Numerical modelling of the biophysical feedbacks of Salicornia at the constructed Marconi salt marsh

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Master Thesis

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Author:

J.F. (Jesse) van den Broek

Graduation committee:

Prof. dr. K.M. Wijnberg Dr. ir. E.M. Horstman Ir. P.W.J.M. Willemsen Dr. Ir. J. Dijkstra University of Twente University of Twente University of Twente and Deltares Deltares





Abstract

Salt marshes are valuable intertidal ecosystems because they can increase flood safety and ecological value of the coastal area simultaneously. An important part of the salt marsh ecosystem is its vegetation, which is known to trap and bind sediments and reduce the erosion of the soil due to dissipation of hydrodynamic energy. Recently, worldwide efforts have been made to restore and create these salt marshes. One of the recently constructed marshes is the Marconi salt marsh, which was constructed in the Ems-Dollard estuary at the end of 2018. The Marconi marsh is used to study the effects of different sediment compositions and sowing of seeds on salt marsh establishment and development. Despite the variability of characteristics between species, research on the development of salt marsh vegetation is limited to only a few genera. Therefore, the sowing of *Salicornia Europaea* (glasswort) at the Marconi marsh gives an interesting opportunity to gain more knowledge on the establishment and development in a salt marsh of an important pioneer species. By using the Marconi project as a case study, this thesis aims to determine the impact of hydrodynamics and morphodynamics on the development of the pioneer vegetation *Salicornia Europaea* at a (artificial) salt marsh by using a numerical modelling approach.

To study the development of *Salicornia*, this study used a brand new hydrodynamic model (DFM) and combined it with a separate wave propagation model (D-Waves) as well as a vegetation growth model which comprises of the well-established Windows of Opportunity and population dynamics concepts for vegetation growth and simulates one growth season taking place between April-October. The Windows of Opportunity account for the relation of inundation and bed level dynamics with seedling establishment, which takes up the first few months of the vegetation development, while population dynamics govern the growth and decay of established salt marsh vegetation and addresses the rest of the plants life-cycle over the years. The characteristics of the Marconi site and *Salicornia* were determined by combining literature with elevation and stem density measurements of the site.

The model results suggest that the morphodynamics are the most limiting factor for Salicornia's development, since Salicornia was found to die due to bed level change, even when forced by calm hydrodynamic conditions. Furthermore, establishment of Salicornia seeds was found to be sensitive to hydrodynamics, with the model revealing a significant impact of the inundation frequency on the establishment of Salicornia and the resulting vegetation pattern found in the marsh. On the other hand, fully developed Salicornia clusters were found to be much more resilient to hydrodynamic factors. Due to this resilience, high-density groups were observed throughout the modelled site and appeared to form when two requirements were met; an early establishment to give Salicornia time to grow into fully-developed vegetation and a location that is protected well-enough from hydrodynamic energy to prevent excessive erosion or an excess of the bed shear stress threshold for plant mortality. The overall elevation of the marsh was found to affect the development of *Salicornia* in three stages. At elevations above the mean high water, *Salicornia* was well-established throughout the site, while, when lowered to below this water level, vegetation became sparse. Finally, at elevations of more than 1 metre below this mean high water level, all vegetation disappeared from the area. In addition, sediment compositions were found to have different effects on Salicornia as, according to field observations, layers with a high clay content promoted plant growth, while compositions with sand were found to increase the vegetation's resistance to erosion in the model.

This thesis has shown the sensitivity of *Salicornia's* development to bed level change as well as the negative impact of inundation on the establishment of *Salicornia*. Furthermore, this study contributes to formulating requirements for high-density *Salicornia* vegetation at salt marshes and discovered different growth rates for *Salicornia* depending on its sediment composition.

Preface

This thesis forms the end of my master's in water engineering and Management at the University of Twente. The project introduced me to the modelling of vegetation development in intertidal systems, from which I learned a lot of new things.

This thesis would not have been possible without the supervision and support of my committee throughout this project. I would like to thank Erik Horstman for giving me the opportunity to work on this project and for his great insight into intertidal ecosystems. Furthermore, I would like to thank Pim Willemsen for his help with creating the model and his critical views on my report which greatly helped me to improve it. I would like to thank Jasper Dijkstra for taking time off from his work at Deltares to help me with the DFM model and his fresh perspective during our meetings. Lastly, I want to thank Kathelijne Wijnberg for leading the committee and for her feedback and critical views during our meetings.

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1. Introduction

During the last century, a considerable decline in salt marsh area has been observed worldwide. This decline was in large part due to land reclamation for the development of socio-economic activities (Crooks et al., 2011; Duarte et al., 2008; Mariotti & Carr, 2014). The Atlantic salt marshes in the European Union (EU) countries have undergone an area reduction of about 26% during the last 50 years and consequently were identified as vulnerable by the European Red List of Habitats in 2016 (Janssen et al., 2016). However, the societal and scientific perception of salt marshes has nowadays changed towards that of a valuable ecosystem.

Salt marsh vegetation is known to trap and bind sediments and reduce the erosion of the soil due to energy dissipation (Borsje et al., 2011), thereby contributing to coastal safety. Furthermore, salt marshes provide a unique habitat and nursery ground for many species that cannot survive in other habitats (Townend et al., 2010), provide recreational opportunities and filter water (Roman, 2012; Vernberg, 1993). In a healthy marsh system under mild sea-level rise, carbon is buried in the seabed, turning into peat, coal or oil when left alone long enough. Therefore, salt marshes also form sinks for carbon dioxide, one of the major greenhouse gases (Chmura et al., 2003). By using natural systems such as salt marshes, engineers can increase the flood safety and ecological value of coastal areas at the same time.

The revaluation of salt marshes has led to worldwide efforts to restore and create salt marshes, with many projects in mostly Europe and the United States (Roman, 2012; P. Williams & Faber, 2001; Wolters et al., 2005). One of these new marshes is the Marconi salt marsh, which was constructed in the Ems-Dollard estuary, near the Dutch city of Delfzijl, at the end of 2018. The marsh is part of a larger project to increase the local spatial quality but is also used by Ecoshape to study the effect of different sediment compositions and vegetation on salt marsh establishment and development. Ecoshape is a foundation formed by different contractors, engineering companies, research institutions, governments and NGOs. The foundation aims to develop and spread knowledge about Building with Nature, a new philosophy in hydraulic engineering that takes 'building with natural materials and the use of forces and interactions within the natural system as the starting point' (Ecoshape, n.d.). With the Marconi salt marsh experiments, Ecoshape hopes to obtain generally applicable knowledge for future projects with artificial salt marshes.

Ecoshape's Marconi experiments make use of the pioneer species *Salicornia* (glasswort), which was sown to investigate how the settlement of this pioneer species can be accelerated and how it affects the morphological development of a salt marsh. To look at the effects of sowing and natural establishment, part of the salt marsh has been sown in with *Salicornia Maritima* seeds while other areas make use of the natural supply of *Salicornia Europaea*.

1.1. Dynamics of the salt marsh system

Salt marshes are intertidal ecosystems and form part of the boundary between dry land and oceans throughout the world. As a coastal ecosystem it is located between land and sea in the upper parts of the intertidal zone. Salt marshes can typically be found in estuaries, but can also occur at low-energy deltas, rias and open coasts (Allen, 2000; Allen & Pye, 1992; Doody, 2008; Hansen & Reiss, 2015; van Loon-Steensma, 2015). The lower marsh is found just below the mean high tide, while the upper marsh is located right above the mean high tide until around exceptional high tides (Esselink et al., 2017). For the Netherlands, the mean high tide varies between 0.5-2 m +NAP along the coast (van Maren et al., 2016), while exceptional high tides and surges can go up to 5 m +NAP. (Rijkswaterstaat, n.d.). This means that salt marshes along the Dutch coast can be found at around 0-5 m +NAP.

They are populated by patches or continuous covers of salt-tolerant plants such as herbs, grasses, or low shrubs (Adam, 1990).

An overview of a temperate intertidal zone with a salt marsh can be found in Figure 1-1. The salt marsh vegetation is located from the high marsh to the low marsh, while some pioneer species such as *Spartina Anglica* (cordgrass) and *Salicornia Europaea* (glasswort), see Figure 1-2, can also be found in the pioneer zone. The unvegetated intertidal mudflat is only dry during ebb tide and can contain microphytobenthos such as algae and seagrasses such as *Zostera Marina* (eelgrass).



Figure 1-1: Sections in a typical coastal system containing salt marshes. Salt marsh vegetation can mostly be found in the high to the low marsh and some pioneer species in the pioneer zone. Seagrass is located at the unvegetated intertidal mudflat along with microphytobenthos, such as algae. Obtained from Deltares ("Habitat requirements for salt marshes," n.d.).



Figure 1-2: A tussock of Spartina Anglica vegetation, which is surrounded by Salicornia Europaea vegetation, at a salt marsh near Moddergat, at the Dutch Wadden Sea. Obtained from Braam (n.d.).

The salt marsh vegetation has an important role in the area's morphodynamics, because of positive feedback between salt-marsh vegetation and sedimentation (Allen, 2000). During the formation of salt marshes, pioneers such as *Salicornia* are the first to colonise an intertidal area at the pioneer zone (Boorman et al., 2002). By retaining sediment washed in from the rising tide around their stems and leaves (Bird, 2008) and stabilizing sediments with their roots (Möller et al., 1999), they contribute to the formation of low muddy mounds which eventually add up to form depositional terraces. The erosion-reducing effect of the roots for a large extent depends on root system type, which varies over plant species (De Baets et al., 2007; Reubens et al., 2007; Stokes et al., 2009). Once the depth and duration of the tidal flooding has reduced enough, competitive species such as *Distichlis spicata* (spike grass) and *Juncus geradii* (black grass) which prefer higher elevations relative to the sea level can inhabit the area and often outcompete the pioneer species, resulting in a succession of plant communities (Adam, 1990; Allen, 2000).

In general, two growth patterns for intertidal vegetation can be differentiated. First there are species such as *Spartina Anglica* which are known to grow in dense formations which allows it to outcompete other vegetation (Roman, 2012). On the other hand, *Salicornia Europaea* has a relatively sparse growth form with a lower density overall (Figure 1-2). Besides the vegetation itself, salinity, water content, and soil texture are also known to influence the vegetation pattern in the salt marsh (Moffett et al., 2010). However, the multivariate relationships between abiotic and biotic ecosystem patterns are difficult to assess without high-resolution spatially distributed data, meaning that it is difficult to predict the vegetation distribution of intertidal salt marsh ecosystems (Moffett et al., 2010).

Remote sensing and field studies indicate that the population of salt marsh vegetation varies over the seasons, showing clear peaks in population during spring and summer and relatively low values during winter (Lopes et al., 2019). The seasonal variation of the intertidal vegetation is dependent on the life cycle of the plant.

Salt marsh vegetation is capable of affecting the hydrodynamic climate by causing flow resistance and altering the flow direction (Bouma et al., 2005; Carpenter & Lodge, 1986; Koch et al., 2006; Peralta et al., 2006). Furthermore, the vegetation has been revealed to efficiently dissipate wave energy, both in calm and storm conditions (Möller et al., 2014). The growth patterns and seasonal variations of the intertidal vegetation have a significant impact on the wave attenuation and flow altering of the vegetation and consequently even on the sedimentation and erosion in the area (Bouma et al., 2005; Lopes et al., 2019).

On the other hand, hydrodynamics (currents and waves) in the salt marsh are also known to inhibit seedling establishment and negatively influence the densities and length of the shoots of the plant population (Balke et al., 2014; Schanz & Asmus, 2003). The effects differ over vegetation types, since the establishment of seedlings under certain hydrodynamic and morphodynamic conditions is dependent on the type of plant and the availability of their seeds. Furthermore, different plants have created different survival techniques such as flexibility to reduce damage versus rigid to bear the stress, in order to withstand the hydrodynamic climate (Rupprecht et al., 2017).

1.2. Research Aim

While a lot is already known about salt marshes and the effects of vegetation, most studies have been performed by using the same plant; *Spartina Anglica*. While plant species are known to compete for establishment in the area (Adam, 1990; Allen, 2000; Roman, 2012), specific differences between plant species and their establishment requirements have not yet been filled in, which makes it difficult to predict which vegetation will outcompete the others.

Since it is known that the type of vegetation impacts its establishment (Adam, 1990; Boorman et al., 2002), resistance to flow (Balke et al., 2014; Rupprecht et al., 2017; Schanz & Asmus, 2003), wave attenuation (Möller et al., 2014), alteration of the flow (Bouma et al., 2005; Carpenter & Lodge, 1986; Koch et al., 2006; Peralta et al., 2006), sedimentation (Möller et al., 1999), erosion (De Baets et al., 2007; Reubens et al., 2007; Stokes et al., 2009) and even varies differently over seasons depending on the plant (Lopes et al., 2019), there is still much to learn regarding the formation and evolution of salt marshes. Furthermore, the effect of combinations of species on the morphological development in a salt marsh area has received little attention.

Sediment characteristics affect the erosion/sedimentation rates and influence the survival rate of vegetation in the salt marsh (Balke et al., 2014; Furukawa & Wolanski, 1996). However, the effects of hydrodynamics and morphodynamics on the growth of salt marsh vegetation other than *Spartina* is relatively unknown.

The usage of the pioneer species *Salicornia Europaea* at the Marconi marsh gives an interesting opportunity to gain more knowledge on the establishment and development over a salt marsh of this important pioneer specie. Furthermore, due to the close collaboration of researchers at the University of Twente with Ecoshape in their Marconi project, it is relatively easy to obtain the data required to set up a numerical model study. By using a numerical model study, data from the Marconi project could be extended to also gain more knowledge on the short-term development of artificial salt marshes, which are known to often lack the same biodiversity as their natural counterparts with implications for their functioning and the ecosystem services that they provide (Mossman et al., 2012; Tempest et al., 2015). By using the Marconi project as a case study, this study aims to determine the impact of hydrodynamics and morphodynamics on the development of the pioneer vegetation *Salicornia Europaea* at a (artificial) salt marsh by using a numerical modelling approach.

1.3. Research questions

To reach this goal, the main research question and its respective sub questions are the following:

How do hydrodynamic and morphodynamic processes affect the numerically modelled development of Salicornia Europaea at an intra-annual time scale in a constructed salt marsh?

Sub questions:

- 1. How do the hydrodynamics affect the establishment and population development of Salicornia Europaea?
 - 1.1. What is the effect of inundation on the vegetation establishment of Salicornia Europaea?
 - 1.2. What are the effects of inundation and bed shear stress on the population development of Salicornia Europaea?
- 2. What morphodynamic factors affect the establishment of Salicornia Europaea?2.1. What is the effect of bed level change on the development of Salicornia Europaea?
- 3. Is the vegetation development primarily limited by hydro- or morphodynamics and can we determine a threshold for the limiting processes?
- 4. What are the effects of the elevation of the constructed salt marsh and brushwood dams on the vegetation?
 - 4.1. At what elevations can the vegetation establish and what is the effect of the elevation of the constructed salt marsh on the morphodynamics and consequently the vegetation?
 - 4.2. Does the impact of sediment composition on the morphodynamics change when lowering the marsh?
 - 4.3. What is the impact of the brushwood dams on the morphodynamics and consequently the vegetation?

