number of knowledge-gaps need to be verified in order to implement these solutions on a large scale, such as the reliability under extreme hydraulic forcing. Several guidelines exist for artificial development of salt marshes, but they primarily focus on ecosystem recovery. Therefore, the aim of this research is to include salt marshes in hydraulic infrastructure projects. From previous studies, it follows that tall and dense vegetation is more effective in dissipating wave energy than short and low density vegetation. Salt marshes are often grazed to maintain biodiversity, which leads to defoliation and trampling of vegetation, thus it is expected that grazing negatively affects coastal protection. Consequently, the effect of grazing is analysed into detail within this research, in order to generate better understanding of the behaviour of salt marshes as a coastal protection solution. This leads to the following main and secondary objective:

1. To develop guidelines for engineers to include salt marshes in hydraulic infrastructure projects, subject to the Building with Nature philosophy.
2. To investigate the effect of grazing at salt marshes on the coastal protection property.

This research is based on a literature study about the natural and artificial development of salt marsh. Thereafter, the effect of grazing on wave attenuation is modelled by the numerical model SWAN (Simulating WAves Nearshore) in the in-depth research. The the effect of vegetation and the bathymetry is analysed. The vegetation data results from a grazing experiment at a salt marsh at Noord Friesland Buitendijks, in the north of the Netherlands. The results from the literature study and the in-depth research are translated to important design aspects within the engineering design guidelines for salt marsh development.

The main conclusion of the in-depth research is that the effect of vegetation on wave attenuation is small, compared to the effect of wave breaking and bottom friction. As base for this research the most severe hydraulic and biotic conditions are considered for the reference location NFB. This results in an absolute wave height reduction of $\Delta H = 0.20m$ at a 100 m wide bare foreshore, which is a reduction of 13% of the significant wave height. The presence of vegetation leads to an additional wave height reduction of $\Delta H_{veg} = 0.06m$. The contribution to the wave height reduction by the dissipation mechanisms is as follows: 59% results from wave breaking, 22% results from wave attenuation by vegetation and the resulting 19% is induced by bottom friction. The effect of different grazing strategies on the vegetation properties and wave attenuation is small, as this effect varies between $10 - 22\%$ of the total wave height reduction. The lower contribution of vegetation to wave

attenuation compared to previous studies results from the selection of biotic factors and hydraulic conditions. For this research, the vegetation properties were used at the end of the storm season, whereas in the other studies the vegetation state at the begin of the storm season is considered, the latter is more effective in dissipating wave energy. Also, the hydraulic conditions at NFB are more extreme than those that are applied in previous studies.

Regarding coastal safety, it is of higher importance for an engineer to consider the abiotic parameters at the project site, rather than focusing on target species and grazing strategies. However, grazing could be used as an ecosystem management strategy, as from literature it follows that grazing positively affects biodiversity. This could be valuable as artificial salt marsh development often goes at cost of the ecosystem at mudflats, which is an important food source for many fish and bird species. An engineer should also take into account that BwN solutions contain multifunctional objectives which may counteract each other. The major trade-off between these two ecosystem services is the efficiency of salt marshes during extreme events. The main driver for wave energy dissipation is depth-induced wave breaking, this effect increases with larger bottom profile elevations. However, regarding biodiversity, the lower lying salt marsh areas are more productive. Moreover, the reliability of salt marshes increases when the marsh surface is stable. Hard techniques are often more reliable than soft measures, although these hard structures counteract the natural development of the marsh. Regarding the engineering design guidelines, it is recommended to investigate the effectiveness of soft methods, such as oyster reefs to prevent erosion protection of the marsh edge, to guarantee coastal protection under design conditions.

Research shows that the bathymetry at salt marshes provides a more substantial contribution to wave energy dissipation than the effect of vegetation. However, the presence of a salt marsh indirectly affects wave attenuation. The salt marsh vegetation enhances sediment accumulation, which leads to a higher bottom profile elevation compared to the bare foreshore. This should be substantiated by future research. Lastly, to achieve large scale implementation of these Building with Nature solutions, the salt marsh dimensions, such as the slope and elevation, should be translated to design parameters with respect to wave attenuation within the engineering design guidelines for salt marsh development.

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List of abbreviations

Abbreviation	*Description*
BE SAFE	Bio-Engineering for SAFEty
BwN	Building with Nature
EwN	Engineering with Nature
HAT	Highest Astronomical Tide
LIDAR	Laser Imaging Detection And Ranging
MHW	Mean High Water
MHWN	Mean High Water Neap
MHWS	Mean High Water Spring
MLW	Mean Low Water
MSL	Mean Sea Level
NFB	Noord Friesland Buitendijks
NIOZ	Royal Netherlands Institute for Sea Research
PIANC	Permanent International Association of Navigation Congress
SSC	Suspended Sediment Concentration
SWAN	Simulating WAves Nearshore
UAV	Unmanned Aerial Vehicle
USACE	United States Army Corps of Engineers
WoO	Window of Opportunity
WwN	Working with Nature

Nomenclature

Symbol	*Description*
A_c	Correction factor
b_v	Outer stem diameter
$b_{v,in}$	Inner stem diameter
C_a	Cauchy number
C_d	Drag coefficient
D_v	Dissipation by vegetation term
d_v	Stem diameter
E	Young's modulus
E	Wave energy
F_{max}	Maximum bending force
g	Gravitational acceleration term
h	Water depth
$H_{1/10}$	Highest percent wave height
H_{rms}	Root mean square wave height
h_v	Stem height
I	Second moment of inertia
k	Wave number
l	Stem length
L_{span}	Span width (see l)
M_{max}	Maximum bending moment
N_v	Stem density
T	Wave period
u	Wave induced velocity
u_{crit}	Critical wave induced velocity
U_w	Current speed
z	Distance to the water surface
α	Relative submerged vegetation height
ϵ	Elongation
Θ	Leaning angle
λ	Wave length
ρ_w	Density of water
σ	Angular frequency
σ_{max}	Maximum stress
ω	Angular frequency

Part I

Introduction

Chapter 1

Introduction

1.1 Background

1.1.1 Problem statement

For ages, people have tended to live in coastal environments, which is why most economic activity and populations are concentrated in those areas. The demand for food, energy, health and mobilization is rising as the global population is rapidly increasing (WorldBank, 2010). On the other hand, these areas are challenged by the pressure of anthropogenic climate change and sea level rise (IPCC, 2007). Therefore, these areas require a well-organised planning of the infrastructure in order to satisfy the demands of society and to guarantee future economic development and coastal safety (De Vriend & Van Koningsveld, 2011). This resulted in a re-evaluation of coastal flood risk reduction methods (Möller et al., 2014). The inclusion of ecosystem-based solutions in coastal zone management is increasingly mentioned as supplemental method for traditional solutions (Boersma, 2014). Coastal ecosystems such as dunes can function in the same way as artificial flood defences, such as dikes and dams (Möller et al., 2014; Vuik, Jonkman, Borsje, & Suzuki, 2016), whereas foreshore vegetation, such as mangroves and salt marshes can be used to reduce the impact of storm surges on the coastline (Vuik et al., 2016). Certain ecosystem-based solutions are called 'Building with Nature' (BwN) projects, as hydraulic infrastructure is developed in such a manner that it utilizes the processes of nature, thereby creates opportunities for nature, economy and society (Ecoshape, 2017a). This research focusses on the coastal protection function of salt marshes, which can be seen in Figure 1.1.

(a) Natural salt marsh. **(b)** Artificial salt marsh.

Figure 1.1: Two types of salt marshes (Van Loon-Steensma, 2014).

Salt marshes

These ecosystems can be found on the interface of land and sea with limited wave action. They frequently become flooded by tides, which allows halophytic vegetation to establish. The vegetation accumulates sediment and the roots stabilise the soil, whereby salt marshes enhance their own development.

These ecosystems can be described by means of the blue box (Esselink, 2016; Van Loon-Steensma, 2014). In the past, large parts of the coastlines in temperate areas were covered by salt marshes. Unfortunately, due to anthropogenic and natural challenges, such as land reclamation and sea level rise, their extend has declined over the past centuries (Ecomare, 2016). Salt marshes are some of the most productive ecosystems in the world, providing a unique habitat for many species (Niedowski, 2000). Therefore, the conservation of these ecosystems is important. Moreover, salt marshes provide multiple benefits for society, such as erosion and flood control, regulation of water quality and recreational values (Adnitt et al., 2007; Niedowski, 2000). The function of these ecosystems as a coastal protection solution has been the topic of recent studies. It follows that the presence of salt marsh vegetation can lead to a wave load reduction up to 60% compared to the bare foreshore (Möller et al., 2014; Vuik et al., 2016). However, Building with Nature solutions inherently include the dynamic behaviour of nature, which results in a large degree of uncertainty (Vuik et al., 2016). Although the natural importance and societal benefits of these ecosystems is clear, numerous knowledge gaps need to be verified to generate full understanding of the underlying physics of this promising Building with Nature solution (Vuik et al., 2016).

Figure 1.1 displays the difference in composition between a natural and artificial salt marsh. Several guidelines exist on artificial development of salt marshes, however these guidelines primarily focus on ecosystem recovery, rather than on the coastal protection property. One of the guidelines that particularly focuses on the implementation of salt marshes in BwN projects is the 'Building with Nature design guidelines', which is developed by the Ecoshape consortium, the executor of the Building with Nature innovation program (Ecoshape, 2017a). These guidelines are an online database for Building with Nature that provides examples and design tools for project developers (Ecoshape, 2017a; Van Koningsveld & Van Raalte, 2011). However, from a recent use-case it emerged that these guidelines are rarely consulted and the question arises how practical these guidelines are for engineers and consultants.

1.1.2 Objective & research questions

The problem definition described in Section 1.1.1 can be summarised as follows: *although salt marshes provide clear benefits for nature and society, the question arises on how a reliable salt marsh should be designed* (Möller et al., 2014; Vuik et al., 2016). Moreover, current salt marsh development guidelines primarily focus on ecosystem recovery, rather than on other coastal protection (Adnitt et al., 2007; Atkinson, Crooks, Grant, & Rehfisch, 2001; Colenutt, 2001; Niedowski, 2000). Therefore, the effect of salt marshes as coastal protection method should be verified and combined into the Building with Nature guidelines, in order to include salt marshes in engineering projects. This can be translated into the main objective and the corresponding focus point, the secondary objective of this research, which are as follows:

Objective

"Develop guidelines for engineers to include salt marshes in hydraulic infrastructure projects within the Building with Nature philosophy, based on scientific knowledge and practical know-how."

Secondary objective: Analysing the effect of different grazing strategies at salt marshes on the coastal protection property.

This research concerns the development of engineering guidelines for salt marshes, the emphasis being placed on the coastal protection properties of these ecosystems. To obtain more insight into this ecosystem service, this research focuses on the effect of the management of salt marshes after construction, as grazing is often applied as salt marsh management method in order to maintain biodiversity (Van Klink et al., 2016). The following questions support the main objective of this research:

1. What are the ecosystem services that can be derived from salt marshes and how can they be included in engineering projects?
2. What can be considered as important design aspects for engineers?
3. How can these design aspects be included in engineering guidelines for salt marsh development?
4. How do different grazing strategies at salt marshes contribute to the coastal protection property, i.e. wave attenuation?

Research question 4 corresponds to the secondary objective of this research and is discussed more extensively in Part III of the research.

1.2 Approach

The approach adopted towards this research can be divided into three components: (1) a literature study about Building with Nature and salt marshes (2) an in-depth research about the effect of grazing strategies on the coastal protection value of salt marshes and (3) a synthesis in which the in-depth research is integrated into guidelines for the inclusion of salt marshes in engineering projects.

In the first part of this research a literature study is executed to examine the existing knowledge of the Building with Nature design approach, salt marshes and their development. The Building with Nature design approach is what provides the background for this research. Gaining an understanding of the natural development of salt marshes provides the required knowledge for engineers to embed these ecosystems in hydraulic infrastructure projects. Moreover, making an inventory of existing guidelines and adaptive measures for salt marsh development will provide a reference for the engineering guidelines that are developed within this research.

Thereafter, one aspect will be analysed in detail, namely examining the effect of different grazing strategies at salt marshes on the coastal protection property. This aspect corresponds to the main research in two ways, first it focuses on one ecosystem service of salt marshes, by quantifying the wave energy reduction on the foreshore. Second, this in-depth research provides insight into the management of salt marshes after construction, i.e. what would be the best management strategy with respect to flood safety, but also with an eye on biodiversity. The computation of the effect of different grazing strategies on coastal safety is analysed by the numerical model SWAN, which gives an expression of wave energy dissipation in terms of wave height reduction. The vegetation data results from a grazing experiment at a salt marsh at Noord Friesland Buitendijks in the north of the Netherlands.

Lastly, the results obtained from the literature review and the in-depth research are combined into a synthesis to form practical guidelines. These guidelines include the important aspects that an engineer should take into account while he is developing a salt marsh as coastal protection solution.

1.3 Thesis outline

This research is subdivided into five parts: (1) Introduction, (2) Theoretical framework, (3) In-depth research, (4) Synthesis and (5) Conclusions & Recommendations. The five parts and the corresponding chapters are compiled in such a way that the content goes from a broad range in Part I, to a specific focus point in Part III. Thereafter, the research zooms out, to translate the lesson-learned from the in-depth research to generic design guidelines (Part IV). The structure of the report and chapter arrangement can be seen in Figure 1.2. The content of the report is as follows.

- *Part I: Introduction*
  The first part presents the background of the research and the corresponding objectives and the research questions (Chapter 1).

- *Part II: Theoretical framework*
  Part II contains the theoretical background to this research, which goes into more detail on the topic starting with the Building with Nature principle (Chapter 2). This concept is compared with the traditional design approach, and a five-step approach is presented to develop a BwN project. Thereafter, the focus moves to the understanding of the salt marsh system, which is the first step in the BwN approach. Insight is generated into the natural development and habitat requirements for salt marshes as outlined in Chapter 3. In the last chapter of this part the artificial development of salt marshes is considered, based on existing guidelines and adaptive measures for salt marsh development.

- *Part III: In-depth research*
  The in-depth research is described and analysed in Part III. The methodology for the modelling of the wave attenuation values of foreshore vegetation and an introduction to the case study located at Noord Friesland Buitendijks is presented in Chapter 5. In Chapter 6 the analysis of the effect of the different grazing strategies at salt marshes on the coastal protection property is discussed.

- *Part IV: Synthesis*
  Part IV couples the in-depth research with the main research. The final result presented in Chapter 7 concerns the engineering design guidelines for salt marsh development.

- *Part V: Conclusion & recommendations*
  In the last part, the research questions are answered and discussed and recommendations are given for further research on this topic in Chapter 8.

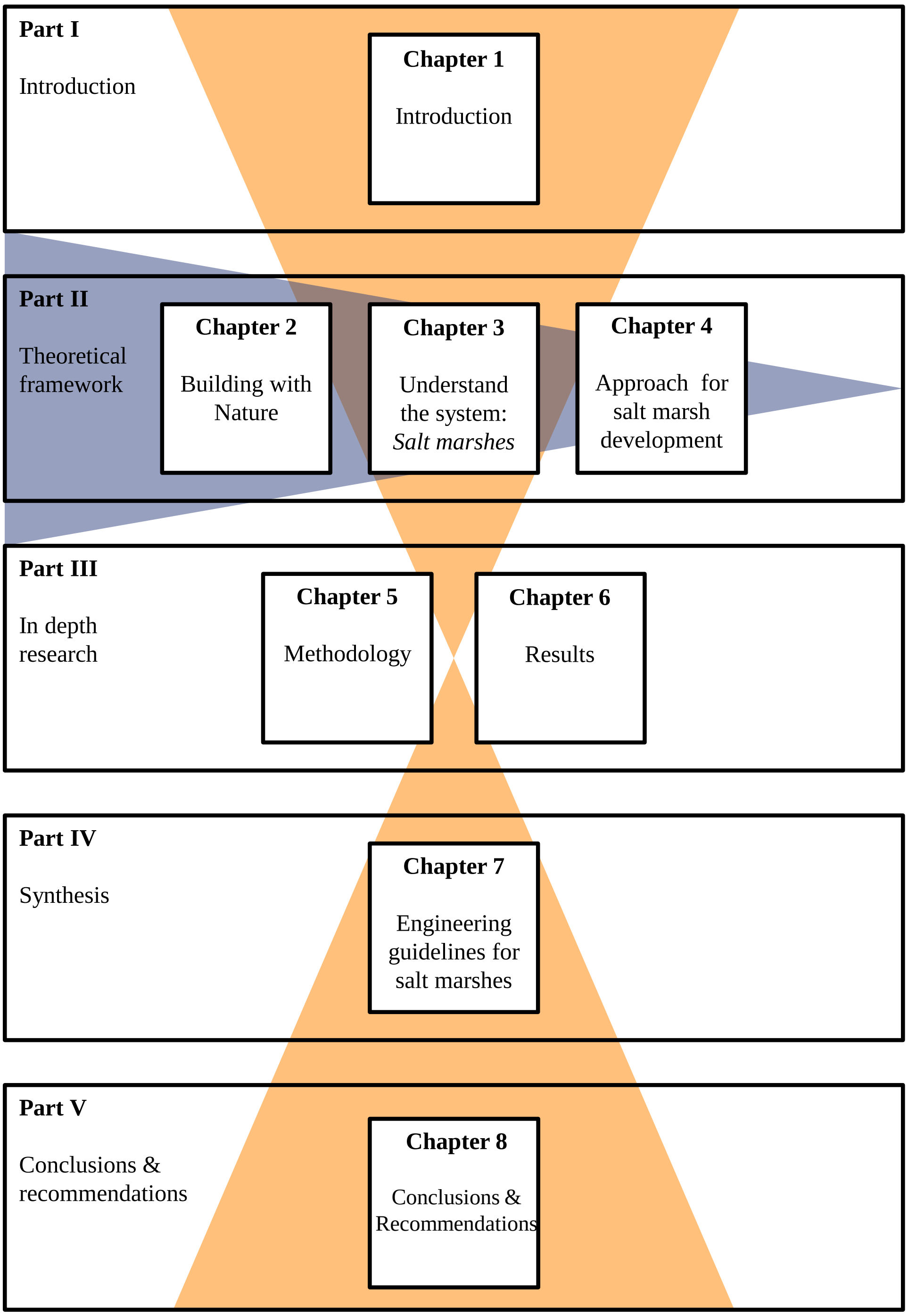


Figure 1.2: Report structure.

Part II

Theoretical framework

Chapter 2

Building with Nature

This chapter gives an introduction to the 'Building with Nature' principle (BwN). This philosophy is compared with the traditional design approach, including the five phases of project development. Additionally, this chapters presents the five-step approach corresponding to the Building with Nature philosophy.

2.1 What is Building with Nature?

2.1.1 Origin

During the past decades the attitude of people towards the environment has shifted from minimizing negative impacts, towards creating opportunities for nature development (Van Koningsveld & Van Raalte, 2011). Over fifty years ago, not much attention was paid for the environment, the approach was mainly *building instead of nature*. Due to new legislation during the seventies and nineties, nature compensation is included in project development, leading to *building of nature* (Van Koningsveld & Van Raalte, 2011). The latest development is a proactive approach that utilized natural processes and generates opportunities for nature while developing hydraulic infrastructure, which is the *Building with Nature* concept (De Vriend & Van Koningsveld, 2011; Van Koningsveld & Van Raalte, 2011). This design approach is a global concept, described by several international innovation programs, such as Ecoshape (Building with Nature), USACE (Engineering with Nature) and PIANC (Working with Nature) (Aarninkhof & Bridges, 2016).

2.1.2 Key-considerations

As it is described in Chapter 1, Building with Nature refers to an innovative approach, wherein hydraulic infrastructure is designed in such a way that natural processes are utilized to generate benefits for the socio-economic and natural system (Ecoshape, 2017a). The key-consideration of this design approach is to include natural processes in project development. This widens the scope and possibilities of the projects and enables the application of ecosystem services (De Vriend & Van Koningsveld, 2011). These ecosystem services are the direct and indirect benefits that human derive from nature (De Vriend & Van Koningsveld, 2011), the following four categories can be distinguished (TEEB, 2016):

- *Provisioning services*: These provide society food, biofuels and other products
- *Regulatory services*: These include natural processes such as flood control, air quality and climate regulation
- *Cultural services*: These are related to non-material benefits that people acquire from nature, such as education, recreation and spiritual experience
- *Support services*: These are essential to enable all other ecosystem services.

An example of certain ecosystem services is to utilize natural processes, such as wind and waves to transport sand from beach nourishments, in order to enhance dune formation. These dunes function as a natural flood control solution. More examples of ecosystem services are provided in Section 3.4.

2.2 Building with Nature & Traditional Design Approach

The predecessor of Building with Nature is the 'traditional' approach. The latter utilizes 'hard' structures for hydraulic infrastructure development. Typical examples are sea walls and stone revetments. These solutions often conflict with the ecosystem (Colenutt, 2001), which results in a negative impact on nature (Boersma, 2014). This usually originates from the early stages of project development, as the project developers primary focus on the main objective (Ecoshape, 2017b), such as flood safety and land reclamation, which narrows the scope of the project. Considerations for the environment are only included if it is prescribed in the boundary conditions of the project (Ecoshape, 2017b). The main driver for this design approach is that a project should be realized within a limited time frame for minimal investments.

As result of the increasing awareness for the environment the Building with Nature approach is gaining momentum since the past decade (Aarninkhof & Bridges, 2016; Van Koningsveld & Van Raalte, 2011). The BwN approach gives preference to 'soft' techniques, rather than hard structures that used in the traditional approach. This allows a more natural development of the system, which leads to resilience against e.g. climate change and sea level rise. Eventually, these measures reduce maintenance activities and costs, as the system is self-sustaining due the utilization of natural processes (Colenutt, 2001). Moreover, this inclusion of nature generates added values for nature and society in form of ecosystem services. However, due to the inclusion of these dynamic processes, the scope of the project becomes more complex (De Vriend, Van Koningsveld, Aarninkhof, De Vries, & Baptist, 2014). Instead of primarily focussing on the main objective, the project developer strives towards enabling additional benefits for the socio-economic and environmental system (Ecoshape, 2017b), which requires a different way of thinking, acting and interacting compared to the traditional approach (De Vriend et al., 2014; Ecoshape, 2017b):

- *Thinking*: The project developer should not only consider the main objective of the project, he should also look into other benefits that can be derived from nature. One should strive towards an optimum between the social, economic and natural system.
- *Acting*: The scope of BwN projects is complex, due to the inclusion of natural processes that can be difficult to predict. Moreover, contrary to traditional designs, the project is not 'finished' after implementation, as natural processes need a certain time to develop. It should be guaranteed that the anticipated outcome will be achieved, which requires monitoring after construction and taking adaptive measures where needed.
- *Interacting*: Engineers are no longer the only project developers, as they may require additional input from other disciplines to achieve an optimum between the socio-economic and natural system. This requires a strong collaboration.

2.3 Project development

Both the traditional approach as Building with Nature characterize successive phases in project development, these are the 'initiation', 'planning & design', 'construction', 'operation & maintenance' and 'closure' phases, see Figure 2.1 (Ecoshape, 2017b).

Figure 2.1: Five project phases.

Building with Nature looks from the natural system to achieve combined benefits for the socio-economic and natural system, by means of including ecosystem services in project development. Each phase contains opportunities for BwN, however the earlier it is included in the development process, the more valuable this is for the project benefits. This can be achieved in the following way during successive phases in the design process:

1. *Initiation*
   In this phase the idea of the project is examined and elaborated. The main objective is to determine the feasibility of the project (Projectmanagement, 2016). The initiator determines the main objective and scope, including boundary conditions, functional and operational requirements, sources of funding and involved partners (Projectmanagement, 2016; Twynstra-Gudde, 2016). Regarding BwN, this phase includes the highest potential to develop ecosystem-based solutions, as the initiator can include secondary objectives in the design, such as targets for ecological and recreational purposes (Ecoshape, 2017b).

2. *Planning and design*
   In this phase the involved parties can develop different alternatives to achieve the objectives. Subsequently, the alternatives are assessed and elaborated into more detail. The final result is a detailed project plan, including detailed designs, investments, a time schedule, etc. (Ecoshape, 2017b; Projectmanagement, 2016; Twynstra-Gudde, 2016). Opportunities for BwN can be found in generating multifunctional alternatives, which additionally may open doors to extra funding resources and public support (Ecoshape, 2017b).

3. *Execution*
   In this phase the project becomes 'visible', as the design of the previous phases is brought into practice (Projectmanagement, 2016). At the end of this phase the project is monitored and the development, regarding the objectives, is examined. BwN can be included in the optimization of the design, e.g. by utilizing natural processes or carefully select materials, to create additional benefits and reduce costs. Moreover, a management or monitoring plan should be developed, in order to verify whether the dynamic processes behave as expected (Ecoshape, 2017b).

4. *Operation & maintenance*
   This covers the largest time span of the project life cycle. The original state of the project should be guaranteed, by means of quality checks and reparations where they are needed (Ecoshape, 2017b; Projectmanagement, 2016). Usually these interventions are costly for traditional projects. BwN aims at self-sustaining solutions, resulting in less maintenance activities, hence lower corresponding costs. However, due to the utilization of dynamic processes, risk reduction and contingency plans are important, in order to guarantee successfully achieving of the objectives (Ecoshape, 2017b).

5. *Closure*
   In the final phase of the project, it should be examined whether the objectives are achieved. The results and lessons learned should be documented carefully as assistance for future projects (Nicholas & Steyn, 2012). As BwN is presently applied in pilot projects, these lessons are important, in order to optimize and scale-up the projects for future applications (Ecoshape, 2017a).

Additionally, the Building with Nature philosophy is translated into a five-step approach, to assist the project developer in designing an eco-dynamic solution for the project. The steps should be repeated in each phase, which determines the level of detail of the activity (Ecoshape, 2017b). The following five steps can be distinguished (De Vriend et al., 2014; Ecoshape, 2017b):

1. *Understand the system*
   Analyse the physical-, socio-economic and governmental context and try to optimize the interaction between these systems. Look into various sources while obtaining knowledge (e.g. historic, academic and local data). Moreover, look further than the main objective (e.g. ascertain natural and recreational values) in order to maximize the outcome of the project.

2. *Identify realistic alternatives*
   Use a proactive approach by utilizing ecosystem services, i.e. How can the concerned ecosystem benefit from the project and how can the project benefit from the ecosystem services? Involve stakeholders with different backgrounds, such as engineers, ecologists and decision makers, in the development of alternatives.

3. *Evaluate the qualities of each alternative and preselect an integral solution*
   Try to think of innovative ideas and substantiate them with tests and practical examples. Apply a cost-benefit analysis, including a valuation for non-monetary benefits and involve stakeholders in the decision-making process.

4. *Fine-tune selected alternative(s)*
   Elaborate the alternative in such a way that it is executable. Think of work methods and planning aspects, such as growing seasons, time to achieve final state, etc.. Involve stakeholders in the elaboration of the alternatives and make sure that the lessons-learned are documented to provide assistance for future projects.

5. *Prepare the project for implementation*
   The level of detail in this step depends on the project phase. During the initiation phase this step may include the testing of the alternative and the execution of field work. In later phases, a technical work plan should be composed and the permitting be organised. Moreover, the funding should be organised with the stakeholders. Lastly, risk management should be organised by composing contingency plans, as BwN deals with dynamic processes.

Chapter 3

Understand the system: Salt marshes

The first step within the Building with Nature design approach is to 'understand the system', which in this research is related to the ecosystem salt marshes. This chapter discusses the general functioning of salt marshes, their natural development process and which functions they can provide to society.

3.1 General

3.1.1 What is a salt marsh?

Salt marshes are covered by halophytic vegetation and can be found at the upper intertidal zone, where they often become flooded by tides (Atkinson et al., 2001). They grow on gentle slopes from the mean waterline (MSL) until the highest water elevation line (HAT), the pioneer zone until upper marsh respectively (Figure 3.1). Whereas the surface elevation is above the HAT, the marsh is no longer inundated and the halophytic salt marsh vegetation is outcompeted by glycophytes (upper marsh, Figure 3.1). The roots of salt marsh vegetation stabilise the soil, which is generally a composition of fine sediments, such as clay and peat. When these areas are flooded, the vegetation is able to capture sediment, which results in an increased surface elevation. By means of this process salt marshes enhance their own growth (Esselink, 2016), more about this process can be read in Section 3.3.

3.1.2 Flora & fauna

Salt marshes host a lot of different species and might be considered as one of the most productive ecosystems in the world (Niedowski, 2000). The vegetation shows a clear zonation, which varies on both spatial (low to high salt marsh) and time scale (pioneer to climax vegetation, Figure 3.1) (De Groot & Van Duin, 2013). The spatial distribution of salt marshes can be characterized by mud flats, low, mid and high marshes, looking from seaward direction. Mud flats do not grow rooted vegetation and are often covered by different kinds of algae (left in Figure 3.1). The pioneer zone is where the first vegetation colonizes as it is flooded twice daily during high tide. This zone is primary covered by smooth cordgrass (*Spartina alterniflora*) and glasswort (*Salicornia europaea*) (Figure 3.1.2). Between the everyday high tide (MHW) and the occasional highest water elevation line (HAT) the vegetation is dominated by common saltmarsh-grass (*Puccinellia maritima*) and red fescue (*Festuca rubra*) (Niedowski, 2000).

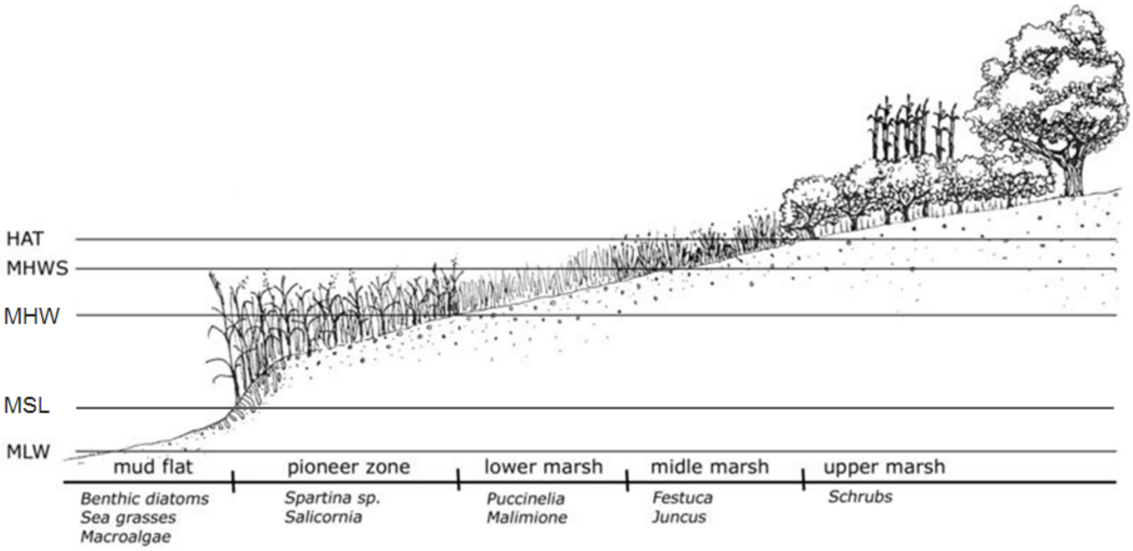


Figure 3.1: Salt marsh zonation (Van Belzen et al., 2013).