1.5. Report approach

Chapter 2 will present the methodology; introducing the study area, growth concepts of vegetation, numerical model and the collected data. Chapter 3 will continue with the set-up of the D-Flow Flexible Mesh (DFM) model, which simulates the hydro- and morphodynamic processes in the area. The chapter describes the domain, boundary and initial conditions as well as some of the input parameters of the DFM model. Chapter 4 provides more information on the vegetation dynamics and the modelling thereof. This starts with a literature study on the life cycle of *Salicornia Europaea* and how this will be used in this thesis, followed by the setup of the windows of opportunity and population dynamics modules. The chapter ends with field measurements of the research, which focusses on development of *Salicornia Europaea* during its growth season inside the Marconi marsh. Finally, chapter 6 discusses the limitations and implications of this study, followed by the conclusion in chapter 7 and the recommendations for future research in chapter 8.

2. Methodology

This chapter presents the methods used during this research. It starts with a description of the Marconi project site. Next, the vegetation growth concepts of Windows of Opportunity and population dynamics, which were combined into one vegetation model in this thesis, are explained. The next section explains how both concepts were implemented as the vegetation model and how this model is connected to D-Flow Flexible mesh (Deltares, n.d.), the hydrodynamic model used in this thesis. The last section describes what data was used and how it was collected.

2.1. The study area

The Marconi salt marsh is a pioneer salt marsh that has been constructed at Delfzijl, a coastal city in the north of the Netherlands (Figure 2-1). Salt marshes are indigenous to the area and several natural marshes can be found around the estuary (Figure 2-1b). The project site is located in the estuary of the Ems river. It is part of a larger project to increase the spatial quality and quality of living in Delfzijl and to improve its connection with the sea by using salt marshes and beaches (Figure 2-2) (De Groot & Van Duin, 2013; Municipality Delfzijl, 2016). At the Marconi marsh, experiments are being conducted by Ecoshape (2019) with *Salicornia* and with alterations in sediment compositions. The goal is to create greater insight into the effects of the *Salicornia* pioneer vegetation and sediment characteristics on the morphological development of the area as well as finding out which setup is preferable for the ecological and morphodynamic development of artificial salt marshes.



Figure 2-1: (a) The location of the Marconi project within Europe. (b) A map of Delfzijl and its surroundings. The black boxes indicate project areas of this thesis and authors which are referenced in Chapter 0, while the circles indicate nearby natural salt marshes. Obtained from Poppema (2017).



Figure 2-2: An impression of the Marconi project at Delfzijl (view to the south-west, obtained from Ecoshape (2019).

Chapter 2: Methodology

The Marconi salt marsh (Figure 2-3) is elevated between 0 m +NAP in the foreland to up to 3 m +NAP at the landward edges of the high marsh. Eight sections, of widths and lengths varying between 100 to 400 metres, were made in the area which start at around 1 m +NAP at the seaward side up to the 3 m +NAP landward edge of the high marsh (Figure 2-4). The sections have been divided using brushwood dams of roughly 20 cm width and 40 cm height. These brushwood dams not only serve as borders between the sections, but also partly shelter the sections from incoming waves. The mean high tide at Delfzijl is 1.4 m +NAP (Groningen Seaports, n.d.). Therefore, as Figure 2-4 shows, most of the area inside the sections is located above the mean high tide. This means that a large part of the Marconi marsh floods irregularly and falls into the high marsh category (Figure 1-1). The Marconi site was built in a relatively shallow area, some distance away from the fairway. Furthermore, due to rubble mound jetties and dikes, as indicated by the red lines in Figure 2-4, the area is sheltered from most of the wave energy, creating a suitable location for salt marsh formation.





Figure 2-3: An aerial photo of the Marconi salt marsh which was made in September 2019 by van Puijenbroek (2019).

Figure 2-4: The bed level of the Marconi area ranging from just below 0 in the forelands to close to 3 m +NAP at the landward edges of the sections. The brushwood dams, indicated in black, are roughly 20 cm wide and 40 cm high. The red lines indicate bigger dikes/jetties that do not allow flow over/through it.

For Ecoshape's experiments, the eight test sections were created with sediment compositions of varying sand/clay ratios, see Chapter 2.3, and three of the sections have been partly sown with *Salicornia* seeds. Sedimentation erosion bars (SEB stations) are used to measure the bed level change in most of the sections. An overview of the experimental setup is shown in Figure 2-5. Water is able to flow towards the area from the north and east, while the western and southern side of the marsh are blocked by land and rubble mound jetties.

In this thesis, the project site has been modelled and combined with results of field measurements at the sections to simulate the development of *Salicornia Europaea* in sections E, F and G (Figure 2-5) since these are the most interesting due to the sown *Salicornia*.



Figure 2-5: The experimental setup of the Marconi salt marsh project in which the sections are lettered. The arrow points in the northern direction. Sections A-D have no planted Salicornia and a varying clay concentration of 5, 20 or 50% (the remaining percentages are sand). Sections E-G have the same altering clay concentrations of 5, 20 or 50%, but half of the area also contains sown Salicornia seeds (green areas). The SEB stations (green dots) are sedimentation-erosion bars which will be used to measure the bed level change in the sections (van Puijenbroek, 2019). In sections E-G 6 SEB points are present; 3 left and 3 right. Moving from north to south these are denoted as low, middle and high. Furthermore, there are two measurement points of the model outside of the sections (E_{north} and G_{north}). These points will be used later to present results in Chapter 5.

2.2. Salt marsh development concepts

This study combines two vegetation growth concepts into one vegetation development model for *Salicornia* which will be parameterised in Chapter 4.3. Several growth concepts have been formulated to address the development process of intertidal vegetation. Two well-established concepts are the Windows of Opportunity (WoO) by Balke et al. (2011) and the population dynamics by Temmerman et al. (2007). WoO focuses on the possibilities for establishment of new vegetation, while population dynamics is primarily focused on the development of vegetation after an initially successful establishment. Since the concepts focus on different parts of the development of intertidal vegetation, a combination of both concepts could form a great model for the growth of intertidal vegetation.

2.2.1. Windows of Opportunity: Vegetation establishment

Figure 2-6 shows the Windows of Opportunity framework as adjusted for *Spartina Anglica*, a perennial plant, using three windows as obtained from Poppema (2017). The windows indicate phases in the establishment process of seedlings. The first window (WoO1) is required to be disturbance-free from hydrodynamic forces, so that the seeds can strand, develop roots and withstand the stress of flooding. This can be modelled as an inundation-free period (Attema, 2014; Hu et al., 2015). After a successful first window, there is an initial stress, in this case parameterised as the critical disturbance depth (CDD) or bed level change, that the plant can withstand.

In the second window (WoO2), this disturbance depth then slowly increases with increasing root length of the seedling until it reaches maturity and the CDD stops increasing (and reaches WoO3). The third window starts after the second window, at the end of the growing season, and lasts until the end of the winter. Therefore, the window can only be used for perennial plants, since annual plants would not last until the end of winter. The third window tests whether the plant can withstand the increased erosion of winter storms. This means that window 1 and 2 should be finished before the end of the growing season, otherwise it is assumed that the plants have failed to fully develop (Poppema, 2017), even though the plant could still be strong enough to survive the winter storms.

For windows 2 and 3, two boundaries have been set up; long-term bed level change and short-term erosion. A too large long-term sedimentation rate will bury the plant, while too much long- or short-term erosion restricts its nutrient absorption rate and can dislodge the plant. Plants that have failed during window 2 and 3 are either buried completely due to excessive sedimentation or dislodged due to erosion rates exceeding the critical bed erosion. What is important to realise, is that the plant can also be damaged or break off during storms. The concept does not take this into account. If the plant has survived the final window, the establishment is regarded as successful.

In this concept, establishment is deemed possible when all subsequent windows have successfully been completed. It should be noted that a successful WoO does not guarantee vegetation establishment, since this is also dependent on availability of seeds in the area.



Figure 2-6: The Windows of Opportunity framework (Obtained from Poppema (2017)). CDD is the critical bed level change the plant can withstand. H_{max} is the inundation depth and the two boundaries at windows 2 and 3 are long- and short-term bed level change boundaries, with δz indicating the bed level change and $E_{avg, max}$ and $S_{avg, max}$ being the maximum average long-term erosion and sedimentation, respectively.

The long-term erosion and sedimentation thresholds ($E_{avg, max}$ and $S_{avg, max}$ in ms⁻¹ respectively) are imposed by the growth rate of the plant. Since it is assumed that the growth rate is relatively constant (Figure 2-6), these limits are time-independent limits on the average erosion and sedimentation rate. On the other hand, the short-term erosion limit is governed by the depth at which a seed is located and its root length (Poppema, 2017). Because the root length increases over time, the limit should also increase over time. Besides the age of the plant, the short-term erosion limit is also affected by bed level dynamics. If during the plant's life sediment is placed on top of its roots, more sediment can be eroded before the roots are uncovered and the plant fails. This sensitivity to bed level change has been expressed by the parameter α in Equation (2.2.1.1) and (2.2.1.2) (Poppema (2017)). Equation (2.2.1.1) describes the development of the critical disturbance depth (m) of the plant during the growth phase (window 2), while Equation (2.2.1.2) is for determining the critical disturbance depth after window 2 has ended.

$$CDD = CDD_{initial} + \alpha * \delta z_{life} + \frac{t - T_{WoO1}}{T_{WoO2}} * ((CDD_{mature} - CDD_{initial})$$
(2.2.1.1)

$$CDD = CDD_{mature} + \alpha * \delta z_{life}$$
(2.2.1.2)

In which:	
CDD	= Short-term erosion limit (critical disturbance depth [m]
CDD _{initial}	= Initial critical disturbance depth [m]
α	= Sensitivity to bed level change [-]
δz_{life}	= Bed level change during life plant [m]
t	= Time since establishment (age of plant) [day]
TwoO1	= Duration of window 1 [day]
T _{WoO2}	= Duration of window 2 [day]
CDD_{mature}	= Critical disturbance depth of mature plant [m]
T _{WoO1} T _{WoO2} CDD _{mature}	 = Duration of window 1 [day] = Duration of window 2 [day] = Critical disturbance depth of mature plant [m]

2.2.2. Population dynamics

The population dynamics concept of Temmerman et al. (2007) was conceptualised to simulate colonization of *Spartina* and channel formation on an initially bare, flat substrate found in the Western Scheldt estuary. The concept thereby focuses on the dynamics of the entire vegetation population in an intertidal area. This concept can be parameterised into a model and used to research the feedbacks between vegetation dynamics and hydrodynamics, which is known to have an important influence on the landscape evolution (Temmerman et al., 2007). Temmerman's (2007) plant growth model simulates spatial and temporal changes in stem density of the intertidal vegetation as the sum of five parts (Equation (2.2.2.1)):

$$\frac{\delta n_b}{\delta t} = \left(\frac{\delta n_b}{\delta t}\right)_{est} + \left(\frac{\delta n_b}{\delta t}\right)_{diff} + \left(\frac{\delta n_b}{\delta t}\right)_{growth} - \left(\frac{\delta n_b}{\delta t}\right)_{flow} - \left(\frac{\delta n_b}{\delta t}\right)_{inund}$$
(2.2.2.1)

Of which the five terms are: establishment of seedlings (Equation (2.2.2.2)), lateral expansion (Equation (2.2.2.3)), logarithmic growth of stem density (Equation (2.2.2.4)), plant mortality caused by tidal bed shear stress (Equation (2.2.2.5)) and plant mortality caused by tidal inundation stress (Equation (2.2.2.6)). The terms are:

$$\left(\frac{\delta n_b}{\delta t}\right)_{est} = P_{est} n_{b,est} \tag{2.2.2.2}$$

$$\left(\frac{\delta n_b}{\delta t}\right)_{diff} = D\left(\frac{\delta^2 n_b}{\delta x^2} + \frac{\delta^2 n_b}{\delta y^2}\right)$$
(2.2.2.3)

$$\left(\frac{\delta n_b}{\delta t}\right)_{growth} = r\left(1 - \frac{n_b}{K}\right)n_b \tag{2.2.2.4}$$

$$\left(\frac{\delta n_b}{\delta t}\right)_{flow} = PE_{\tau}(\tau - \tau_{cr,p}), \quad when \, \tau > \tau_{cr,p}$$
(2.2.2.5)

$$\left(\frac{\delta n_b}{\delta t}\right)_{inund} = PE_H (H - H_{cr,p}), \quad when H > H_{cr,p}$$
(2.2.2.6)

In which:

Part	= chance of plant establishment [vr ⁻¹]
• est	
n _b	= stem density at the bottom [m ⁻²]
n _{b,est}	= stem density of new established tussock [m ⁻²]
D	= plant diffusion coefficient [m ² yr ⁻¹]
r	= intrinsic growth rate of stem density [yr ⁻¹]
К	= max. carrying capacity of stem density [m ⁻²]
PE_{τ}	= plant mortality coefficient related to flow stress [m ⁻² s ⁻¹]
τ	= bottom shear stress [Nm ⁻²]
τ _{cr,p}	= critical shear stress for plant mortality [Nm ⁻²]
PEн	= plant mortality coefficient related to inundation stress [m ³ yr ⁻¹]
H _{cr.p}	= critical inundation height for plant mortality [m]

The establishment of vegetation is determined by defining a probability of plant establishment and stem density of newly established tussocks (Equation (2.2.2.2)). The lateral expansion of plants to neighbouring cells is modelled using a diffusion equation (Equation (2.2.2.3)). Growth is allowed and defined by the stem density which logistically increases up to a specified maximum carrying capacity (Equation (2.2.2.4)). Growth in a cell can either occur by new plants establishing or the increasing stem number of a previously established plant. The maximum carrying capacity is based on the available resources for growth in each grid cell and ensures that this is not exceeded (Best et al., 2018). The growth in each cell is limited by the inundation and shear stresses which either drown or uproot the plants (Equation (2.2.2.5) and Equation (2.2.2.6)).

When either inundated beyond a certain critical inundation height or the bed shear stresses exceed the critical shear stress for erosion of the vegetation, growth is not permitted or the stem density is reduced (Best et al., 2018). More information on the model used can be found in the Appendix of Temmerman et al. (2007).

2.3. Model description

In this thesis, D-Flow Flexible Mesh (DFM), a hydro- and morphodynamic computational model, has been combined with the establishment concept of Balke et al. (2011) and the population development concept of Temmerman et al. (2007) to create a process based vegetation development model based on *Salicornia Europaea*. A numerical model is a representation of a real-world system via mathematical formulations that can then be analysed by computational methods. It enables solutions of complex problems with a great number of simple operations.

Chapter 2: Methodology

Using a numerical model allows us to expand on the field observations at Marconi by simulating the development of *Salicornia* affected by external factors such as hydro- and morphodynamics. Numerical models can therefore lead to a much deeper understanding of the entire system and can be used to simulate alternative scenarios.

The model comprises of three parts; hydrodynamics, morphodynamics and vegetation dynamics. The hydro- and morphodynamics have both been computed in D-Flow Flexible Mesh (Deltares, n.d.). For more information on DFM and the morphological computations, see the user manuals for DFM and D-Morphology respectively (Deltares, 2019a, 2019b). DFM is a new model engine developed by Deltares (n.d.). It is the successor of Delft3D-FLOW and SOBEK-FLOW and can be used for hydrodynamical simulations on unstructured grids in 1D, 2D and 3D. The unstructured grids make it a computationally effective model to use for this thesis, since the overall domain of the Ems estuary can be modelled with large cells while the Marconi site can be computed in detail.