Besides the flora, extensive species of benthic fauna, fish and birds can be found at salt marshes. Characteristic macro-fauna species are lugworms, tubeworms, cockles and mussels, which live at the permanently flooded mud flats (Ecomare, 2016). Also different types of fish find their food and have their nurseries at salt marshes, such as sea bass and mullet (Niedowski, 2000). Moreover, the benthic fauna and fish serve as source of food for birds that come to hibernate and breed at salt marshes. Typical examples are terns, oystercatchers and brants (Figure 3.2c) (Ecomare, 2016).

(a) *Salicornia.*

(b) *Spartina anglica.*

(c) Brant.

Figure 3.2: Characteristic flora and fauna at a salt marsh (Ecomare, 2016).

3.2 Habitat requirements

3.2.1 Global distribution

Salt marshes can be found in mid to high latitudes, whereby fifty percent of its global distribution can be found along the gulf coast. Figure 3.3a represents the global salt marsh distribution. In Figure 3.3b the salt marsh distribution in the Netherlands is presented, where they can be found in the Wadden Sea area in the north and in the delta area in the south. Different types of salt marshes can be characterized based on geomorphology and origin of the sediment. In the Netherlands three different types can be distinguished:

- Salt marshes that are directly connected to the shoreline, these types develop at barrier beaches or in front of dune rows. Usually these marshes consist of sandy sediment. Examples are the marshes at the Wadden islands and at Kwade Hoek in the Dutch delta area (Esselink, 2016).
- An other type of salt marshes are 'foreland' marshes. These develop by accumulation of fine sediment on the lee side of protected shorelines, shallow bays or behind sand and mudflats. Examples are the salt marshes at the Dutch mainland side of the Wadden Sea at Friesland and Groningen (Esselink, 2016).
- The last type are brackish marshes, which develop in partially protected coastal areas where rivers discharge into the sea and a mixture of salt and fresh water is formed. These marshes are often covered by freshwater vegetation such as common reed (Ecoshape, 2017b). They can be found at the Western Scheldt and the Ems-Dollard (Esselink, 2016).

(a) Global distribution.

(b) Distribution in the Netherlands.

Figure 3.3: Salt marsh distribution (Ecomare, 2016; Mcowen et al., 2017).

3.2.2 Environmental conditions

Salt marshes primarily grow in sheltered environments such as embankments, estuaries, or at the leeward side of barrier islands (Esselink, 2016). The following environmental conditions largely determine whether salt marsh development is possible:

- *Slope*: The slope reduces the incoming hydrodynamic forcing, therefore the tendency of the marsh edge to erode. Usually, salt marshes grow at slopes of 1:50 to 1:500 (De Groot & Van Duin, 2013), however at the salt marsh works along the Wadden Sea slopes up to 1:1000 are common. For artificial development slopes of 1:100 are advised to initiate pioneer vegetation establishment (Van Duin & Dijkema, 2012).
- *Grain size*: Salt marshes favour fine grained sediment, such as clay and peat, corresponding to a grain size of approximately 2 – 500 μm (Folk, 2017).
- *Elevation*: For the colonization of pioneer vegetation the tidal inundation should be limited, corresponding to a bottom profile elevation of approximately 20 cm below the MHW line (De Groot & Van Duin, 2013).
- *Vegetation*: Salt marshes are covered by halophytic vegetation, which is characterised by zonation, this process is described in Section 3.1.
- *Moderate climate*: Salt marshes grow in temperate zones (green in Figure 3.3a).
- *Salinity*: The average salinity at salt marshes is about 18.0 and 35.0 ppt and it reduces in landward direction of the marsh (Odum, 1988).
- *Suspended sediment concentration (SSC)*: To achieve salt marsh development, the sediment supply needs to be sufficient. Approximately 20 mg/l is given as a minimum for salt marsh growth to keep up with land subsidence and sea level rise (Kirwan et al., 2010). Typical annual vertical growth rates are: 10 mm for lower marshes, 6.4 mm for middle marshes and 2.3 mm for high marshes (Doody, 2008).

- *Seeds*: The salt marsh site should be accessible for seeds or propagules (Wolters, 2006), which need a certain time for germination (Hu et al., 2015), this process is described in Section 3.3.
- *Tide*: Salt marshes accumulate the sediment that is transported by tides. The pioneer zone is flooded two times a day and the mid to high marshes approximately 100 to only a couple of times a year (De Groot & Van Duin, 2013).
- *Sheltered conditions*: Salt marshes grow in sheltered environments, as sediment needs time to accumulate and seedlings need time for germination (Hu et al., 2015). Therefore, wave action and tidal currents should be limited to below velocities of approximately 1.2 m/s (Van Loon-Steensma, de Groot, Van Duin, Van Wesenbeeck, & Smale, 2012).

3.3 Natural development

This section goes into more detail about the key-processes that enable salt marshes development, which is described in Figure 3.4, The main driver is the sediment balance of the system, indicated in orange.

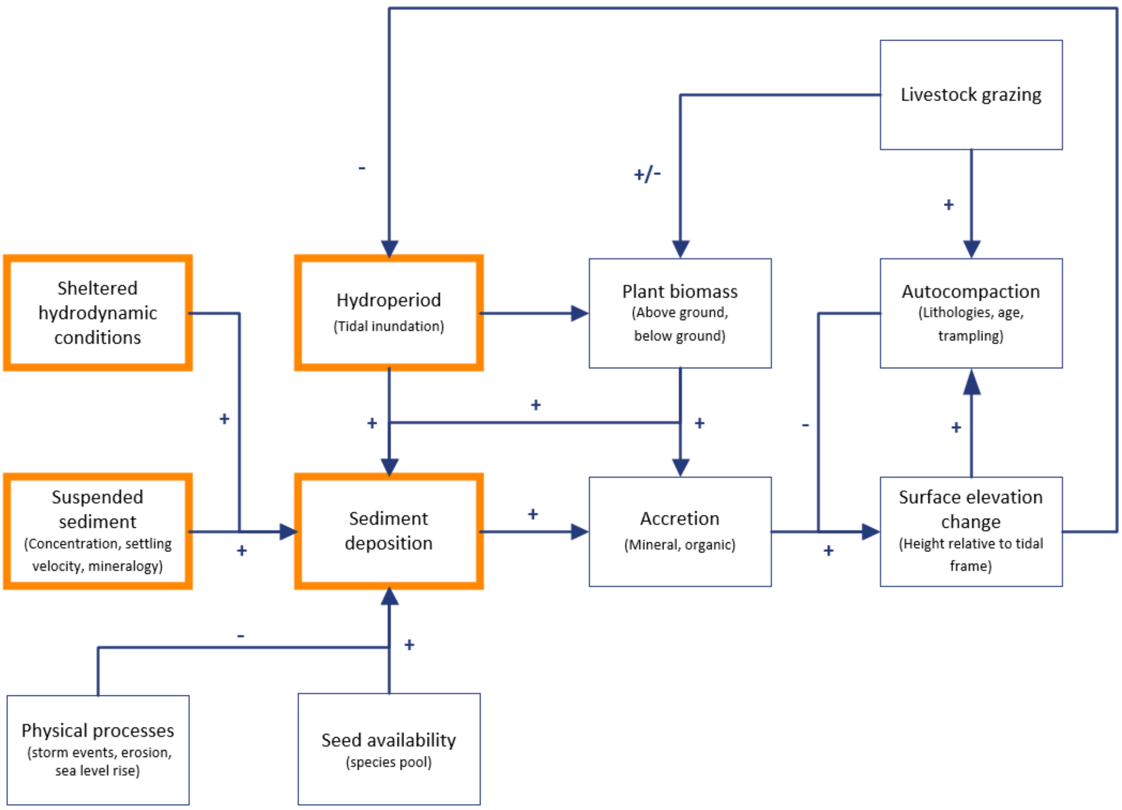


Figure 3.4: Conceptual model for natural salt marsh development. A '+' indicates a positive feedback, whereas a '−' implies a negative effect, which can be both positive as negative for salt marsh development. The orange boxes indicate the key-processes, which is the sediment balance.

Initially, salt marshes develop from sediment accumulation at sand or mudflats at the intertidal zone (left of Figure 3.1). Sediment is suspended in the water column, which can settle when tidal velocities are below the critical bed shear stress. When the combination of tidal movement and wave action is insufficient to keep the sediment in suspension, accretion takes place. By means of this process, sediment accumulates and the shoreline becomes free of inundation for increasingly longer periods. These key-processes are highlighted in orange in Figure 3.4. By means of this sediment balance, halophytic vegetation can colonise around the MHW line when the site is accessible by seeds (Doody, 2008). The presence of vegetation reduces the hydrodynamic forcing, which results in a positive feedback on the sediment accumulation process (Dijkema, Van Duin, & Van Dobben, 2005; Esselink, 2016). On the contrary, storm events and regular wave impact on steep slopes between the marsh edge and tidal flats, as a result of the seaward expansion of the salt marsh, may lead to erosion (Callaghan et al., 2010; Esselink, 2016). Autocompaction and artificial management by means of grazing also counteract the growth rates of the marsh, the latter is discussed more extensively in Chapter 5 and 6.

Whether a seedling can survive the local hydrodynamic forcing is determined by the so-called 'Window of Opportunity' (WoO), which implies a sufficiently long inundation free period to enable germination. Subsequently, a second WoO is required to grow roots that are long enough to withstand the hydrodynamic forcing (Hu et al., 2015). According to Wiehe (1935), for the pioneer specie *Salicornia europea*, the first WoO requires an inundation free period of 2 - 3 days. The salt marsh further develops after colonization of vegetation (Dijkema et al., 2005). At 'open' areas between the vegetation patches, the water flows away more efficiently. In those faster flow fields the sedimentation rates are lower and even scour can occur, which results in creek development. As the salt marsh develops in landward direction, so does the main channel and a corresponding subsystem of creeks develops (Dijkema et al., 2005). This natural drainage system is essential for succession of the salt marsh, as this system transports water, sediment and nutrients towards the marsh interior during high water (Van Loon-Steensma, 2011). Moreover, these creeks provide habitat for invertebrates, fish and shelter for birds (Atkinson et al., 2001). In the final stage, the climax vegetation establishes. Where the elevation is at a certain height that salt marshes are no longer inundated by tides, the halophytic vegetation is outcompeted by glycophytes (right of Figure 3.1) (Esselink, 2016).

3.4 Functions

In Section 2.1.2 the concept of ecosystem services is presented, these are benefits that human can derive from nature (Adnitt et al., 2007; TEEB, 2016). This section discusses several ecosystem services that can be derived from salt marshes.

3.4.1 Coastal safety

Flood control

Salt marshes can often be found in front of sea defence structures. These vegetated foreshores result in wave reflection and wave attenuation. This reduces the incoming wave energy, hence the risk of overtopping of the adjacent defence structure. Additionally, this reduces maintenance activities and costs at the dike (Adnitt et al., 2007; Niedowski, 2000). Adnitt et al. (2007) present a cost indication for a 80 m wide salt marsh foreshore combined with a 3 m high dike, which results in €400/m seawall, instead €5000/m for a 12 m high dike without a fronting salt marsh. Recently, more detailed research is executed in order to determine the wave reduction capacity of different types of vegetation, to provide more insight in the efficiency and reliability of foreshore vegetation. It followed that the presence of vegetation at a foreshore can lead to wave height reduction up to 60% compared to the bare foreshore (Möller et al., 2014; Vuik et al., 2016). This ecosystem service is discussed more extensively in Chapter 5 and 6.

Soil stabilisation

Coastal wetland vegetation can affect physical processes on shorelines via both direct and in direct effects. Direct effects include erosion control due to the presence of vegetation, whereas indirect effects refer to long-term decomposition of mineral and organic matter. Eventually, this can increase the coastal safety of traditional solutions.

Several studies have pointed out that the presence of vegetation avoids the soil from erosion, even under storm conditions (Möller et al., 2014; Spencer, Brooks, Evans, Tempest, & Möller, 2015). A direct effect is that the presence of vegetation reduces turbulence, slows down tidal and wave-induced currents and diminishes the bed shear stress (Gedan, Kirwan, Wolanski, Barbier, & Silliman, 2011). This process primarily holds for submerged vegetation, as the water velocities and bed shear stress, which are the main drivers for erosion, are dampened and decoupled from the wave-induced velocities at the water surface (Gedan et al., 2011; Neumeier & Ciavola, 2004). A second direct mechanism, is the stabilisation of the soil by the below-ground biomass, the root system, as it enhances the cohesion and tensile strength of the substrate (Gedan et al., 2011; Van Eerdt, 1985). The physical protection against erosion is limited to the depth of the roots, typically up to 1 m (Gedan et al., 2011). It is found that the soil stability, hence lower erosion rates, is positively associated with plant diversity (Ford, Garbutt, Ladd, Malarkey, & Skov, 2015). Species richness and plant cover are the most important explanatory factors for root biomass. Especially dichotomous branching is efficient in stabilising the soil, which is more common at the higher marsh than at slow-growing herringbone root structures that are common at salt marsh grasses at lower elevations. Therefore, erosion protection by roots is stronger at the high marsh, further away from the salt marsh edge, where it is less efficient (Ford et al., 2015).

According to Feagin et al. (2009) the soil type is the primary variable that influences lateral erosion and the presence of salt marsh vegetation indirectly affects erosion by modifying the soil parameters. For this indirect mechanism, vegetation enriches the organic content of the subsoil and fine organic matter tends to erode more slowly than coarse mineral soils (Gedan et al., 2011). On the long term, which is up to decades to centuries, the presence of vegetation can lead to decompositions of mineral and organic matter up to meters higher than it would be the case at the bare foreshore (Gedan et al., 2011). The foreshore wave height is limited by the water depth, as waves break when the wave height to depth ratio becomes larger than 0.75. However, this ratio may vary due to the bottom slope and wave steepness, wind, etc. (Holthuijsen, 2007). The presence of vegetation increases the bed level elevation (Figure 3.4), therefore the location where the waves break is moved in seaward direction (Feagin et al., 2009; Gedan et al., 2011).

3.4.2 Pollution control and water quality regulation

Salt marshes can improve the water quality and control pollution, by means of nutrient cycling and sediment retention (Adnitt et al., 2007; Niedowski, 2000). Several compounds that are considered as pollutants, such as herbicides, pesticides and heavy metals, are filtered from the water column. These pollutants are deposited on the salt marsh surface and buried by sediment deposition, which inactivates these potentially toxic materials (Adnitt et al., 2007). Moreover, salt marshes reduce turbidity by accumulating suspended sediment from the water column (Adnitt et al., 2007). Amongst others, this enhances the productivity of the benthic fauna (Niedowski, 2000).

3.4.3 Recreation, educative values and cultural heritage

People visit salt marshes for bird watching, fishing and other recreational activities. Moreover, salt marshes can be seen as cultural heritage, as these ecosystems are the remains of natural landscapes before people started with the reclamation of land and and interrupting the coastline with hard structures for coastal protection (Natuurmonumenten, 2015). However, conservation of salt marsh areas gained momentum over the past decades (Adnitt et al., 2007).

3.4.4 Habitat provisioning and support of food web dynamics

Salt marshes provide habitat for lots of different plant and animal species, certain habitat characteristics are rare in the world (Ecomare, 2016). Research increasingly points to aquatic wildlife as the main recipient of marsh production. Bacteria and small insects break down the vegetation directly, subsequently this fauna is eaten by larger insects, fish and mussels that reside in the marsh soils and ditches, where they find protection from predators. Eventually, during higher water levels the predators are able to capture the smaller critters and these predator fish species are important for the fish industry (Niedowski, 2000). Moreover, these invertebrates and fish provide food for wading and migratory birds that come to hybernate and breed at the salt marshes (Doody, 2008; Ecomare, 2016; Van Klink et al., 2016). Thus, conservation these ecosystems results in a balanced food web, hence ecosystem (Adnitt et al., 2007; Niedowski, 2000).

Chapter 4

Approach towards artificial salt marsh development

Several guidelines exist for salt marsh development, principally focusing on ecosystem restoration (Adnitt et al., 2007; Doody, 2008; Niedowski, 2000), rather than the utilization of other ecosystem services. This chapter presents a review of the existing salt marsh guidelines (Section 4.1) and the different measures that can be applied to artificially develop these ecosystems (Section 4.2).

4.1 Artificial salt marsh development guidelines

The aim of this research is to develop guidelines to include salt marshes in engineering projects, subject to the Building with Nature design approach. A basis for certain guidelines already exists, which are the Building with Nature design guidelines. These guidelines have been developed by the Ecoshape consortium and it concerns an online and publicly accessible database, to assist the reader with the Building with Nature design approach (Van Koningsveld & Van Raalte, 2011). The building block 'salt marshes' provides an introduction to these ecosystems, including corresponding habitat requirements, which are discussed in Section 3.2.2. In case several environmental conditions are inadequate, this flow chart suggests which adaptive measures can be applied. Section 4.2 goes more into detail about these measures. Furthermore, these guidelines present two practical examples of salt marshes included in engineering projects: Marconi (Delfzijl) and the Mud Motor (Koehoal), both in the Netherlands. The Building with Nature design guideline can be accessed via this *link*.

Besides the Building with Nature design guidelines other guidelines can be found for salt marsh development. These guidelines principally focus on ecosystem recovery. Examples are the: 'New York State salt marsh restoration and monitoring guidelines' (Niedowski, 2000), 'Salt marsh management manual' (Adnitt et al., 2007) and 'Saltmarsh Conservation, Management and Restoration' (Doody, 2008). These guidelines largely have a similar content, which contains the following aspects:

- The salt marsh ecosystem in general
- Restoration methods and corresponding reference projects
- Survey and monitoring of salt marshes after the artificial development.

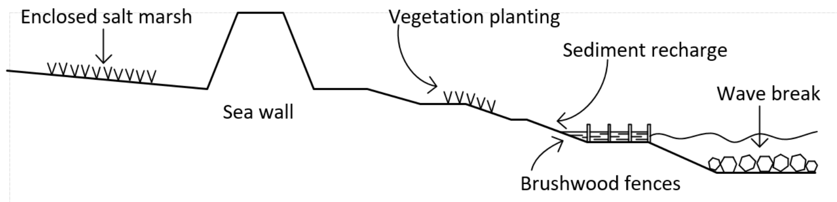
Niedowski (2000) couples knowledge about salt marshes to project development, as she presents an basic approach towards the restoration of salt marshes. She suggests that it is important to determined the objectives of the salt marsh development project early in the process. This will help the project developer with the selection of adequate restoration methods and finally determine the assessment criteria for the monitoring and management phase. Atkinson et al. (2001) presents an approach that should assist the project developer in assessing whether the site characteristic are suitable for salt marsh establishment. First, the project developer should look at historical site data, to assess if salt marshes were present at the site in the past. If so, hydraulic conditions should be examined and if it is required the site should be modified to achieve salt marsh development (Atkinson et al., 2001). Additionally, these guidelines include monitoring of salt marshes, as it should be analysed if the vegetation develops corresponding to the objectives of the project. This is also an important aspect of Building with Nature (Section 2.3). Prior to the project the baseline data should be collected at the restoration site, as after the execution phase it is possible to monitor the development of the salt marsh and apply adaptive measures where needed (Adnitt et al., 2007).

4.2 Salt marsh restoration methods

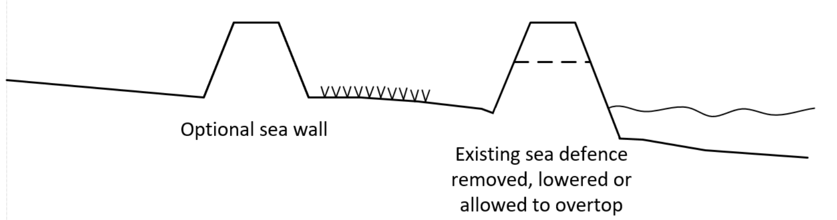
This section focuses on different techniques that can be applied to initiate salt marsh development if natural development is not possible due to restrictions of the site characteristics (Section 3.3). Artificial development can be desired to achieve the following objectives (Colenutt, 2001):

- To recover and manage the coastal ecosystem
- To restore engineering and ecological functions
- To reduce wave energy
- To manage and control the sedimentation process
- To create a seaward extending salt marsh in the most ideal situation.

Figure 4.1a presents several adaptive measures for salt marsh development to the seaward extend. Moreover, extensions in landward direction are also possible, whereby an existing sea defence is allowed to overtop and a salt marsh is applied to reduce wave energy in order to guarantee flood safety (Figure 4.1b), this is called 'managed realignment'.



(a) Seaward extend



(b) Landward extend

Figure 4.1: Adaptive measures for salt marsh development based on Doody (2008).

The adaptive measures presented in Figure 4.1 can be divided into the following four categories (Colenutt, 2001):

- Increased sediment supply (Section 4.2.1)
- Stabilisation and retention of sediment (Section 4.2.2)
- Managed realignment (Section 4.2.3)
- Management techniques after construction (Section 4.2.4).

4.2.1 Increasing sediment supply

The sediment for these measures usually originates from dredging activities retracted from access channels and harbours, however other sources of sediment are also considered (Adnitt et al., 2007). Generally, fine-grained sediment (silts and clays) are more favourable for vegetation restoration than coarser material (Colenutt, 2001; Niedowski, 2000). However, course sandy sediment, is easier to handle for direct placement, as its behaviour after deposition is better predictable. To raise the surface of salt marshes or to place at landward side of deposited sand, fines can be considered as suitable. Otherwise fine sediment is not likely to remain at the disposal location and adaptive measures might be needed to trap the sediment (Adnitt et al., 2007). Concluding, it appears that sedimentation selection depends on the restoration technique and purpose, the following restoration measures can be distinguished within 'increasing sediment supply' (Adnitt et al., 2007; Colenutt, 2001):

- Recharge of reclaimed area, prior to managed realignment (Section 4.2.3)
- Direct recharge of existing salt marsh to enhance vegetation colonization
- Sub-tidal placement of sediment ('water column recharge')
- Foreshore placement to dissipate wave energy, reduce erosion and/or to bring more sediment into the system.

The last two measures are most often applied (Adnitt et al., 2007). Although salt marsh development results in socio-economic and environmental benefits, several disadvantages may come with increasing the sediment supply, as the disposal may harm the benthic fauna and increase the local turbidity. Moreover, this technique could be unprofitable in monetary terms, due to difficulties in accessibility and finding suitable extraction sites (Adnitt et al., 2007).

Direct placement of sediment

The purpose of this technique is to dispose sediment onto existing salt marshes and mudflats, in order to modify the morphology and to enable more sediment for salt marsh accretion (Colenutt, 2001). Two methods can be distinguished: via a pipeline or by rainbow dispersal. An advantage of pipelines is cost efficiency, in case the transport distances are small, as the sediment can be disposed quite accurately. The major disadvantage is that the pipeline should be placed permanently or repeatedly be removed and replaced at the site. The other alternative is 'rainbowing', whereby the dredging vessel disposes (rainbows) muddy slurry on the foreshore. This method strongly depends on the local bathymetry, as this determines the accessibility for dredging vessels (Colenutt, 2001). An alternative of this solution is 'thin layer' placement, which is often applied at salt marshes in the United States of America. For this method a layer of a several centimetres of inorganic sediment is disposed on top of the foreshore, which enables the pioneer vegetation to establish (Ray, 2007).

Water column recharge

This technique is usually applied to reduce the tendency of local salt marshes to erode (Adnitt et al., 2007). The basic idea is to directly bring sediment into suspension, which is done by gradually disposing sediment into the water column. This can be achieved by pumping or rainbowing, whereby the sediment is released with small amounts, so that the sediment-water mixture is not too dense and does not directly settle. The most favourable dispersal technique is from a moving dredger (Adnitt et al., 2007). Tidal currents have limited transport capacity, as the current induced turbulence must balance the force of gravity. Therefore, it is recommended to dispose fine sediment, as it has a relatively low settling velocity (0.2 - 2.0 mm/s). By means of this process the currents can transport the sediment in landward direction before it is deposited (Adnitt et al., 2007).

Foreshore placement

This method can be described as artificially elevating the intertidal and subtidal area with disposed sediment, in order to develop an elevation where vegetation can naturally colonize (Colenutt, 2001). Generally, cutter suction hopper dredgers and trailing suction dredgers are best suited for foreshore recharge, whereby two methods can be characterized: direct and indirect placement. Methods for direct placement are similar to that of direct recharge. For some projects, especially in case of fine grained sediment, retaining structures are required to prevent the accreted sediment from erosion (Adnitt et al., 2007).

Indirect placement aims at increasing the surface elevation and correspondingly develop salt marshes, by means of increasing the sediment availability and utilize natural processes to redistribute the dredged material (Colenutt, 2001). A bank of sediment is disposed by a dredging vessel in the intertidal zone, whereby physical tidal currents transport the sediment towards the restoration site. This results in a 'natural' foreshore development (Colenutt, 2001). The main disadvantages are that this process develops much slower than direct pumping and sediment might get 'lost' in the system, resulting in increased turbidity (Adnitt et al., 2007). An example of this measure is the Mud Motor project at Koehoal, near Harlingen, where a it is attempted to develop a salt marsh by increasing the sediment supply. This is one of the reference projects in the Building with Nature design guidelines (Section 4.1).

4.2.2 Stabilisation and retention of sediment

This category of salt marsh restoration methods includes different techniques, varying between structures to enhance sedimentation and measures to stabilise the soil against erosion. Often different techniques are combined. As example, in the Netherlands salt marsh development often occurs in three phases, first the brushwood groin fields are constructed in order to improve sedimentation. Thereafter, when the elevation of the site is sufficiently high, a drainage system is dredged to improve aeration (Section 4.2.4). Meanwhile, seaward of the groin field, a second groin field is applied to continue the sedimentation process. If it is considered as necessary, in phase 3, a similar third field is constructed (Colenutt, 2001).

Brushwood groins (Sleeswijk-Holstein method)

Brushwood groins or breakwaters are applied to reduce hydrodynamic forcing to enhance sedimentation, hence initiate vegetation colonization (De Groot & Van Duin, 2013). These structures are designed in such a manner that they slow down the bypassing water, thereby increase the deposition rates of the suspended sediment (Adnitt et al., 2007). This method has been applied on a large scale in the Netherlands in the past at the 'salt marsh works' in Friesland an Groningen, whereby the naturalness of formerly land reclamations is recovered by reintroduction of salt marshes (Dijkema et al., 2011).

Two types can be distinguished: brushwood groins and sedimentation polders. Brushwood groins consist of two parallel rows of wooden stakes, with 300 – 600 mm intervals, driven into the soil, usually in shore normal direction. The recommended height of these piles is a couple of decimetres above the mean water line (De Groot & Van Duin, 2013). Different materials can be placed between the piles (brushwood, geotextile, straw), however brushwood is the most durable (Adnitt et al., 2007). These structures reduce waves, currents and the regression of ebb, therefore enhance sedimentation (Colenutt, 2001). For the sedimentation polder method existing salt marsh areas and adjacent mud flats are fenced-off by brushwood groins (Figure 4.2b). During flood, the water can flow through openings in the fences into the polder, whereby sediment accumulates by the same process as for brushwood groins. The inner drainage system redistributes the water and sediment inside the salt marsh area (Colenutt, 2001). Management of the drainage system may be required to enhance the development of the inner marsh system (Adnitt et al., 2007), this is discussed in Section 4.2.4.

(a) Installation of brushwood fences.

(b) Brushwood groins and stone revetment.

Figure 4.2: Brushwood fences and erosion protection (Ecomare, 2016; Van Loon-Steensma, 2014).

Stone, concrete or geotube breakwaters

Offshore and nearshore breakwaters enhance the development of the salt marsh profile by reducing of the hydrodynamic forcing (Adnitt et al., 2007). Different materials are possible (stone, concrete, geotube), whereby in-situ filled geotubes are usually the cheapest solution (Adnitt et al., 2007). Also oyster and mussel reefs can function as breakwater, however this method is still experimental (De Groot & Van Duin, 2013). Sometimes these breakwaters are combined with brushwood fences to connect the breakwater with the shoreline to form a polder (Adnitt et al., 2007). This technique can also be combined with foreshore recharge (Section 4.2.1) or vegetation planting, in order to increase the overall effectiveness of the restoration project (Adnitt et al., 2007). It is recommended to construct the breakwaters near the low water line, where it has the largest efficiency (Adnitt et al., 2007).

Manipulate vegetation

When the abiotic conditions are favourable for salt marsh development, natural colonization of vegetation is preferred. However, occasionally natural vegetation establishment might not occur, e.g. due to isolation of the site for seedlings, or the time is limited and it is required to accelerate the process (Niedowski, 2000). Planting can also be applied to prevent erosion, however most commonly this technique is combined with other restoration methods (Colenutt, 2001). Planting is usually executed for *Spartina* species and can be done by the following techniques (Knutson, Allen, & Webb, 1990; Niedowski, 2000):

- Planting seeds, which is not recommended in most cases, as germination is a difficult and uncertain process. However, an advantage of this solution is that no investments have to be made in pre-growing of plants.
- Planting semi-mature plants, by using stems (no soil around roots) or plugs (soil mat around roots). Plants may come from greenhouses or from other salt marsh sites.

Planting can be done both manually as mechanized, however the latter is required for intertidal planting (Niedowski, 2000). In case it is considered to initiate vegetation establishment it is recommended to take the following aspects into account (Adnitt et al., 2007):

- Are there historical records of salt marsh growth? If so, the environmental conditions are favourable for salt marsh growth and seeds can be present in this area.
- Is there a rapid coastal erosion? If so, other adaptive measures might be required to guarantee successful salt marsh establishment.
- Is the mudflat elevation sufficient for vegetation establishment? The minimum elevation can be determined by pioneer zone of local salt marshes.
- Is the salinity, hydrodynamic forcing and substrate suitable for vegetation? This can be determined by measuring and recording soil properties and hydrodynamic data.

The main drawback of this method is that the site characteristics should be examined carefully, in order to determine if the environmental conditions are suitable for salt marsh development, or prior adaptive measures are required. Moreover, one should be careful with plant selection, as the introduction of invasive species might disturb the local ecosystem (Adnitt et al., 2007).

Stone revetment against erosion

For this technique stones are placed directly on the eroding salt marsh edge (Figure 4.2b), in order to prevent the system from further erosion (De Groot & Van Duin, 2013). This introduces a fully unnatural element to the system (Doody, 2008), which limits it expansion (Adnitt et al., 2007). This method is only used as last resort when other measures are not sufficient (De Groot & Van Duin, 2013). Instead of stone or concrete, more natural elements can be applied, such as coconut mats. The main disadvantage is that biodegradable materials decay and need to be frequently replaced (Adnitt et al., 2007).

4.2.3 Managed realignment

For this restoration method the formerly sea defence line (e.g. dike) is set back, in order to create a new line of defence in combination with accommodation space for nature, indicated in Figure 4.1b (Colenutt, 2001; Leggett, Cooper, & Harvey, 2004). Usually, this measure is applied in areas where the shoreline is structurally eroding or lost by formerly land reclamations or coastal squeeze, and there is no space for restoration due to coastal intervention by hard structures (Adnitt et al., 2007; Colenutt, 2001).

The approach towards this technique is to create a secondary inner line of sea defence. Thereafter, breaching-off is applied on the primary sea defence, which allows ecological development of the intermediate area. Finally, the formerly sea defence is removed partially of wholly (Adnitt et al., 2007; Colenutt, 2001). Tidal flushing and overtopping waves makes halophytic vegetation establishment possible (Adnitt et al., 2007). Most likely, this produces intertidal flats and low to mid salt marshes (Colenutt, 2001). Recharge of the intermediate area can be required, as it is disconnected from the sea and could not accumulate as the outer area (Adnitt et al., 2007), see Section 4.2.1. A disadvantage of this measure is the loss of terrestrial habitat and temporary or permanent loss of grazing area. However, it results in salt marsh ecosystem recovery. Additionally, salt marshes can contribute to flood safety by means of reducing wave energy, which can result in lower investment and maintenance costs at the secondary sea defence.

4.2.4 Adaptive measures after restoration

Grazing

After a salt marsh has developed naturally or artificially, management is possible by grazing. This is desired to manage the biodiversity, as usually the climax state of salt marshes is monotonous, which principally consists of Sea Couch (*Elymus repens*) (Dijkema et al., 2011). For over centuries, salt marshes provided pasture for livestock (Doody, 2008). This management technique at salt marshes varies per continent, for instance the European, Chinese and South American salt marshes are intensively grazed. Conversely, in North America grazing at salt marshes is less common (Davidson et al., 2017). Different degrees of grazing can be applied, in order to improve the biodiversity of the ecosystem, as usually grazed salt marshes have a higher natural diversity than those that are not (Adnitt et al., 2007). The selection of the grazing type depends on the objectives that are set for the site, e.g. the target-species. Thereafter, the grazing intensity and type of livestock is determined. These measures can be summarised into the following three categories (Adnitt et al., 2007):

- *Lightly grazed*: This degree of grazing most closely represents the natural ungrazed state, which usually provides a high diversity of vegetation and invertebrates. Usually grazing is done by native herbivores, such as duck and geese or by small densities of livestock (2-3 sheep, < 1 cattle or < 1 horse per hectare).
- *Moderately grazed*: This grazing measure results in a varying ecosystem that strongly depends on the livestock that is grazing, as cattle provides more biodiversity than sheep. Typical livestock densities are 5-6 sheep, 1-1.5 cattle or ~ 1 horse per hectare.
- *Heavily grazed*: This degree of grazing is beneficial for agricultural purposes rather than ecological values, as biodiversity of vegetation and invertebrates is low and bird nests can be harmed by livestock trampling(Van Klink et al., 2016). Typical grazing densities are ~ 10 sheep, 2-2.5 cattle or 2 horses per hectare.

This type of management is discussed more extensively in Chapter 5 and 6.

Digging drainage channels

This measure is usually combined with other restoration techniques, such as sedimentation polders and foreshore recharge. By means of artificially digging drainage channels, the aeration is increased and the site is accessible for tidal flushing and nutrients, which enhances vegetation establishment (De Groot & Van Duin, 2013). The natural development of the drainage system should be monitored, if this does not develop or the salt marsh development should be accelerated, one can consider this management method, otherwise natural development is recommended to maintain the naturalness of the system (De Groot & Van Duin, 2013).

Part III

In-depth research

Chapter 5

Methodology

The approach towards the in-depth research is discussed in this chapter, which concerns the modelling of wave attenuation values that result from different grazing strategies. The vegetation data is collected at the salt marsh at Noord Friesland Buitendijks.

5.1 Background

5.1.1 Coastal protection by salt marshes

The main objective of this research is to develop guidelines for engineers to include salt marshes in engineering projects, where the focus lies on the ecosystem service of coastal protection (Chapter 1). The potential to integrate ecosystem services in hydraulic infrastructure projects is increasingly being mentioned as a supplemental measure for traditional solutions (Boersma, 2014). The inclusion of salt marshes in coastal protection systems has been the topic of recent studies (e.g. Anderson and Smith (2014); Möller et al. (2014); Vuik et al. (2016)). From numerical modelling and experiments it follows that the presence of vegetation can lead to wave load reduction up to 60% compared to the bare foreshore (Möller et al., 2014; Vuik et al., 2016). However, Building with Nature solutions, inherently include the dynamic behaviour of nature, which results in a large degree of uncertainty (Anderson & Smith, 2014; Möller et al., 2014; Vuik et al., 2016). In order to obtain more insight into those physical processes, the effect of different grazing strategies at salt marshes on the coastal protection property is assessed in this in-depth research.

5.1.2 Effect of grazing at salt marshes

In Section 4.2.4 different grazing strategies for salt marshes management are discussed. Currently, grazing at salt marshes is applied as a ecosystem conservation tool. During the past fifty years, these ecosystems fell into abandonment, as livestock grazing became less profitable (Van Klink et al., 2016). This led to an invasion by dominant species such as sea purslane (*Artiplex portulacoides*) on the lower marsh and sea couch grass (*Elytrigia atherica*) on the higher marsh. This threatens the existence of short saturated vegetation species, invertebrates and migratory birds (Van Klink et al., 2016). In Northwest Europe, the conservation of these ecosystems is of high interest, as numerous plant, invertebrate and bird species require this specific habitat and the area of salt marshes is declining (Ecomare, 2016; Van Klink et al., 2016). Therefore, certain species, such as the redshank and oystercatcher have nearly disappeared in this part of the world (Doody, 2008; Van Klink et al., 2016).

Previous studies showed that grazing positively affects plant-biodiversity (Andresen, Bakker, Brongers, Heydemann, & Irmler, 1990; De Vlas, Mandema, Nolte, Van Klink, & Esselink, 2013; Van Klink et al., 2016). Conversely, grazing has a negative effect on sedimentation rates at salt marshes. Grazing alters vegetation by defoliation, which leads to less sediment accumulation (Andresen et al., 1990; De Vlas et al., 2013). Additionally, soil compaction occurs due to trampling (De Vlas et al., 2013). Moreover, tall and dense vegetation is more effective in dissipating wave energy than short low-density vegetation (Davidson et al., 2017), where the latter corresponds to grazed marshes. Although these researches have studied the effect of grazing, the effect on the interaction between coastal protection and biodiversity has not yet been studied.

5.1.3 Case study 'Noord Friesland Buitendijks'

To examine the effect of grazing on coastal safety and biodiversity, a case study is carried out on a salt marsh at 'Noord Friesland Buitendijks' (NFB) in the Netherlands (Figure 5.1). This location is a former land reclamation area, where Dutch farmers enhanced salt marsh development by digging ditches on the seaward side of the dike in the 17th century. In the beginning of the past century this method was replaced by the Sleeswijk-Holstein method (Section 4.2.2), which resulted in 6000 ha of reclaimed land, designated for agricultural purposes (Dijkema et al., 2011). At this location a grazing-experiment was executed between 2009 and 2016. Different grazing strategies were applied to eleven paddocks, with varying livestock species and livestock intensity. The following strategies can be distinguished: no grazing, low intensity grazing by cattle or horses (0.5 livestock per hectare), high intensity grazing by cattle or horses (1.0 livestock per hectare) and rotational grazing, which is one year intensive grazing by cattle followed by one year of abandonment. The arrangement of the paddocks can be seen in Figure 5.1.

Figure 5.1: Location of the grazing experiment at Noord Friesland Buitendijks. The cross indicates the ungrazed paddock, one cattle/horse in the figure represents a grazing intensity of 0.5 livestock per hectare and the rotational grazing strategies are indicated by the arrows.

A distinction can be made between the paddock groups in the south-west (SW) and north-east (NE) at NFB, this is an important aspect within the analysis. In Chapter 6 the different grazing strategies are indicated as follows: No grazing: N, low intensity grazing by cattle: 0.5C, low intensity grazing by horses: 0.5H, high intensity grazing by cattle: 1.0C, high intensity grazing by horses: 1.0H and rotational grazing by cattle: R.

5.2 Objective & research questions

The main objective of this research is to determine the effect of different grazing strategies at salt marshes on values for coastal safety, expressed in terms of wave attenuation. This can be translated into the following research question:

Main research question in-depth research

"How do different grazing strategies at salt marshes contribute to the coastal protection property, i.e. wave attenuation?"

The experiment at Noord Friesland Buitendijks is used as reference case for this research, translated to generic lessons for salt marsh management. From previous studies it follows that grazing can positively affect the salt marsh biodiversity, however, little is known about the effect on coastal protection. Therefore, these two ecosystem services are compared in this research. This can assist a project developer in the choice of which grazing strategy should be applied to achieve the objectives of the project. The following research questions support the main question:

1. How do different grazing strategies affect vegetation properties in terms of vegetation biomass and spatial patterns?
2. How do wave attenuation values of marsh vegetation relate to varying vegetation properties caused by different grazing strategies?
3. How does wave attenuation at salt marshes depend on diverse biotic and abiotic parameters?
4. How do different grazing strategies affect the interaction between two ecosystem services: biodiversity and coastal protection, expressed in wave attenuation and soil stabilisation?

From previous studies it follows that tall and dense vegetation is more effective in dissipating wave energy than short low density vegetation (Davidson et al., 2017). Therefore, it is expected that the Sea aster (*Aster tripolium*) will lead to the highest wave energy dissipation at NFB, as this is the tallest and thickest vegetation at this site. Further, it is expected that the ungrazed salt marsh will lead to the highest wave attenuation values, as the vegetation is not altered by defoliation or trampling. From literature it follows that grazing positively affects the biodiversity at the marsh. Therefore, the interaction between biodiversity and the coastal protection property at salt marshes is analysed within this in-depth research.

5.3 Approach

The effect of the different grazing strategies on wave attenuation is computed with the numerical model SWAN. This section provides the theoretical background of this model in Section 5.3.1. The effect of grazing strategies is analysed on the vegetation properties, followed by an expression for the wave attenuation potential of the vegetation (Section 5.3.2). Thereafter, the approach toward the wave modelling is presented in Section 5.3.3. Lastly, the effect of grazing on coastal safety (wave attenuation and soil stabilisation) and biodiversity is analysed by means of a literature study.

5.3.1 Modelling

Theoretical background of SWAN

The calculation of wave attenuation by salt marsh vegetation is executed by an one-dimensional approach by SWAN (**S**imulating **WA**ves **N**earshore). This numerical model can provide realistic estimates for wave parameters resulting from given wind, bottom and current conditions ('the SWAN team', 2017). The model is based on the wave action balance with sources and sinks, which reduces to the wave energy balance for a one-dimensional and stationary assumption (Holthuijsen, 2007):

$$\frac{\delta E c_g}{\delta x} = - < D_b > - < D_{nf} > - < D_v > \tag{5.1}$$

In Equation 5.1 E $[J/m^2]$ accounts for the energy density, c_g $[m/s]$ is the wave group velocity and D_b, D_f and D_v $[Jm^{-2}s^{-1}]$ are energy dissipation terms. As a wave propagates in onshore direction, it loses energy due to several processes, such as dissipation by depth-induced wave breaking, bottom friction and vegetation (right-hand side of Equation 5.1). This research primarily focusses on the wave attenuation by vegetation, whereas the theoretical background of SWAN is discussed more extensively in Appendix A.

Dissipation by vegetation results from drag forces, which are induced by waves performing work on vegetation stems, branches and leaves (Dalrymple, Kirby, & Hwang, 1984; Vuik et al., 2016). Wave attenuation by foreshore vegetation depends on both vegetation properties and hydraulic conditions (Möller et al., 2014; Vuik et al., 2016), this leads to the following expression (Mendez & Losada, 2004):

$$D_v = \underbrace{\frac{\rho g}{2\sqrt{\pi}}}_{constant} \underbrace{C_d d_v N_v \frac{sinh^3(kh_v) + 3sinh(kh_v)}{3k}}_{vegetation} \underbrace{\left(\frac{kH_{rms}}{2\sigma cosh(kh)}\right)^3}_{wave} \tag{5.2}$$

Where C_d $[-]$ is the drag coefficient, d_v $[m]$ is the stem diameter, N_v $[stems/m^2]$ is the stem density per square meter, k $[m^{-1}]$ is the wave number, σ $[s^{-1}]$ is the wave angular frequency, h $[m]$ is the water depth and H_{rms} $[m]$ is the mean wave height. Equation 5.2 can be divided into a constant part, a vegetation related part and a wave related part (terms on the right-hand side of Equation 5.2). For deeply submerged vegetation ($h >> h_v$) the vegetation related part of Equation 5.2 reduces to $h_v \cdot b_v \cdot N_v \cdot C_d$, this holds for storm events. This simplification can be applied to express the wave attenuation potential of vegetation species, which is further discussed in Section 5.3.2.

Required input for SWAN

In order to model the wave energy dissipation, several input parameters are required to express the site characteristics, hydrodynamic conditions and vegetation properties. In Figure 5.2 a schematic view is displayed for the input of the model. Regarding the vegetation properties, SWAN requires data for the stem height, diameter, density, drag coefficient and the contribution of individual vegetation species. For this research it is important to combine multiple species in order to properly represent the biotic conditions that correspond to the different grazing strategies. Originally, SWAN is only capable of including the properties of one species in the computations. Therefore, prior to this research, the source code of SWAN is adapted to enable spatial variations of vegetation properties in the model. A brief explanation to these adaptations can be found in Appendix B. The vegetation input parameters are discussed in Section 5.3.2 and an overview of the hydrodynamic conditions and site characteristics is presented in Section 5.3.3.

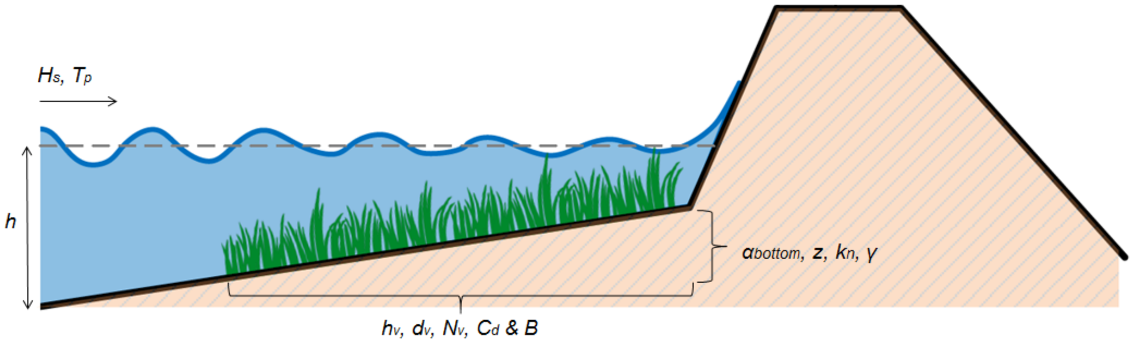


Figure 5.2: Schematic view of a one-dimensional vegetated foreshore system. With hydraulic conditions: significant wave height (H_s), peak period (T_p) and water depth (h), vegetation properties: stem height (h_v), diameter (d_v), density (N_v), drag coefficient (C_d) and vegetation width per species (B) and site characteristics: slope (α_{bottom}), bottom profile elevation (z), friction (k_z) and breaker parameter (γ).

5.3.2 Data

The vegetation at Noord Friesland Buitendijks is characterised by fifteen species, which are presented in Figure 5.3. The following data has been collected prior to this research:

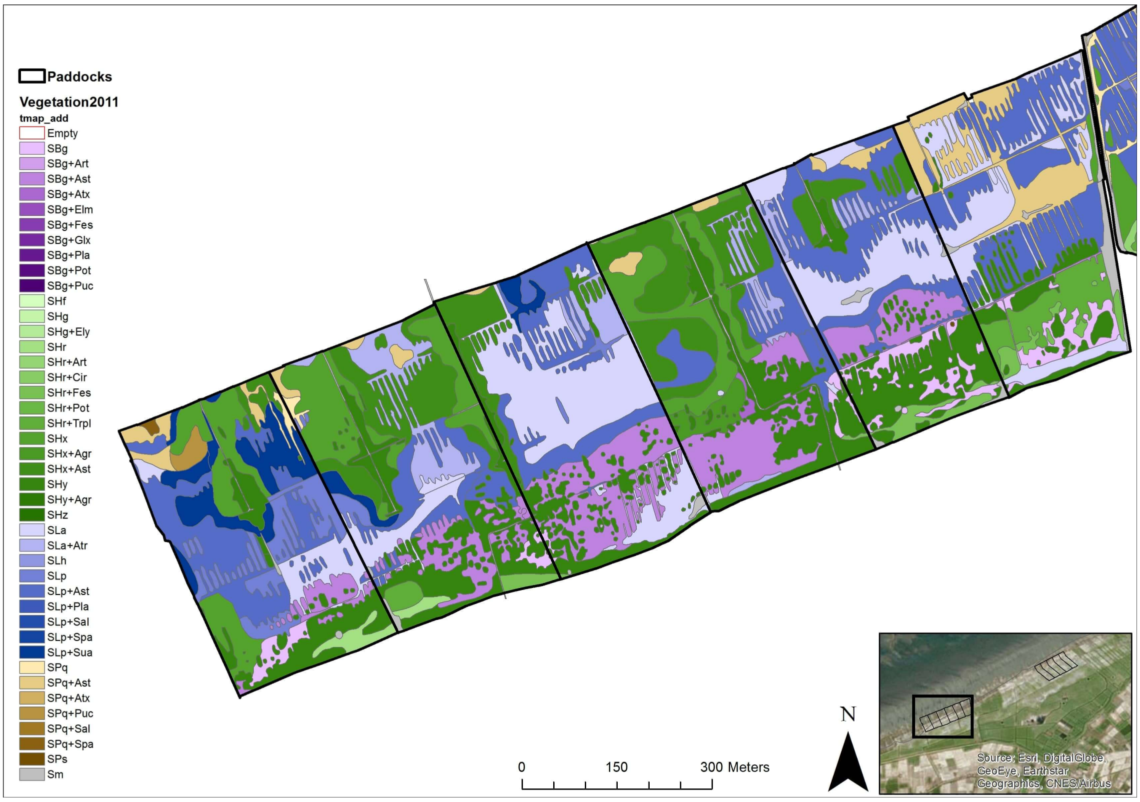
- *Spatial distribution*: This is based on aerial photographs and field measurements during the growing season (September). The data is combined into vegetation maps that represent the spatial distribution of the vegetation along the different grazing strategies.
- *Vegetation properties*: Data has been collected for the stem height, diameter and density, based on 30 samples from six spots at each paddock. This data is collected in four different seasons.
- *Bending data*: The flexibility and maximum load are based on a three-point bending test in the laboratory of NIOZ. The bending data only includes seasonal variations, as no distinction is made between variations along the different grazing strategies.

Spatial distribution

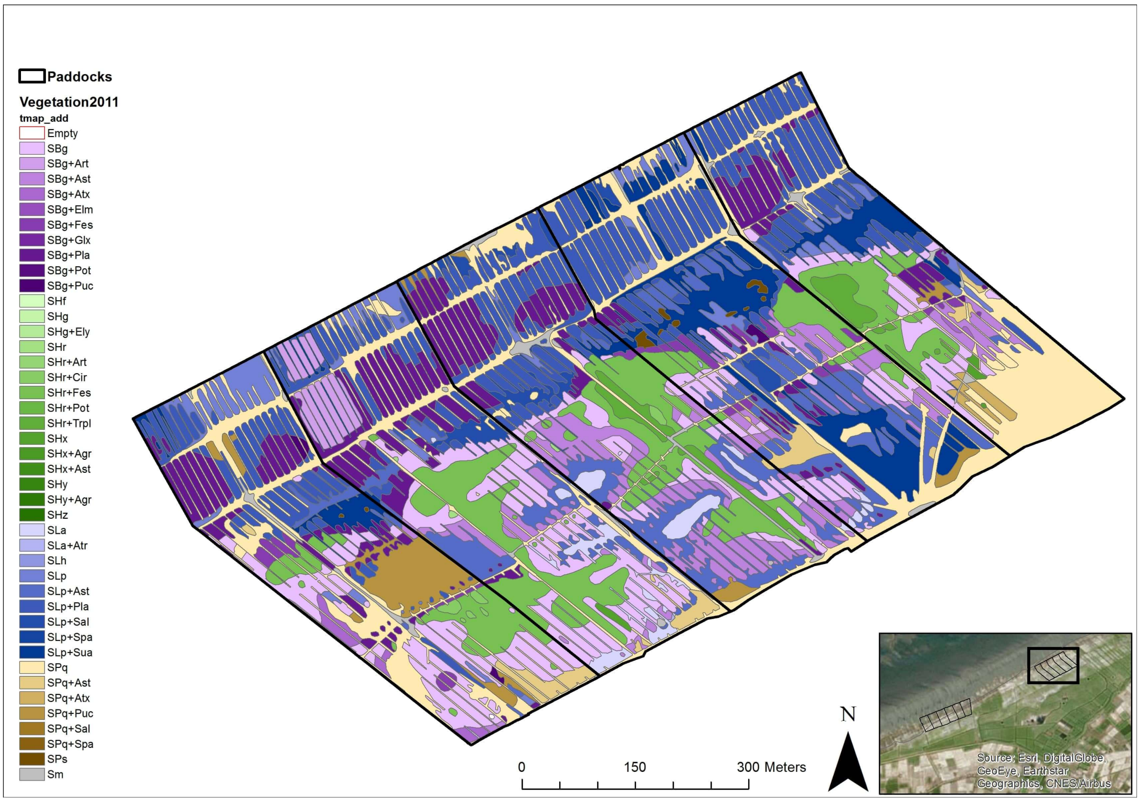
The spatial distribution of the vegetation results from the vegetation maps. Usually, a small area (∼ a square metre) of a salt marsh is covered by several species. Therefore, the different colors at the vegetation maps (Figure 5.4) indicate different species-groups, rather than individual species. The left image in Figure 5.5 presents a schematic view of the vegetation maps. In this research it is assumed that the ratio between the surface area of the species-groups compared to the total paddock represents a one-dimensional cross-section of the paddock in cross-shore direction. This results in (a) in Figure 5.5. Each species-group consists of one or two dominant species (main species) and optionally a less dominant sub-species (con-species). Within a species-group each individual species has a characteristic contribution to the surface area of the group, e.g. 60% for a main species and 40% for a sub-species, which is expressed as the 'species-key' in Table C.3 (Appendix C). Based on the ratios of individual species related to the species-groups the surface area of each individual species is determined, expressed in percentages of the total paddock area, e.g. a% of *Aster* and b% of *Elymus*. This is implied by (b) in Figure 5.5. Lastly, some species decay in winter, therefore for the wave model, cross-section (b) reduces to (c), where the cover of PUC (*Puccinellia*) is simulated as a bare surface. Each species has characteristic properties as indicated in Figure 5.2.

(a) *Agrostis stolonifera* (b) *Artemisia maritime* (c) *Aster tripolium*
(d) *Artiplex* (e) *Cirsium vulgare* (f) *Elymus repens*
(g) *Festuca rubra* (h) *Glaux maritime* (i) *Plantago maritime*
(j) *Potentilla anserinea* (k) *Puccinellia maritime* (l) *Salicornia spp.*
(m) *Spartina anglica* (n) *Suaeda maritime* (o) *Tripleurosp. mar.*

Figure 5.3: Vegetation species at NFB (Dijkstra, 2017).



(a) Vegetation map paddocks south-west.



(b) Vegetation map paddocks north-east

Figure 5.4: Vegetation maps Noord Friesland Buitendijks (2011) compiled by A. Wielemaker (NIOZ). The colors indicate species-groups, consisting of one or more individual species.

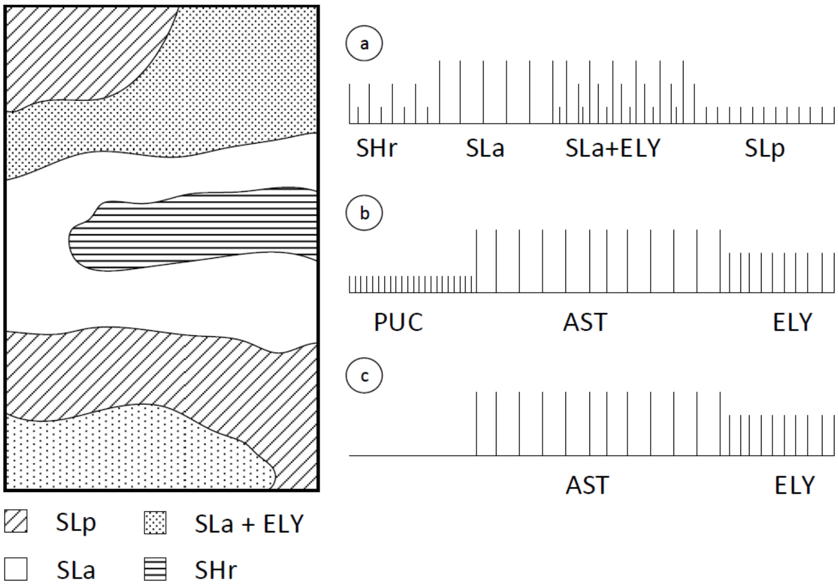


Figure 5.5: Approach towards the input of the spatial distribution for the wave model. At the left image a paddock is displayed covered by four species groups. At (a) the total vegetation surface area is translated to one cross-section. At (b) the cover of the specie-groups is divided into three individual species. (c) represents the winter state of the vegetation, as some species decay during winter, which is simulated as a bare surface.

Vegetation properties (stem height, diameter and density)

The mean values and standard deviations are determined for the vegetation properties that are measured in the field. A distinction should be made between the different paddocks, as well as the seasonal variation of the properties. The mean values and standard deviations give an expression for the sensitivity of these parameters within the wave modelling.

Drag coefficient

The drag coefficient is an expression for the drag force that is exerted by the vegetation on the waves and flow (Section 5.3.1). This parameter depends on multiple factors, such as plant swaying, orbital motions induced by the vegetation stem and the effect of branches and leaves (Vuik et al., 2016). Due to the complex physics that underlie the drag coefficient, this parameter should be determined carefully. Usually, this is done by calibration of this parameter with respect to the Reynolds number resulting from measurements (Mendez & Losada, 2004; Möller et al., 2014; Vuik et al., 2016). However, there are no wave measurements executed at NFB. It is not straightforward to determine the drag coefficient without calibration, however it is possible to use an approach with a simple array of rigid cylinders (Suzuki, 2011). From literature it follows that the theoretical upper limit for rigid columns corresponds to a drag coefficient in the order of 1.0 - 1.2 (Suzuki, 2011). Luhar and Nepf (2016) present an approach in which vegetation stems can be modelled as flexible, inextensible blades. If one-dimensional flow is exerted on the stem, this results in bending. Luhar and Nepf (2016) express the ratio between the hydrodynamic forcing and the restoring force due to stem stiffness by a dimensionless parameter: the Cauchy number (Ca) (Equation 5.3).

$$Ca = \frac{\rho b U_w^2 l^3}{EI} \tag{5.3}$$

Where Ca $[-]$ is the Cauchy number, ρ $[kg/m^3]$ is the density of water, b $[m]$ is the width of the stems, U_w $[m/s]$ is the current speed, l $[m]$ is the length of the stems, I $[m^4]$ is second moment of inertia and E $[kgm^{-1}s^{-2}]$ is the Young's Modulus of the stems.

For this research the bulk drag coefficient is determined by means of the method presented by Luhar and Nepf (2016). Following from Equation 5.3, the drag coefficient depends on the flexural rigidity (EI) of the vegetation stems. The flexural rigidity can be determined by the data that results from the three-point bending test. Several expressions can be found for calibrated values of the drag coefficient, related to the flexural rigidity of different salt marsh species. Based on these values a ratio can be determined between the flexural rigidity and the drag coefficient for the species at NFB. High values for the flexural rigidity EI ($Ca < 1.0$) result in stiff stems ($C_d \sim 1.0$) and very flexible stems (short grasses) obtain low values for the drag coefficient ($C_d \sim 0.01$).

Wave attenuation potential

Prior to the wave modelling, the wave attenuation potential of the vegetation species at NFB is analysed. This analysis gives an expression for the capacity of the vegetation to dissipate wave energy. A distinction is made between the different grazing strategies. The wave attenuation potential can be divided into three parameters:

- *Vegetation coefficient*: This parameter represents the vegetation-related part of the wave energy dissipation by vegetation formula ($h_v \cdot b_v \cdot N_v \cdot C_d$) (Equation 5.2). A large vegetation coefficient results in a large contribution of a species to wave attenuation.
- *Spatial distribution*: This parameter gives an expression for the ratio between the surface area of an individual species compared to the total paddock area. The combination of high values for the vegetation coefficient and the spatial distribution of one species results in high values for wave attenuation.
- *Stem breakage*: This parameter gives an expression for the reliability of the salt marsh during exposure to hydrodynamic forcing. A scope of this research is to verify if the vegetation stems can resist the wave forcing. This can be determined by computing the critical velocity at which the stems break (u_{crit}) related to the wave-induced velocity ($u(z)$). If the wave-induced velocity exceeds the critical velocity, this results in stem breakage ($u(z) > u_{crit}$) (Vuik, Suh Heo, Z, Borsje, & Jonkman, 2017). These velocities can be computed by means of the approach presented in Appendix A.4.

5.3.3 Wave modelling in SWAN

As base for the wave model, the site characteristics and hydrodynamic conditions at Noord Friesland Buitendijks are included. Thereafter, the effect of different abiotic conditions (bathymetry) on wave energy dissipation is analysed. The bathymetry along four cross-sections at NFB, that corresponds to the high marsh, is displayed in Figure 5.6.

The wave attenuation property of salt marsh vegetation has seasonal variations, as salt marshes lose above-ground biomass in winter (Vuik et al., 2017). Most severe weather conditions in Europe occur in winter (November - February), whereas at the Atlantic coast of the USA the hurricane season takes place in summer (August - October). Therefore the effect of seasonal variations should be included in this research. Lastly, the sensitivity of the biotic parameters is analysed. The following scenarios are computed in SWAN:

- *Biotic conditions*
  - Effect vegetation compared to the bare foreshore (100 m)
  - Effect vegetation at full width foreshore at NFB (1000 m)
  - Effect of seasonal cycle vegetation (100 m)
- *Abiotic conditions*
  - Effect slope foreshore (0 to 2 m+NAP)
  - Effect bottom profile elevation (100 m)
  - Effect different bottom profiles along the Wadden Sea (1000 m)
- *Sensitivity*
  - Effect of standard deviation vegetation properties (100 m)
  - Effect of stem breakage (100 m)
  - Effect of inclusion lacking vegetation properties (100 m)

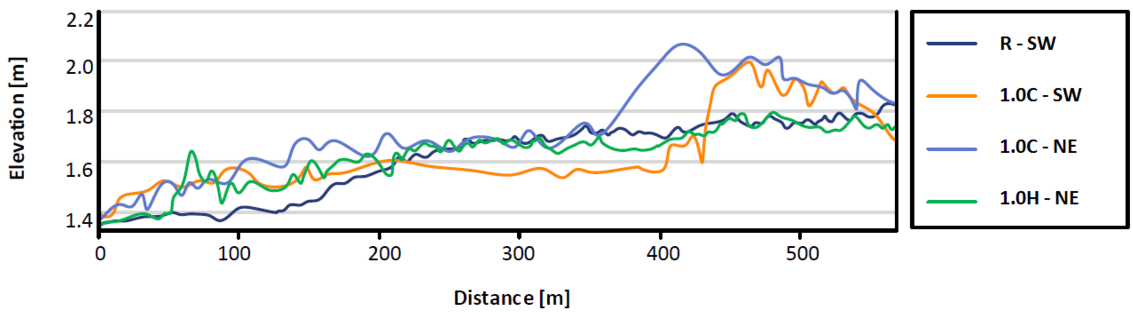


Figure 5.6: Bathymetry at four cross-sections at Noord Friesland Buitendijks [m]. Based on data from the GPS measurements of NIOZ and AHN (Rijkswaterstaat, 2017).