Water flow is directly calculated in DFM, while waves have been determined by calling on a separate Delft3D model, which calculates wave creation due to wind speed and direction over the domain. The external wave model then uses refraction, wave breaking and wave setup to calculate the additional bed shear stress due to wave action, which is used as input for the main flow model. More information regarding the wave model can be found in the D-Waves user manual (Deltares, 2019c).

Finally, Python was used to model the vegetation dynamics and forms the main script, which calls on the DFM model to calculate the hydro- and morphodynamics. The script was written in Spyder (2018), an integrated development environment for scientific programming in Python code, and combined with the 'Basic Model Interface' (BMI) designed by Peckham et al. (2013). The Python code consists of two modules which address the vegetation establishment and population dynamics respectively, namely the growth concepts by; Balke et al. (2011) and Temmerman et al. (2007). Combined, the two modules form the vegetation dynamics of the model. It is important to mention that aspects of both concepts have been selected to be used in the model, as seen in Figure 2-7. The third window of Balke's WoO concept was not included in the vegetation model. Instead this stage of the vegetation dynamics is simulated by the population dynamics of Temmerman et al. (2007). Meanwhile, the establishment term of the population dynamics of Temmerman has been replaced by the vegetation establishment section.

The model's Windows of Opportunity process starts based on the establishment probability (*EP*, Table 4-2). This EP indicates the chance that seeds are available in a cell of the grid. During the WoO process, unless the inundation threshold or the bed level change threshold is exceeded, the seeds develop into plants and start the population dynamics process. This initial growth of the seedlings is simulated in two ways; an instant increase of plant density after a successful window 1 (n_{WoO2} , in stems/m²) and window 2 (n_{ini}) and linear growth of the critical disturbance depth (*CDD*) over time during window 2. After the WoO has completed, the population dynamics process starts in which the plants can increase in density until they reach the maximum stem density (*K*) but can also decrease based on the plant mortality factors due to flow and inundation $\left(\left(\frac{\delta n_b}{\delta t}\right)_{flow}, \left(\frac{\delta n_b}{\delta t}\right)_{inund}\right)$. An overview of the integrated vegetation model can be found in Figure 2-7. Its parameters have been defined in Table 4-1 and Table 4-2 in Chapter 4.3.



Figure 2-7: The combined WoO and Population Dynamics vegetation models displaying the conditions in window 1 and window 2 which should be fulfilled in order for vegetation to establish and the population dynamics equations governing the temporal variation in stem densities. Parameters of both growth rules have been defined in Table 4-1 and Table 4-2 in Chapter 4.3. Adapted from Odink (2019).

This report makes use of three scenarios; a standard run, one in which the marsh is lowered in intervals of 0.25 m up to 1 metre and one scenario in which the brushwood dams have been removed. Every scenario was simulated for one growth season which takes place between April-October, i.e. 180 days. Test runs with the model indicated that run times for one growth season would exceed 30 hours. Therefore, the model has to make use of a morphological factor (Morfac) in the DFM model to decrease the simulation time. The Morfac is a concept introduced to coastal morphodynamic modelling by Lesser et al. (2004) and Roelvink (2006). Morfac essentially multiplies the bed levels computed after each hydrodynamic time step by a factor to enable much faster computation. The significantly upscaled new bathymetry is then used in the next hydrodynamic step. For this thesis, the Morfac has been set at 4 which means that for each timestep completed in the DFM model, the morphological equations are multiplied by 4. Essentially this means that the hydrodynamic input of one timestep of 5 minutes is used for 20 minutes of morphological changes instead. Therefore, in order to simulate one growth season of 180 days, 45 days need to be simulated.

In the vegetation model, the lengths of the windows in WoO have been divided by the Morfac while the change in stem density calculated by the population dynamics have been multiplied by the Morfac for every timestep. The timesteps of the vegetation model are still 12 hours. In other words, taking into account the Morfac the vegetation model is updated for 2 days per timestep. The implications of the Morfac are discussed in Chapter 6.2.4.

The model is run via the Python code which calls forth the DFM model at the start. The DFM model simulates the water flow through the domain for every 5 minutes and determines the corresponding sediment transport and bed level changes with the use of a Morfac of 4. This means that every timestep is equal to 4 timesteps in terms of morphodynamics. After 1 hour of simulation of the DFM model, without taking into account the Morfac, the DFM model interacts with the D-Waves model. D-Waves receives parameters such as bed level, flow velocity, water level and wind data and uses it to calculate wave setup in the domain for 1 hour. It gives back the wave speed and direction for 1 hour to the DFM model, which is used as part of the hydrodynamics. Every 6 hours, hydro- and morphodynamic parameters such as water and bottom level are saved by the DFM model.

After 12 hours, the DFM model provides parameters such as the bed level, water level and shear stresses to the vegetation model in Python. These parameters are used to determine whether the WoO succeed and whether the stem density will decrease due to inundation and shear stresses in the population dynamics. The python model updates every cell located between -1 to +3 m +NAP for the development of vegetation. This range was chosen to reduce the computation time and is based on the elevation of the Marconi salt marsh. The vegetation model uses timesteps of 12 hours but does take into account the Morfac. Therefore, in terms of vegetation development 1 timestep equals 2 days of development. After its update, the vegetation model gives back the stem density, height and diameter to the DFM model and stores the parameters in a table. These parameters are then used by the DFM model to calculate the roughness field in each cell. The setup of the overall model and its interactions can be seen in Figure 2-8.



Figure 2-8: The interaction between the hydrodynamic model (DFM, top left), wave model (D-waves, bottom) and the vegetation model in Python (right) along with the phenomena the separate sections calculate and pass on.

2.4. Data collection

For this thesis, data was primarily collected from literature and measuring stations near the Ems-Dollard. Sources which were used for the setup of the DFM model and the parameterisation of the vegetation model are discussed in Chapter 3 and 0 respectively. Data regarding the bed level change at Marconi and the water level at Delfzijl have been used to compare to results in Chapter 5.1 and will be shown here.

Bed level change data of half a year, between February and August 2019, at the Marconi marsh was obtained from M. van Puijenbroek (2019) of the Wageningen University who used the SEB stations at the sections (Figure 2-5) to measure the bed level change. This data will be compared to the model results of one growth season. As an example, one of the measured bed level changes at section F can be found below (Figure 2-9).

For the lower areas of the marsh we are thus looking for bed level changes of a couple centimetres in half a year in the model. For the higher areas this decreases to around a couple millimetres to 1 cm in a half year.

Water level data from the harbour of Delfzijl in 2019 was obtained from Rijkswaterstaat (2019). The water levels will be compared to the model results of one growth season to check whether the model is potentially underestimating the water level at the Marconi site. As an example, the water level during April, the first month of the growth season, can be found below in Figure 2-10. In this first month, the water level seems to fluctuate gradually between -2 m +NAP and 1.5 m +NAP. Storm surges do not seem to have occurred during this period.

Besides external data, field measurements were also performed during a one-day excursion to the Marconi salt marsh by using a GPS to measure elevation of the sections. Transect elevation data was collected cross-shore in every section except section X, see Figure 2-5. This is because the section contains a large heap of sand which significantly disturbs the flow field and morphodynamics in the section and will therefore not be taken into account.

The excursion was focused on measuring the bed level of sections E, F and G, since these are the most interesting sections due to the sown *Salicornia*. Other data such as the stem densities in the sown and unsown sides of section E, F and G and the dimensions of the brushwood dams were also collected although at a limited sample size. An overview of the bed level data points can be found in Appendix A, while the brushwood dams and stem densities are discussed in Chapter 3.2 and 4.4 respectively.



Figure 2-9: The measured bed level change (in cm) in section F from February to August 2019. This means that we are looking for a couple of cm's of bed level change per half year in the sections. At the channels, this is slightly higher at one dm of most likely erosion per half year. See Figure 2-5 for the location of the section. The data was obtained from M. van Puijenbroek (2019) of the Wageningen University who used the SEB stations to create these measurements.



Figure 2-10: Water level (m) at the harbour of Delfzijl during April 2019. Water level data of the entire year 2019 was obtained from Rijkswaterstaat (2019).

3. DFM model set-up

3.1. Domain and time frame

A first version of the domain was obtained from one of the supervisors, Jasper Dijkstra from Deltares. The first version's grid, boundaries and elevation of the domain have been used for the domain of the DFM model. It is important to note that, in particular, the grid and elevation throughout the domain could have used refinement. However, since the dynamics inside the Ems-Dollard are not the focus of this research, the required time was deemed to outweigh the potential gain. On the other hand, the input of the boundaries, sediment characteristics, wind data as well as the elevation and brushwood dams at the Marconi marsh were added by this thesis based on collected field measurements and data.

The domain, shown in Figure 3-1 combined with its geographical location, is of the Ems-Dollard estuary from just below Eemshaven in the north to around Termunterzijl in the east. Two open boundaries have been made in the domain; one towards the North Sea near Eemshaven and one towards the Ems near Termunterzijl. Water levels are defined at the northern boundary, while the discharge is defined at the eastern boundary. Wind waves are locally generated by using wind speeds and wind directions over the domain.

No waves have been imposed at the boundaries, since these are not expected to reach the sheltered position of the Marconi marsh due to surrounding jetties blocking the incoming waves. The same boundaries were used for the sediment input. The input of these boundaries will be discussed in the next section.

The grid is asymmetric with roughly 10,000 cells and the resolution of the cells ranging from 350x350 metres at the deeper parts to 10x10 metres near the Marconi marsh (i.e. the area of interest). The bed level, seen in Figure 3-2, ranges from -15 m +NAP at the shipping routes in the estuary to 10 m +NAP at land. It should be noted that 10 metres is much higher than the elevation in reality. This is done to ensure that these areas do not flood. In order to model the bed level at Marconi, elevation measurements were collected at the field site as discussed in Chapter 2.4. DFM was used to interpolate the elevation between the data points. The bed level in Marconi along with the brushwood dams can be found in Figure 2-4.

The model has a start-up time of 3 months from January 1st to March 31st and simulates for April 1st to November 1st using the water levels obtained at Eemshaven from 2012. The model simulation time could be extended to include the winter season (October-March), since parameters for the winter have been incorporated in the model. Simulations of one year were not performed because of the long computation times (see Chapter 2.3) and the lack of importance of the winter season in the intraannual development of *Salicornia* after the initial disappearance of the plant. It is important to mention that, while the model does use real values as hydrodynamic and wind input, it has not been calibrated to hydrodynamics during 2019, the year that Marconi was constructed and the measurements at Marconi have been performed. Instead of simulating the dynamics of 2019, the focus of this thesis is to study the dynamics between the used parameters.

Chapter 3: DFM model set-up



Figure 3-1: The domain of the Marconi model taken out of the DFM model along with the geographical location in the background. At the location of the Marconi marsh, the grid is finer than at the edges of the system. In the north is the boundary to the Wadden Sea and North Sea, while in the east the boundary towards the rest of the Ems-Dollard can be found.



Figure 3-2: The elevation of the Ems-Dollard estuary domain compared to NAP. Elevation ranges from -15 metres at the main shipping route to +10 metres at land. In reality the land is not as high, but this has been done to prevent flooding in the model.

3.2. Boundary and initial conditions

Hydrodynamic conditions are forced at the boundaries shown in Figure 3-1. At the North Sea boundary, a water level has been imposed ranging between -2.6 m +NAP and 3 m +NAP, see Figure 3-3. The data was measured at Eemshaven in 2012 and obtained from Rijkswaterstaat (2012). It includes all tidal constituents (i.e. M2, S2) as well as the water level setup due to wind. While the Ems only has an average discharge of 80 m³/s, the discharge of the eastern boundary needs to be much larger. This is because the boundary starts in the middle of the Ems-Dollard estuary instead of at the end of the Ems river. The actual discharge of the boundary is primarily affected by the tidal flow as well as the discharge of the Ems and other small rivers. However, modelling the tidal lag would have been too complicated and does not form an important part of this study. Therefore, a constant discharge of 1000 m³/s was used for the eastern boundary, which was based on the required stability of the boundary's bed level. The actual discharge observed in the model varies over time because of the influence from the North Sea boundary conditions on the flow at the eastern boundary. This effect can be seen in Figure 3-4. The boundary conditions can be found in Table 3-2.

Besides the water flow conditions, it is also crucial to take the wave conditions in the Ems-Dollard estuary into account in the morpho- and vegetation dynamics model. This is due to the significant bed shear stresses at the bed and shoreline that shallow water waves are known to create (Myrhaug, 2017). Wind data obtained from the Winschoten weather station of KNMI (2018) has been used as input over the entire domain in a wave model linked to the hydrodynamic DFM model (Deltares, 2019d). The data comprises wind direction and speed from 2018 and is defined in 4-hour intervals. While the obtained data is of a different year than the water level data, it was used because detailed wind data sources near Delfzijl for 2012 were not available. This dissimilarity will likely have a significant impact on the generated hydrodynamics and is therefore brought up in the discussion (Chapter 6.2.2). The wind has been found to originate primarily from western and southern directions with wind speeds of up to 18 m/s (Figure 3-5). Since waves generated in the North Sea and Wadden Sea are unlikely to reach the sheltered Marconi marsh, these have been neglected.



Figure 3-3: The Water level (in m) at the North Sea boundary measured at Eemshaven in 2012 (Rijkswaterstaat, 2012). This is almost exclusively due to the tides. Interestingly, the actual tidal range is between -2.56 m +NAP to 3 m +NAP However, these extremes rarely occur, with the water levels usually varying between -1.5 m to 1.5 m +NAP



Figure 3-4: Modelled discharge (m^3/s) over time at the Ems boundary. While the boundary uses 1000 m^3/s as discharge, the modelled discharge differs due to the influence of the tides originating from the North Sea boundary. Without the tidal influence, the discharge would therefore be 1000 m^3/s .



Figure 3-5: Wind rose chart of the 2018 wind data obtained from the Winschoten weather station roughly 20 km from Delfzijl (KNMI, 2018). Percentages have been used to indicate how often a combination between direction and speed is reached. The wind direction seems to be primarily from southwestern direction with wind speeds of up to 18 m/s.

The hydrodynamic conditions at the open boundaries are accompanied by sediment input. At the North Sea boundary, a varying clay concentration (in kg/m³) has been imposed. The clay concentration starts at 0.2 kg/m³ in January before linearly decreasing to 0.05 kg/m³ In June and going back up to 0.2 kg/m³ at the January of next year. This was based on the variation in clay concentration measured northwest of Marconi in one of the channels by van Maren et al. (2015) (Figure 3-7). In these measurements a monthly variation in clay concentration can be seen which was emulated in the model. At the Ems boundary to the east, the constant discharge is joined by a constant sediment input of 0.05 kg/m³ clay. The clay concentrations have been set up in such a way that the suspended sediment concentration at the Marconi marsh (Figure 3-6) are in a similar order of magnitude as in the data shown in Figure 3-7. However, the modelled clay concentration appears to be mainly caused by large peaks in concentration, with very little suspended sediment during calm conditions.



Figure 3-6: The clay concentration (in kg/m^3) outside of the Marconi marsh (north) during the first month of the growth season. Concentrations are in the same order of magnitude as the data shown in Figure 3-7.