The hydraulic conditions at Noord Friesland result from the "Hydraulische Randvoorwaarden 2006". These guidelines present the safety criteria for the primary flood defences along the Dutch coastline, determined at a distance of 50 m in front of the dike. Therefore, the design conditions are extrapolated by the WTI-2011 SWAN model of HKV to larger water depths. The corresponding bathymetry is measured with a GPS by NIOZ. To model the bottom friction, a Nikuradse roughness length scale of $k_n = 0.02m$ is selected, which is a characteristic value for a bottom with ripples (Babanin, Young, & Mirfenderesk, 2005). The breaker parameter is estimated by means of the method presented by Ruessink, Walstra, and Southgate (2003). The theoretical background of these parameters can be found in Appendix A. Table 5.1 presents the site characteristics and hydraulic conditions at NFB.

Table 5.1: Site characteristics and hydraulic conditions at Noord Friesland Buiteindijks, corresponding to the 1/4000 year storm (Ministerie van Verkeer en Waterstaat, 2007).

Hydraulic conditions	*Design water level*	h	4.80 m
	Design wave height	H_s	1.90 m
	Peak period	T_p	6.40 s
Site characteristics	*Site elevation (SW)*	z	1.01 - 1.91 m+NAP
	Site elevation (NE)	z	1.26 - 2.01 m+NAP
	Average slope	α_{bot}	1:1000
	Breaker parameter	γ	0.82
	Bottom friction	k_n	0.02 m

Chapter 6

Results

This chapter discusses the main results related to the research questions presented in Section 5.2. Prior to the model results, the effect of grazing on the vegetation properties and the wave attenuation potential is analysed in Section 6.1 and 6.2. The wave model results are presented in Section 6.3, where the effect of different biotic and abiotic parameters is analysed on wave attenuation. Lastly, the effect of grazing on wave attenuation is compared with the effect on two other ecosystem services: soil stabilisation and biodiversity by means of a literature review. The grazing types are indicated in Section 5.1.3.

6.1 Vegetation data

This section discusses the most important remarks about the vegetation properties that are used as input for the wave model (Section 6.3). A full overview of the vegetation data can be found in Appendix C.

6.1.1 Species distribution

It is found that there are seven dominant species at Noord Friesland Buitendijks (NFB), which have a surface area of > 5% of the total paddock area. These are the following species: *Puccinellia*, *Aster*, *Agrostis*, *Elymus*, *Artemisia*, *Suaeda* and *Salicornia*. Figure 6.1 presents the contribution of these seven species to the total area of each paddock. The major observation is that for this location, the effect of grazing has a minor influence compared to the variations in site characteristics between the two paddock groups. A grazing-related difference is the surface area covered by *Puccinellia* and *Aster*, which is low at the ungrazed paddock (N-SW). The area covered by *Salicornia* and *Suaeda* is larger for the paddocks with high grazing intensities (1.0C and 1.0H). This suggests that these are non-dominant species, which is in agreement with Bakker (1985), who found that *Puccinellia* and *Aster* are replaced by succession after a salt marsh falls into abandonment.

The other vegetation patters that are observed result from spatial variations. The elevation is the key-factor in vegetation succession. However, other abiotic factors, such as soil salinity and composition of the substrate, may influence the vegetation patterns (Bockelmann, Bakker, Neuhaus, & Lage, 2002; Silvestri, Defina, & Marani, 2005). The abundance of *Puccinellia* and *Elymus* can be explained by the dominance of these species at the Wadden Sea region and at the higher marsh respectively (Bockelmann et al., 2002; De Leeuw, De Munch, Olff, & Bakker, 1993). A difference in the spatial distribution of the vegetation species is observed between the two paddock groups. The difference in elevation (0.10 - 0.20 m) between the two paddock groups can explain the spatial distribution of *Artemisia*, *Aster* and *Agrostis*. The spatial distribution of *Salicornia* and

Suaeda could not be explained by the elevation, as their cover is larger at the paddocks at higher elevation, whereas these are typical pioneer species. An explanation might be a difference in the development of the drainage system between the two paddock groups, as pioneer species prefer to grow near creeks (Silvestri et al., 2005). This was also observed in the field where pioneer species can be found along the ditches, even at the high marsh (Appendix E).

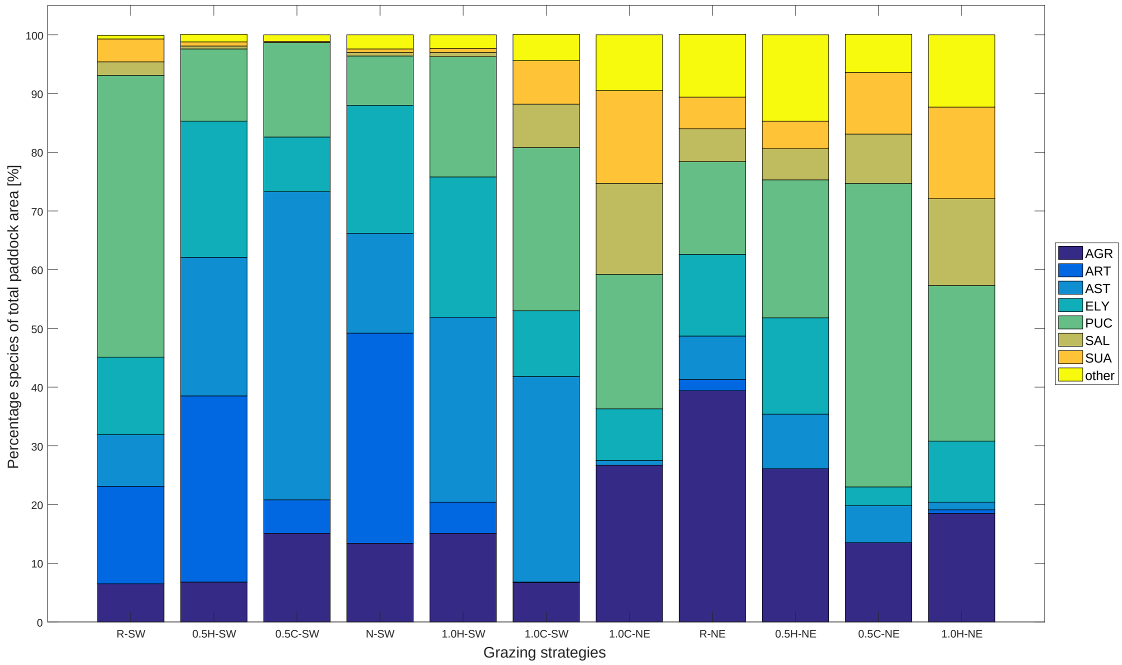


Figure 6.1: Surface area of the seven dominant species corresponding to the grazing strategies at NFB in percentages of the total paddock area.

6.1.2 Vegetation properties

Stem height h_v, diameter d_v and density N_v

Most of the species start to grow in summer (June - August) and decay in winter (Dijkstra, 2017). Therefore, the species properties are the lowest between March and June. It is found that *Aster* and *Elymus* are the tallest species at NFB. The effect of grazing is observed for *Aster*, *Puccinellia* and *Suaeda*, which have a lower stem height at paddocks with high grazing intensities, due to defoliation. Furthermore, a difference is observed between the two paddock groups, as *Aster* and *Suaeda* are taller at the paddock group in the south-west, which probably results from differences in site characteristics (Section 6.1.1). Lastly, it should be noted that the vegetation vegetation properties of *Agrostis*, *Elymus* and *Salicornia* are only measured at a few paddocks, whereas these species also have a significant contribution to the cover of the area of the resulting paddocks.

Drag coefficient C_d

The drag coefficient is determined by the stem flexibility resulting from the three-point bending test (Section 5.3.1). The flexibility from the bending data is compared with values from literature based on the properties of three salt marsh species: *Spartina*, *Elymus* and *Scirpus maritimus* (Vuik et al., 2017). It is assumed that the ratio between the stem flexibility and the drag coefficient can be approached logarithmically, as the drag coefficient increases with increasing flexural rigidity (lower stem-flexibility). Seasonal variations are observed for these parameters. Largest values for the drag coefficient are found between August and November, whereas low values occur in June, as the vegetation became brittle due to age and exposure to environmental forcing. *Aster*, *Elymus* and *Suaeda* have a relatively large drag coefficient in winter ($C_d = 0.45 - 0.59$), which could be valuable for wave attenuation. The results of this analysis can be found in Appendix C.4.

6.2 Wave attenuation potential

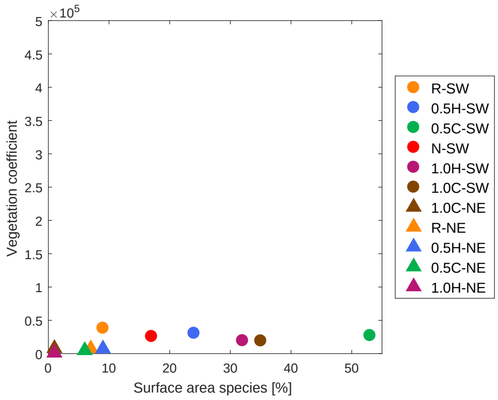
This section discusses three parameters that can be used to express the wave attenuation potential of the vegetation, which gives a prediction for the wave model results. The approach towards the computation of the wave attenuation potential is presented in Section 5.3.2. For this analysis the most severe conditions are considered for both the hydrodynamics as for the vegetation properties, which occur in winter (vegetation properties of March). During this season, three species can be found at NFB: *Aster*, *Elymus* and *Suaeda*, the other species are decayed during winter. From this analysis it is expected that the ungrazed paddock (N-SW) and the paddock with low intensity grazing by horses (0.5H-SW) lead to the largest value for wave attenuation, as the ratio between the vegetation coefficient and the area of *Elymus* is large for these grazing strategies (Figure 6.2b).

In Figure 6.2, it can be seen that *Suaeda* has the largest value for the vegetation coefficient ($h_v \cdot b_v \cdot N_v \cdot C_d$). This principally originates from the large density compared to that of the other species. Several grazing strategy-related remarks can be made for this parameter. The paddock with no grazing (N-SW) has the largest value for the vegetation coefficient of *Elymus*, whereas the paddocks with high intensity cattle (1.0C-SW) and low intensity cattle (0.5C-SW) have the largest value for *Suaeda*. Conversely, high intensity grazing by horses leads to most unfavourable conditions for the vegetation coefficient. For *Aster* a large variation can be seen between the two paddock groups, which results from smaller vegetation properties (height, diameter and density) at the paddock group in the north-east.

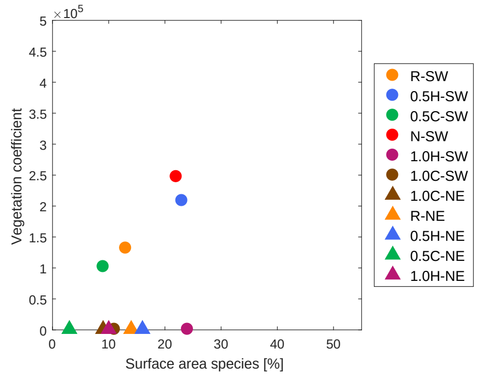
Figure 6.2d presents the stem breakage of the three species, expressed in the critical velocity versus the wave-induced velocity. The wave-induced velocity is $u(z) = 1.06$ m/s for all species, indicated by the red line. From this analysis, it follows that under design conditions it is probable that *Aster* will break ($u(z) > u_{crit}$), which can be explained by the low flexural rigidity of this species in winter. This is also observed in the field, where the *Aster* stems were brittle and partially broken (Figure E.1 in Appendix E). The difference in critical velocity for *Aster* between the two paddock groups results from the lower stem height at the group in the north-west, hence a larger critical velocity (Equation A.18).

6.3 Model results

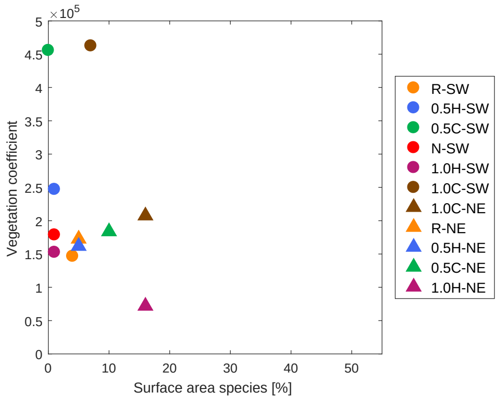
In this section the results from the numerical modelling in SWAN are discussed. The vegetation properties, site characteristics and hydraulic conditions at Noord Friesland Buitendijks are used as reference for this analysis. The contribution of the dissipation mechanisms is determined by integrating the dissipation velocities over the cross-section. A full overview of the model results can be seen in Appendix D.3.



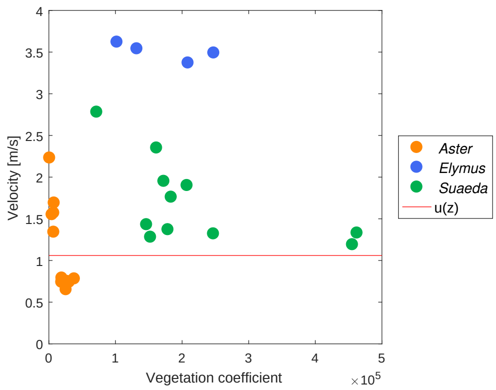
(a) Vegetation coefficient *Aster*.



(b) Vegetation coefficient *Elymus*.



(c) Vegetation coefficient *Suaeda*.



(d) Stem breakage (critical velocities).

Figure 6.2: Wave attenuation potential of dominant species in winter state along the different grazing strategies. Sub-figures (a)-(c) present the vegetation coefficient, expressed in $h_v \cdot b_v \cdot N_v \cdot C_d$ [mm^2], related to the species area [%]. Sub-figure (d) presents the stem breakage, expressed in critical velocity u_{crit} and wave induced velocity $u(z)$ (red line) in [m/s]. The vegetation properties of *Elymus* are only measured at four paddocks.

6.3.1 Effect of biotic parameters on wave attenuation

Vegetated foreshores

This section evaluates the effect of vegetation under most severe conditions: design-storm conditions and for vegetation in its winter state. For this analysis a flat bottom profile at 1.50 m+NAP is assumed, which is the average elevation of the paddocks at NFB (Section 5.3.3). The significant wave height (H_s) is scaled to this depth, which results in $H_s = 1.52$ m. The vegetation properties of the eleven paddocks are scaled to 100 m foreshore. The effect of the vegetation at each paddock is compared with the bare foreshore, the result can be seen in Figure 6.3.

For the bare foreshore the absolute wave height reduction is in the order of $\Delta H = 0.20$ m, which reduces the wave height by 13.5%. This is due to dissipation by wave breaking and bottom friction. As it can be seen in Figure 6.3, the additional effect of vegetation is in the order of maximum 0.06 m, which is 22% of the absolute wave height reduction ($\Delta H = 0.26m$). The largest effect of wave attenuation by vegetation is observed at the ungrazed paddock (N-SW in Figure 6.3). This is in agreement with the expectation of Section 5.2. The second largest contributor to wave attenuation by vegetation is the paddock with low intensity grazing by horses (0.5C-SW in Figure 6.3). The relatively large

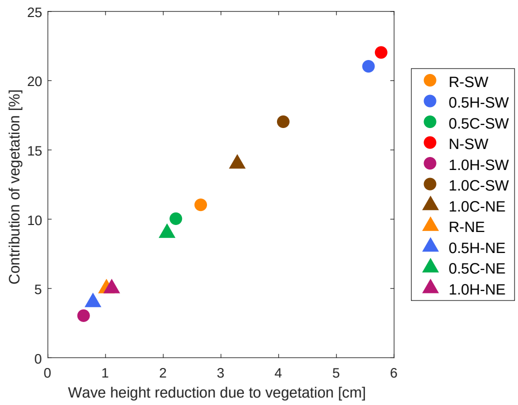


Figure 6.3: Wave height reduction [cm] at all paddocks in winter state at a 100 m wide foreshore, with hydraulic conditions: Hs = 1.52 m, Tp = 4.50 s and h = 4.80 m.

amount of wave height reduction by these two paddocks can be explained by the wave attenuation potential (Section 6.2), as both paddocks contain a large wave attenuation potential for *Elymus* and *Suaeda*. The paddocks with a contribution of vegetation below $\Delta H_{veg} = 0.03$ m, originates from the absence of measured vegetation properties for *Elymus*. This is further discussed in Section 6.3.3.

The effect of vegetation on wave attenuation is also computed for the actual conditions at Noord Friesland Buitendijks, for a 1000 m wide foreshore. Figure 6.4 presents the effect on wave attenuation of the vegetation at the ungrazed paddock compared to the bare foreshore. At the bare foreshore the total wave height reduction is in the order of $\Delta H = 0.36$ m, which results from breaking ($\sim 65\%$) and bottom friction ($\sim 35\%$). The minor effect of wave energy dissipation due to white capping is disregarded in this research. At the ungrazed paddock the effect of vegetation accounts for an additional wave height reduction of $\Delta H_{veg} = 0.20$ m, which accounts for 29% of the total wave height reduction. The difference in the contribution of vegetation compared to a 100 m foreshore results from the incoming wave height. The waves already break at the boundary of the SWAN model for the full-scale cross-section. This lowers the wave height, hence the effect of breaking. This is probably caused by the difference in bottom profile which is measured by the RTK-GPS by NIOZ and the WTI-2011 SWAN data which is used to determine the design conditions, this comparison can be seen in Appendix D.2. Therefore, it is expected that the contribution of wave breaking compared to vegetation is larger in practice, hence the result from the 100 m profile gives a better estimation. The panel in the middle of Figure 6.4 represents the effect of the dissipation mechanisms on wave attenuation. The presence of vegetation increases the total wave energy dissipation, whereas it decreases the effect of wave breaking (right panel in Figure 6.4), as vegetation acts on smaller wave height to depth ratios than wave breaking (Vuik et al., 2016).

For the best case scenario, at the ungrazed paddock, the effect of vegetation accounts for 29% of the total wave height reduction, which is an absolute difference in wave height of $\Delta H = 0.20$ m. In terms of wave run-up at the dike at NFB this could lead to a reduction of the run-up of 0.40 m due to the effect of vegetation. This results from the rule-of-thumb calculation of the wave run-up for a dike slope of $\alpha = 1:4$ in Equation 6.1 (Schiereck, 2001).

$$R_{2\%} = 8 H_s tan\alpha \approx 2 H_s \tag{6.1}$$

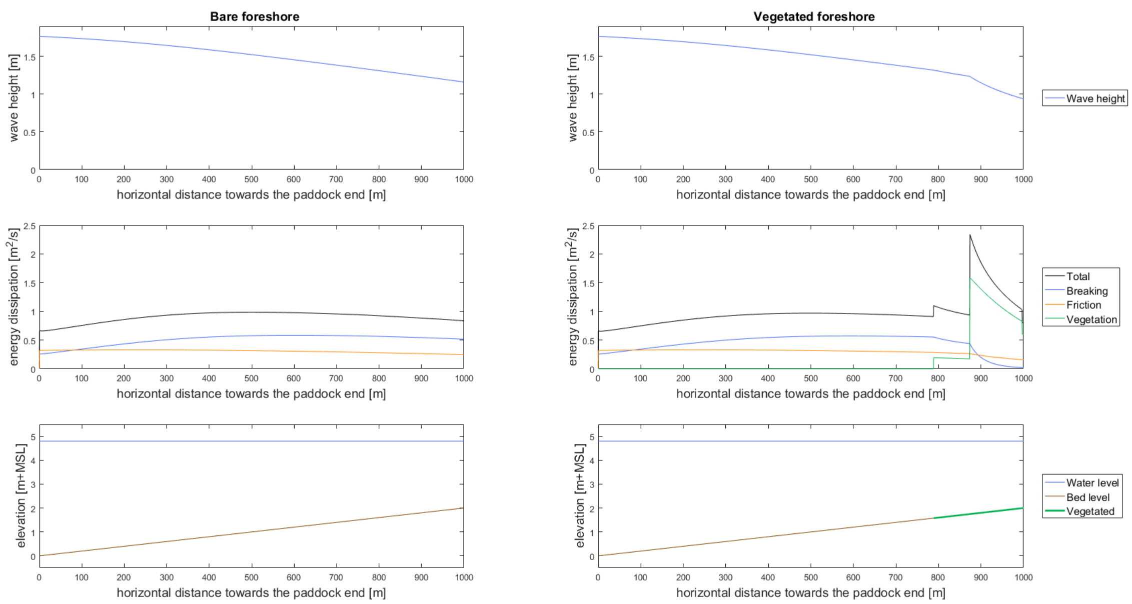


Figure 6.4: Wave attenuation at a vegetated foreshore compared to the 1000 m bare foreshore, with hydraulic conditions Hs = 1.90 m, Tp = 6.40 s and h = 4.80 m. The upper panels present the wave height reduction over a 1000 m foreshore, with a constant slope from 0 to 2 m+NAP. The panels in the middle show the contribution of the wave energy dissipation mechanisms. The lower panels represent the bathymetry, the paddock is located at 500 - 1000 m. Approximately 50% of the paddock is vegetated in winter. The vegetation properties of the ungrazed paddock are used as input.

From this analysis can be concluded that the ungrazed marsh leads to the highest values for wave attenuation by vegetation. However, the effect of vegetation (22%) is relatively small compared to that of wave breaking (60%). The remaining 18% results from bottom friction. For a full-scale simulation of the paddocks at NFB, a 500 m wide paddock, the effect of vegetation is larger (29%), compared to that of breaking (53%). However, it is expected that the 100 m foreshore results in a more accurate representation of the hydraulic conditions at this location.

Seasonal cycle vegetation

The seasonal cycle of the vegetation has a significant effect on the reduction of the wave height under design conditions. For most paddocks the wave attenuation due to vegetation is lowest in June, as this is the very begin of the growing season. The vegetation from previous year is decayed and new vegetation just starts to establish. Between August and November the vegetation has the largest effect on wave attenuation compared to the other seasons, as the vegetation properties have reached their maximum by the end of the growing season. The wave attenuation potential reduces over winter (November - March) as some species decay in winter and stems may break as they are exposed to wave forcing (Section 6.2). The fluctuation in seasonal variation of the vegetation, hence wave attenuation, is most significant at the paddock with low intensity grazing by horses (0.5C-SW). This results from favourable properties of *Aster* during the growing season and this specie covers more than half of the area of this paddock. The large amount of biomass during August - November could be favourable for salt marshes at other continents where the storm season takes place in this season. For the salt marsh at Noord Friesland Buitendijks and other parts of Europe the vegetation state in winter is more significant.

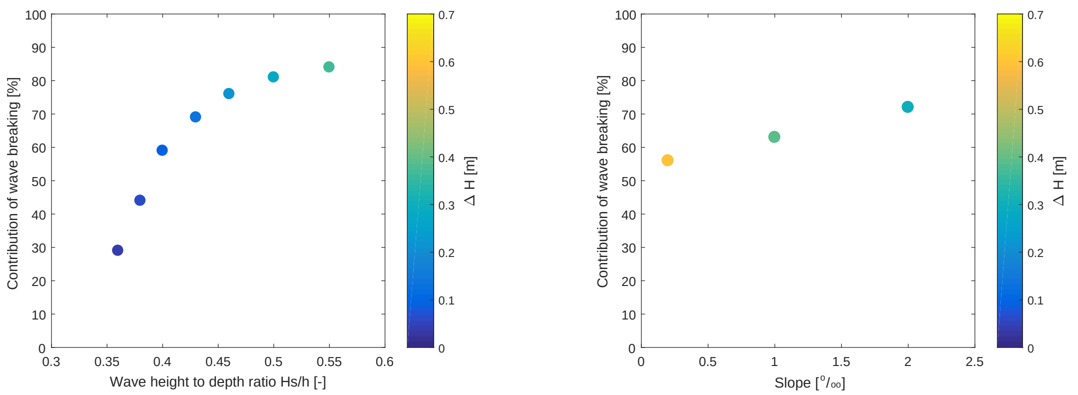
6.3.2 Effect of abiotic parameters on wave attenuation

From Section 6.3.1, it follows that even at a bare foreshore wave energy dissipation is observed. This results from the sink terms, breaking and friction, in the wave energy balance (Equation 5.1). Moreover, it is found that the effect of vegetation on wave attenuation is relatively small compared to that of wave breaking and bottom friction. Therefore this section analyses the relative importance of the bathymetry on wave energy dissipation.

Bottom profile elevation and slope

Figure 6.5 gives an overview of the effect of the wave height to depth ratio (left) and the slope (right) on wave attenuation. For this analysis the characteristic bottom profile elevation and slopes are included that correspond to salt marshes (Section 3.2.2). It can be seen that the contribution of wave breaking increases for larger wave height to depth ratios, which results in a larger reduction of the wave height (ΔH). For a 100 m wide bare foreshore, with a water depth of $h = 3.3m$ and a wave height to depth ratio of $H_s/h = 0.46$, this leads to a wave height reduction $\Delta H = 0.20m$. This is more than twice as large as for a water depth of $h = 3.8m$ ($H_s/h = 0.40$). This effect primarily results form depth-induced wave breaking, which accounts for a reduction in wave height of 76% and 59% respectively.

Typical slopes at salt marshes are 1:50 (2‰), 1:100 (1‰) and 1:500 (0.2‰), which are modelled from 0 to 2m+NAP. The 1:500 slope leads to the largest wave height reduction (ΔH), as the width of the foreshore is large compared to that of the steeper slopes. However, the contribution of wave breaking is smaller at the 1:500 slope, which implies that the effect of breaking is less dominant at mild slopes than at steeper slopes.



(a) Wave height to depth ratio. **(b)** Bottom slope.

Figure 6.5: Effect of bottom profile on wave attenuation. The left panel presents the contribution of wave breaking to the total wave height reduction for different wave height to depth ratios at a 100 m foreshore. The right panel presents the contribution of wave breaking to the total wave height reduction for different bottom slopes between 0 and 2 m+NAP.

Bottom profiles at the Wadden Sea

The effect of the bottom profile is analysed for three locations at the Wadden Sea, indicated in Figure 6.6. The reference location is Noord Friesland Buitendijks, which contains a wide salt marsh at the foreshore of the dike. At Westhoek a small salt marsh is present (order of ~ 200 m) and at Koehoal there is no salt marsh in front of the dike. It is found that the bottom profile of the foreshore is an important contributor to dissipation of wave energy, the result can be seen in Figure 6.7. At Koehoal there is barely a wave height reduction during extreme events. This is due to the large water depth in front of the dike, as waves do not break and even shoaling may occur. The bathymetry at NFB leads to higher wave energy dissipation than the salt marsh at Westhoek, however this effect is in the same order of $\Delta H_{\%} \sim 35\%$. The lower elevation of the bathymetry at Koehoal may result from the presence of salt marshes at Noord Friesland Buitendijks and Koehoal, however this should be verified by future research.

Figure 6.6: Location Noord Friesland Buitendijks, Westhoek and Koehoal. The primary flood defence, the dike, is indicated in red. The salt marsh edge is indicated in blue.

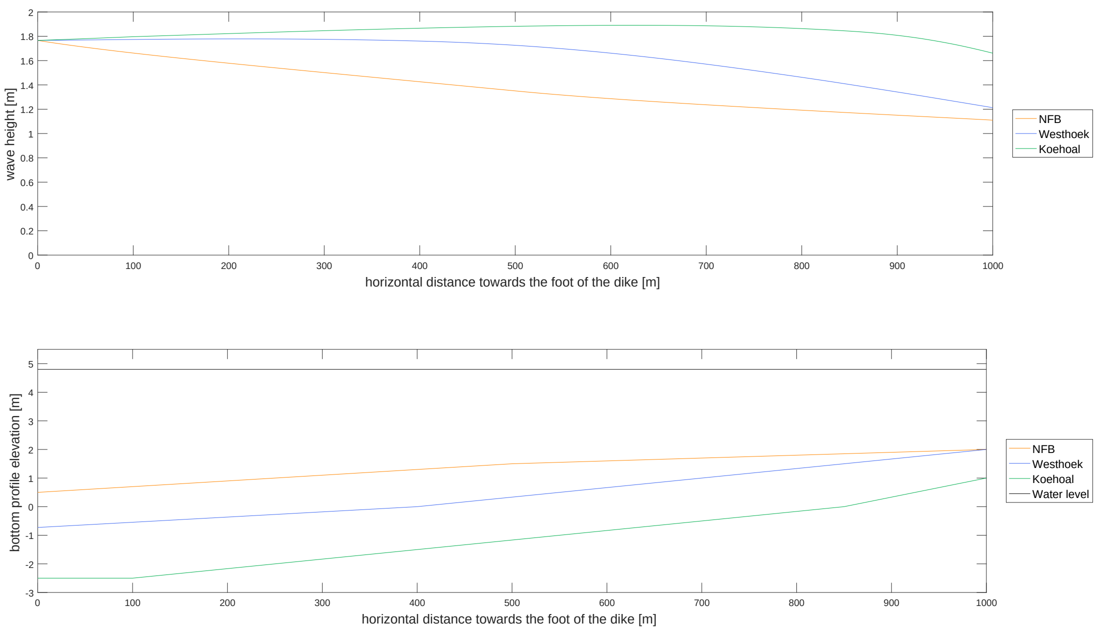


Figure 6.7: Effect of bottom profile on wave attenuation at three locations at the Wadden Sea: Noord Friesland Buitendijks, Westhoek and Koehoal. The first is the reference location with a wide salt marsh, the second foreshore contains a small salt marsh and the last location does not contain a salt marsh in front of the dike. The bathymetry at these location is estimated based on the vakloding-data and reference levels from Rijkswaterstaat (2017).

6.3.3 Sensitivity

This section analyses the sensitivity of the wave model to several parameters. First, the sensitivity of the vegetation properties is analysed, including the standard deviations of the field measurements. Thereafter, the effect of stem breakage of *Aster* and the inclusion of *Elymus* at the paddocks at the north-west is analysed.

Effect of standard deviation vegetation properties

The wave height reduction at the paddocks (Figure 6.3) is based on the mean values of the vegetation properties that are measured in the field. For certain species large deviations are present in vegetation properties within individual paddocks (Appendix D). Therefore, the effect of the standard deviation of the vegetation properties is analysed, the result of this analysis can be seen in Figure 6.8.

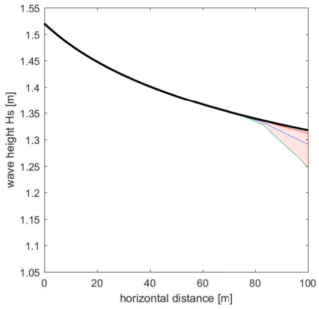
In Figure 6.8 it can be seen that the inclusion of the deviations in vegetation properties significantly affects the wave height reduction. For the least-favourable conditions ($\mu - \sigma$, indicated in red) it appears that the wave height reduction at each paddock is just about the same value as for the bare foreshore, hence the effect of vegetation is negligible. For this analysis the minimum ($\mu - \sigma$) and maximum ($\mu + \sigma$) values for the stem height, diameter and density are included in the wave model. It is assumed that the range of the drag coefficient depends on a deviation of $\pm$ 50% from its mean value. For the most favourable vegetation conditions ($\mu + \sigma$, indicated in green), the contribution of vegetation can lead to an additional wave height reduction of 0.16 m, compared to the mean vegetation properties. This results from large standard deviations, especially for the stem density, up to 1.5 times the mean value, and the assumed standard deviation of the drag coefficient.