Besides the sediment source at the boundaries, the following initial conditions have been used to model the sediment dynamics at each of the sections in Figure 2-5 and the rest of the domain; the sediment thickness (in m) and critical bed shear stress (in N/m^2). For the sediment thickness a well-mixed 1 metre thick layer of sand and clay in the Marconi marsh is used of which the fractions, based on grain size measurements for each section, can be found in Table 3-2. Note that the actual sediment composition is different from the experimental setup seen in Figure 2-5. This is because the mixing of solid clay clumps and sand was difficult to perform. The rest of the domain contains a well-mixed 4-metre-thick layer of sand (75%) and clay (25%). The layers at the domain were made larger because of large amounts of erosion and deposition found at the boundaries of the system during the growth season simulation (Figure 3-8).



Figure 3-7: Timestack plot of suspended sediment concentration in kg/m3 at Delfzijl. Obtained from Van Maren et al. (2015).



Figure 3-8: The bed level change (m) over the domain of the DFM model after a simulation of the growth season (180 days). Erosion at the North Sea boundary is significant. This is why the layers of the domain were enlarged to 4 metres deep instead of the 1 metre at Marconi.

Finally, the brushwood dams (Figure 2-3 & Figure 2-5) were modelled in DFM based on field measurements made at the Marconi marsh with the GPS. During the field trip, one measurement was made of the elevation of the dams at the waterside of section A to D, while E, F and G had three measurements. An overview of the measured elevation compared to NAP can be found in Table 2 below. The width of all brushwood dams was assumed to be roughly 20 cm based on a measurement at section E. The measured elevation of the dams at each section was used along with the width of 20 cm, as the dimensions of the section's brushwood dams (e.g. section A was surrounded by dams with a height of 1.6 m +NAP while section F was surrounded by dams with a height of 1.5 m +NAP).

Table 3-1: Height measurements (in m + NAP) of the brushwood dams found at the waterside of the sections. One measurement was made at section A to D respectively while three measurements were made at E, F and G each. Measurements were done with a GPS.

Sections	Avg. height of brushwood dam (m)
А	1.6
В	1.6
С	1.7
D	1.7
E	1.6
F	1.5
G	1.4

3.3. Sediment characteristics

The critical bed shear stress determines at what bed shear stress the sediment starts to erode. This was only parameterised for clay, since the erosion of sand can already be determined with its median sediment diameter (Table 3-2). Several researchers have looked at critical bed shear stresses of clay layers in the Wadden Sea or Ems.

Maerz & Wirtz (2009) did their research on the dynamics of suspended particulate matter (SPM, i.e. amount of suspended particles) at Spiekeroog, a German island in the Wadden Sea (Figure 2-1). By using parameter variation in their model and comparing it to measurements near Spiekeroog, they discovered that the critical bottom shear stress varies over the seasons; with a bed shear stress of 0.29 N/m² during winter and 0.36 N/m² during summer. This is due to the influence of biological processes on the dynamics of SPM, such as algae.

Another study by Houwing (1999) looked at the critical erosion threshold of cohesive sediments at the Groningen Wadden Sea Coast, see Figure 2-1. These measurements were performed at the intertidal flats just in front of the dikes and calculated the critical erosion thresholds of mud contents ($\tau_{b,o}$) found at the site. Compared to the research of Maerz & Wirtz (2009), these critical bed shear stresses are low, at only 0.10-0.18 N/m². Since the paper by Maerz & Wirtz (2009) measured critical bed shear stresses for the sea bottom, these measurements have been used for the domain of the Delft-3D FM model, while the critical bed shear stress at Marconi is based on the measurements at the intertidal flats in Groningen. For the greater model domain, a critical bed shear stress of 0.3 N/m² has been defined, while in the Marconi marsh it was changed to 0.15 N/m². The sediment characteristics of sand and clay are summarized in Table 3-2.

Table 3-2: The input parameters of the hydrodynamic model. Boundary conditions and initial conditions are discussed in Chapter 3.2, while the sediment characteristics are discussed in Chapter 3.3.

Input type	Parameters	Value		Source
Boundary conditions & wind	Hydrodynamic input			
(Chapter 3.2)	Tidal Range Eemshaven	-2.56 to 3m	+NAP	(Rijkswaterstaat, 2012)
	Discharge Ems	1000 m³/s		-
	Sediment input	Clay	Sand	
	Suspended sediment Eemshaven	0.2 to 0.05 kg/m ³ (January- June)	-	Adapted from van Maren et al. (2015)
	Clay concentration Ems	0.05 kg/m ³	-	Adapted from van Maren et al. (2015)
	Wind speed and direction	See Figure 3	-5	(KNMI, 2018)
				I
Sediment composition	Sections (Figure 2-5) 1-metre-thick layers	Clay	Sand	
(Chapter 3.2)	A	10%	90%	Grain size
	В	10%	90%	measurements obtained
	С	25%	75%	from Deltares (Pim
	D	45%	55%	Willemsen)
	E	40%	60%	
	F	25%	75%	
	G	5%	95%	
	Х	5%	95%	
	Outer area Marconi	50%	50%	
	Rest of domain	75%	25%	-
	4 metres thick layer			
			·	
Sediment characteristics		Clay	Sand	
(Chapter 3.3)	Specific density	2650 kg/m ³	2650 kg/m ³	(Deltares, 2019d)
	Dry bed density	500 kg/m ³	1600 kg/m ³	
	Median sediment diameter	-	0.0002 m	
	Current related roughness (k _s)	-	0.01	
	Settling velocity	0.00025 m/s	-	
	Erosion parameter	0.0001	-	
	Crit. Stress for sedimentation	1000 N/m ²	-	-
	Crit. Stress for erosion in Domain	0.3 N/m ²	-	(Maerz & Wirtz, 2009)
	Crit. Stress for erosion in Marconi	0.15 N/m ²	-	(Houwing, 1999)
	Crit. Stress for erosion in forelands Marconi	0.25 N/m ²	-	-

4. Vegetation modelling

This thesis uses the Marconi salt marsh to investigate the development of *Salicornia Europaea* on an intra-annual time scale. As mentioned before, the Marconi site is home to two different *Salicornia* species; *Europaea* and *Maritima*. The former occurs naturally throughout the salt marsh as it is supplied by other salt marshes in the Ems-Dollard area (Figure 2-1). *Salicornia Maritima* was sown by Ecoshape in half of the sections E, F and G (Figure 2-5). Despite the presence of two different species, due to the lack of research on *Maritima*, this thesis has parameterised all *Salicornia* vegetation as *Europaea*.

Before being able to simulate the development of *Salicornia* with the vegetation model, the important characteristics such as its life cycle and establishment process had to be investigated. The parameters of the WoO and population dynamics models have been defined by using the characteristics of *Salicornia Europaea* and other pioneer species such as *Spartina Anglica*. The two conceptual models have been combined into one python code to form the vegetation dynamics of this model study.

4.1. Life cycle of Salicornia

Salicornia Europaea is a halophytic plant which grows in various zones of the intertidal salt marshes. This species can tolerate high salinity (Rubio-Casal et al., 2003) and has substantial phenotypic plasticity. Phenotypic plasticity refers to changes in an organism's behaviour, morphology and physiology in response to a unique environment (Price et al., 2003). Upper- and lower-marsh *Salicornia* populations show substantial genetic differentiation which is evident in their growth, life cycle, and patterns of mortality and density dependent fertility (A J Davy & Smith, 1985).

Typically, the life cycle of *Salicornia* is summer-annual, although in subtropical environments the plants have been able to persist for more than a year (A.J. Davy et al., 2001). In the Netherlands, *Salicornia* dies off starting at October-November during which the flowers of the plants shed their seeds (Beeftink, 1985). Over the winter most seeds get taken away by the tide, however some remain and are able to germinate near its parent. Germination (Figure 4-1b) occurs when the seeds get in contact with fresh water and temperatures are suitable. This process usually occurs at the end of winter, but can potentially be protracted in mild winters (Beeftink, 1985). After germination, the seed will attempt to establish in the area and will evolve into a seedling (Figure 4-1c). Figure 4-1 shows the development of *Salicornia Europaea* seeds from a seed towards a developing seedling at the start of its growing phase.



Figure 4-1: Germination and seedling development in Salicornia Europaea agg. (a) seed, (b) germination, and (c-g) developing seedling. Obtained from Davy et al. (2001).

4.2. Salicornia establishment and die-off

Because of its short life cycle, the seasonal variability of *Salicornia* greatly affects the population development. *Salicornia Europaea* produces seeds only as the plant dies. Since *Salicornia* dies off at the start of winter (Beeftink, 1985), this creates a peak in seed density which then decreases over time due to seed dispersion and seed mortality (Chang et al., 2007; Pons, 1991). Figure 4-2 shows temporal patterns in seed density over two years of measurements at Schiermonnikoog (Chang et al., 2007). Not only does the graph show an increasing seed production during the winter, but it also shows the effect a storm can have on the seed density in an area. Storms at the end of the winter disperse most of the seeds (Figure 4-2a), decreasing the seed density in the area. On the other hand, the storm at the start of winter created a temporary increase in seed density the month after (Figure 4-2b). However, it decreased the seed density over the rest of the year. While significant for the future population in the salt marsh, the effect of storms on the seed distribution in an area is not taken into account in this thesis.



Figure 4-2: Temporal patterns in seed density of a combination of 29 species (including Salicornia Europaea and Spartina Anglica) over two seasons. Measurements were taken at Salt marshes on the Wadden island of Schiermonnikoog, The Netherlands. S indicates a storm hitting the salt marsh. Obtained from Chang et al. (2007).

Based on field measurements at the Western Scheldt estuary, Schwarz et al. (2018) determined a probability of establishment of 8% for *Salicornia* over the entire first year. Essentially, this means that there is an 8% chance that seeds were available on any location. Figure 4-3 shows the simulations of *Spartina* and *Salicornia* made by Schwarz et al. (2018). The population development over multiple years of the numerical model (Figure 4-3) showed similarities with the field observations.

Besides temporal (seasonal) variability, spatial variability can also affect the location of newly establishing vegetation. *Salicornia* seeds are known to be able to behave as suspended sediment particles (Watkinson & Davy, 1985). The rapid colonization of the polders in The Netherlands by *Salicornia*, *Atriplex* (saltbush) and *Suaeda* (seepweeds) is witness to the effectiveness of long distance dispersal in these intertidal species (Joenje, 1978). On the other hand individual plants containing seeds can also be buried where they have grown so that dispersal is extremely restricted (Watkinson & Davy, 1985). Unfortunately, there are no quantitative estimates of the dispersal of salt marsh annuals. Some seeds travel a long distance but a number of authors have observed that many seeds germinate near the parent plant (Jefferies et al., 1983; Joenje, 1978).


Figure 4-3: Simulations of the fast colonizer Spartina (dark green lines) and the slow colonizer Salicornia (light green lines). VC is the vegetation cover in the area over the years. mUPL is the average distance water has to travel to run-off towards one of the channels. The initial bathymetry is based on Hooge Platen in 2006. Obtained from Schwarz et al. (2018).

4.3. WoO and population dynamics

The processes of the Windows of Opportunity and population dynamics had to be parameterised for *Salicornia Europaea*. Starting with the Windows of Opportunity, the first window is, as discussed before in Chapter 2.2, required to be disturbance-free from hydrodynamic forces, so that the seeds can strand, develop roots and withstand the stress of flooding. This can be modelled as an inundation-free period (Attema, 2014; Hu et al., 2015). However, while theoretically the inundation threshold should be at 0 m, since the DFM model can create unrealistically small inundations in its cells, the critical inundation depth (H_{inund}) for the model was set to 0.1 to increase stability. The duration of this first window (T_{WoO1}) was set to 2.5 days, which is based on the results of Hu et al. (2015) found when hindcasting salt marsh establishment in the Western Scheldt.

For the second window parameters, root lengths from field measurements in Momonoki & Kamimura (1994) were used to determine an initial critical disturbance depth ($CDD_{initial}$) 8 mm of *Salicornia Europaea*. Figure 4-4 shows the change in root length (in mm) of *Salicornia Europaea* over time. After 90 days, the growth rate decreases significantly. Therefore, the duration of the second window (T_{WoO2}) was estimated to be 90 days (starting from 2.5 days). Furthermore, Poppema (2017) performed a flume experiment for *Salicornia Europaea* in which he measured an average critical disturbance depth (CDD) of 12.15 mm after 20 days. By combining these two points and assuming a linear growth rate (α_3) of the CDD, a final critical disturbance depth for mature vegetation (CDD_{mature}) can be determined after 90 days of growth (Equation (4.3.1):

$$CDD_{mature} = \alpha_3 * T_{Wo02} + CDD_{initial}$$

$$\alpha_3 = \frac{12.15 - 8}{20} = 0.21 \ mm/day$$

$$CDD_{mature} = 0.21 * 90 + 8 = 26.9 \approx 27 \ mm$$
(4.3.1)



Figure 4-4: The change in root length (mm) over time of Salicornia as obtained from Momonooki & Kamimura (1994). As can be seen in the figure at the dashed line, around 90 days the growth of the roots decreases significantly. Therefore, the second window was estimated to last for 90 days. With an initial critical disturbance depth equal to the root length.

All the vegetation establishment parameters along with their meaning, value and source which are used in the WoO framework are given in Table 4-1. Because of a lack of better data, the long-term erosion and sedimentation limits of *Salicornia* have been based on the mortality rates that occurred for *Spartina* when the values were exceeded in the experiments of Cao et al. (2017). It is assumed that these are similar. The value for the averaging period for short-term erosion (T_{avg}) was found in the research of Poppema (2017). The sensitivity to bed level change (α_2) was obtained from the flume experiments performed by Poppema (2017) for *Salicornia*. Finally, the plant density at the start of window 2 (n_{woO2}) was based on field measurements of *Salicornia*, which are addressed in Chapter 4.4. The parameterised development of *Salicornia* is represented in Figure 4-5.

Chapter 4: Vegetation modelling

Table 4-1: The parameter values of Salicornia Europaea that are used for the WoO framework. The first seven parameters were obtained from literature, while the last two were calculated by combining data from Momonoki & Kamimura (1994) and Poppema (2017).

Parameter	Meaning	Unit	Value	Source
T _{WoO1}	Duration of window 1	[days]	2.5	(Hu et al., 2015)
T _{WoO2}	Duration of window 2	[days]	90	Based on field measurements of <i>Salicornia</i> <i>Europaea</i> (Momonoki & Kamimura, 1994)
E _{avg, max}	Max long- term erosion	[mm week ⁻¹]	5	Based on flume experiments for <i>Spartina</i> (Cao et al., 2017)
S _{avg, max}	Max long- term sedimentation	[mm week ⁻¹]	15	Based on flume experiments for <i>Spartina</i> (Cao et al., 2017)
T _{avg}	Averaging period for short-term erosion	[days]	7	Obtained from a salt marsh study for <i>Spartina</i> (Poppema, 2017)
$CDD_{initial}/\alpha_1$	CDD at start of window 2	[mm]	8	Based on field measurements of <i>Salicornia Europaea</i> (Momonoki & Kamimura, 1994)
α ₂	Sensitivity to bed level change	[-]	1.52	Obtained from the flume experiments performed by Poppema (2017).
α ₃	Growth rate CDD	[mm day ⁻¹]	0.21	Based on field measurements of <i>Salicornia</i> <i>Europaea</i> (Momonoki & Kamimura, 1994) and the flume experiments performed by Poppema (2017).
CDD _{mature}	CDD of mature vegetation	[mm]	27	Based on field measurements of <i>Salicornia</i> <i>Europaea</i> (Momonoki & Kamimura, 1994) and the flume experiments performed by Poppema (2017).
H _{inund}	The critical inundation depth for window 1 of the WoO's model.	[m]	0.01	(Attema, 2014; Hu et al., 2015)
n _{w002}	Plant density of seedlings during Window 2	[stems m²]	20	Based on field measurements (Chapter 4.4)



Figure 4-5: The critical erosion depth (in mm) of Salicornia Europaea during window 2 as proposed by the used parameters from Table 4.