Effect of stem breakage

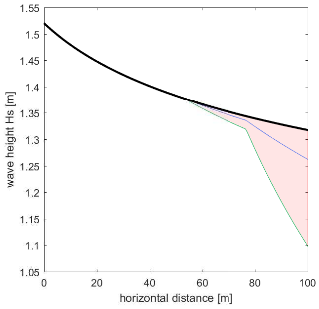
From Section 6.2, it follows that (1) the vegetation properties for *Elymus* are not measured for certain grazing strategies and (2) that it is probable that stem breakage occurs at the *Aster* stems during storm conditions. The effect of these species on wave attenuation is analysed in this section.

For this analysis it is assumed that for the paddocks where no properties are measured for *Elymus*, the properties are the same as that of the least-favourable conditions for the wave attenuation potential of this specie, which is at the paddock with low intensity grazing by cattle (0.5C-SW). It follows that the inclusion of *Elymus* in the wave model results in smaller deviations of the wave height reduction along the different grazing strategies. This implies that the effect of grazing has a minor influence on the total wave energy dissipation.

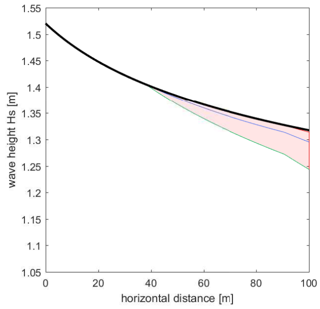
The reliability of the salt marsh during storm conditions is analysed with respect to breakage of the stems of *Aster*. It is assumed that after breakage, *Aster* does not contribute to the dissipation of wave energy, hence this specie is not included in the model. It follows that the stem breakage of this specie has no significant effect on the wave height reduction under design conditions.



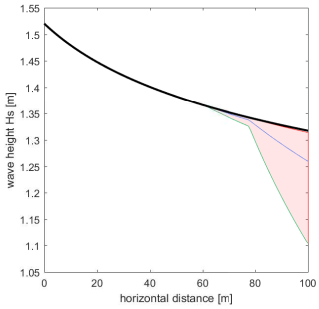
(a) R-SW



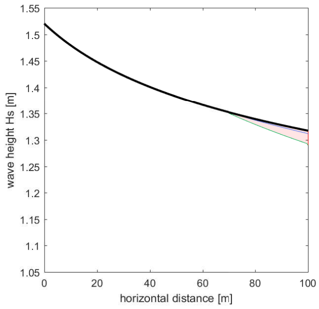
(b) 0.5H-SW



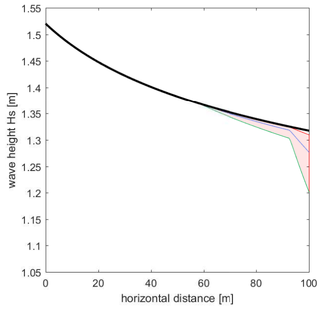
(c) 0.5C-SW



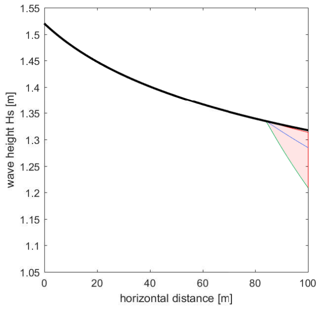
(d) N-SW



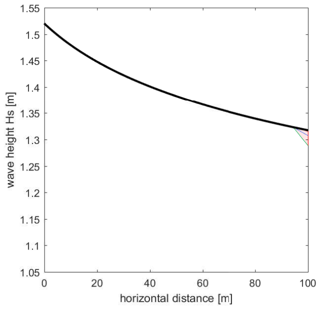
(e) 1.0H-SW



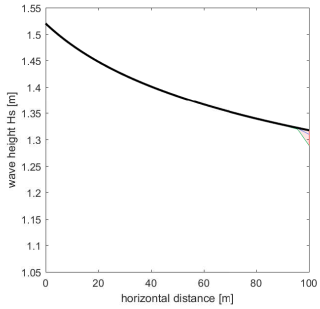
(f) 1.0C-SW



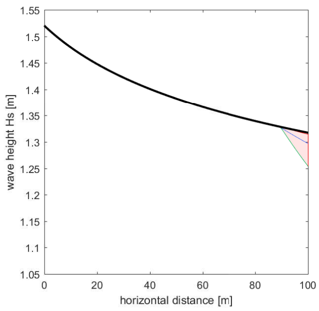
(g) 1.0C-NE



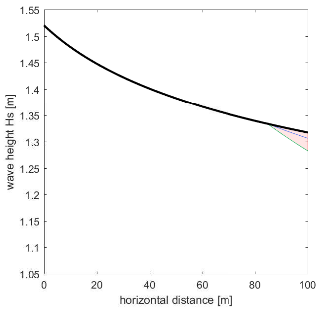
(h) R-NE



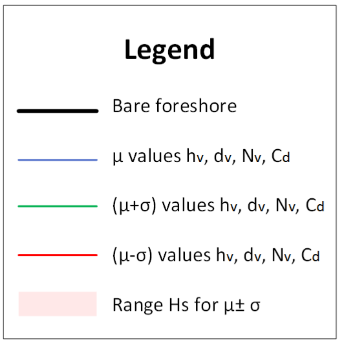
(i) 0.5H-NE



(j) 0.5C-NE



(k) 1.0H-NE



(l) Legend

Figure 6.8: Sensitivity of the wave height reduction related to the measured vegetation properties.

6.4 Grazing and other ecosystem services

In Section 3.4 several ecosystem services are described that can be derived from salt marshes. This research focusses on the function of salt marsh vegetation as coastal protection solution, more specifically on the effect of grazing on wave attenuation. As it follows from the model results, the effect of grazing has a minor effect on wave attenuation. Therefore, this section analyses the effect of grazing on two other ecosystem services, soil stabilisation and biodiversity, and the trade-offs between the coastal protection function of salt marshes and biodiversity.

6.4.1 Soil stabilisation

Usually, the sedimentation rates for grazed salt marshes are lower than for ungrazed marshes, since less sediment is trapped by the vegetation stems, as the vegetation height and density are altered by defoliation and trampling (Andresen et al., 1990; De Vlas et al., 2013; Esselink, Dijkema, Reents, & Hageman, 1998; Yang et al., 2008). This effect is larger at marshes with high intensity horse grazing (De Vlas et al., 2013; Esselink et al., 1998). The vegetation degradation may also enhance erosion, as the sediment surface is more exposed to waves and tidal flow. Moreover, grazing affects the sediment grain size distribution, thereby alters the long-term development of the marsh, as it is found that buffalo-grazed sites consist of coarser sediment than ungrazed marshes at the same area (Yang et al., 2008). Conversely, it is found that grazing at salt marshes has a positive effect on soil stabilisation, as trampling by livestock makes the soil more compact, hence more resistant against erosion (Davidson et al., 2017).

6.4.2 Biodiversity

This research exclusively focuses on the vegetation-biodiversity. Grazing is often applied at salt marshes as nature conservation tool (De Vlas et al., 2013). Abandonment of salt marshes results in unfavourable conditions for the ecosystem, as it is likely that higher marsh species colonise the lower lying areas, due to the high sedimentation rates, which can lead to monotonous vegetation patterns (Andresen et al., 1990). Typical dominant species are *Elymus* at the high marsh and *Artiplex* at the lower marsh (Van Klink et al., 2016). Contrariwise, high stocking rates cause a decrease in cover of *Pucinellia*, *Artemisia* and *Elymus* due to trampling and feeding of herbivores.

In previous research, it is found that the effect on biodiversity is more significant for livestock intensity than the selection of livestock species (Van Klink et al., 2016). Low stocking densities are favourable for the formation of vegetation patterns and species-diversity, whereas high intensity grazing can counteract the distribution of *Elymus*. Moreover, grazing by cattle results in higher values for biodiversity and grazing by horses is beneficial to reduce the cover of dominant species such as *Aster*. Additionally, De Vlas et al. (2013) suggests that the management of salt marshes is site-specific and should be selected carefully, as management of a target species may result in the loss of other species. If one would like to strive towards high values of biodiversity, it is recommended to apply different grazing strategies side by side within a salt marsh area (De Vlas et al., 2013).

6.4.3 Trade-offs between coastal protection and biodiversity

As it is discussed in Section 5.1.1, finding the optimum salt marsh management solution regarding coastal protection and high values for ecology has not been studied yet. Therefore, this section focuses on the effect of artificial salt marsh development and management on coastal protection and biodiversity.

The difference in requirements for salt marsh development as coastal protection solution and biodiversity chiefly originates from the fact that flood protection is mostly required during extreme events, which has other needs than biodiversity conservation (Van Loon-Steensma, 2014). One trade-off is related to the elevation of the marsh, as flood protection increases with higher bathymetry. However, this conflicts with biodiversity, as the lower-lying areas are more productive, since vegetation diversity reduces due to ongoing succession (Andresen et al., 1990). Secondly, measures to protect salt marshes from erosion and/or to reduce wave action often conflict with the ecosystem. The reliability of flood protection increases when the marsh surface is stable. Hard techniques are often more reliable than of soft measures (Section 4.2). However, these hard structures counteract the natural development of the marsh (Van Loon-Steensma, 2014). Another trade-off considers the compensation for structurally reducing sediment supply, by e.g. sea level rise (Section 4.2.1). Soil properties of dredged sediment can deviate from the salt marsh soil, which can result in immature marsh development (Feagin et al., 2009). Furthermore, nourishments can increase the local turbidity, which disturbs the primary production of the water-body. Therefore, sediment should be extracted and disposed with minimal impact on the environment (Van Loon-Steensma, 2014). Moreover, the effect of grazing also influences the interaction between coastal safety and ecological values at salt marshes. As is discussed in Section 5.2, taller and dense vegetation increases the sedimentation rates, which corresponds to ungrazed salt marshes. This is favourable for coastal protection, but leads to lower values of biodiversity (Andresen et al., 1990). However, as it is discussed in Section 3.4.1, the stability of the soil increases with increasing species richness (Davidson et al., 2017; Ford et al., 2015), which may lead to a win-win management strategy for both coastal safety and biodiversity.

Therefore, in case one would like to develop a salt marsh as coastal protection solution, it is desired to apply soft strategies for the artificial development (Section 4.2). Since vegetation has a minor effect on wave attenuation compared to that of depth-induced wave breaking, it could be valuable to focus on the management of biodiversity at the salt marsh. The selection of the grazing strategy depends on the objectives and target species of at the salt marsh (Section 6.4.2).

Part IV

Synthesis

Chapter 7

Salt marsh design guidelines for engineers

Within this chapter the lessons-learned from the main and in-depth research are combined into salt marsh development guidelines for engineers, focused on the flood protection property.

7.1 Background of the guidelines

The scope of this research is subject to the Building with Nature philosophy, as discussed in Chapter 2. Similar to traditional project development, BwN projects consist of five project phases (Figure 7.1). Additionally, the BwN approach distinguishes a five-step approach that a project developer should go through while designing a project (Section 2.3), which are as follows:

1. Understand the system
2. Identify realistic alternatives
3. Evaluate the alternatives
4. Elaborate the selected alternatives
5. Prepare the solution for the next project phase.

Figure 7.1: Five project phases.

The first step of the Building with Nature design-approach is 'understand the system', which relates to the ecosystem of salt marshes within this research. The lessons-learned from this research and important design aspects for engineers are combined into salt marsh development guidelines for engineers. The focus of these guidelines is on the planning and design phase in Figure 7.1. The result of the guidelines is discussed in Sections 7.2-7.5.

7.2 Identify alternatives

This design step exists of two actions, namely quantifying the design criteria and identifying possibilities to develop a salt marsh that satisfies these criteria at the project location.

7.2.1 Objectify criteria

After the opportunities of the system have been analysed, an engineer should objectify the project-goals, by means of quantifying assessment-criteria for the project. Important aspects corresponding to this step are as follows.

- *Determine target ecosystem services.* The focus of this research lies on the coastal protection function of salt marshes, however these ecosystems provide multiple other ecosystem services (Section 3.4). This ecosystem services can be expressed in terms of wave height reduction, run-up and over topping on the adjacent dike-foreshore system. As it was found in Section 6.3 wave energy dissipation by salt marshes depends on both biotic and abiotic factors. Therefore, it is important to consider the site characteristics regarding spatial scales and time scales, corresponding aspects are amongst others:
  - What are the local design conditions?
  - How much wave energy dissipation should be achieved in terms of wave height reduction, run-up and overtopping?
  - How much space is available for the project?
  - Which bottom profile elevation is required to achieve the desired wave energy dissipation?
  - How can the design-criteria be achieved with minimum investments?
- *Determine time scales.* These assessment-criteria include the boundary conditions of the project, such as the time scale for realisation of the project. The semi-natural development of salt marshes may take decades, which may not fit in the project-schedule. Therefore, the possibilities towards acceleration of the corresponding natural processes should be taken into account, such as increasing the surface elevation or planting of vegetation (Section 4.2).
- *Determine spatial scales.* Another boundary condition for the project corresponds to the spatial limitations of the project site. In terms of coastal protection, the effect of the bathymetry of the site is important (Section 6.3), i.e. which width, slope and elevation of the bottom profile is required to achieve a certain amount of wave height reduction.
- *Determine target species.* Corresponding to the objectives the target species should be determined. From Section 6.2 followed that *Elymus* is the largest contributor to wave energy dissipation at the high salt marsh, whereas *Suaeda* is an important specie at the lower marsh. It followed from Section 6.3 that the bottom elevation is an important factor to wave energy dissipation, due to wave breaking. Moreover, vegetation can stabilise the soil more efficiently at higher elevations. Therefore, higher marshes are more favourable for coastal protection. In case the development of a high salt marsh is feasible, applying no grazing regime is the best solution, as it enhances the distribution of *Elymus*. However, in case biodiversity is desired within the project, this results in other target species as for coastal safety, since species richness is desired rather than a species monoculture of *Elymus* or *Suaeda*.
- *The project should be resilient.* Building with Nature solutions should be resilient against e.g. erosion, land subsidence and sea level rise. This can be achieved by integrating natural elements in the project system, rather than an abrupt interference with hard structures. This makes the solution more resilient against long-term changes (Van Slobbe et al., 2013). If this can not be achieved in a natural way, than adaptive measures should be taken (Figure 7.3), this is discussed in Section 4.2.
- *The project should be self-sustainable.* One of the requirements of BwN projects is that the project should be self-sustaining. However, this may counteract the coastal protection function of salt marshes, since the reliability of BwN solutions depends on

their stability during storm events. In order to guarantee their functioning during extreme events, often hard measures are applied to reduce hydrodynamic forcing or to protect the salt marsh edge from erosion (Section 4.2). This limits the natural development of the salt marsh, as it can not expand in offshore direction (Van Loon-Steensma, 2014). Therefore, an engineer should take these trade-offs between reliability and naturalness into account carefully, as a project might not be considered as 'Building with Nature' when too many adaptive measures are taken.

7.2.2 Research salt marsh development site

When the objectives and assessment-criteria are determined, the feasibility of salt marsh development need to be determined. Whether salt marsh development is possible depends on the local site characteristics and hydrodynamic conditions. Figure 3.4 describes the natural development of a salt marsh and how certain (a)biotic parameters influence its growth. In Figure 7.2 and 7.3 two flow charts are presented that an engineer should consult while determining if salt marsh development is possible at the project site and if not, which adaptive measures can be taken to initiate the process. These adaptive techniques are discussed in Section 4.2. To determine the site characteristics of the project area the engineer should look into the following data.

- *Historical data.* It is likely that salt marsh development is possible at the site if salt marshes were present in the past. However, an engineer should ascertain why the salt marshes have disappeared. This gives an indication about which site characteristics should be altered to achieve salt marsh development.
- *Landscape setting.* Within this step an engineer should look into the bathymetry data of the project site. As it appeared from Section 6.3, the bottom profile of the site is an important contributor to wave energy dissipation, hence to coastal protection. Important parameters are the elevation and the slope of the bottom profile.
- *Seed sources.* It should be analysed if vegetation seedlings are present in the so-called species pool, which is implies that these seedlings need to be able to access the site by the adjacent water-body and/or being disposed by bird faeces.
- *Degree of (physical and biological) alteration.* In this step an engineer should considered which site characteristics need to be altered to initiate salt marsh development. Figure 7.2 shows which conditions need to be realised to achieve salt marsh development. Moreover, Figure 7.3 presents which possible alterations are needed to develop a mature salt marsh, as it should be resistant against e.g. extreme storm events and the structural impact of sea level rise. It should be noted that salt marsh development might not be feasible if the level of alteration of the site is too large.

7.3 Evaluate alternatives

In this step the project solution should be translated into different alternatives, following from the results of step 2 (Section 7.2). Within this research two extreme alternatives can be distinguished: maximum values for coastal safety and optimal conditions for the ecosystem. Van Loon-Steensma (2014) indicates that there is often a trade-off between these two ecosystem services. Coastal safety needs to be guaranteed during extreme storm events, where hard measures (Section 4.2) are often more reliable than soft measures, the latter corresponds to Building with Nature solutions (Van Loon-Steensma, 2014). Furthermore, high bottom profile elevations are more favourable for dissipating wave energy, whereas a higher elevation of the marsh is less beneficial to biodiversity. Therefore, an engineer

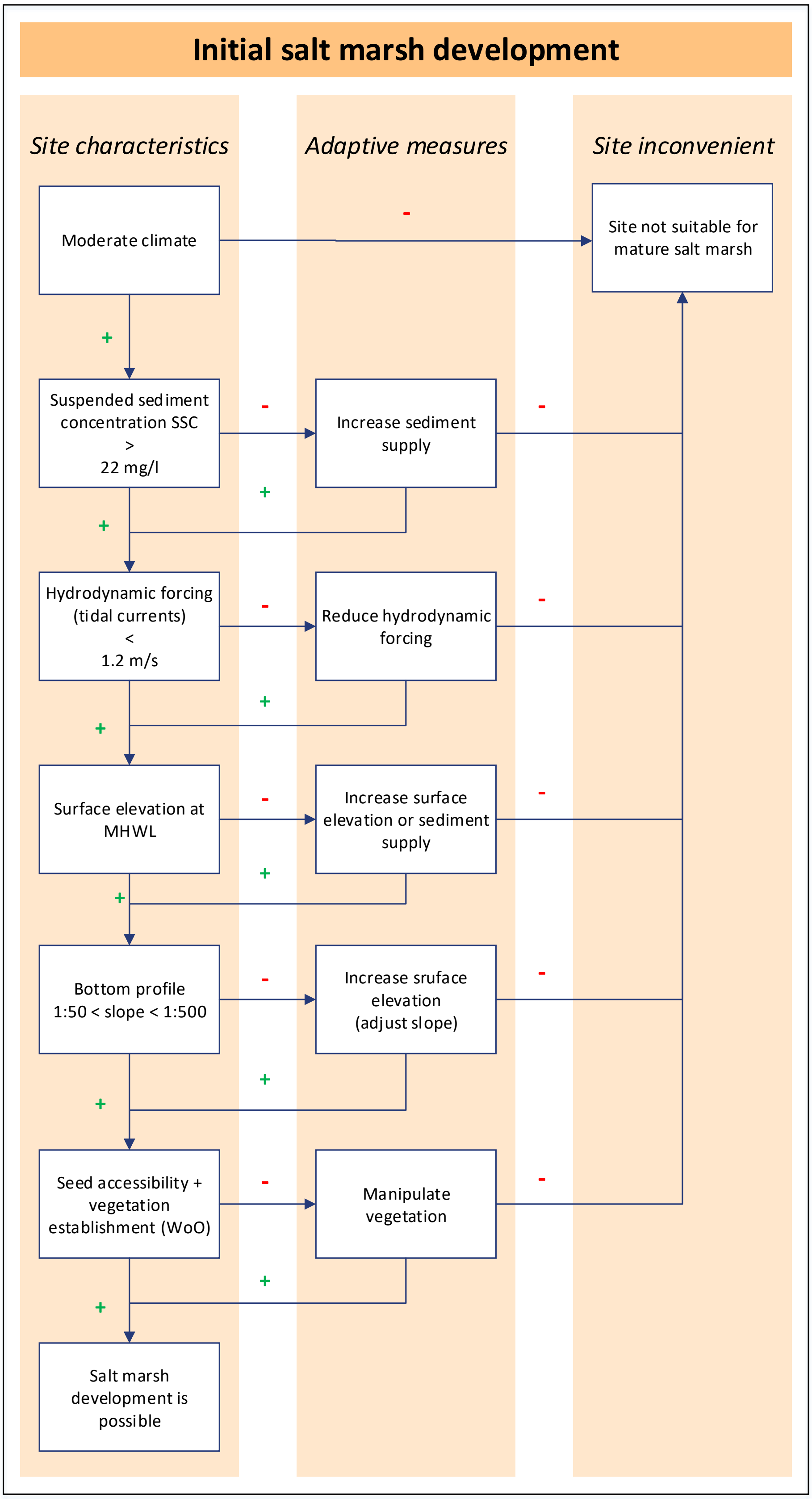


Figure 7.2: Initial salt marsh development and adaptive measures.

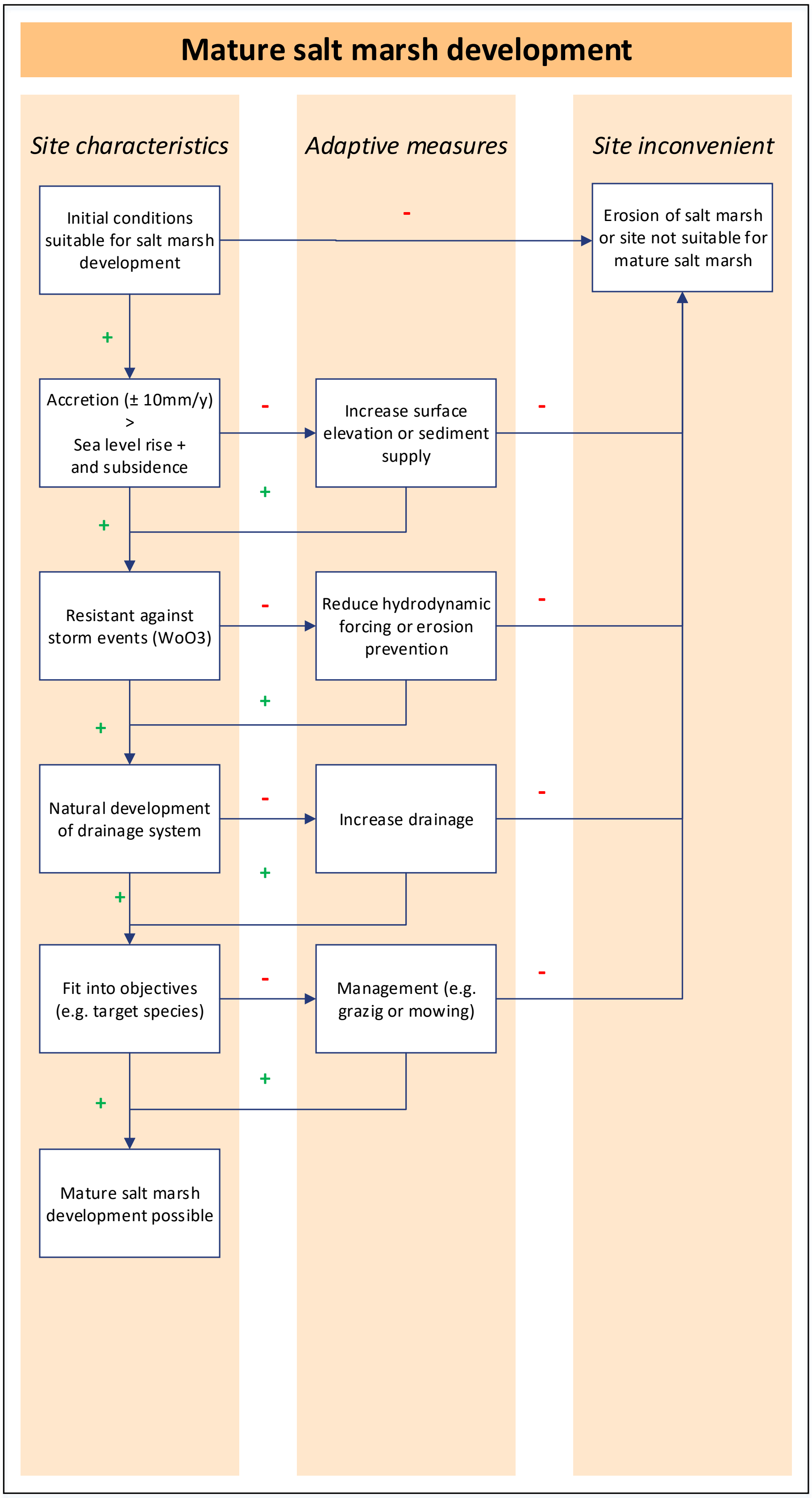


Figure 7.3: Mature salt marsh development and adaptive measures.

should take the design-criteria which are established in step 2 (Section 7.2) into account. At the end, the alternatives should be evaluated based on assessment-criteria, the most promising alternative(s) will be elaborated into more detail in step 4 (Section 7.4).

7.4 Elaborate alternatives

In this step the selected alternative(s) will be fine-tuned with respect to the project's objectives. The adaptive measures that are necessary to initiate salt marsh development are elaborated. An engineer should look into aspects such as quantities and timing aspects. As it follows from Section 3.4.1, the soil characteristics are important for the stability and development of the salt marsh. Therefore, the selection of the retraction site should be done carefully, in order to dispose sediment with favourable gradation and to minimise the impact on the environment (Section 6.4.3). The timing aspects are also important, as an engineer is dealing with a natural system. Consequently, an engineer should account for aspects such as the growing season of salt marsh vegetation and the breading season of wading birds (Ecoshape, 2017a). Lastly, the management of the salt marsh should be taken into account, such as digging drainage channels to accelerate the development process (Section 4.2.2) or apply grazing to increase the biodiversity (Section 6.4.2). The latter can be valuable, as artificial salt marsh development often goes at cost of the rich ecosystem at mudflats. Grazing can be applied to avoid monotonous vegetation and to achieve bio-diverse vegetation patterns, which is additionally favourable for the salt marsh fauna.

7.5 Prepare for next phase

Before the solution is completed to go on to the next project phase, the execution phase, the risks of the project should be taken into account. As it is discussed in Chapter 3, Building with Nature solutions inherently include the dynamic processes of nature, which result in a large degree of uncertainty. Therefore, a contingency-plan should be developed in order to include adaptive measures in the project-plan, which should be applied if the project does not develop as it was expected. When salt marshes are included in engineering projects as flood protection solutions, the risk primarily results from the stability of the salt marsh during storm events. The presence of vegetation can stabilise the soil by its under-ground biomass, however its effectiveness during large wave-impact is not fully understood yet (Feagin et al., 2009). Consequently, hard structures such as erosion control or breakwaters may be necessary to maintain the stability of the salt marsh (Van Loon-Steensma, 2014). An other risk factor is the reliability of the vegetation stems on the dissipation of wave energy under design conditions (Section 6.2). Vegetation stems may break or fold when they are exposed to extreme hydrodynamic forcing (Vuik et al., 2017). This reduces the above-ground biomass, hence the wave attenuation capacity of vegetation. Therefore, if an engineer assesses the dimension of the salt marsh corresponding to the desired wave energy dissipation, the possible stem breakage should be included in the model (Section 6.2 and A.4). Other risks are disease of the vegetation or that the vegetation does not start to grow. In this case (re)planting of vegetation or increasing the bottom profile should be added to the contingency plan (Niedowski, 2000).

Part V

Conclusions & recommendations

Chapter 8

Conclusions & recommendations

This research consists of two elements: (1) the in-depth research, in which the effect of different grazing strategies and other biotic and abiotic parameters is analysed on the flood protection property of salt marshes and (2) the main research on how to develop guidelines to include salt marshes in engineering projects. This chapter presents and discusses the main conclusions of the research, whereafter recommendations are given for further research.

8.1 Conclusions

The objective of this research and corresponding research questions is as follows:

"To develop guidelines for engineers to include salt marshes in hydraulic infrastructure projects within the Building with Nature philosophy, based on scientific knowledge and practical know-how. Focused on the analysis of the effect of grazing strategies on the coastal protection property."

1. What are the ecosystem services that can be derived from salt marshes and how can they be included in engineering projects?
2. What can be considered as important design aspects for engineers?
3. How can these design aspects be included in engineering guidelines for salt marsh development?
4. How do different grazing strategies at salt marshes contribute to the coastal protection property, i.e. wave attenuation?

Research questions 1-3 correspond to the main research, whereas research question 4 corresponds to the in-depth research, which focuses on the effect of grazing on the coastal protection property. This chapter presents the conclusions of the in-depth research, whereafter the lessons-learned are translated to design aspects for engineers, corresponding to the main objective.

8.1.1 In-depth research

The main conclusion of the in-depth research is that the effect of vegetation on wave attenuation is small, compared to the effect of wave breaking and bottom friction. As base for this research the most severe hydraulic and biotic conditions are considered for the reference location Noord Friesland Buitendijks (NFB). This is the vegetation in winter state, when approximately 50% of the salt marsh is covered by vegetation. The design conditions are determined at the salt marsh edge, at a water depth of $h = 3.8m$ and a significant wave height of $H_s = 1.52m$. This results in an absolute wave height reduction of $\Delta H = 0.20m$ at a 100 m wide bare foreshore. The presence of vegetation leads to an additional wave height reduction of $\Delta H_{veg} = 0.06m$. The contribution to the wave height reduction ($\Delta H = 0.26m$) by the dissipation mechanisms is as follows: 59% results from wave breaking, 22% results from wave attenuation by vegetation and the resulting 19% is induced by bottom friction. In case the minimum vegetation properties are included in the wave model, mean minus the standard deviation, the contribution of vegetation is negligible ($\Delta H_{veg}/\Delta H < 5\%$). For the actual bathymetry at NFB, for a salt marsh width of 500 m, the effect of vegetation becomes more significant ($\Delta H_{veg}/\Delta H \sim 29\%$), which results in a reduction of the wave height of $\Delta H_{veg}/H_s = 13\%$. This is due to the smaller wave height to depth ratio at the salt marsh edge, as dissipation by vegetation acts on smaller wave height to depth ratios than depth-induced breaking. Moreover, the presence of vegetation results in more gradual breaking of waves, as wave energy dissipation due to depth-induced wave breaking is shifted to dissipation by vegetation. The effect of different grazing strategies on the vegetation properties and wave attenuation is small, as this contribution varies between $10 - 22\%$ of the total wave height reduction.