Next, the parameters for the population dynamics model are summarized in Table 4-2. Most of these have been determined based on the recent paper of Schwarz et al. (2018). Five noteworthy parameters are the establishment probability (*EP*), the plant diffusion coefficient (*D*), the initial plant density (n_{ini}), maximum stem density (K) and the intrinsic growth rate (r). The establishment probability is used because the vegetation establishment model (WoO) only looks at the possibility of establishment. The EP is therefore the chance that seeds are actually available for this establishment process. This chance is used at the start of the vegetation establishment model. The establishment probability has been adjusted based on vegetation measurements at Marconi (Chapter 4.4). Furthermore, instead of using the EP every time window 2 completes, as done by Schwarz et al. (2018), it is now done before the start of the WoO's. This enables us to take into account the developing vegetation during this stage. Furthermore, an EP for the sown areas has been used separately to indicate the higher chance of establishment in these areas. This EP_{sown} gives a 55% chance of establishment in the sown areas during the first timestep of the model and was based on field measurements discussed in Chapter 4.4. The plant diffusion coefficient is set at 0 since Salicornia is known to lack clonal growth and therefore grows homogeneous and spreads out over the region (Bouma et al., 2013; Friess et al., 2012; Schwarz et al., 2018; Temmerman et al., 2007). This forms an important difference with Spartina which is known for its patchy growth due to its clonal growth. The initial plant density (n_{ini}) , maximum stem density (K)and the intrinsic growth rate (r) were calibrated using field measurements discussed in Chapter 4.4. More information on the effects of the diffusion parameter and the change in establishment probability as compared to Schwarz et al. (2018) can be found in Appendix B.

Finally, it should be noted that a plant mortality for winter has been added to the population dynamics model. This is necessary because *Salicornia* is known to be an annual plant (Chapter 4.1). The value has been set up so that the maximum plant density of 600 stems/m² would take 2 months to disappear. This was based on observations by Beeftink (1985) previously discussed in Chapter 4.2. The python code of the vegetation dynamics can be found in Appendix C.

Table 4-2: The parameter values of the population dynamics model of Temmerman et al. (2007) that were determined for Salicornia Europaea and updated in the DFM model.

Parameter	Meaning	Unit	Value	Source
n _b	The number of	[Stems	Equation	(Temmerman et al., 2007)
	stems	m⁻²]	(2.2.2.1)	
n _{ini}	Initial plant	[Stems	60	Based on field measurements
	density of	m⁻²]		
	seedlings			
EP	Establishment	[hr-1]	0.0075/12(dt)	Calibrated based on field
	probability before		= 6.25*10 ⁻⁴	observations
	starting the WoO's			
EPsown	n Establishment		0.55/12= 0.046	Calibrated based on field
	probability of the			observations
	sown areas for the			
	first timestep (12			
	hrs)			
D	Plant diffusion	[m²yr⁻	0	(Bouma et al., 2013; Friess et al.,
	coefficient	1]		2012; Schwarz et al., 2018;
				Temmerman et al., 2007)
r	Intrinsic growth	[yr⁻¹]	20	Based on field measurements
	rate of stem			
	density			
К	Max. carrying	[stems	600	Based on field measurements
	capacity of stem	m²j		
05	density	F. 2 .	20	(T
ΡΕτ	Plant mortality	[m -s	30	(Temmerman et al., 2007; Van
	coefficient related	-]		Huizen et al., 2007)
-	Critical chear	[NImo-2]	0.25	(Sobwarz et al. 2018)
L _{cr, p}	chucal shear	[INTR -]	0.25	(Schwarz et al., 2018)
	mortality			
DF.,	Plant mortality	[m ³ vr ⁻	3000	(Schwarz et al. 2018: Temmerman
ΓLH	coefficient related	1]	5000	(Jeffwarz et al., 2018, Terrinerman
	to inundation	1		2007
	stress			
H _{cr. n}	Critical inundation	[m]	1.0	(Temmerman et al., 2007)
<i>ci, p</i>	height for plant		-	
	mortality			
D	, Default diameter	[m]	0.005	(Bouma et al., 2013)
	stems			
h_{v}	Default height	[m]	0.28	(Bouma et al., 2013)
	stems			
PE _W	Plant mortality	[Stems	0.42	(Beeftink, 1985)
	due to the start of	m⁻² hr⁻		
	winter	¹]		
Cb	Stem stiffness	[-]	0.7	Standard DFM value
Cd	Drag coefficient	[-]	0.7	Standard DFM value

4.4. Vegetation parameters based on field measurements

From Table 4-2, initial plant density (n_{ini}) , maximum stem density (K) and the intrinsic growth rate (r)have been calibrated based on field measurements. Photographs were taken at sections E-G at the Marconi marsh of a 0.25 m² square surrounding *Salicornia* (Figure 4-6). By counting the number of individual Salicornia plants, the plant density of sections E-G's sown and unsown areas was determined (Table 4-3). Based on the measurements, the initial plant density at the start of the population dynamics stage was estimated to be 60 plants/m²; the same for each section. Because there is no diffusion (D), this amount also does not change over time in the cell. Based on Jefferies et al. (1981), it was assumed that each plant can maximally create 10 stems. Combining this with the field measurements thus led to a maximum carrying capacity of stem density (K) of 600 stems/m². Furthermore, observations showed that areas with vegetation in their early development stages had a much lower plant density which was estimated at around 20 plants/m². The stem density during the second window of the WoO model was therefore set at 20 stems/ m^2 . The intrinsic growth rate of the stem density (r) has been calibrated such that only cells with a fast establishment at the start of the growth season get close to the maximum carrying capacity. This prevents every cell with vegetation to develop the maximum density, but does allow in particular the sown sections to develop dense vegetation patches as was the case at the Marconi site (Figure 4-6). Finally, the establishment probability of the unsown and sown areas (EP, EPsown) were calibrated from the original 8% of Schwarz et al. (2018) by comparing model runs with the stem densities found in the sown and unsown sections of the Marconi marsh. The modelled and measured stem densities are compared in Chapter 5.1.



Figure 4-6: Stem density measurement using a 0.25 m^2 square (i.e. stems/m²) inside section E at the Marconi marsh.

Table 4-3: Counting of individual Salicornia plants at sections E-G in the Marconi marsh. The measurements were done via squares of 0.25 m^2 (Figure 4-6). The last column translates this to an average density per square metre. Note that two pictures were used for the unsown areas. For the sown areas, one measurement was done per section.

Sections	Sown	Not sown	Average/m2
	(0.25 m²)	(0.25 m²)	
E	30	17.5	95
F	28	8.5	73
G	12	6.5	37

5. Results of the model and field measurements

This chapter presents the results of this study, which were all created by running the model for 45 days along with a Morfac of 4 to simulate one growth season (180 days) lasting from April to October. First, the model results are validated by comparing them to the water levels, bed level change and vegetation development measured at the Marconi marsh. Next, the hydrodynamic results are shown, which comprise of the inundation time (%), bed shear stress (N/m²), wave height (m) and classifies water levels and wave heights into a high and general category to help compare the data to the results of the morphodynamics and vegetation dynamics. These hydrodynamic parameters influence the morphodynamic results (bed shear stress affects bed level change) and the vegetation results (bed level change and inundation affect vegetation) which are respectively presented in the remaining two sections. Both the morphodynamics and vegetation dynamics results will also investigate their sensitivity to the brushwood dams and the high water levels and wave heights.

5.1. Comparison of model results

The modelled water levels at the Marconi marsh, obtained from observation points G_{north} (Figure 2-5), were compared to water levels of inside the harbour of Delfzijl in 2019, which were obtained from Rijkswaterstaat (2019) and are discussed further in Chapter 2.4. It should be noted that the North Sea boundary uses a water level dataset from 2012. Therefore, the comparison is not to check whether modelled and measured agree over time, but rather whether their tidal range is similar. Figure 5-1 shows the measured and modelled water levels plotted over the simulation time (45 days), while Figure 5-2 and Figure 5-3 show histograms of the measured and modelled water levels near Marconi respectively.



Figure 5-1: The Measured water level (m) at the Delfzijl harbour (Rijkswaterstaat, 2019), see Chapter 2.4, along with the modelled water level (m), obtained from observation points G_{north} (Figure 2-5), over time during the growth season. Since a Morfac of 4 is used, the hydrodynamic run time is only from April 1st to May 16th.

From Figure 5-1, we can conclude that the modelled and measured water levels are reasonably in sync, with peaks and throughs occurring around the same time. Furthermore, the tidal range of both the model and measurements are around 3.5 m. However, the modelled system is much more variable in its water level during this spring-neap cycle. Relatively low peaks during spring can be observed around the 5th of April, while a high peak during neap can be seen around the 13th of May. This discrepancy could be caused by the wind data from 2018, which is from a different year then the North Sea boundary data and could therefore have distorted the graph. Another possibility is the tidal input of the North Sea boundary not being as impactful on the water level throughout the domain as in reality, therefore allowing for larger distortions in the spring-neap cycle.

The histograms reveal that average water levels are more frequent in the model, while the measurements reveal a higher occurrence of low (-2 to -1.75 m) and in particular high water levels (1-1.5 m). In other words, the model does underestimate the frequency of extreme water levels, while being in reasonable agreement with the average water levels found in the measurements.



Figure 5-2: Histogram of the frequency of water level bins for the measured water level at Delfzijl during one growth season.



Figure 5-3: Histogram of the frequency of water level bins for the modelled water level at the Marconi marsh during one growth season. Obtained from observation points G_{north} (Figure 2-5).

Next, the modelled bed level changes (cm) at the SEBs inside sections E-G (i.e. E_{low,middle,high}) have been plotted against the measured bed level changes (cm) at these positions (Figure 5-4). Unfortunately, there was no SEB data available to compare with the bed level dynamics of the forelands. The modelled bed level changes show no correlation with the measured bed level changes. Points located at the higher elevations show no modelled bed level change at all, while the measured bed level change is around a couple cm's in half a year. At the lower sections, the modelled bed level changes seem to be a factor 10 smaller than their measured counterparts. Furthermore, the modelled results are inclined towards sedimentation while the measurements are inclined towards erosion. Potential improvements for the modelled morphodynamics are discussed in Chapter 6.3.



Figure 5-4: The bed level change (cm) at the sedimentation erosion bars (SEB's) inside sections E-G as modelled compared to the actual measured bed level change. The dashed red line shows where modelled would equal measured.

Finally, to compare the modelled and measured vegetation dynamics, sections E, F and G have been divided in sown and unsown sections. The simulated average stem density in these sections was then compared to the field measurements at the Marconi site (Figure 5-5). The modelled density shows reasonable similarity with the field measurements (R^2 = 0.61), especially at the unsown areas where the density is relatively low. However, the denser the vegetation becomes the larger the inaccuracies. From another perspective one could say the field measurements show a clear decreasing trend between the sections from E towards G. The modelled vegetation does not follow this trend and instead remains relatively constant.

Overall, the modelled vegetation seems to be well-calibrated with respect to the field measurements. This was achieved by calibrating the establishment probabilities of the unsown areas to 0.0075 (*EP*, with dt=12 hrs) and of the sown areas to 0.55 (*EP*_{sown}, with dt=12 hrs) based on the field measurements as discussed in Chapter 4.4. The correlation between the modelled and measured stem densities was therefore to be expected. Other important parameters for the vegetation dynamics are the critical inundation depths for window 1 (*H*_{inund}=0.01 m, Table 4-1), the critical disturbance depth of window 2 (*CDD*=8-27 mm, Table 4-1) the critical shear stress for plant mortality ($\tau_{cr, p}$ =0.25 N/m², Table 4-2) and the critical inundation height for plant mortality (*H*_{cr, p}=1.0 m, Table 4-2) as these form the negative effects of the hydrodynamics and morphodynamics on the vegetation population.





Figure 5-5: The modelled stem density (stems/ m^2) of both the sown (3 larger values) and unsown (3 values at the lower left) areas in sections E-G compared to the actual measured stem density. The dashed red line shows where modelled would equal measured. R^2 denotes the correlation between the modelled and measured stem densities of the six points.

5.2. Hydrodynamic results

The inundation time for two different thresholds expressed in percentages during one spring-neap cycle can be found in Figure 5-6 & Figure 5-7. Each cell was checked every 6 hours, which is the timestep for which DFM saved its hydro- and morphodynamic parameters. Figure 5-6 shows percentage of time a cell was inundation by 0.01 m or higher, while Figure 5-7 checks for inundations of 0.15 m or higher. The former was picked because it equals the critical inundation depth for establishment during window 1 in the WoO model. The latter shows the inundations that have effect on the morphology, since the inundation threshold for sediment calculations (*Sed*_{thr}) was set at 0.15 m. This threshold is a parameter used in DFM to prevent instabilities in the model. While the model's vegetation establishment is often hindered by inundation at the seaward side of the sections, the morphodynamics are rarely affected. This is due to the inundation inside the sections rarely exceeding this inundation threshold for sediment calculations should therefore have been lowered, with its final value depending on the stability of the model.

Figure 5-6 also shows a few irregularities with water that is likely unable to flow back after inundation at section B (northwest, 2nd from top section) and section F (southeast, 2nd from right section). This would be due to the difference in elevation between these and their surrounding cells as can be seen in Figure 2-4 and Figure 5-7. Comparing the figures to the location of the sedimentation erosion bars (SEB's, Figure 2-5), the lack of inundation at the highly elevated SEB's (Figure 5-7) seems to limit the possibility of bed level change.





Figure 5-6: The percentage of time during one spring-neap cycles (14 days) that an inundation depth of 0.01 m is exceeded on the right colourbar plotted along with the bed level compared to NAP (m) on the left colourbar. Percentages of 0 were cut, revealing the bed level underneath. 0.01 m was chosen because it is the critical inundation depth for window 1 establishment. The marsh was plotted using the x- and y-coordinates (m) of the domain.



Figure 5-7: The percentage of time during one spring-neap cycle (28 days) that an inundation depth of 0.15 m is exceeded on the right colourbar plotted along with the bed level (m) on the left colourbar. Percentages of 0 were cut, revealing the bed level underneath. 0.15 m was chosen because it is the threshold value for the morphology to be calculated. The marsh was plotted using the x- and y-coordinates (m) of the domain.