Although the effect of vegetation is small compared to that of the bathymetry, the presence of a salt marsh indirectly affects wave attenuation. The salt marsh vegetation enhances sediment accumulation, which leads to a higher bottom profile elevation compared to the bare foreshore. This is analysed by the comparison of three locations at the Wadden Sea: (1) Noord Friesland Buitendijks, with a wide salt marsh of several hundreds metres, (2) Westhoek, with a narrow salt marsh of approximately 200 m, and (3) Koehoal, where no salt marsh is present in front of the dike. The bathymetry at both locations with salt marshes is 1 - 2 m higher than the bare foreshore at Koehoal. At Noord Friesland Buitendijks and Westhoek the effect of the bottom profile can lead to a wave height reduction in the order of 35% of the significant wave height. For Koehoal this effect is in the order of 6%. Therefore, the expectation that the presence of a salt marsh indirectly reduces the wave energy could be substantiated. This should be verified by future research.

8.1.2 Main research

Salt marshes provide multiple benefits to society, whereof this research focused on the coastal protection value of salt marshes. This can be divided into flood control and erosion regulation. From the in-depth research, it follows that wave attenuation due to vegetation is less significant than the effect of wave breaking. However, salt marshes indirectly affect wave energy dissipation by an increased bottom profile elevation compared to the bare foreshore (Section 8.1.1). Therefore, regarding coastal safety, it is of higher importance for an engineer to consider the abiotic parameters at the project site, rather than focusing on target species and grazing strategies. Grazing could be used as strategy to enhance the biodiversity. This could be valuable as artificial salt marsh development often goes at cost of nature at the mudflats or terrestrial habitat in case of management realignment. The most suitable strategy is site depended and should be determined regarding the desired target species, although it is expected that applying different strategies within one salt marsh system results in the most diverse ecosystem.

An engineer should take into account that the coastal protection property of salt marshes often conflicts with the ecosystem. The major trade-off for these two ecosystem services is the efficiency of salt marshes during extreme events. As it follows from the in-depth research, the main driver for wave energy dissipation is depth-induced wave breaking, this increases with larger bottom profile elevations. However, regarding biodiversity, the lower lying salt marsh areas are more productive, as the biodiversity reduces with ongoing vegetation succession. Another trade-off is the reliability of salt marshes as coastal protection solution, which increases when the marsh surface is stable. Hard techniques are often more reliable than soft measures, although these hard structures counteract the natural development of the marsh. This limits the seaward expansion of the salt marsh, hence the self-sustainable function that characterises Building with Nature solutions. A positive interaction between these two ecosystem services may result from the stabilisation of the subsoil, which increases with species richness.

8.1.3 Discussion of results

This section discusses the data which is used for the in-depth research, the results of the wave modelling and the implication of this research on a larger scale.

Data

The approach towards this research is limited by the availability of the data. The vegetation properties of certain species were not measured for each grazing strategy. Therefore, it was not trivial to determine the exact effect of the grazing strategies on the wave energy dissipation by vegetation. Secondly, no wave measurements were executed at NFB. Wave measurements at the begin and end of the paddock could give insight in the wave height reduction over the paddock. Those measurements could also give a more accurate estimation for input of the wave characteristics in the numerical model. The hydraulic conditions are based on statistical within this research, however it is expected that this results in an overestimation of the wave height to depth ratio, which could not be verified by wave measurements. Additionally, wave measurements can also be used to calibrate the computed drag coefficient. This can verify whether the calculation of the drag coefficient, based on the flexural rigidity of the vegetation stems, is an accurate method, as in practice this parameter depends on multiple other factors, such as leaves and branches, the effect of 'crowding' and hydraulic conditions (Vuik et al., 2016). From the bending data, it results that the flexural rigidity has large standard deviations, which results in a large uncertainty for the drag coefficient.

Model used

The contribution of vegetation to wave attenuation, which results from the wave modelling, is lower than values presented in literature by e.g. Möller et al. (2014) and Vuik et al. (2016), who found wave attenuation values due to vegetation up to 60% of the total wave height reduction. These deviations from the model results can be explained by several factors. Both studies in literature are based on vegetation properties that are collected at the begin of the storm season. From the vegetation data at Noord Friesland Buitendijks, it follows that the vegetation properties at the end of the storm season are less favourable with respect to wave energy dissipation. Moreover, the hydraulic conditions are less severe at those two locations than for NFB. In this study the effect of vegetation is less significant due to the larger water depths. Lastly, the other researchers considered different vegetation species, with a larger density than the species at NFB.

The reliability of the salt marsh as coastal protection method is only based on possible breakage of the stems within this research. The accuracy of the computation of stem breakage increases if a more comprehensive method would be applied, such as a Monte-Carlo simulation in combination with field measurements to estimate the fraction of broken stems. Moreover, other factors may also be decisive for the stability of the marsh during storm events, such as uprooting and erosion.

Building with Nature

It is arguable in which case the salt marsh development project can be considered as 'Building with Nature'. One of the key-considerations of this design approach is that the solution should be self-sustaining and resilient. If a salt marsh is implemented as coastal protection solution, the reliability of this system should be guaranteed during exposure to storm conditions. Usually, hard structures increase the reliability of the stabilisation of the salt marsh during extreme events. However, this limits the natural development of the salt marsh in seaward direction. Than the project is more or less subject to 'Building of Nature', rather than Building with Nature.

8.2 Recommendations for future research

Several recommendations can be made for the optimisation of the wave model results. It is recommended to execute wave measurements at Noord Friesland Buitendijks. This generates insight in the wave energy dissipation over the salt marsh, provides a more accurate estimation of the hydraulic conditions and it can be used to calibrate the drag coefficient. This can verify whether the computation of the drag coefficient based on the flexural rigidity of the stems is an accurate approach, hence if this approach could be used in future studies. Furthermore, the effect of grazing on biodiversity should be analysed at NFB, as this data has been collected as well. This can create a better understanding in the interaction between coastal protection and biodiversity.

Also, from a broad perspective several recommendations can be made. The long-term development of salt marshes should be studied, as it is expected that the presence of the salt marshes at Noord Friesland Buitendijks and Westhoek contribute to higher bed level elevations, hence more wave attenuation, than at the bare foreshore at Koehoal. Furthermore, the reliability of salt marshes as coastal protection solution should be analysed. Although it is expected from previous studies that vegetation provides resistance against hydrodynamic forcing, it should be verified for large scale projects exposed to design conditions, as these findings are based on few practical observations and small scale flume experiments. Corresponding processes are erosion of the marsh surface, uprooting and stem breakage. From this research, it follows that spatial variation have a more significant effect on vegetation properties, hence wave attenuation, than the different grazing strategies. It is expected that the larger contribution of these variation originates from the small scale grazing experiment, as usually grazing is applied on larger areas. An analysis of large scale grazing could generate better understanding in the best management strategy with respect to ecosystem services of salt marshes. Regarding the engineering guidelines, it is valuable to study the soft measures to improve the reliability of salt marshes as coastal protection solution. For example, oyster reefs are promising solutions to reduce hydrodynamic forcing. However, their efficiency to prevent salt marshes from erosion has not yet been verified. Lastly, the salt marsh dimensions, such as the width and elevation, should be translated to design parameters expressed in terms of wave attenuation.

Part VI

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Part VII

Appendices

Appendix A

Theoretical background

A.1 Model description SWAN

The model used for this research is SWAN (**S**imulating **WA**ves **N**earshore). This program is developed by the Delft University of Technology, and is able to simulate the propagation of waves in deep, intermediate and shallow waters. SWAN can provide realistic estimates for wave parameters in coastal, lakes and estuaries, resulting from given wind, bottom and current conditions ('the SWAN team', 2017). The model is based on the wave action balance with sources and sinks (Holthuijsen, 2007):

$$\frac{\delta N}{\delta t} + \frac{\delta}{\delta x}(c_x N) + \frac{\delta}{\delta y}(c_y N) + \frac{\delta}{\delta \sigma}(c_\sigma N) + \frac{\delta}{\delta \Theta}(c_\theta N) = \frac{S_{tot}}{\sigma} \tag{A.1}$$

With N is the action density, t is the time scale, x and y are the length scale, c represents the velocities in x, y, σ and θ space, σ is the frequency and Θ represents the direction. The first term on the left-hand side represents the local rate of change in action density in time. The second and third term represent the propagation of action in space (with velocities $c_{g,x}$ and $c_{g,y}$, and therefore account for shoaling). Current-induced refraction is represented by the fourth term. The last term on the right-hand side accounts for shifting of the relative frequency due to variations in depth and currents. On the right hand-side S gives the source and sink terms (Holthuijsen, 2007). For this research the one-dimensional[1] model of SWAN is used, thus there is not accounted for variations in y-direction. Moreover, the model is set to stationary mode, which removes the time dependency from the equation. The remaining energy balance becomes (including absence of currents):

$$\frac{\delta c_{g,x} E(\omega, \Theta; x, y, t)}{\delta x} + \frac{\delta c_\Theta E(\omega, \Theta; x, y, t)}{\delta \Theta} = S(\omega, \Theta; x, y, t) \tag{A.2}$$

In equation A.2 $c_{g,x}$ represents the group-propagation of waves in x-direction and E accounts for the wave energy density. As this research focuses on the wave attenuation property of salt marshes, three mechanisms are dominant for wave energy reduction (the sink terms): (1) depth-induced wave breaking, (2) energy dissipation due to bottom friction and (3) lose of energy due to reflection, transmission and absorption (Holthuijsen, 2007). Wave attenuation due to interactions with vegetation corresponds to the last type (3) of wave energy reduction (Vuik et al., 2016). Assuming the one-dimensional energy balance presented in Equation A.2, energy conservation yields:

[1] In this case one-dimensional implies that variations in y-direction (parallel to the coastline) are absent when the x-direction is normal to the coastline. This implies that the depth-contours must be straight parallel lines.

$$\frac{\delta E c_g}{\delta x} = -< D_b > - < Dn_f > - < D_v > \tag{A.3}$$

Wherein E $[N/m]$ accounts for the energy density, c_g $[m/s]$ for the group velocity, D_b $[N/ms]$ for the energy dissipation by depth-induced breaking, D_f $[N/ms]$ for dissipation due to bottom friction and D_v $[N/ms]$ for wave attenuation by vegetation. The wave energy E can be expressed via the following formula:

$$E = \frac{1}{8}\rho_w g(H_{rms}^2) \tag{A.4}$$

Wherein ρ_w $[kg/m^3]$ is the density of water, g $[m/s^2]$ is the gravitational acceleration and H_{rms} $[m]$is the root mean square wave height. Key to this research is the wave energy is the dissipation by vegetation, the explanation of this term and the other dissipation terms can be found in Section A.2.

A.2 Foreshore processes

This section presents an overview of the wave energy dissipation terms of Equation A.3, which is discussed in Section A.1.

Depth-induced wave breaking

In order to simulate the depth-induced wave breaking, SWAN applies the theory presented by Battjes and Janssen (1978). Wave breaking occurs in case the wave height in shallow water exceeds a maximum steepness (Holthuijsen, 2007). This wave height can be determined by the following formula (Holthuijsen, 2007):

$$H_{max} = h * \gamma \tag{A.5}$$

In which H_{max} $[m]$ is the maximum possible wave height, h $[m]$ is the water depth and γ [-]. The breaker parameter can be estimated by means of the wave number and water depth by means of Equation A.6 (Ruessink et al., 2003):

$$\gamma = 0.76kh + 0.29 \tag{A.6}$$

With γ [-] is the breaker parameter, k $[m^{-1}]$ and h $[m]$ the water depth. Within this research it is assumed that $\gamma = 0.75$ resulting from Equation A.6 and the design condtions at Noord Friesland Buitendijks. When a wave enters shallow water conditions, the steepness increases. Eventually, when the maximum steepness from Equation A.5 is reached, the wave will break and hence energy is dissipated. The method presented by Battjes and Janssen (1978) assumes that depth-induced wave breaking can be modelled as dissipation by a bore (Holthuijsen, 2007). For a one-dimensional energy balance this finally yields in Equation A.7:

$$D_b = \frac{B}{4} Q_b f \rho g \frac{H^3}{h} \tag{A.7}$$

In which D_b $[N/ms]$ is the dissipated energy per unit area, B [-] a calibration parameter, Q_b [-] the fraction of breaking waves, f $[T^{-1}]$ the representative frequency of the random wave, g $[m/s^2]$ the gravitational acceleration, ρ $[kg/m^3]$ the fluid density, H $[m]$ the maximum wave height and h $[m]$ the water depth (Battjes & Janssen, 1978; Holthuijsen, 2007).

Bottom friction

SWAN includes multiple theories for wave breaking due to friction. In this research the method of Madsen (1988) is applied, which leads to Equation A.8 to calculate the wave energy dissipation due to bottom friction:

$$D_f = -\frac{C_{Bfr}}{g}[\frac{2\pi f}{sinh(kh)}]^2 E u_{rms,bottom} \quad \text{(A.8)}$$

In which D_f is the dissipated wave energy by bottom friction, C_{bfr} is a bottom-friction coefficient, f the frequency, k the wave number, h the water depth, E the wave energy and $u_{rms,bottom}$ the root-mean-square orbital bottom velocity (Holthuijsen, 2007; Madsen, 1988). Within this a Nikuradse roughness length scale of $k_n = 0.02m$ is selected to represent the bottom friction, which is a characteristic value for a bottom with ripples (Babanin et al., 2005).

Dissipation due to vegetation

Thirdly, wave energy is dissipated by vegetation, as waves perform work on vegetation stems, branches and leaves (Dalrymple et al., 1984; Vuik et al., 2016). Wave attenuation by foreshore vegetation does not only depend on vegetation properties (e.g. height, density, etc.), but also on hydraulic conditions (e.g. wave height and water depth) (Möller et al., 2014; Vuik et al., 2016). Mendez and Losada (2004) describe the wave energy dissipation due to vegetation by Equation A.9:

$$D_v = \underbrace{\frac{\rho g}{2\sqrt{\pi}}}_{constant} \underbrace{C_d d_v N_v \frac{sinh^3(kh_v) + 3sinh(kh_v)}{3k}}_{vegetation} \underbrace{\left(\frac{kH_{rms}}{2\sigma cosh(kh)}\right)^3}_{wave} \quad \text{(A.9)}$$

In which the left hand side of the formula consists of a constant part, vegetation-related part and wave-related part respectively. Where C_d $[-]$ is the drag coefficient, d_v $[m]$ is the stem diameter, N_v $[stems/m^2]$ is the stem density per square meter, k $[m^{-1}]$ is the wave number, σ $[s^{-1}]$ is the wave angular frequency, h $[m]$ is the water depth and H_{rms} $[m]$ is the mean wave height. The drag coefficient is a complex parameter, which depends on multiple factors, such as plant swaying and the plant geometry (branches and leaves). The computation of this parameter is discussed in Section A.3. Equation 5.2 can be divided into a constant part, a vegetation related part and a wave related part (terms on the right-hand side of Equation 5.2). For deeply submerged vegetation ($h >> h_v$) the vegetation related part of Equation 5.2 reduces to $h_v \cdot b_v \cdot N_v \cdot C_d$, this holds for storm events.

A.3 Drag coefficient

As it is mentioned in Section A.2, the bulk drag coefficient in a complex parameter. Usually, the bulk drag coefficient is determined by calibration of this parameter with respect to the Reynolds number (Re), based on experiments (Mendez & Losada, 2004; Möller et al., 2014; Vuik et al., 2016). It is not trivial to determine the bulk drag coefficient under different vegetation and hydraulic conditions without calibration, however it is possible to use an approach with a simple array of rigid cylinders (Suzuki, 2011). From literature follows that a rigid column has a drag coefficient of $C_D = 1.0$ (Suzuki, 2011). Luhar and Nepf (2016) presented a model in which vegetation stems can be modelled as flexible, inextensible blades, with width b, thickness d, length l, elastic modulus e and density ρ_v. One-dimensional flow is exerted on the total width and height of the stem, which makes the stem bend. Luhar and Nepf (2016) express the ratio between hydrodynamic forcing to the restoring force due to stem stiffness by a dimensionless parameter, the Cauchy number (Ca), Equation A.10. High values for the flexural rigidity EI ($Ca < 1.0$) result in stiff stems, for which the stems behave more as rigid columns ($C_D \sim 1.0$).

$$Ca = \frac{\rho b U_w^2 l^3}{EI} \tag{A.10}$$

Where Ca $[-]$ is the Cauchy number, ρ $[kg/m^3]$ is the density of water, b $[m]$ is the width of the stems, U_w $[m/s]$ is the current speed, l $[m]$ is the length of the stems, I $[m^4]$ is second moment of inertia and E $[kgm^{-1}s^{-2}]$ is the Young's Modulus of the stems. The Young's Modulus can be determined by the slope of the force-displacement curve of the material (Figure A.1a), which are the stems in this case (Equation A.16).

$$\sigma_{max} = \frac{M_{max} y}{I} \tag{A.11}$$

Where Equations A.3-A.16 hold for hollow circular stems:

$$y = \frac{b_v}{2} \tag{A.12}$$

$$M_{max} = \frac{F_{max} L_{span}}{4} \tag{A.13}$$

$$I = \frac{\pi}{64}(b_v^4 - b_{v,in}^4) \tag{A.14}$$

$$\epsilon = \frac{6 d b_v}{L_{span}^2} \tag{A.15}$$

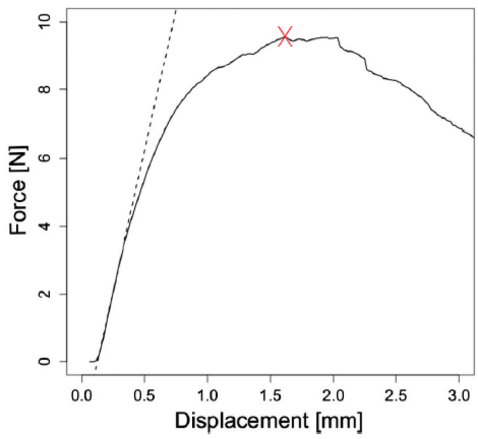
$$E = \frac{\sigma}{\epsilon} \tag{A.16}$$

With σ $[N/m^2]$ is the maximum stress of the stems, M $[Nm]$ is the bending moment, y $[m]$ is the perpendicular distance to the neutral axis, b_v $[m]$ is the outer diameter of the stem, F_{max} $[N]$ is the maximum allowable force on the stem, L_{span} is the length of the stem that is exposed to the three-point bending test, $b_{v,in}$ $[m]$ is the inner diameter of the stem, d $[m]$ is the displacement and ϵ [-] is the elongation of the stem during exposure to the three-point bending test. Combining equations A.11 - A.16 results in Equation A.17, the expression for the E-Modulus of the vegetation stems:

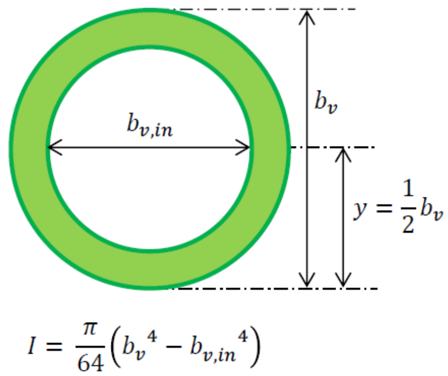
$$E = \frac{\Delta F}{\Delta d} \frac{L_{span}^3}{48 I} \tag{A.17}$$

Where ΔF Δd can be determined from the force-displacement diagram resulting from the three-point bending test (Figure A.1a), the second moment of inertia (I) follows from Equation A.14 which is displayed in Figure A.1b.

The bulk drag coefficient is determined by means of the method presented by Luhar and Nepf (2016). For Smooth cordgrass (*Spartina anglica*) the bulk drag coefficient is determined and calibrated based on experiments, which results in a value of $C_D = 0.4$ in its winter state (Vuik et al., 2017). For each specie the flexural rigidity is determined and compared with that of *Spartina anglica*. Flexible stems (e.g. short grasses) obtain a small bulk drag coefficient in the order of $C_D \sim 0.01$ and stiff stems obtain a bulk drag coefficient in de order of $C_D \sim 0.5 - 1.0$.



(a) Force-displacement diagram three-point bending tests



(b) Moment of inertia hollow cylinder

Figure A.1: Determination E-modulus from force-displacement diagram

A.4 Stem breakage

The reliability of foreshore vegetation as coastal protection measure depends on the stability during storm events. Therefore, this section focuses on the stem breakage model, which determines which wave loads plants can resist before they break or fold (Vuik et al., 2017). For hollow, circular stems the maximum tolerable bending stress σ_{max} can be determined by Equation A.18.

$$\sigma_{max} = \frac{8F_{max}L_{span}b_v}{\pi(b_v^4 - b_{v,in}^4)} \tag{A.18}$$

Where F_{max} $[N]$ is the maximum force, L_{span} $[m]$ is the testing length of the vegetation stems, b_v $[m]$ is the outer diameter of the stem and $b_{v,in}$ $[m]$ is the inner diameter of the stem (Vuik et al., 2017). Wave-induced stresses in shallow water at hollow, circular stems can be expressed as Equation A.19.

$$\sigma_{wave} = 2A_c\rho g C_D\left(\frac{b_v^2(\alpha h)^2 cos^2\theta}{\pi(b_v^4 - b_{v,in}^4)}\right)\left(\frac{H_{1/10}^2}{h}\right) \tag{A.19}$$

Where A_c [-] is a correction factor with a typical value in the order of 1, Θ $[rad]$ is the leaning angle of the stem under exposed conditions and $H_{1/10}$ $[m]$ is the 10 percent largest wave height. Factors such as the selection of the wave height within the spectrum, the selection of Θ, fatigue due to repeated wave loads and crowding, where neighbouring plants provide physical support may result in a deviation of A_c from 1. An other newly introduced parameter is Θ, which is the leaning factor of the stems. Vegetation stems can be seen as flexible columns, which may bend when they are exerted to wave forcing. Stems with a higher flexibility (lower EI) lead to higher leaning angles (Vuik et al., 2017). This process can be seen in Figure A.2. Theta is determined in the similar way as the drag coefficient, based on values from literature. The result can be seen in Appendix C.4.

Stems break when the flexural strength (σ_{max}) is smaller than the wave induced load (σ_{wave}). Equation A.18 and A.19 can be combined into the so-called critical velocity, which gives a measure for the maximum flow velocity that the stems can withstand before they break (Equation A.20) (Vuik et al., 2017).

$$u_{crit} = \sqrt{\frac{\sigma_{max}\pi(b_v^4 - b_{v,in}^4)}{4A_c\rho C_d(\alpha h)^2 cos^2\Theta}} \tag{A.20}$$

In which u_{crit} $[m/s]$ is the critical velocity and α [-] is the ratio between the stem height and water depth (h_v/h). The higher the critical velocity the greater the wave loads are that the stem can withstand before it breaks. The wave induced velocity can be approximated by Equation A.21.

$$u(z) = \frac{\sigma H}{2}\frac{cosh(k(z+h))}{sinh(kh)} \tag{A.21}$$

Where $\sigma = 2\pi/T$ is the angular frequency [rad/s], z the distance to the water surface ($z = -h$ at the bottom) and k the wave number [rad/m] (Vuik et al., 2017).

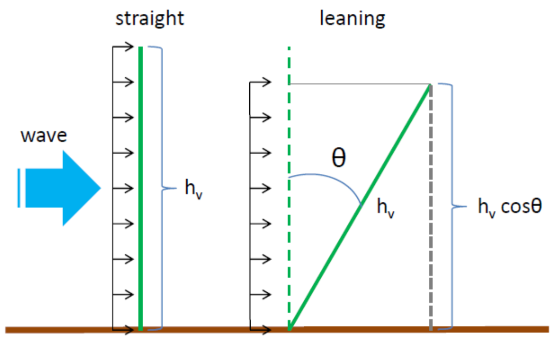


Figure A.2: Leaning angle Θ. When a stem is exposed to wave forcing the flexible stem will bend under an angle Θ. Due to this the stem (right) experiences a smaller wave load due to the reduces height of $h_v cos\Theta$ (Vuik et al., 2017).

Appendix B

Adaptations SWAN

This chapter briefly discusses the adaptations of the source code of the numerical model SWAN. Initially, SWAN is was not able to include variable vegetation properties in the model, as it was only possible to include one value for the stem height, diameter and the drag coefficient along the transect. It was possible to vary the stem density spatially. These adaptations made it possible to include multiple vegetation specie, hence properties, along the transect, which is a better approximation for the vegetation properties at Noord Friesland Buitendijks.

The basic idea of the adaptations in SWAN is to make the stem height, diameter and the drag coefficient variable in space just as the stem diameter is. For this approach the vegetation properties are adapted in the '∗.ftn'-files in the source code of SWAN. The following files are adapted, as these are the files that contain the vegetation properties for the computation:

- swanpre1.ftn
- swmod1.ftn
- swmod2.ftn
- swancom1.ftn
- swancom2.ftn
- swanmain.ftn

The basis for the adaptations is the reference parameter of the vegetation density, which is already variable in space in the initial source code of SWAN. The other vegetation properties have to be altered in the similar way as the density. This is done by adding variable properties for the parameters in the form of 'VARHPLA', 'VARDPLA' and 'VARCPLA' for the vegetation height, diameter and the drag coefficient respectively. Certain adaptations are applied on each subroutine where the variable vegetation density (NPLA) was present. An example can be found in the 'swanmain'-file, where SWAN calculates the variable number of stems, which is as follows:

```
IF (VARNPL) THEN
COMPDA(1,JNPLA2) = 0.
COMPDA(1,JNPLA3) = 0.
ENDIF
```

The same code is created for the stem height, diameter and the drag coefficient. The other adaptations are executed in a similar way.

Appendix C

Vegetation data Noord Friesland Buitendijks

This appendix provides supplemental data to the vegetation properties used in the main report. This appendix provides supplemental data to the spatial distribution of the vegetation, the vegetation properties and the bending data.

The vegetation properties (stem height, density, diameter and flexibility) data used in this report was collected by Z. Zhu from NIOZ, and people are not allowed to use these data without the permission of Z. Zhu and T. Bouma from NIOZ.

C.1 Species type

The salt marsh at Noord Friesland Buitendijks can be characterised by fifteen species. Table C.1 presents these species including their common names and the classification of these species (column 3).

Table C.1: Species types at Noord Friesland Buitendijks, abbreviations, English names and species types.

Specie	**English**	**Type**
Agrsostis stolonifera (AGR)	Creeping bentgrass	Short grass
Artemisia maritime (ART)	Sea wormwood	Forb
Aster tripolium (AST)	Sea Aster	Forb
Atriplex portulacoides (ATX)	Sea purslane	Forb
Cirsium vulgare (CIR)	Thistle	Forb
Elymus repens (ELY)	Sea couch grass	Tall grass
Festuca rubra (FES)	Red fescue	Short grass
Glaux maritime (GLA)	Sea milkwort	Short grass
Plantago maritime (PLA)	Sea plantain	Forb
Potentilla anserinea (POT)	Silverweed	Forb
Puccinellia maritime (PUC)	Common saltmarsh grass	Short grass
Salicornia spp. (SAL)	Glasswort	Forb
Spartina anglica (SPA)	Common cord grass	Tall grass
Suaeda maritime (SUA)	Annual sea-blite	Forb
Tripleurospermum maritime (TRPL)	Scentless mayweed	Forb

C.2 Spatial distribution

This section provides supplemental data for the determination of the spatial distribution of the vegetation species at Noord Friesland Buitendijks, which is discussed in Section 6.1 of the main report. Firstly, Table C.2 gives the contribution of individual species to the total paddock area. Figure C.1 gives an overview of the cover of the seven dominant species at NFB, which are *Puccinellia*, *Aster*, *Agrostis*, *Elymus*, *Artemisia*, *Suaeda* and *Salicornia*. The analysis of the spatial distribution of the vegetation is based on the vegetation maps that are collected by aerial photographs and field measurements at NFB. The different colors in the vegetation maps indicate different species groups. In Table C.3 the species-key is given which indicates what the contribution of individual species is compared to that of the species group.

Table C.2: Surface area of vegetation species at Noord Friesland Buitendijks related to total paddock area in absolute values [m^2] an percentages [%]. These percentages are based on the vegetation maps of 2011.

Species	*Area*	*Percentage*	*Specie*	*Area*	*Percentage*
Puccinellia	258750	24.73	*Festuca*	13418	1.28
Aster	189402	18.10	*Bare*	7860	0.75
Agrostis	176194	16.84	*Tripl.*	4418	0.42
Elymus	148487	14.19	*Artiplex*	3651	0.35
Artemisia	99257	9.49	*Spartina*	994	0.09
Suaeda	58946	5.63	*Cirsium*	306	0.03
Salicornia	54847	5.24	*Glaux*	24	0.00
Plantago	29689	2.84	*Potentilla*	18	0.00

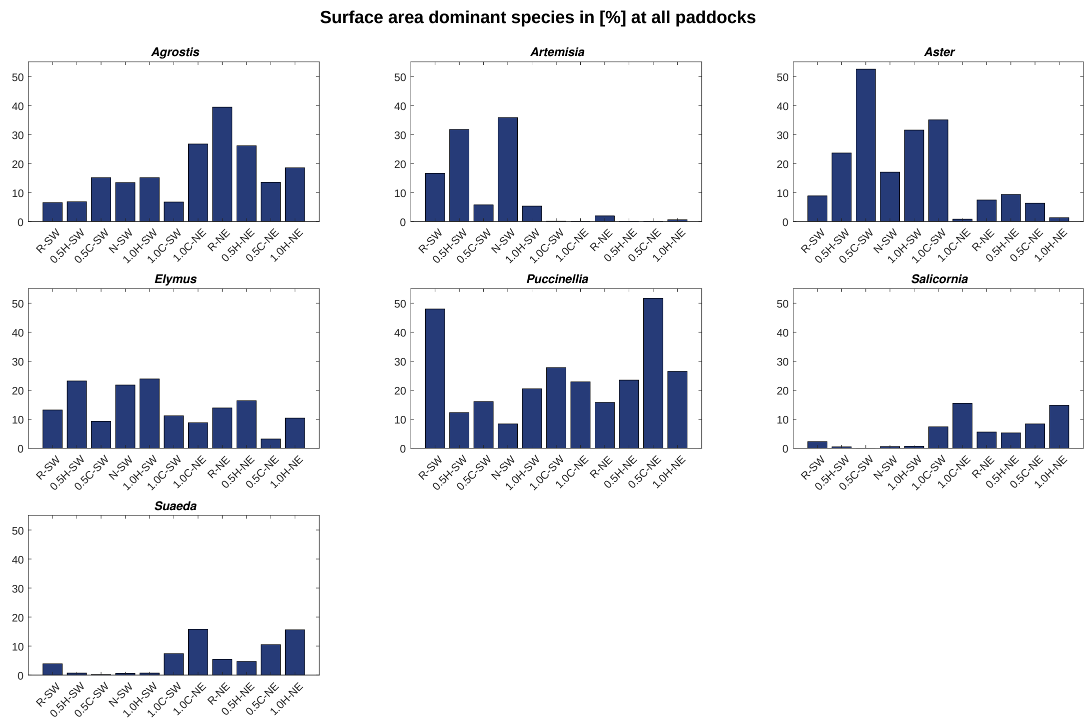


Figure C.1: Surface area of cover dominant species [%].

Table C.3: Overview species key corresponding to vegetation maps. All species groups contain one or two main species and optionally one sub-specie. The corresponding percentages of each specie within a group are presented in column 5-7.

Group	Main1	Main2	Con	% Main1	% Main2	% Con
SBg	AGR	-	-	100	0	0
SBg+Art	AGR	-	ART	85	0	15
SBg+Ast	AGR	-	AST	75	0	25
SBg+Atx	AGR	-	ATX	75	0	25
SBg+Elm	AGR	-	ELY	60	0	40
SBg+Fes	AGR	-	FES	65	0	35
SBg+Glx	AGR	-	GLX	60	0	40
SBg+Pla	AGR	-	PLA	70	0	30
SBg+Pot	AGR	-	POT	60	0	40
SBg+Puc	AGR	-	PUC	60	0	40
SHf	FES	-	-	100	0	0
SHg	AGR	TRIF	-	50	50	0
SHg+Ely	AGR	TRIF	ELY	37.5	37.5	25
SHr	ELY	-	-	100	0	0
SHr+Art	ELY	-	ART	75	0	25
SHr+Cir	ELY	-	CIR	75	0	25
SHr+Fes	ELY	-	FES	75	0	25
SHr+Pot	ELY	-	POT	75	0	25
SHr+Trpl	ELY	-	TRPL	75	0	25
SHx	ART	-	-	100	0	0
SHx+Agr	ART	-	AGR	75	0	25
SHx+Ast	ART	-	AST	75	0	25
SHy	ELY	-	-	100	0	0
SHy+Agr	ELY	-	AGR	75	0	25
SHz	ART	FES	-	50	50	0
SLa	AST	PUC	-	100	0	0
SLa+Atr	AST	PUC	ATX	75	0	25
SLh	ATX	PUC	-	50	50	0
SLp	PUC	-	-	100	0	0
SLp+Ast	PUC	-	AST	75	0	25
SLp+Pla	PUC	-	PLA	75	0	25
SLp+Sal	PUC	-	SAL	80	0	20
SLp+Spa	PUC	-	SPA	90	0	10
SLp+Sua	PUC	-	SUA	90	0	10
Sm	BARE	-	-	100	0	0
SPq	SAL	SUA	-	50	50	0
SPq+Ast	SAL	SUA	AST	40	40	20
SPq+Atx	SAL	SUA	ATX	40	40	20
SPq+Puc	SAL	SUA	PUC	40	40	20
SPq+Sal	SAL	SUA	SAL	50	40	10
SPs	SPA	-	-	100	0	0

C.3 Properties

C.3.1 Stem height h_v

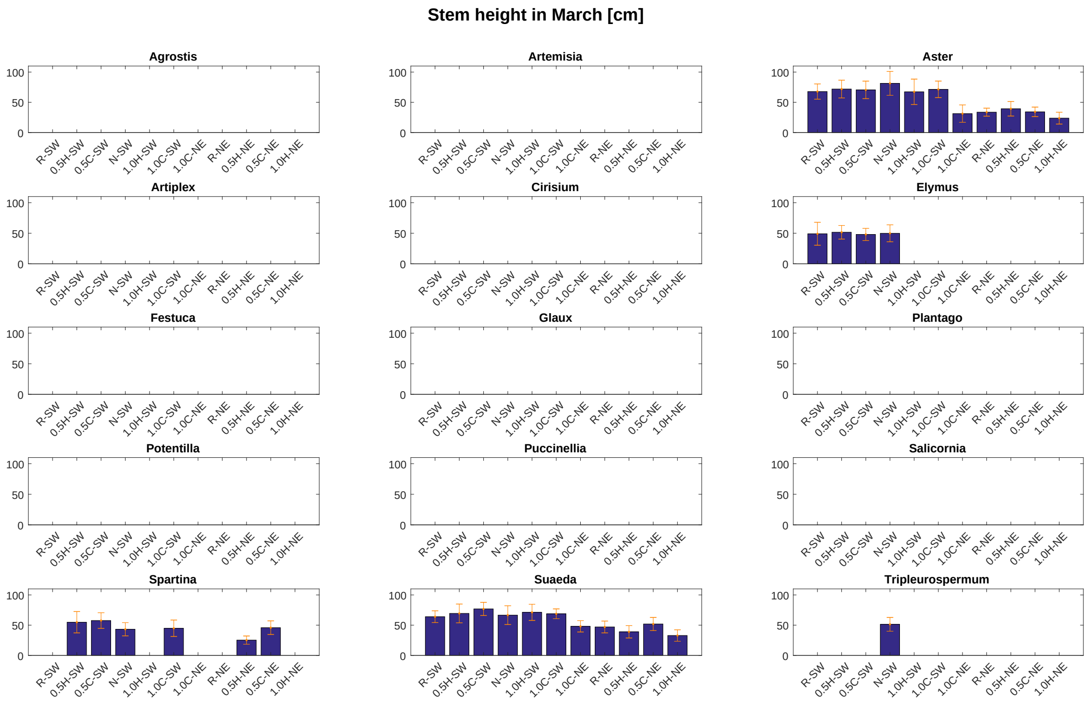


Figure C.2: Vegetation height h_v in March [cm]

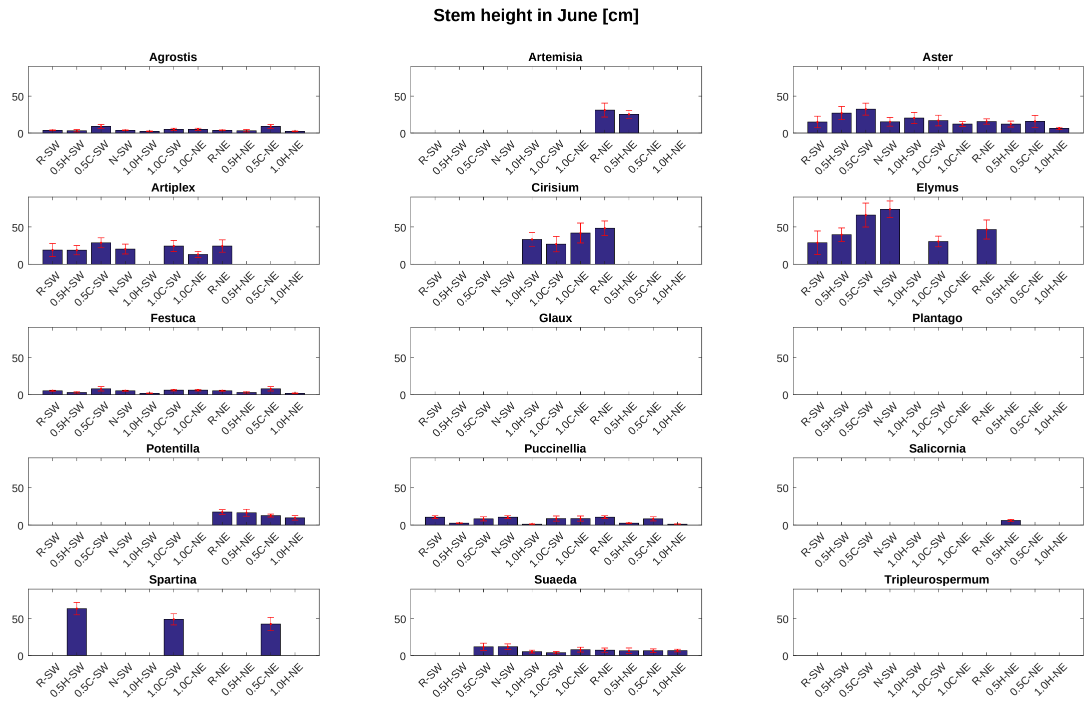


Figure C.3: Vegetation height h_v in June [cm]

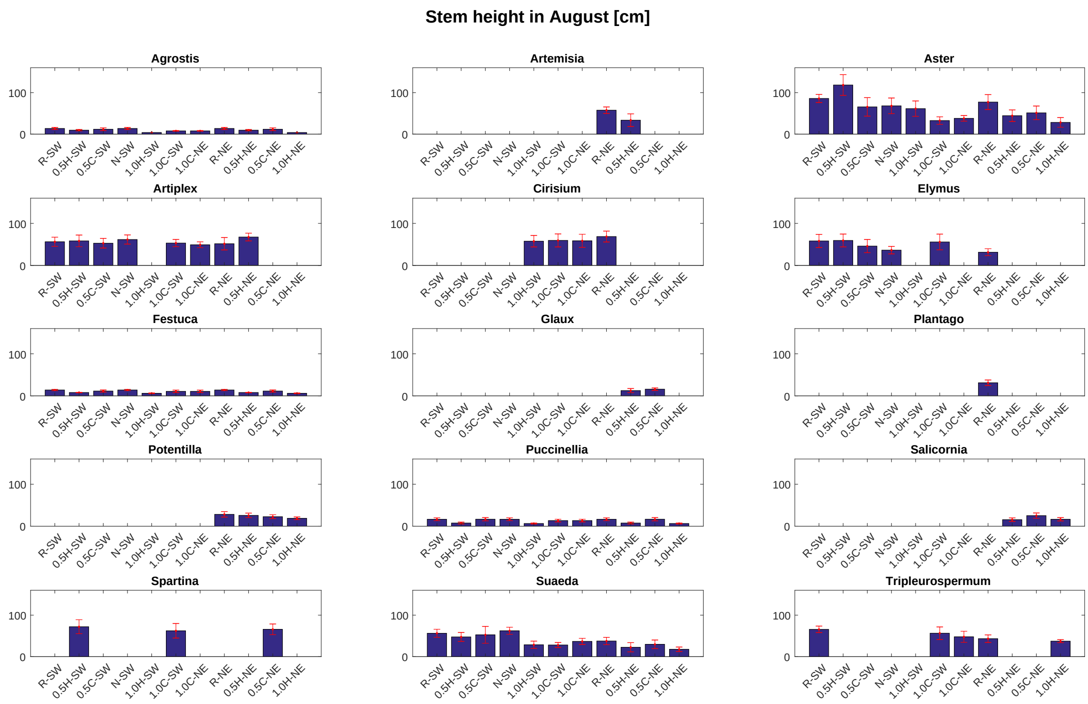


Figure C.4: Vegetation height h_v in August [cm]

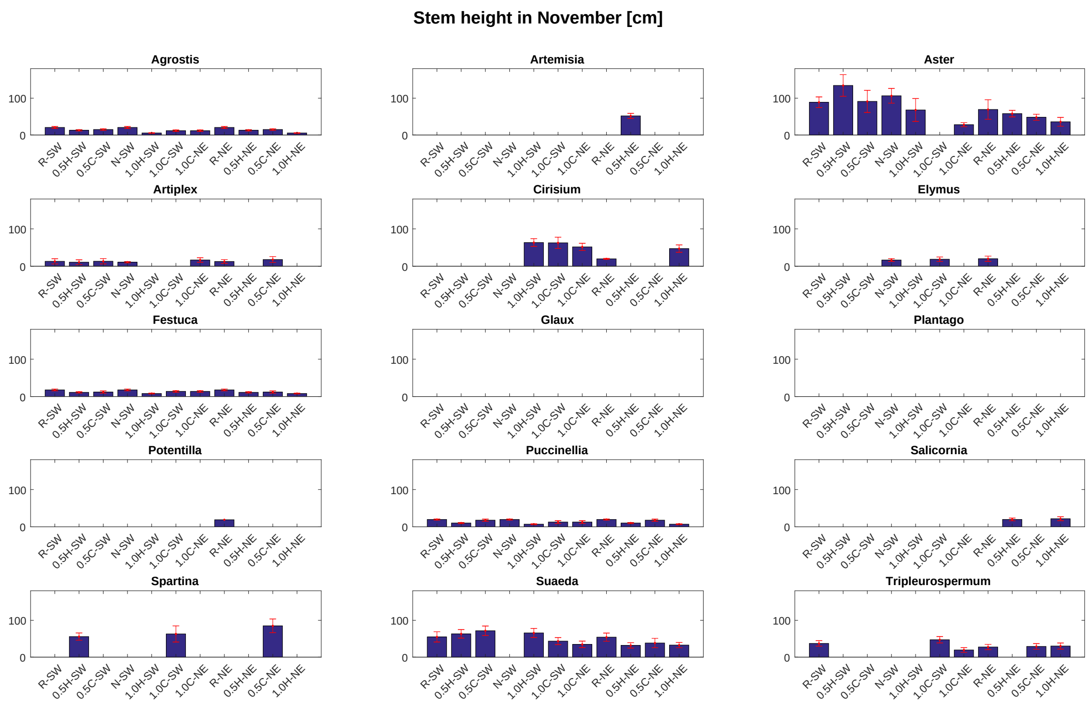


Figure C.5: Vegetation height h_v in November [cm]

C.3.2 Stem diameter d_v

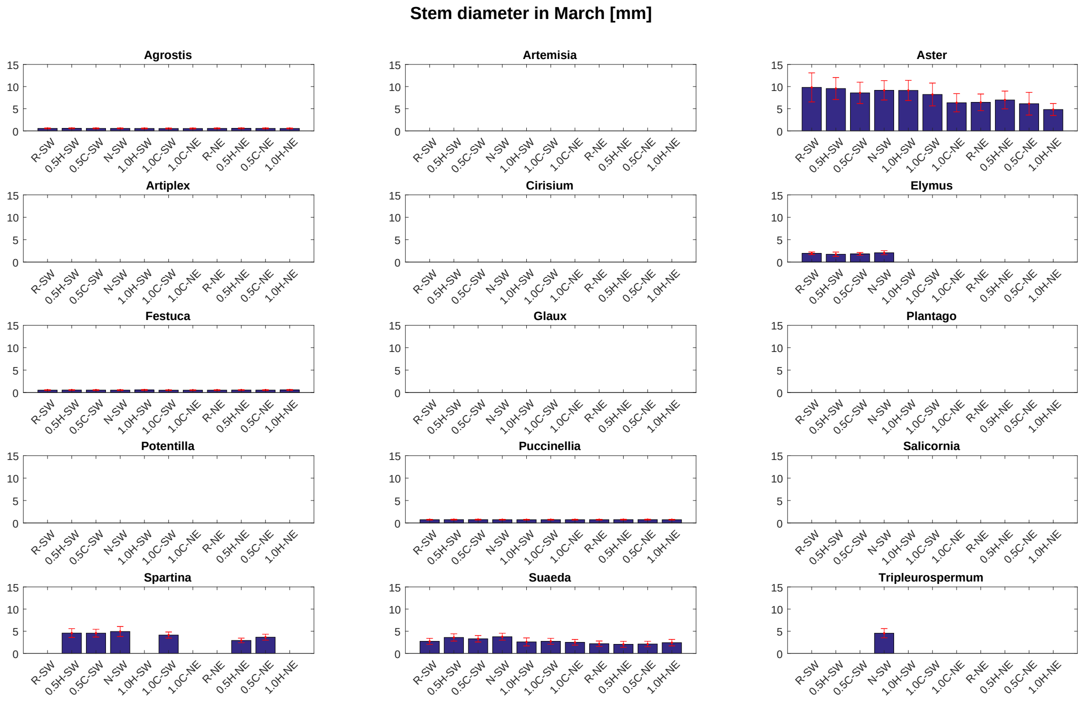


Figure C.6: Vegetation diameter d_v in March [mm]

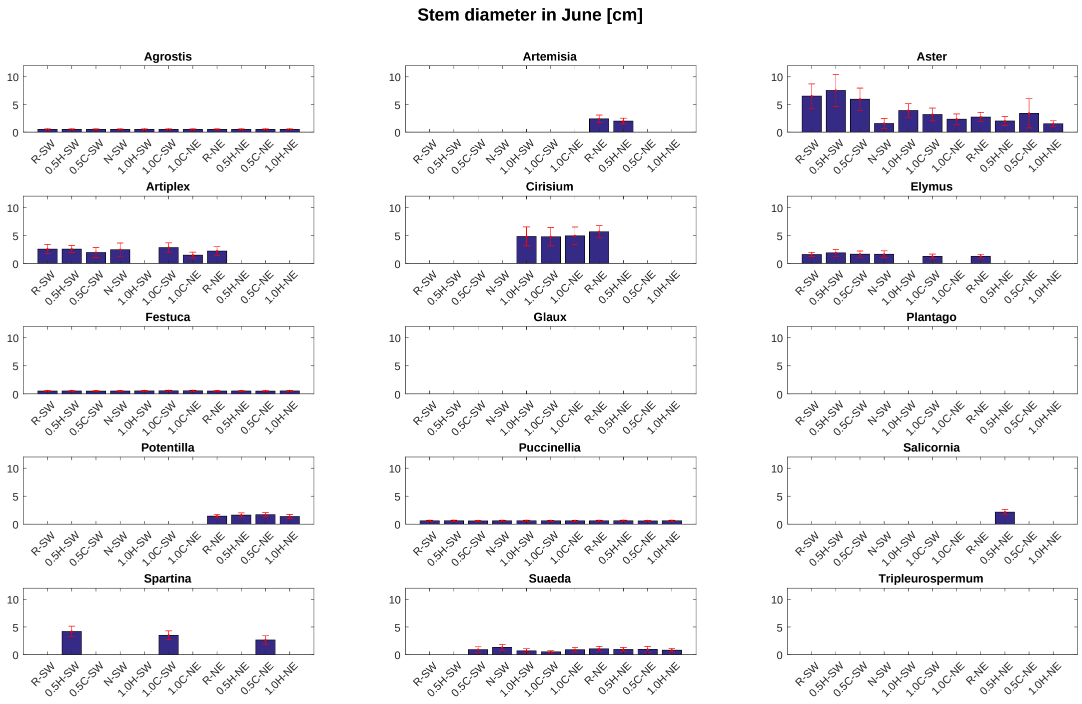


Figure C.7: Vegetation diameter d_v in June [mm]

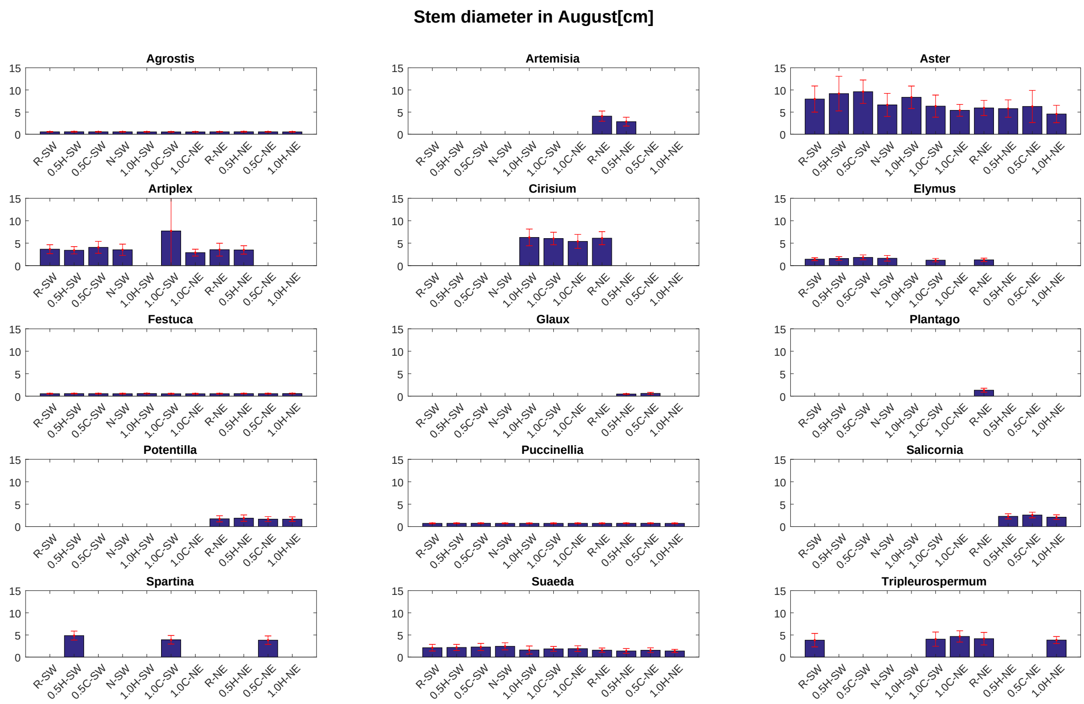


Figure C.8: Vegetation diameter d_v in August [mm]

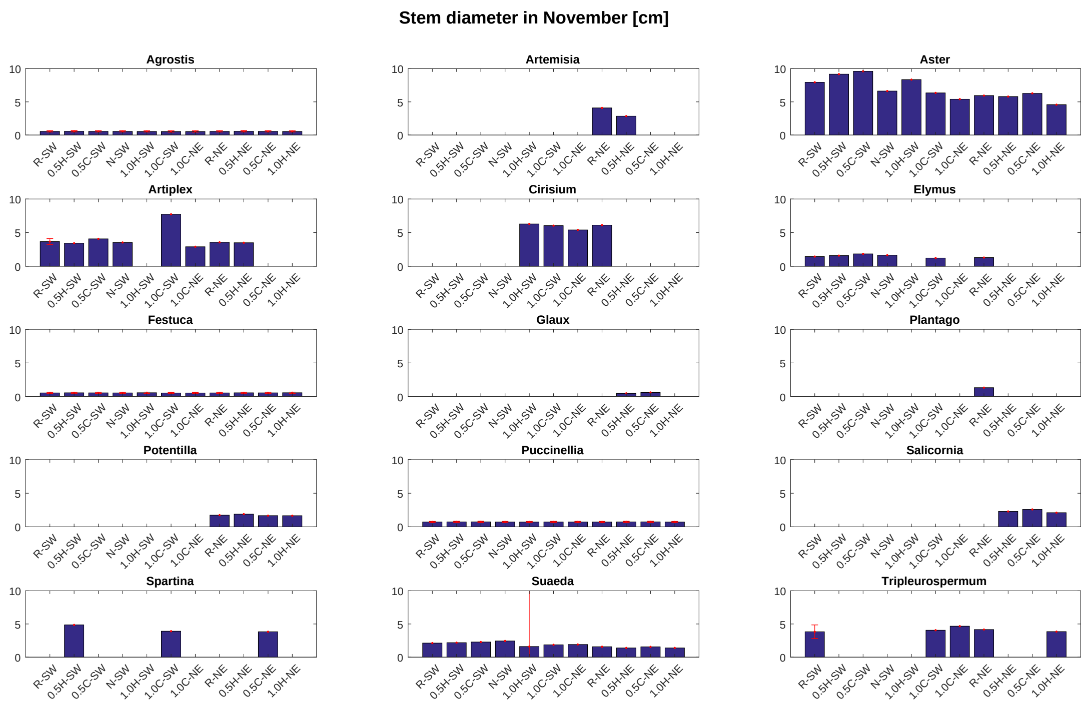


Figure C.9: Vegetation diameter d_v in November [mm]

C.3.3 Stem density N_v

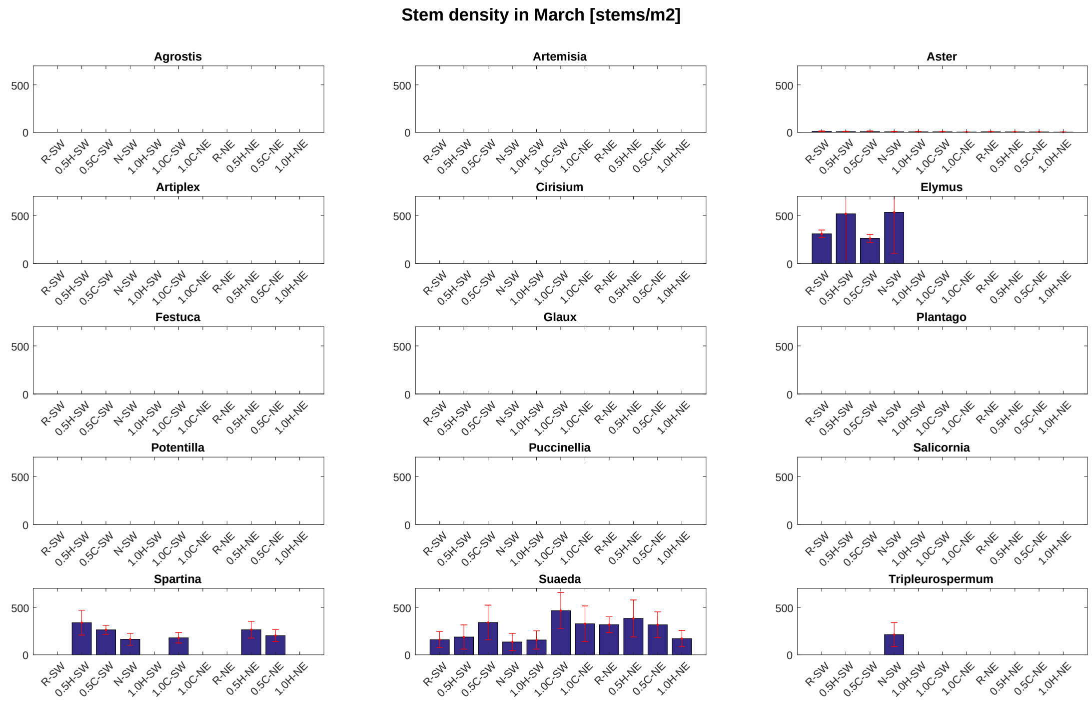


Figure C.10: Vegetation density N_v in March [stems/m2]

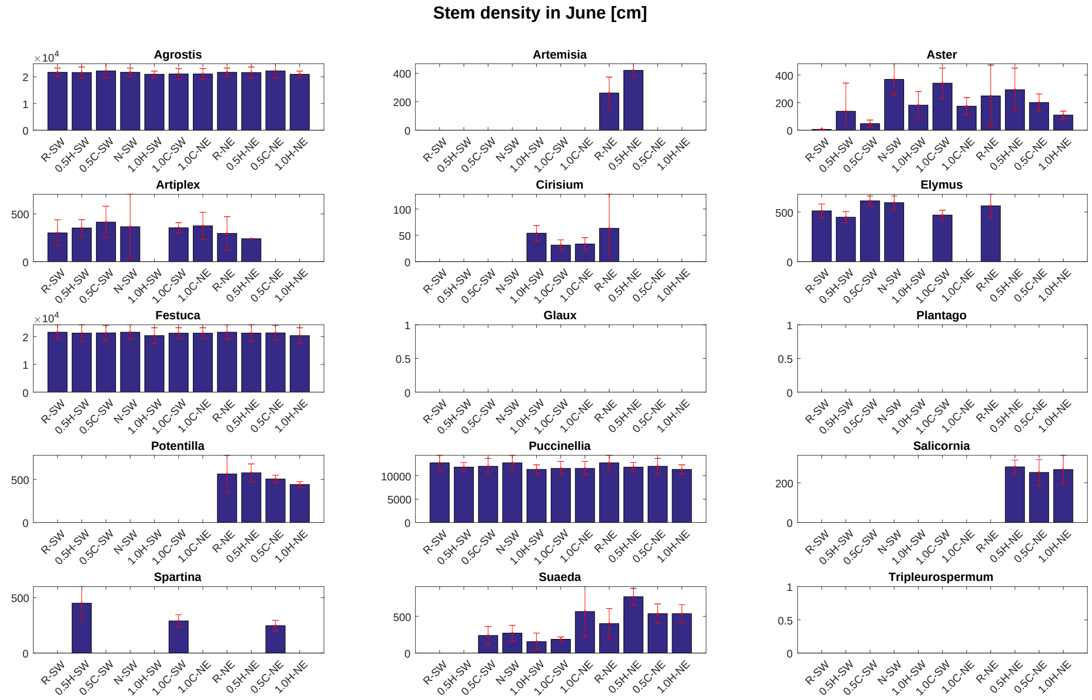


Figure C.11: Vegetation density N_v in June [stems/m2]

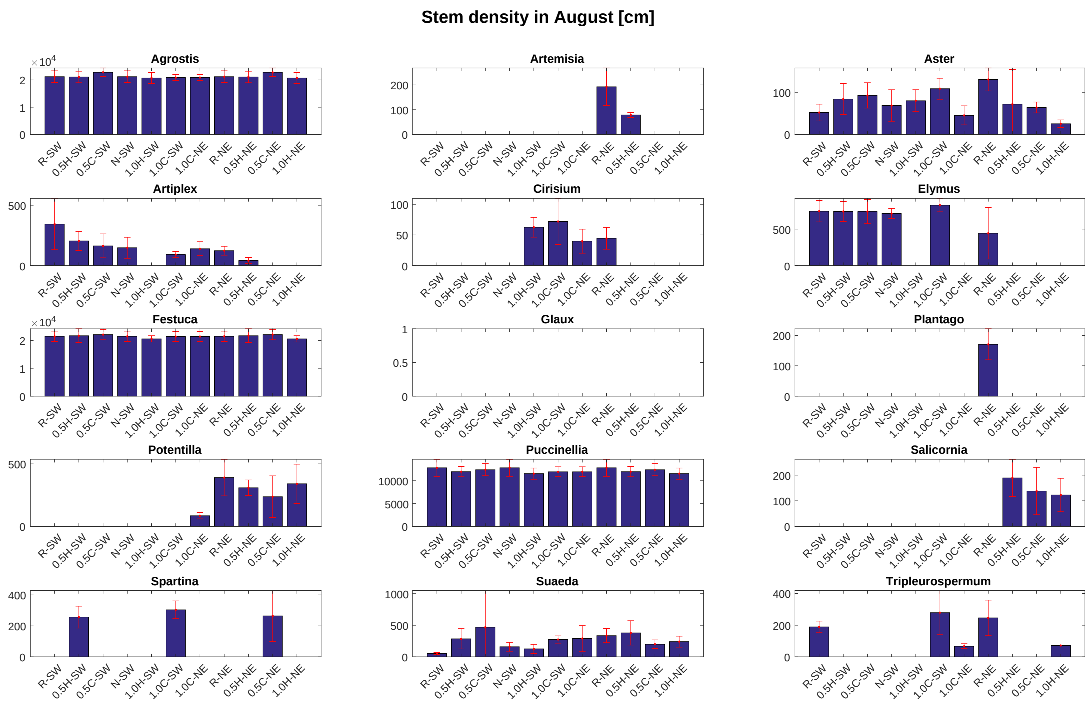


Figure C.12: Vegetation density N_v in August [stems/m2]

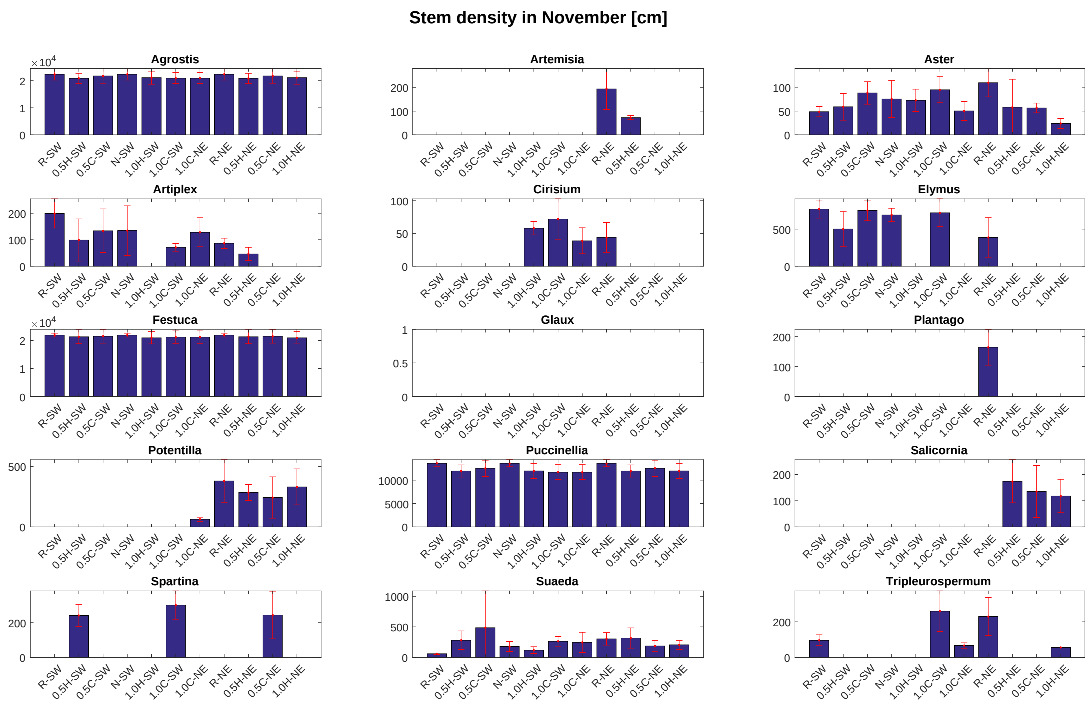


Figure C.13: Vegetation density N_v in November [stems/m2]

C.4 Results from the three-point beding test

This section provides the results that follow from the three-point bending test that is applied on the stems of the different species at Noord Friesland Buitendijks. The data is used to calculate (1) the maximum stress (σ_{max}), (2) the second moment of inertia (I), (3) the flexibility or Young's-modulus (E), (4) the flexural rigidity (EI), (5) the drag coefficient (C_d) and (6) the leaning angle (Θ) that corresponds to the stems of the different species. The approach towards the calculation of the flexural rigidity is given in Appendix A.3, this is used to find an expression for the drag coefficient that corresponds to each specie.