Figure 5-8 presents the maximum root-mean-square wave height (H_{rms} , in m) during the growth season (April-October) plotted along with the bed level (m). Wave height computations are limited in the model to a minimum water depth of 0.05 m. Furthermore, for this figure, any wave heights of below 0.01 m were cut in order to show at what locations no meaningful waves occurred. The results at sections A-D show wave heights of up to 0.25 m in their lower areas, while sections E-G only have wave heights of up to 0.1 m at the start of the sections. Moving from north of sections E, F and G towards the brushwood dams, we can see a sharp decline in maximum wave heights from 0.25 m towards 0.1 m between in front and behind the brushwood dams. This decrease is likely caused by a combination of the bed slope and the brushwood dams (dimensions defined in Table 3-1) breaking the waves. Similar to the inundation depths in Figure 5-6, Figure 5-8 again shows some irregularities with waves of up to 0.1 m that have formed at the backs of section B (northwest, 2nd from top section) and section F (southeast, 2nd from right section). However, these waves cannot affect the model's morphodynamics due to the inundation threshold for sediment calculations (0.15 m) being set too high (Figure 5-7). Furthermore, the vegetation development is not directly dependent on wave heights, but instead on the bed level change that it causes in case of enough inundation.

The frequency during the growth season at which wave heights (H_{rms}) of 0.05 m were exceeded can be found in Figure 5-9. 0.05 m was chosen as a limit above which waves were estimated to be significant for the bed shear stress and vegetation establishment in the area. Apart from section A, waves (H_{rms}) above 5 cm appear to be rare, only occurring a handful of times during the half year. Comparing both figures, it seems that, while large waves do occur at sections B-D, these are rare. On the other hand, at sections E-G large waves are completely absent. Finally, by comparing Figure 5-7 & Figure 5-9, we see that waves of above 0.05 m reach further into sections E-G than the inundation depth of above 0.15 m. This again indicates that the inundation threshold for sediment transport often limits the model's bed level change and should have been lowered.



Figure 5-8: The maximum root-mean-square wave height (H_{rms} , m) per cell during the growth season on the right colourbar plotted along with the bed level (m) on the left colourbar. Wave heights of under 0.01 m were cut, revealing the bed level underneath. The marsh was plotted using the x- and y-coordinates (m) of the domain.

Chapter 5: Results of the model and field measurements



Figure 5-9: The number of times a wave height of 0.05 m was exceeded on the right colourbar plotted along with the bed level (m) on the left colourbar. Values were cut if they had 0 occurrences, revealing the bed level underneath. 0.05 m was estimated as a threshold which would be significant for bed shear stresses and vegetation establishment. The marsh was plotted using the x- and y-coordinates (m) of the domain.

Next, Figure 5-10 presents the frequency of bed shear stresses above 0.15 N/m^2 during the entire growth season. By using a lower limit of 0.15 N/m^2 , the frequency at which the critical bed shear stress of clay at the sections is exceeded (Table 3-2) is shown. Comparing the frequency of the bed shear stresses above 0.15 N/m^2 (Figure 5-10) to the frequency of significant wave heights (Figure 5-9), we can see a clear similarity in their occurrence. Similar to the wave heights, significant bed shear stresses occur only a handful of times inside sections E-G. The similarity with the wave heights indicates the importance of waves for the total bed shear stress. The figure again shows the same irregularities near section B and F. Significant bed shear stresses of above 0.15 N/m^2 in these areas occurred more than 30 times during the growth season. On the other hand, the waves at these locations are not that large, as can be seen in Figure 5-8. By comparing the bed shear stresses of Figure 5-10 to the inundations of Figure 5-7 which exceed 0.15 m, we can conclude that the simulated erosion/deposition rates do not include all the significant bed shear stresses (>0.15 N/m²) because of the inundation threshold of 15 cm for the usage of sediment equations. This arbitrary threshold is presumably one of the main reasons for the lack of bed level change at the sections and forms a big limitation to this thesis, further addressed in Chapter 6.2.3.





Figure 5-10: The number of times a bed shear stress of 0.15 N/m^2 was exceeded during the growth season on the right colourbar plotted along with the bed level (m) on the left colourbar. The cells of nCount were cut if they had 0 occurrences, revealing the bed level underneath. 0.15 N/m^2 was chosen because it equals the critical bed shear stress of clay. Meaning that this is a good indicator for the frequency of erosion during the growth season. The marsh was plotted using the x- and y-coordinates (m) of the domain.

This thesis attempts to find the thresholds for which the water levels and wave heights impact the morpho- and vegetation dynamics. For this we have compared high water levels and wave heights from a location just north of the Marconi marsh (G_{north}, Figure 2-5) with the conditions at the lower SEB locations found inside sections E-G (Figure 2-5). These lower SEB points were found to inundate for more than 0.15 m (i.e. the sediment threshold, *Sed_{thr}*) for water levels above 1.45 m while waves were found to reach these points for wave heights at G_{north} exceeding 0.4 m. The water levels and wave heights during the growth season simulation which exceed these values can be found in Figure 5-11 and Figure 5-12 respectively. The water level threshold is particularly exceeded around the 7th until 12th of April, 6th of May and between 11th until the 16th of May, while the wave height threshold is mostly exceeded around the 8th of April, 12th of April and 15th of May. By looking at the morphodynamics and vegetation dynamics of cells in the Marconi marsh during these times, we could discover whether the dynamics are significantly affected by these infrequent rougher conditions.



Figure 5-11: The simulated water levels (m) over the time (date) during the growth season at observation G_{north} (Figure 2-5) along with a threshold of 1.45 m +NAP above which the low SEB points inside sections E-G (Figure 2-5) have been found to inundate by more than 0.15 m.



Figure 5-12: The simulated wave height (m) over the time (date) during the growth season at observation G_{north} (Figure 2-5) along with a threshold of 0.4 m above which waves have been found to propagate inside sections E-G.

5.3. Morphodynamic development

The bed level change after one growth season (half a year) over the Marconi site can be found in Figure 5-13. Bed level changes of under 0.5 mm were cut. Overall, there is limited bed level change at the sections, with the exception of the lower areas of section A and C. As expected, the location of these bed level changes are very similar to the artificial inundation threshold found in Figure 5-7, which is exceeded at locations with elevations of up to 1.5 m +NAP. Unlike most of the sections, the areas north of the Marconi site do show significant bed level change, ± 0.3 m in some parts (Figure 5-13).



Figure 5-13: The bed level change (m) at Marconi over half a year on the right colourbar plotted along with the bed level (m) on the left colourbar. Bed level changes of under 0.5 mm were cut, revealing the bed level underneath. In this figure we can see that bed level change does not occur above 1.5 m. The marsh was plotted using the x- and y-coordinates (m) of the domain.

Looking at the wave height (Figure 5-9) in front of sections E and F, it seems like the waves break right in front of the sections, causing most of the bed level dynamics there (Figure 5-13). Based on the frequency of the significant bed shear stress in the lower areas of the sections, one would expect more bed level dynamics there as well. However, according to Figure 5-13, the bed level change there is minimal. The dynamics in the lower areas seem to be limited by the inundation threshold which is harder to reach than the wave height of 0.05 m (Figure 5-7 & Figure 5-9). Lowering the threshold will likely increase the bed level dynamics. At the higher areas there is too little inundation as well as wave action (Figure 5-7 & Figure 5-9), meaning that changing the threshold will likely not increase the bed level dynamics here.

The effect of the brushwood dams on the morphodynamics was investigated by subtracting the bed level dynamics of a run with dams from a run without any brushwood dams (Figure 5-14). Even though the initial bed level is the same in both runs, the largest net bed level changes (m) can be found outside of the Marconi marsh. This indicates that the dams not only impact the morphodynamics of the sections, but also other areas nearby. Particularly at section G, the removal of the brushwood dams has resulted in more erosion of the area directly north of G as well as part of the lower area inside the section itself.

Perhaps the removal has caused more wave action in this area by removing potential obstacles. Other sections also show net bed level changes, although minor. Since the modelled morphodynamics are not in sync with measurements in the area, no conclusions can be reached regarding the importance of the dams at the actual Marconi site. However, what can be said is that with the exception of the lower areas of section G, the dams in the simulations do not have a large impact on the morphodynamics of the sections.



Figure 5-14: The net bed level change (m) at Marconi between two runs of half a year, one without the dams and one with, on the right colourbar plotted along with the bed level (m) on the left colourbar. Net bed level changes of under 0.5 mm were cut, revealing the bed level underneath. The marsh was plotted using x- and y-coordinates (m) of the domain.

Finally, Figure 5-15 and Figure 5-16 show the simulated cumulative bed level change of observation points inside the lower areas of sections E, F and G (1.3, 1.3 and 1.2 m +NAP) and a point northward of section E (-0.5 m +NAP) respectively. The first figure shows that bed level change in the sections does not occur gradually but is mainly driven by a few moments in the simulation. Apart from the observation point at section G which shows minor changes during the rest of the run, the bed level of the sections only changes between the 7th and 13th of April and the 11th and 16th of May. Comparing the time at which these changes occur with the rough waves and high water levels found in Figure 5-11, we see a similarity between the relatively rough hydrodynamic conditions and the bed level change in the section. Almost all of the bed level change has occurred during high water levels. Rough waves do not appear to initiate bed level change on their own, since during the rough waves of the 2nd of April no bed level change is observed. Because of the artificial inundation threshold for sediment calculations, it remains the question whether these results are realistic. Looking at the lower elevated observation point just north of section E (E_{North} , Figure 2-5) in Figure 5-16, we indeed see a more gradual change in bed level over time. While partly due to the higher bed shear stresses measured in the area (Figure 5-10), the gradual change is also enabled by the artificial inundation threshold being exceeded regularly (Figure 5-7). Even though changes in the modelled bed level in the sections have shown to be infrequent and dependent on high water level, it is assumed that the actual bed level change at the Marconi marsh is more gradual as seen in the lower elevated point found in Figure 5-16.





Figure 5-15: The cumulative bed level change (m) during the growth season simulation at cells in the lower area of sections E, F and G. The points are elevated at 1.3, 1.3 and 1.2 m +NAP respectively.



Figure 5-16: The cumulative bed level change (m) during the growth season simulation at an observation point just north of section E (E_{North}). The point is elevated at -0.5 m +NAP.

5.4. Vegetation development

Figure 5-17 shows the stem density (stems/m²) per cell of the simulated Marconi marsh. The sown sections in E-G are clearly distinguishable and contain the densest vegetation in the marsh, getting close to the maximum 600 stems/m² (as defined by K). However, there are also cells outside of the sown sections which reach a high stem density. There are two requirements to reach a high stem density in this model; an early establishment such that there is plenty of time to grow and a location that is elevated enough such that the vegetation does not experience significant inundation stresses.

The negative effects of the hydrodynamics on vegetation establishment are most evident at section C, where the lower part of the section is devoid of vegetation. Most sections also contain much denser vegetation at the back of the marsh, indicating that at the lower sections the vegetation seems to experience significant inundation or bed shear stresses which decrease the plant density.

The population dynamics model uses two limits for the negative effects of the hydrodynamics; the critical bed shear stress (N/m^2) and the critical inundation height for plant mortality (m). The critical bed shear stress for vegetation mortality is 0.25 N/m², while the critical inundation height is 1.0 m, as both seen in Table 4-2. Comparing the critical bed shear stress to Figure 5-10, it appears that bed shear stresses of above 0.25 N/m² are rare inside of the sections. Furthermore, an inundation depth of more than 1.0 m is even more infrequent for these sections, since the areas are around 1.2 m +NAP and the high water levels of the northern boundary are up to 1.7 m +NAP (Figure 5-11). Therefore, it is likely that, during the calm periods, the limiting parameter of the vegetation establishment inside the sections is the critical inundation height during window 1 of the WoO's model. Since the critical inundation height of only 0.01 m occurs frequently at Marconi (Figure 5-6), the vegetation should regularly fail to reach window 2.



Figure 5-17: The stem density (stems/ m^2) at the end of the growth season (October) per cell at the Marconi marsh on the right colourbar along with the bed level (m) on the left colourbar. The black lines indicate the dikes separating the sections. The marsh was plotted using the x- and y-coordinates (m) of the domain.

The impact of the critical inundation depth of window 1 can also be seen when looking at the inundations in the northwest of section B and southside of section F (Figure 5-6). The cells at these locations are regularly inundated. However, we can conclude that this is by a small amount, since Figure 5-7 shows that, when looking at inundations of above 0.15 m, these irregularities have disappeared. These inundated cells indeed show an absence in vegetation growth as can be seen in Figure 5-17, but can have no bed level change due to the threshold (Figure 5-13). This only leaves the critical inundation depth during window 1 as the main limiting factor of the vegetation establishment in these cells.

On the other hand, vegetation does occur outside of the sections in the lower forelands where inundations are also frequent. The plants in these cells are sparse and most seem to disappear quickly after their initial establishment. This is likely caused by the significant bed level change that occurs over the growth season (Figure 5-13).

Next, Figure 5-18 and Figure 5-19 show the total and the change in number of cells found throughout the model's Marconi marsh that enter window 2 of the WoO or start the population dynamics. The first figure is plotted along with water levels above 1.45 m as measured at G_{north} (Figure 5-11), while the latter is plotted with a reference line after which cells are able to enter the population dynamics. The two largest peaks around the 2nd and 25th of April are not caused by hydro- or morphodynamics but are rather large amounts of cells entering or completing the vegetation development phases. The first peak is caused by the first batch of cells completing window 1, which is much larger than subsequent batches due to the one time usage of the establishment probability for sown sections ($EP_{sown} = 55\%$, Table 4-2). The second pair of peaks is caused by window 2 being completed in this first batch and therefore moving on into the population dynamics phase. In general, the total number of cells increases over time due to the regular establishment probability (EP = 0.75%, Table 4-2) being more impactful than the negative effects of the inundation, bed shear stress and bed level change.

Nonetheless, decreases in the cell numbers do occur during the simulation and can best be observed in Figure 5-19. Some of the major decreases of the number of cells in window 2, excluding the aforementioned completion of the phase, occurred during the 8th of April and between the 7th until the 16th of May. Comparing the vegetation development graphs with the hydrodynamics found in Figure 5-18 and the bed level changes during these time periods found in Figure 5-15, we can see that the decrease in cells is related to the occurrence of the high water levels and bed level change. While small decreases can be seen during periods were high water levels and bed level change are absent, the majority of failures in the vegetation development do indeed occur during these irregular rougher conditions. Since window 2 can only fail due to erosion and sedimentation, the decreases indicate that cells have indeed failed throughout the simulation due to the excessive amounts of bed level change during the short time window of these rough hydrodynamic conditions. However, it should be considered that starting from the reference line found in Figure 5-19, the number of cells in window 2 can also decrease due to cells starting with the population dynamics. For the population dynamics, we can only see one decrease during the 15th of May. Negative effects on the population dynamics are either caused by large inundations of over 1.0 m ($H_{cr,p}$) or bed shear stresses exceeding 0.25 N/m² ($\tau_{cr,c}$) _p). Since such inundations are not possible in a marsh that is elevated above 1 m +NAP (Figure 2-4), the critical bed shear stress ($\tau_{cr, p}$) must have been exceeded during this period.





Figure 5-18: The number of cells (-) inside the model's Marconi marsh over time (date) during the growth season that have either entered window 2 of the WoO or have started the population dynamics plotted along with the modelled water level (m) at G_{North} (Figure 5-11) that exceeded 1.45 m.



Figure 5-19: The change in the number of cells (-) inside the model's Marconi marsh over time (date) during the growth season that have either entered window 2 of the WoO or have started the population dynamics. The reference line indicates the moment after which cells can enter the population dynamics phase. This start contains a peak due to the higher establishment probability of EP_{sown}.

The effect of the brushwood dams on the vegetation dynamics was investigated by comparing the number of cells in window 2 or the population dynamics over time of a simulation without brushwood dams (Figure 5-20) with the simulation in which they were included (Figure 5-18). While there are some subtle differences between both figures, the shape of both graphs is quite similar. Furthermore, differences are not significant enough to conclude that these are due to the removal of the weirs and not the random aspect of the establishment probabilities. In the model, brushwood dams are not significant for the vegetation development and could be left out.



Figure 5-20: The number of cells (-) inside the model's Marconi marsh over time (date) during the growth season that have either entered window 2 of the WoO or have started the population dynamics. For this simulation the brushwood dams were removed from the sections. The figure can be compared to the results with brushwood dams found in Figure 5-18.

6. Discussion

In this study, the impact of hydrodynamic and morphodynamic parameters on the development of *Salicornia Europaea* at the Marconi marsh has been studied. This chapter will discuss the implications of the generated results and address the limitations of this study. The chapter starts by investigating the effects of lowering the Marconi marsh on the bed level dynamics and the stem densities at the site. It will then continue with the limitations of this thesis and their effect on the model results. Finally, we will reflect upon the model results before discussing the implications of these results for Building with Nature projects.

6.1. Sensitivity of the morpho- and vegetation dynamics to lower marsh elevations

In Chapter 5.2 and 5.3, it was observed that bed level changes occurred up to 1.5 m +NAP and were limited by the inundation depth. Since the majority of the sections is located above this threshold, this meant that there were limited bed level dynamics and inundations in the sections, even more so due to the high artificial inundation threshold for sediment calculations (*Sed*_{thr}). In other words, the hydrodynamics of the model are too low relative to the (rather high) bed level of the Marconi marsh. This resulted in a lack of morphodynamics in the model compared to the actual marsh where significant bed level change was measured at most of the sedimentation erosion bars (SEB, Figure 2-9). It also meant that vegetation was relatively unhindered compared to reality. The discrepancy between elevation and hydrodynamics is likely due to limitations in the model (See Chapter 6.3) causing an underestimation of the hydrodynamics reaching the Marconi marsh. Therefore, it would be interesting to look at the interaction between hydro-, morpho- and vegetation dynamics when reducing this discrepancy. Since it was easier to lower the marsh than to increase the hydrodynamics in the model, the interaction between hydro- and morphodynamics and its effects on the vegetation was investigated by lowering the modelled marsh.

In their paper, Balke et al. (2016) show that, for a mean tidal range of around 3.5 m, the elevation at which pioneer vegetation can establish is around 100 cm below the mean high water. The mean high tide at Delfzijl is 1.4 m +NAP (Groningen Seaports, n.d.), which means that the pioneer vegetation could establish starting at 0.4 m +NAP. Since the lower areas of the sections are located around 1.4 m +NAP, we could lower the marsh by up to 1.0 metres overall in our simulations. For this chapter, the marsh was lowered to 1.0 m in intervals of 0.25 m. The resulting average bed level changes and stem densities in each section during one growing season are discussed below. For more detailed results, please refer to Appendix D & E, which show 2D plots similar to Figure 5-13 & Figure 5-17 of each simulation.

Figure 6-1 shows the change in average bed level change in section E, F and G when lowering the marsh from the standard model towards 1.0 metre below original bed level. The results show a difference in response per section, which is likely influenced by their relative elevation. Section E starts eroding at a 0.25 m lower marsh which increases when lowering further. Unlike section E, sections F and G increase in sedimentation when lowered by 0.25 and 0.5 m. Lowering section F to 0.75 m below the standard model, causes a rapid increase in erosion. Section G is the most stable out of the three and only has slight erosion at 1 metre lower compared to the standard model.

Interestingly, slight variations in bed level can increase the sedimentation in the area, while large changes eventually create significant amounts of erosion over time. The reason the sections start to erode could be linked to their average bed level. Since section E has the lowest elevation out of the three (Figure 2-4), it also starts eroding first. The question remains at what elevation this transition occurs. However, we have concluded previously that the modelled bed level change occurs in areas below 1.5 m +NAP, as can also be seen in Figure 5-13. Therefore, we can argue that this transition occurs when the marsh is below an average elevation of 1.5 m +NAP, i.e. the mean high water.

Figure 6-2 shows the net bed level change (m) of the sections when comparing the lowering of the marsh with the regular simulation of the marsh. Section E is revealed to be the most sensitive to changes, followed by F. Differences in these net bed level changes could indicate towards the effect of the sediment compositions, since this is one of the main differences between the sections. In the current model, the sediment composition is used to determine the critical bed shear stress of the mix of sediments. The clay at the Marconi marsh has a relatively low critical bed shear stress of 0.15 N/m² (Table 3-2). This means that the more clay there is in the composition, the lower the critical bed shear stress and the easier the bed should erode. In other words, section E should have the lowest critical bed shear stress followed by F and then G. Due to the bed level changes in the standard simulation being small, the effect of the sediment composition is limited. However, using Figure 6-2, we can conclude that lowering the marsh would increase the impact of the sediment composition, since bed level changes increase throughout the site.



Figure 6-1: The simulated average bed level change (m) of sections E, F and G when lowering the Marconi marsh by 0.25 to 1.0 m. Section E starts eroding on average at 0.25 m lowering. Section F and G increase in sedimentation until 0.5 m lower. At 0.75 m the sections start to erode rapidly which increases when lowering to 1.0 m.



Figure 6-2: The net bed level change (m) of sections E, F and G when comparing the lowering of the Marconi marsh by 0.25 to 1.0 m to the standard simulation of the Marconi marsh.

Next, Figure 6-3 & Figure 6-4 show the effect of lower marsh elevation on the stem densities (stems/m²) in the sections. The vegetation at section E is the first to drop close to zero at a lower marsh of 0.5 m. However, sparse vegetation is still present until a lowering of 1 m. Interestingly, the stem density at section F and G first increases when the marsh is lowered by 0.25 m. Compared to the framework for the model's vegetation development found in Figure 5-18 and Figure 5-19, the changes in vegetation density are likely related to the failure of window 2 inside cells. The initial increase in stem density could be linked to less cells failing in window 2 due to the reduced erosion (Figure 6-1). However, the increase in vegetation could also be due to the random variation in stem density caused by using an establishment probability.

This random probability, while likely also having affected the sedimentation trend found in Figure 6-1 by creating more flow resistance, is not expected to be the cause of the trend since the vegetation density already decreases for the 0.5 m lowering while the bed level still increases. For future simulations, the same vegetation establishment of the cells should be used for each case to exclude the effect of the establishment probability's randomness on the vegetation dynamics.

After the initial increase in stem density, vegetation in section F and G decreases but remains wellestablished until the marsh is lowered by 0.75 m. At which point all sections have stem densities close to zero. This decrease is likely due to window 2 vegetation inside cells increasing to fail due to the significant increase in erosion throughout the sections (Figure 6-2). Eventually, bed level change throughout the cells becomes so high that cells are unable to complete window 2. This causes the sections to behave like the forelands of Marconi in the standard model (Figure 5-17), with sparse vegetation that quickly disappears after initial establishment. At a lowering of 1 m, section E has likely dropped more than 1 metre below the mean high water, which was determined as the lower limit of the pioneer zone by Balke et al. (2016). This means that vegetation can no longer establish in this area.

While Balke et al. (2016) state that establishment should be possible at elevations of more than 1 metre below the mean high water, field observations revealed that vegetation was not present at areas seaward from the dams, despite the bed level being in this range. This indicates that the vegetation at these unprotected areas must be getting dislodged due to excessive erosion and are unable to establish even though they are in the given elevation range. Therefore, it seems that for this range to hold true in reality, the bed level change in an area cannot be too high. This is in contrast with the model results, which always enable vegetation to briefly establish as long as there is enough time with no inundation.



Figure 6-3: The simulated stem density (stems/ m^2) at the sown parts of sections E, F and G when lowering the Marconi marsh by 0.25 to 1.0 m.



Figure 6-4: The simulated stem density (stems/ m^2) at the unsown parts of sections E, F and G when lowering the Marconi marsh by 0.25 to 1.0 m.

6.2. Limitations of this study

6.2.1. Field measurements

Field measurements were conducted for one day at the Marconi marsh in order to update the bathymetry around the Marconi marsh and calibrate the vegetation parameters. However, there are a few implications with these measurements. Bottom levels to the north of the Marconi sections could not be measured because they were below the sea level at the time. Furthermore, the ground at these lower areas was soggy, making it difficult to cover. This means that some of the bathymetry close to Marconi has not been covered, resulting in an inaccurate bed level. Since the bed level influences the water flow and waves propagating towards Marconi, this could create inaccuracies in the hydrodynamic climate at the site.

While all sections (except X) have been used, the conducted bed level measurements near Marconi were focused on sections E, F and G. Five cross-sections were measured here with an interval of roughly 10 metres, while the other sections contained between one to three cross-sectional measurements. Outside of the sections, one cross-section was measured starting at each of the openings of the brushwood dams and ending as far seaward as possible. The measurements were extrapolated to the rest of the site. This means that any height differences found in between the cross-sections has not been taken into account. Furthermore, at the site small trenches and mounds were found which created minor topography variations in the area. Unfortunately, the measurements were not detailed enough to reveal the minor topography variations. These variations in the local topography could have a significant impact on the flow and the locations at which vegetation can establish.

Another limitation is the height of the brushwood dams, since these were not measured in detail (See Chapters 2.3 & 3.2). The brushwood dams were only measured at a few locations due to time constraints. However, during the measurements it was observed that the dams vary greatly in their height over the site. In particular, at section G, the small dam at the east side of the section was much lower than initially modelled.

This was likely because large portions of the branches which fill up the dams had washed away over time. Therefore, the height of the brushwood dams over the site is likely much more variable in reality than how they were modelled.

What is also important to realize is that the vegetation measurements at sections E-G in Marconi are limited, due to the limited time during the one day of field measuring. Sown areas only have one measurement per section while unsown areas have two. Observations at the area reveal that the vegetation density varies highly within the sections. Especially in the unsown areas of section F and G, there were substantial areas with no or very little vegetation present. However, due to the limited time for measurements, it was assumed better to create plots with vegetation in them, i.e. there was a bias towards denser vegetation plots. Therefore, in reality the vegetation density is likely more varying in the sections than modelled. Furthermore, it should be noted that *Salicornia* was observed to be more developed in section E, than F and in particular G. Differences in growth rate of vegetation, i.e. due to different sediment compositions of sections, was not taken into account in the model but did significantly affect the measured stem densities.

6.2.2. Hydrodynamic limitations

As was mentioned before, the water level input at the North Sea does not correspond to the wind data used. This is because the water level is based on measurements at Eemshaven from 2012 (Rijkswaterstaat, 2012), while the wind data was obtained from measurements near Winschoten in 2018 (KNMI, 2018). This means that high water levels are not joined by strong winds and vice versa likely creating water levels at Marconi which are not as high as they can get in reality.

No data was available for the discharge at the eastern open boundary. Since the boundary was in the middle of the estuary, the discharge of the Ems could not be used. Instead an estimation was made using a constant discharge of 1000 m³/s. In reality, the tides should have a large effect on what flows back into the model during ebb, meaning that the discharge or water level at the open boundary should vary based on the tides with the inclusion of tidal lag. This could be fixed by extending the model boundary towards the river Ems, where we can better estimate the boundary by using a varying discharge over time based on available data. However, the effect on the hydrodynamics at the Marconi marsh would likely be limited since most of the water is expected to flow back using the channel at the centre of the Ems-Dollard (Figure 3-2).

Another limitation of the hydrodynamics is that the diffraction had to be turned off in the wave model due to problems with calculating the propagation of the waves. This has been observed to have substantial effect on the way waves diffract around the thin dams as defined in Figure 2-4. Without diffraction waves approaching near the end of a thin dam appear to flow directly through the dam, instead of having to flow past it. It is likely that the wave propagation around section A is therefore inaccurate. However, it is not expected that it would have had a large impact on sections E, F and G since these are not close to any thin dams.

6.2.3. Morphodynamic limitations

For the sediment characteristics, standard values were used for sand while for clay we based the critical bed shear stress on papers from Houwing (1999) and Maerz & Wirtz (2009). The characteristics were therefore not based on the actual sediment found at Marconi, so it is possible that the sediment differs substantially from the model. Furthermore, the model does not take into account spatial variations in characteristics but uses the same value for all sections. North of Marconi, the critical bed shear stress of clay was also set to be 0.25 N/m^2 . Both the area that it was used for as well as its value were not based on measurements but instead were picked in order to ensure the forelands are not too unstable that it would affect the bed level dynamics at the Marconi sections. Early simulations with the wave model revealed large amounts of erosion at the North Sea boundary which created substantial clay concentrations over the domain site and resulted in significant sedimentation at some areas.

Another limitation of this research regards the inundation threshold for sediment calculations (Sed_{thr} , Chapter 5.3). The threshold was set to 0.15 m at the start of this research before the wave model was implemented because of some stability issues outside of Marconi. This is higher than the value used in the morphology manual of Deltares (2019b) and literature such as Williams et al. (2016) who both used a threshold of 0.10 m. Without waves the model does not show significant bed shear stresses so the sediment calculations were not affected by this threshold. However, this changed after the wave model was implemented and the bed shear stresses at Marconi increased substantially. Therefore, the parameter should have been lowered as far as possible with regards to the stability of the model. As will be discussed in Chapter 6.3, this critical inundation parameter likely has a large impact on the bed level dynamics in the modelled Marconi marsh.

6.2.4. Limitations of the vegetation model

For the vegetation model, some limitations can be found regarding the vegetation parameters and the establishment probability. As can be seen in Table 4-1 & Table 4-2, some of the vegetation parameters for *Salicornia Europaea* were based on previous research using field measurements or model studies of *Spartina*. The lack of direct parameters for *Salicornia Europaea* is caused by a lack of research on *Salicornia* vegetation, which means that the vegetation as defined in the model does not work the same as *Salicornia Europaea* in reality.

Furthermore, factors such as the critical inundation depth for window 1 and critical shear stress and inundation for plant mortality, as seen in Table 4-1 and Table 4-2 respectively, were not calibrated. These were instead based on previous research by Odink (2019) and Temmerman et al. (2007). As discussed later in Chapter 6.3, these parameters have a large impact on the vegetation development at the Marconi marsh.

Due to the computation time, it was necessary to implement a morphological factor (Morfac). Essentially, the Morfac multiplies the morpho- and vegetation dynamic changes occurring during a hydrodynamic timestep by its defined amount. While the Morfac was kept relatively low at 4, this does mean that hydrodynamic input is often overvalued.

This is especially a problem for the Windows of Opportunity in which the first window requires inundation free time-windows to allow establishment. If we multiply the duration of a low water-level by 4, we are allowing vegetation to establish longer than in reality, since it should change between high and low water every 12 hours. According to the required time for window 1 (T_{WoO1} , Table 4-1), the area surrounding a seed is required to be free of inundation for 2.5 days, i.e. during a combination of 5 ebbs and floods in total. However, with the Morfac the area is only required to be inundation free for two timesteps of 12 hours, i.e. 1 ebb and 1 flood. Therefore, vegetation establishment in the lower-lying areas is likely overestimated. A potential solution for this could be to use the EP and Morfac per completion of a 2.5-day cycle (T_{WoO1}) instead of every timestep. The effect of the Morfac will be investigated next section by comparing a simulation without the Morfac with one with a Morfac of 4.