The ratio between the drag coefficient and the flexural rigidity of the stems is based on values that are found in literature. Table C.4 represents the ratios between these two parameters for the salt marsh species *Elymus*, *Scirpus* and *Spartina*. The approach towards the calculation of the leaning angle is executed in the same way, which is based on values from literature for *Scirpus* and *Spartina*.

Table C.4: Relation between the flexural rigidity EI $[Nmm^2]$ and drag coefficient C_d [-] for Elymus, Spartina and Scirpus from literature (Möller et al., 2014; Vuik et al., 2016) and the relation between the flexural rigidity EI $[Nmm^2]$ and the leaning angle Θ [^{0}] (Vuik et al., 2016).

Specie	EI	C_d	$Theta$
Elymus repens	1000	0.25	n.d.
Spartina anglica	3500	0.40	51
Scirpus maritimus	40000	0.80	30

It is found that the ratio between the flexural rigidity and the drag coefficient can be approximated by a logarithmic approach. Based on this assumption the drag coefficient of the different salt marsh species at Noord Friesland Buitendijks could be computed related to flexural rigidity following from the three-point bending test. This approach can be seen in Figure C.14. It followed that the calculated flexural rigidity of *Elymus* is similar to the value found in literature by Möller et al. (2014). The calculated flexural rigidity of *Spartina* at NFB is larger than the value found in literature (3500 compared to 14000 [Nmm^2] respectively) (Vuik et al., 2017), which is results from large stem diameter at for *Spartina* at NFB.

Table C.5-C.8 give an overview of the calculations that follow from the results of the bending data within the months March, June, August and November 2016 respectively.

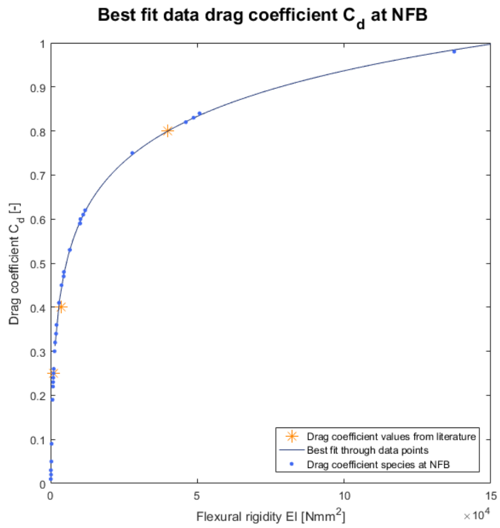


Figure C.14: Drag coefficient species at Noord Friesland Buitendijks derived from values from literature. Based on ratio between flexural rigidity EI and drag coefficient C_d.

Table C.5: Bending data March.

	σ_{max} $[N/mm^2]$	I $[mm^4]$	E $[N/mm^2]$	EI $[Nmm^2]$	C_d [-]	Θ [°]
ART	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*
AST	4 ± 2	423 ± 447	51 ± 50	10990 ± 7290	0.59	40
ATX	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*
CIR	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*
ELY	835 ± 2038	15 ± 85	4.5E5 ± 1.4E6	3629 ± 1378	0.45	50
PLA	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*
POT	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*
SAL	69 ± 57	2 ± 4	6113 ± 6660	1735 ± 1776	0.25	60
SPA	12 ± 6	7 ± 6	328 ± 254	1490 ± 903	0.30	60
SUA	113 ± 122	4 ± 4	22809 ± 41271	8272 ± 4962	0.53	40
TRPL	20 ± 7	45 ± 70	547 ± 321	14468 ± 11065	0.60	40

Table C.6: Bending data June.

	σ_{max} $[N/mm^2]$	I $[mm^4]$	E $[N/mm^2]$	EI $[Nmm^2]$	C_d [-]	Θ [°]
ART	36 ± 12	5 ± 18	2279 ± 1220	12031 ± 37369	0.22	70
AST	1 ± 1	30 ± 17	5 ± 4	91 ± 53	0.02	75
ATX	16 ± 12	3 ± 3	1256 ± 2065	2269 ± 3617	0.23	70
CIR	5 ± 3	71 ± 50	42 ± 44	1897 ± 1028	0.36	50
ELY	79 ± 23	0 ± 0	30621 ± 11892	11340 ± 5788	0.59	40
PLA	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*
POT	10 ± 5	1 ± 1	807 ± 1141	358 ± 340	0.09	70
SAL	1 ± 0	10 ± 5	14 ± 11	127 ± 109	0.02	75
SPA	6 ± 2	35 ± 20	260 ± 169	6639 ± 1723	0.53	40
SUA	13 ± 19	0 ± 0	16188 ± 35142	626 ± 1200	0.05	75
TRPL	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*

Table C.7: Bending data August.

	σ_{max} $[N/mm^2]$	I $[mm^4]$	E $[N/mm^2]$	EI $[Nmm^2]$	C_d [-]	Θ [°]
ART	45 ± 11	12 ± 19	3563 ± 1211	34865 ± 39654	0.75	30
AST	8 ± 5	453 ± 432	875 ± 615	2.5E5 ± 3.2E5	0.98	20
ATX	23 ± 5	38 ± 33	1887 ± 553	72033 ± 71781	0.83	30
CIR	12 ± 4	172 ± 108	1007 ± 437	1.7E5 ± 90229	1.00	20
ELY	43 ± 16	0 ± 0	5703 ± 3102	1518 ± 828	0.32	60
PLA	43 ± 19	1 ± 1	3373 ± 1275	3332 ± 2993	0.41	50
POT	6 ± 1	2 ± 2	118 ± 43	241 ± 188	0.03	75
SAL	25 ± 17	1 ± 1	1869 ± 1554	986 ± 1002	0.19	70
SPA	12 ± 4	20 ± 15	813 ± 219	15447 ± 13591	0.62	40
SUA	33 ± 15	8 ± 13	2472 ± 1290	17397 ± 24463	0.47	50
TRPL	22 ± 5	44 ± 33	2101 ± 422	96859 ± 77848	0.84	30

Table C.8: Bending data November.

	σ_{max} $[N/mm^2]$	I $[mm^4]$	E $[N/mm^2]$	EI $[Nmm^2]$	C_d [-]	Θ [°]
ART	36 ± 8	19 ± 15	3460 ± 936	65574 ± 61056	0.82	30
AST	9 ± 2	413 ± 490	1300 ± 671	4.3E5 ± 4.4E5	1.00	10
ATX	21 ± 10	6 ± 3	2843 ± 1335	19068 ± 12780	0.61	40
CIR	9 ± 5	216 ± 149	1005 ± 425	2.4E5 ± 2.2E5	1.00	20
ELY	13 ± 7	1 ± 1	1235 ± 1045	1105 ± 647	0.24	70
PLA	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*
POT	*nd*	*nd*	*nd*	*nd*	*nd*	*nd*
SAL	14 ± 10	4 ± 4	740 ± 395	2975 ± 1876	0.19	70
SPA	5 ± 3	48 ± 25	356 ± 221	16292 ± 12277	0.34	60
SUA	32 ± 15	6 ± 9	3490 ± 1506	18292 ± 23544	0.48	50
TRPL	12 ± 8	43 ± 35	1179 ± 767	48556 ± 55502	0.26	60

Appendix D

Input data SWAN

This section gives an overview of all the model results that follow from the computations of SWAN, corresponding to Chapter 6. An example input file for SWAN (Table D.1). The bottom profiles at Noord Friesland Buitendijks, Westhoek and Koehoal are presented in Section D.2. Lastly, in Section D.3 an overview of the model results for the different simulations are given.

D.1 Input file SWAN

Table D.1: Example inputfile SWAN. A 1000 m foreshore with vegetation under design conditions.

```
PROJ 'NFB' '5826'
SET NAUTICAL
MODE STATIONARY ONEDIMENSIONAL

CGRID REGULAR 0.0 0 0 1000 0 2000 0 CIRCLE 36 0.143 3.0 36

INPGRID BOTTOM REGULAR 0.0 0 0 2000 0 0.5 0
READINP BOTTOM -1 'bathy.txt' 5 0 FREE

INPGRID WLEVEL REGULAR 0.0 0 0 2000 0 0.5 0
READINP WLEVEL 1 'wlevl.txt' 5 0 FREE

BOUND SHAPESPEC JONSWAP 3.3 PEAK DSPR POWER
BOUNDSPEC SEGMENT XY 0.0 0 UNIFORM PAR 1.90 6.4 270 2

GEN3
BREAK CONstant alpha=1.00 gamma=0.75
WIND 30 270

VEGETATION 1 1 1 1

INPGRID HPLANTS REGULAR 0.0 0 0 2000 0 0.5 0
READINP HPLANTS 1 'vegheight.txt' 5 0 FREE

INPGRID DPLANTS REGULAR 0.0 0 0 2000 0 0.5 0
READINP DPLANTS 1 'vegdiam.txt' 5 0 FREE

INPGRID NPLANTS REGULAR 0.0 0 0 2000 0 0.5 0
READINP NPLANTS 1 'vegcover.txt' 5 0 FREE

INPGRID CPLANTS REGULAR 0.0 0 0 2000 0 0.5 0
READINP CPLANTS 1 'vegdrag.txt' 5 0 FREE

FRICTION MADSEN 0.02

NUMERIC ACCUR 0.01 0.01 0.01 99 STAT 100 0.01

CURVE 'curve' 0.0 0 2000 1000 0
TABLE 'curve' HEAD 'curve.tab' HS TPS TMM10 DISSIP DISSURF DISBOT DISVEG

COMPUTE
STOP
```

D.2 Bottom profiles

This section presents the bathymetry that is used for the wave modelling in Chapter 6. FigureD.1 gives a comparison between the bathymetry at Noord Friesland Buitendijks that is measured by the GPS by Z. Zhu from NIOZ and the bathymetry that results from the WTI-2011 SWAN model that is used to determine the design conditions for the primary flood defences at the coastline at the Wadden Sea area. It can be seen that the bathymetry that results from the GPS data has a higher elevation than that of the WTI-2011 SWAN model. It is expected that the bathymetry of the WTI-2011 SWAN model, which is based on vakloding data, is not fully updated at the salt marshes.

This difference in bathymetry between the two sources also affects the wave model results. The hydraulic conditions are determined by means of the WTI-2011 SWAN model, whereas the bathymetry is used that corresponds to the GPS measurements. Therefore, this could result in deviations from the actual hydraulic conditions at Noord Friesland Buitendijks.

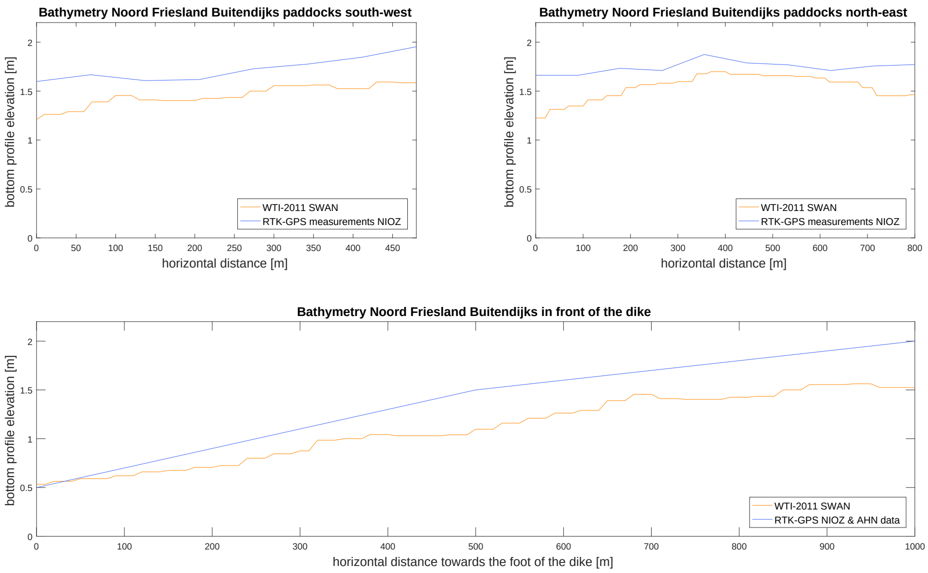


Figure D.1: Bottom profiles at Noord Friesland Buitendijks. A comparison between the bathymerty data from the WTI-2011 SWAN model and the field measurements with the RTK-GPS executed by NIOZ.

Figures D.2-D.4 represent the vakloding data at Noord Friesland Buitendijks, Westhoek and Koehoal respectively. This data is used to determine the bathymetry at the seaward side of the salt marsh edge.

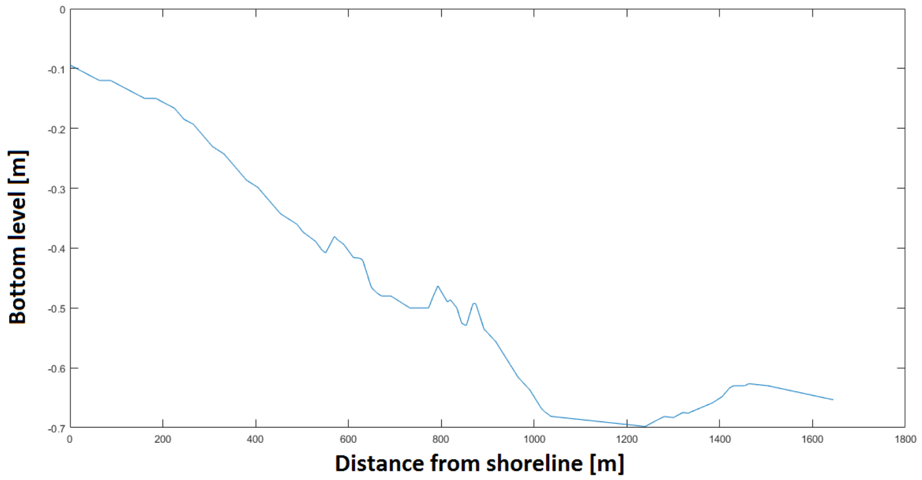


Figure D.2: Bathymetry Noord Friesland Buitendijks from vakloding-data.

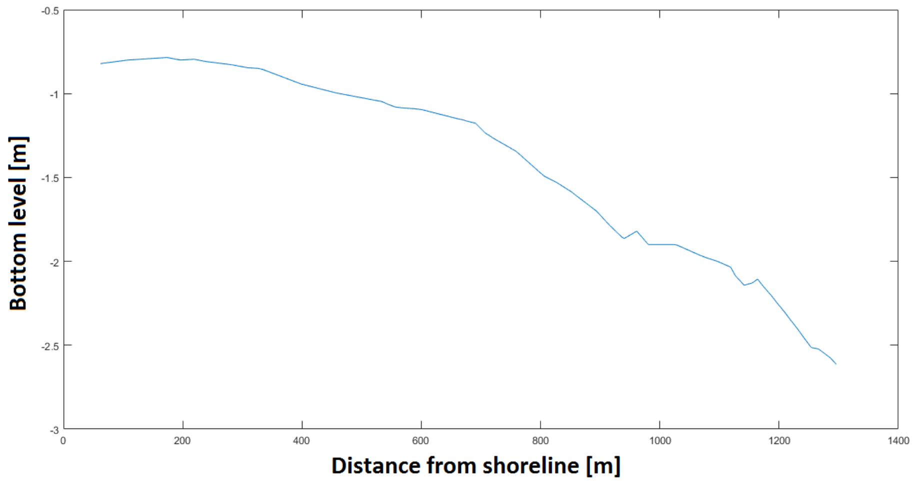


Figure D.3: Bathymetry Westhoek from vakloding-data.

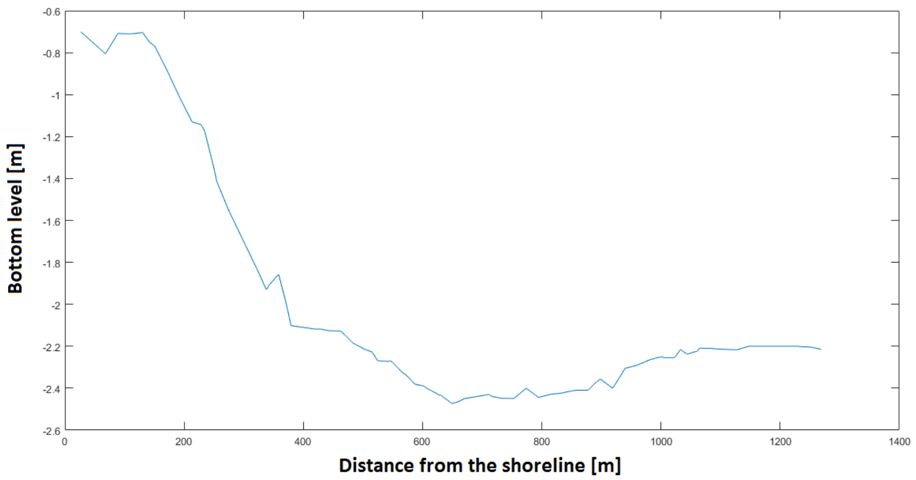


Figure D.4: Bathymetry Koehoal from vakloding-data.

D.3 Results

This section provides a full overview of the results from the wave modelling by SWAN that correspond to Chapter 6. The contribution of the dissipation terms is calculated by integrating the dissipation velocities over the cross-section. For the 100 m cross-sections the design conditions are translated to shallower depth contours by the WTI-2011 SWAN model of HKV.

Table D.2: Effect vegetation at 100 m foreshore in [m]. $\Delta H_{dis}/\Delta H$ represents the contribution of a dissipation mechanism to the total wave height reduction. Hydraulic conditions at the boundary $H_s = 1.52m$, $h = 4.80m$ and $T_p = 4.50s$.

Paddock	H_{begin}	ΔH	$\Delta H/H_{begin}$	ΔH_{veg}	$\Delta H_{veg}/\Delta H$	$\Delta H_{break}/\Delta H$	$\Delta H_{fric}/\Delta H$
Bare	1.52	0.21	0.13	0.00	0%	76%	24%
R-SW	1.52	0.23	0.15	0.03	11%	67%	21%
0.5H-SW	1.52	0.26	0.17	0.06	21%	59%	19%
0.5C-SW	1.52	0.23	0.15	0.02	10%	67%	23%
N-SW	1.52	0.26	0.17	0.06	22%	59%	19%
1.0H-SW	1.52	0.21	0.14	0.01	3%	74%	23%
1.0C-SW	1.52	0.25	0.16	0.04	17%	64%	20%
1.0C-NE	1.52	0.24	0.16	0.03	14%	66%	20%
R-NE	1.52	0.22	0.14	0.01	5%	73%	23%
0.5H-NE	1.52	0.21	0.14	0.01	4%	73%	23%
0.5C-NE	1.52	0.23	0.15	0.02	9%	70%	21%
1.0H-NE	1.52	0.22	0.14	0.01	5%	72%	23%

Table D.3: Effect vegetation on 1000 m foreshore in winter state of the vegatation. Paddocks are located at 500 to 1000 m. $\Delta H_{dis}/\Delta H$ represents the contribution of a dissipation mechanism to the total wave height reduction. Hydraulic conditions at the boundary $H_s = 1.90m$, $h = 4.80m$ and $T_p = 6.20s$, the wave height at the begin of the paddock is $H_{begin} = 1.52m$.

Paddock	H_{begin}	ΔH	$\Delta H/H_{begin}$	ΔH_{veg}	$\Delta H_{veg}/\Delta H$	$\Delta H_{break}/\Delta H$	$\Delta H_{fric}/\Delta H$
Bare	1.52	0.36	24%	0.00	0%	62%	38%
R-SW	1.52	0.46	30%	0.10	14%	51%	28%
0.5H-SW	1.52	0.55	36%	0.19	28%	41%	25%
0.5C-SW	1.52	0.43	28%	0.06	15%	49%	28%
N-SW	1.52	0.58	38%	0.22	29%	40%	25%
1.0H-SW	1.52	0.38	25%	0.02	4%	57%	30%
1.0C-SW	1.52	0.53	35%	0.17	20%	47%	26%
1.0C-NE	1.52	0.49	32%	0.13	16%	49%	27%
R-NE	1.52	0.41	27%	0.05	6%	57%	29%
0.5H-NE	1.52	0.41	27%	0.04	5%	57%	29%
0.5C-NE	1.52	0.45	30%	0.09	10%	54%	28%
1.0H-NE	1.52	0.41	27%	0.04	7%	56%	30%

Table D.4: Effect seasonal cycle of vegetation at 100 m foreshore in [m]. $\Delta H_{veg}/\Delta H$ represents the contribution of vegetation to the total wave height reduction. Hydraulic conditions at the boundary $H_s = 1.52m$, $h = 4.80m$ and $T_p = 4.50s$.

Paddock	*March*		*June*		*August*		*November*	
	ΔH	$\Delta H_{veg}/\Delta H$	ΔH	$\Delta H_{veg}/\Delta H$	ΔH	$\Delta H_{veg}/\Delta H$	ΔH	$\Delta H_{veg}/\Delta H$
Bare	0.21	0%	0.21	0%	0.21	0%	0.21	0%
R-SW	0.23	11%	0.22	8%	0.25	18%	0.26	20%
0.5H-SW	0.26	21%	0.25	17%	0.43	52%	0.37	45%
0.5C-SW	0.23	10%	0.24	16%	0.45	55%	0.52	61%
N-SW	0.26	22%	0.29	30%	0.28	26%	0.30	31%
1.0H-SW	0.21	3%	0.21	0%	0.31	35%	0.32	35%
1.0C-SW	0.25	17%	0.22	6%	0.28	28%	0.27	23%
1.0C-NE	0.24	14%	0.21	1%	0.23	9%	0.22	8%
R-NE	0.22	5%	0.23	12%	0.27	23%	0.26	21%
0.5H-NE	0.21	4%	0.21	1%	0.23	9%	0.23	10%
0.5C-NE	0.23	9%	0.21	1%	0.23	9%	0.23	9%
1.0H-NE	0.22	5%	0.21	0%	0.21	4%	0.22	5%

Table D.5: Effect elevation bottom at 100 m foreshore. The water depth (h) is equal to the water line minus the elevation (z). Hydraulic conditions at the boundary $H_s = 1.52m$, $h = 4.80m$ and $T_p = 4.50s$.

Elevation (z)	H_{begin}	ΔH	$\Delta H/H_{begin}$	$\Delta H_{break}/\Delta H$	$\Delta H_{fric}/\Delta H$
0.50 m	1.52	0.04	3%	29%	71%
0.75 m	1.52	0.06	4%	44%	56%
1.00 m	1.52	0.09	6%	59%	41%
1.25 m	1.52	0.14	9%	69%	31%
1.50 m	1.52	0.21	13%	76%	24%
1.75 m	1.52	0.28	18%	81%	19%
2.00 m	1.52	0.37	24%	84%	16%

Table D.6: Effect of constant bottom slope from 0 to 2 m+NAP. Hydraulic conditions at the boundary $H_s = 1.90m$, $h = 4.80m$ and $T_p = 6.20s$.

Slope	H_{begin}	ΔH	$\Delta H/H_{begin}$	$\Delta H_{break}/\Delta H$	$\Delta H_{fric}/\Delta H$	ΔH_{100m}
1:50	1.68	0.30	18%	72%	28%	0.30
1:100	1.68	0.39	23%	63%	37%	0.19
1:500	1.77	0.61	34%	56%	34%	0.06

Table D.7: Effect of salt marsh on bottom elevation, hence wave attenuation in [m], at Noord Friesland Buitendijks, Westhoek (salt marsh with small width) and Koehoal (no salt marsh). For a 1000 m wide bare foreshore in front of the dike. Hydraulic conditions at the boundary $H_s = 1.90m$, $h = 4.80m$ and $T_p = 6.20s$.

Location	H_{begin}	ΔH	ΔH H_{begin}	$\Delta H_{break}/\Delta H$	$\Delta H_{fric}/\Delta H$
NFB	1.77	0.66	37%	68%	32%
Westhoek	1.77	0.55	31%	66%	34%
Koehoal	1.77	0.11	6%	65%	35%

Table D.8: Effect of sensitivity vegetation properties on wave height reduction at a 100 m foreshore. The first column represents the mean values of the vegetation properties (μ) and the second and third column represent the mean value minus ($\mu - \sigma$) and plus ($\mu + \sigma$) the standard deviation respectively for **all** vegetation properties. Hydraulic conditions at the boundary $H_s = 1.52m$, $h = 4.80m$ and $T_p = 4.50s$.

Paddock	ΔH			$\Delta H/H_{begin}$			$\Delta H_{veg}/\Delta H$		
	μ	$\mu - \sigma$	$\mu + \sigma$	μ	$\mu - \sigma$	$\mu + \sigma$	μ	$\mu - \sigma$	$\mu + \sigma$
Bare	0.205	0.205	0.205	0.135	0.135	0.135	0%	0%	0%
R-SW	0.232	0.211	0.276	0.152	0.138	0.181	11%	3%	26%
0.5H-SW	0.261	0.206	0.425	0.171	0.135	0.279	21%	0%	52%
0.5C-SW	0.228	0.209	0.279	0.149	0.137	0.183	10%	2%	27%
N-SW	0.263	0.209	0.419	0.173	0.137	0.275	22%	2%	51%
1.0H-SW	0.212	0.206	0.233	0.139	0.135	0.153	3%	0%	12%
1.0C-SW	0.246	0.213	0.322	0.162	0.140	0.211	17%	4%	36%
1.0C-NE	0.238	0.209	0.314	0.156	0.137	0.206	14%	2%	35%
R-NE	0.215	0.207	0.234	0.141	0.136	0.154	5%	1%	12%
0.5H-NE	0.213	0.206	0.234	0.140	0.135	0.154	4%	0%	12%
0.5C-NE	0.226	0.208	0.269	0.148	0.137	0.177	9%	1%	24%
1.0H-NE	0.216	0.207	0.240	0.142	0.136	0.158	5%	1%	15%

Table D.9: Effect of no *Aster* due to stem breakage and *Elymus* at all paddocks, with properties of *Elymus* at the paddock with low intensity grazing by cattle (0.5C-SW). At a 100 m wide foreshore with hydraulic conditions at the boundary $H_s = 1.52m$, $h = 4.80m$ and $T_p = 4.50s$.

Paddock	ΔH	ΔH_{veg}	ΔH_{NoAST}	$\Delta H_{NoAST,\%veg}$	ΔH_{ELY}	$\Delta H_{ELY,\%veg}$
Bare	0.21	0%	0.21	0%	0.21	0%
R-SW	0.23	11%	0.23	10%	0.23	11%
0.5H-SW	0.26	21%	0.25	19%	0.26	21%
0.5C-SW	0.23	10%	0.21	5%	0.23	10%
N-SW	0.26	22%	0.26	21%	0.26	22%
1.0H-SW	0.21	3%	0.21	0%	0.21	3%
1.0C-SW	0.25	17%	0.24	14%	0.25	17%
1.0C-NE	0.24	14%	0.24	14%	0.24	14%
R-NE	0.22	5%	0.21	4%	0.22	5%
0.5H-NE	0.21	4%	0.21	4%	0.21	4%
0.5C-NE	0.23	9%	0.23	9%	0.23	9%
1.0H-NE	0.22	5%	0.22	5%	0.22	5%

Appendix E

Site visit Noord Friesland Buitendijks (2017-04-25)

At the 25th of April 2017 a site visit took place to the salt marshes at Noord Friesland Buitendijks. Only the paddocks at the south-west were visited on this day. Several photos where taken from vegetation in its winter state and other species in its early-spring state that were already growing (Figure E.1-E.3). On the same day the salt marsh at Groningen was visited, which is a typical lower salt marsh grazed by sheep. The photo of *Salicornia* in Figure E.4 results from this location. Additionally, a comparison is made between the vegetation at the interface of two paddocks (Figure E.5-E.10). Some remarkable differences in biomass were found between the paddocks, especially the contrast between the paddock with no grazing and high intensity grazing by horses was large Figure E.7. Figure E.7-E.10 compare the seasonal cycle the vegetation at the interface of these two paddocks. The photos from June, August and November were taken in 2016.

Figure E.1: *Aster* at paddock the paddock with high intensity grazing by cattle (1.0C-SW) in April 2017.

Figure E.2: *Elymus* at the paddock with high intensity grazing by cattle (1.0C-SW) in April 2017.

Figure E.3: *Aster* and *Puccinellia* at the ungrazed paddock in April 2017.

Figure E.4: *Salicornia* growing along creek at lower marsh at Groningen in April 2017. This salt marsh is grazed by sheep.

Figure E.5: Border of the paddock with rotational grazing (R-SW) and low intensity grazing by horses (0.5H-SW) in April 2017. In 2016 paddock R-SW was abandoned from grazing.

Figure E.6: Border of the paddock with low intensity grazing by cattle (0.5C-SW) and no grazing (N-SW) in April 2017.

Figure E.7: Border of the paddock with no grazing (N-SW) and the paddock with high intensity grazing by horses (1.0H-SW) in April 2017.

Figure E.8: Border of the paddock with no grazing (N-SW) and the paddock with high intensity grazing by horses (1.0H-SW) in June 2016. This photo is taken by Z. Zhu from NIOZ.

Figure E.9: Border of the paddock with no grazing (N-SW) and the paddock with high intensity grazing by horses (1.0H-SW) in August 2016. This photo is taken by Z. Zhu from NIOZ.

Figure E.10: Border of the paddock with no grazing (N-SW) and the paddock with high intensity grazing by horses (1.0H-SW) in November 2016. This photo is taken by Z. Zhu from NIOZ.