No literature was available that addressed the combination of WoO for vegetation establishment with the use of a morphological factor. The lack of literature is likely due to the short-term focus of the windows of opportunity concept as well as the fact that the combination of WoO with population dynamics as a vegetation development model is a new concept. Other papers such as Attema (2014) and Best et al. (2018) were found to simulate the development of salt marshes using a morphological factor. However, these papers only made use of the population dynamics of Temmerman et al. (2007), which can safely use a Morfac due to its establishment being independent from time windows.

In this study, we modelled EP as a constant. However, in reality, *Salicornia* seeds are abundant at the start of the growth period (April-May) and decrease afterwards due to seed dispersal and mortality. Even though the availability of *Salicornia* seeds is known to vary over time, exact amounts and in particular at the Marconi marsh are unknown. Therefore, a much simpler approach with a constant establishment probability was used based on previous research by Schwarz et al. (2018) and Poppema et al. (2019). The effect is expected to be minor since, in order to complete window 2 of the WoO's model, which takes 90 days, the vegetation needs to establish in the first few months of the growing season regardless. This is at the time when seed availability should be high.

6.3. Limitations affecting model results

Wave climate was observed to be stronger in sections A-D, than at sections E-G (Figure 5-9 & Figure 5-10). This seems counterintuitive since the rubble mound jetty near section A is expected to shelter the upper sections, while the bottom sections lack such a jetty. Potentially, the absence of diffraction in the model could have created an unrealistic wave climate around section A. However, looking at the wind data in Figure 3-5, we can conclude that wind originating from the east is more frequent and stronger than wind from the north. The rubble mound jetty blocking waves from the north, seems to have a limited effect on the modelled wind generated waves reaching the marsh. Therefore, the lack of diffraction is therefore also expected to have a limited impact.

At sections B and F, minor water level inundations and wave heights were found at the back of the sections where there was relatively low elevation (Figure 5-6, Figure 5-7 & Figure 5-10). It seems likely that these small inundations are caused by water not being able to flow back after a high tide has caused minor inundation at these higher areas. Velocity calculations of the water flow are made for water levels above 0.001 m (not the same as Sed_{thr} which is for sediment calculations), which means that it is indeed possible for very small inundations to propagate into the high marsh of the sections. Even though these were not visible in the inundation results (Figure 5-6). Such inundations are not necessarily limitations of the model, but could potentially be overestimated due to the limited bed level measurements extrapolating into larger low-lying areas than in reality (Chapter 6.2.1).

Unlike the SEB measurements at Marconi, model results have shown limited bed level change inside the sections overall (Figure 5-13). Only, at the lower elevated sections of A and C did we observe significant bed level change throughout the lower areas of the sections. The bed level dynamics seem to occur at elevations of up to 1.5 m +NAP, which is similar to the observed inundations (Figure 5-7). Bed level dynamics were only observed on locations where the inundation threshold (Sed_{thr}) is exceeded, which was expected since the threshold should enable the required sediment calculations. However, bed level change was observed at higher elevations than the modelled inundation allows (Figure 5-4). Furthermore, simulated wave heights have also been observed to exceed this threshold, as can be seen in Figure 5-8. Therefore, in order to improve the bed level dynamics of the model, the inundation threshold for sediment calculations should be lowered to enable the effect of all meaningful waves on the morphodynamics.

However, even if the threshold had been lowered to an inundation of 0.01 m or more, the higher elevated areas, including most of the higher SEB points (i.e. Figure 2-9), would still not have been affected (Figure 5-6). This seems to indicate that the water levels simulated at Marconi are lower than the ones found at the actual site. However, looking at the water level comparison in Figure 5-1, while modelled high water levels are less frequent, the tidal range is about the same. The problem here is likely the linked to the limited usage of the time series, since only 1.5 months of the year are used in the model due to the usage of the Morfac. Extreme water levels could occur in the model if this time frame was lengthened. On the other hand, the water level and wind datasets which were obtained from 2012 and 2018 respectively, do not coincide. This means that when high water levels occur in the model, this is not necessarily accompanied by high wind speeds and vice versa. In other words, the setup caused by wind and consequently the water level will not be as high as it should be during storms. Other important limitations which could have affected the model results are the bathymetry and the brushwood dams. The wave height and consequently the morphodynamics are influenced by the dimensions of the brushwood dams surrounding the sections and the bathymetry of the area, which were found to be based on limited measurements (Chapter 6.2.1). The model could have used a bathymetry which is shallower than in reality which could result in waves breaking before reaching the sections. Another example is a section of brushwood dams being much lower at a section than modelled resulting in the simulation underestimating the wave heights propagating inside the section.

To analyse the impact of the Morfac on the development of vegetation during window 1, a model run without a Morfac was performed for one month and compared to one month of the regular run with a Morfac of 4, for which the model thus uses 4 times less timesteps to span the same time. Figure 6-5 shows the total number of cells which have entered window 2 for both model runs. Results show, as was hypothesized in Chapter 6.2.4, the run without a Morfac has less cells in the window 2 phase. Presumably, this is due to the area having to be inundation free for multiple ebbs and floods when not using a Morfac instead of one of either with the Morfac of 4. Another thing that stands out is that the run with the Morfac starts window 2 later than the one without. This is because the first window has a length of 2.5 days, meaning that with a Morfac of 4 (dt=12*4=2 days) the model has to run 2 timesteps which span 4 days instead of 2.5 days before the first window can succeed.



Figure 6-5: The number of cells (-) inside the model's Marconi marsh over time (date) during the growth season that have entered window 2 of the WoO for a run without a Morfac and one with a Morfac of 4.

Finally, as mentioned before in Chapter 4.4, the maximum stem density (K) of 600 stems/m² was partly based on the field measurements at Marconi. It is expected that in subsequent years this maximum stem density will increase. Due to the new vegetation in the area, it is likely that more seeds will be available at Marconi in the subsequent years. Not only would this increase the establishment probability, but it would also increase the amount of plants per square metre (n_{ini}).

Furthermore, the Marconi marsh was created and sown at the end of May, while according to papers by Davy et al. (2001) and van Hulzen et al. (2006) the growing season in the Netherlands would be around 6-8 months and already start in April. Vegetation growth in subsequent years will therefore start earlier, resulting in denser and fuller grown *Salicornia* plants throughout the site.

6.4. Reflection on the model results

In this thesis, D-Flow Flexible Mesh (DFM), a hydro- and morphodynamic computational model, was combined with the establishment concept of Balke et al. (2011) and the population development concept of Temmerman et al. (2007) to create a process based vegetation development model based on *Salicornia Europaea*. The thesis simulated three scenarios of half a year, i.e. one growth season; a standard run, a lowering of the marsh of up to 1 metre with an interval of 0.25 m and the removal of the brushwood dams.

Hydrodynamic results have shown the significant impact of inundation on the vegetation establishment of *Salicornia Europaea* at the Marconi marsh. During the establishment of seeds, an area is required to be disturbance-free in order to allow seeds to strand and develop roots so they can withstand the stress of flooding. However, with the exception of the high marsh (> 1.4 m +NAP), the modelled Marconi marsh was found to inundate regularly and since any inundation would disable seeds from establishing, the hydrodynamic climate has clearly had a large effect on the modelled vegetation establishment and the patterns of vegetation that developed over time.

While vegetation was still able to establish in lower areas due to periods in time where water levels were too low to inundate the marsh, chances of establishment in the higher areas were much higher. This resulted in a vegetation pattern in which the high areas of the marsh had a more developed and spread out population of *Salicornia Europaea* than the lower areas. If one where to disable any inundation from the area for a few days, the pattern would likely change into a seemingly more random one as the only limiting factors for development in an area would become the availability of (germinated) seeds. This factor was addressed in the model by the establishment probability (*EP*), which gives an equal chance of establishment to each cell (apart from the onetime usage of EP_{sown} for the sown areas of sections E-G).

Once the seedlings had formed, inundation did not have a direct effect on the establishment of the *Salicornia Europaea* plants. Instead, inundation forms one of the requirements for morphodynamic changes in the area. Bed level change at the lower sedimentation erosion bars (SEB, Figure 2-5) was found to only occur during high water levels, which shows that morphodynamic changes indeed are related to the hydrodynamic conditions. As expected, during these high water levels and bed level change, seedlings were found to die-off in the marsh. However, die-off of seedlings also occurred during calmer hydrodynamic conditions when bed level change could not have been very large. In other words, *Salicornia Europaea* seedlings are very susceptive to bed level change. Even though the modelled morphodynamics were observed to be limited compared to measurements performed at the actual Marconi marsh, the effect of morphodynamics on the *Salicornia Europaea* vegetation was still recognisable. This indicates how significant bed level change would have been for the modelled *Salicornia Europaea* vegetation, had the morphodynamics been more in-line with the actual marsh.

After the first half of the growth season, seedlings had developed into fully-grown *Salicornia Europaea* plants and formed clusters. These clusters are much more resilient to hydro- and morphodynamic conditions and were found to only die-off during (relatively) rough hydrodynamic conditions. The model used two negative factors for the population development of *Salicornia Europaea*; inundation and bed shear stress. The former was found to have a limited impact on the population development due to its high threshold of 1 metre of inundation. With a maximum water level of around 1.7 m +NAP and a marsh that is almost entirely above 1 m +NAP. Such large inundations never occurred at the marsh area. Furthermore, even if vegetation was inundated by more than 1 metre, the plant mortality rate was too low to have a significant impact on the population development of *Salicornia Europaea*. On the other hand, Bed shear stress was observed to have a significant negative effect on the population development of *Salicornia Europaea*. Not only was the critical shear stress for plant mortality able to be exceeded at the Marconi marsh, but the plant mortality was also so high that any vegetation would instantly disappear when this threshold was exceeded. This occurred during the prior to last day of the growth season, when a large number of *Salicornia Europaea* clusters died-off due to hydrodynamics exceeding this shear stress threshold in parts of the modelled Marconi marsh.

The model's vegetation development appears to be significantly affected by inundation during the establishment of seeds in the area. While no numbers are available for the amount of seeds that failed to establish during the growth season, the frequency at which the lower marsh inundates makes it the primary limitation to the modelled establishment of *Salicornia Europaea*. Once vegetation had established, hydrodynamic conditions became less impactful. These results appear to be in accordance with previous literature such as Bouma et al. (2009), Hu et al. (2015) and Davy et al. (2011) who conclude that zonation of intertidal vegetation is a common feature of natural marshes and is related to tidal inundation.

Clusters of fully developed *Salicornia Europaea* were found to be much more resilient to inundation and shear stresses. Only during rough hydrodynamic conditions, which occurred once in the growth season simulation, did the amount of *Salicornia Europaea* clusters decrease. Due to the infrequency of these rough conditions, high-density clusters were found throughout the site at the end of the growth season. Two requirements for such a high stem density in the model have been discovered; early establishment such that there is plenty of time to grow and a location that is protected enough such that the vegetation does not experience significant bed shear stresses during the growth season.

In their paper, Best et al. (2018) also looked into the interaction between hydrodynamics and vegetation dynamics and the resilience of the vegetation to sea level rise. They observed that, while the vegetation was initially resilient to sea level rise and extreme inundations, the marsh eventually started to drown after numerous years of being exposed to these high water levels. This seems to indicate that fully developed *Salicornia Europaea* and intertidal vegetation in general are indeed resilient to hydrodynamic processes, but in the long-term, likely due to their limited life span, do disappear due to high water levels and shear stresses.

Bed level change was also found to have a clear impact on the development of seedlings, even though the morphodynamics were found to be underestimated compared to the actual Marconi marsh. This is similar to the results of Poppema (2017) who discovered, by using flume experiments of seedlings and a similar vegetation model, that *Spartina* is very sensitive to bed level disturbances. So, while the model's morphodynamics were found to be of limited importance to the vegetation development, the actual *Salicornia Europaea* population of the Marconi marsh is expected to be primarily affected by bed level change.

A threshold for the morphodynamic changes at sections E, F and G that caused die-off of vegetation in the area was successfully determined by comparing water levels and corresponding wave heights at a point just outside of these sections (G_{north}, Figure 2-5) with the simulated water levels and wave heights found inside the sections at the lower sedimentation erosion bars (SEB). These lower SEB points were found to inundate enough to enable erosion for water levels above 1.45 m while significant waves for dislodging of vegetation were found to reach these points for wave heights at G_{north} exceeding 0.4 m. Comparing the values above this threshold that occurred over the growth season with the morphodynamic changes at sections E-G revealed that these excesses indeed do correlate with the modelled bed level change and decreases in vegetation.

Brushwood dams, placed around the sections of the Marconi marsh, protect the vegetation from these morphodynamic changes by breaking the waves reaching the marsh, reducing the erosion inside the sections. The modelled Marconi marsh was simulated with and without these dams to investigate the impact of them on the model's morphodynamics. Interestingly, the removal slightly increased the erosion of the area directly north of section G as well as part of the lower area inside the section. Besides these minor variations in bed level at section G, the removal of the brushwood dams was found to have little effect on the modelled morphodynamics and vegetation dynamics of the marsh. However, while the dams are not important for the bed level change between model and reality were unalike. The results are indeed in contradiction to other literature as the paper of Vuik et al. (2019) also researched the effects of artificial protection such as brushwood dams and concluded that brushwood dams do in fact enhance accretion as well as salt marsh establishment and, although costly due to continuous maintenance, are one of the best interventions for creating a natural salt marsh.

In their paper, Balke et al. (2016) established that pioneer vegetation could establish one metre below the mean high water. In this thesis, we have also looked at the effects of variations of the elevation on the morpho- and vegetation dynamics. Interestingly, the model revealed that slight reductions in bed level can actually increase the sedimentation in the area, while large reductions eventually moved the marsh to a significant amount of erosion over time.

Similarly, the vegetation was found to first increase in density when the marsh was lowered by 0.25 m before decreasing in density when the marsh was lowered by 0.5 m or more. This initial increase could be related to the reduction in overall bed shear stress and bed level dynamics, although this could also be due to the randomness of the establishment probability used in both simulations. On the other hand, the decrease of the vegetation density is clearly related to the increase in the frequency of inundation and bed level change which have significant negative impact on the development of *Salicornia Europaea*.

Results have shown two transitions in the vegetation density when lowering the marsh. The first is a transition from relatively well-established marsh vegetation to sparse vegetation in the pioneer zone, which occurred when the elevation was reduced to below the mean high water. This is likely related to the frequency of inundation which increases when lowering the marsh. During the second transition which occurred when the elevation was reduced to 1 metre below the mean high water, any remaining plants disappeared and could no longer establish in the area. This appears to be in accordance with Balke et al.'s (2016) lower limit of the pioneer zone.

Sediment composition was found to have a limited effect on the modelled morpho- and vegetation dynamics at the current elevation of the Marconi marsh. The modelled sediment composition was varied at sections E, F and G with E having the most clay and G having the most sand. While bed shear stresses at the front of sections E-G were found to be very similar, more erosion was observed at sections E and F than at G. However, the difference was found to be relatively minor and only occurred at a small part of the Marsh. This is likely in large part due to the lack of bed level change at the modelled site.

Indeed, the impact of the sediment composition on the morphodynamics changes when lowering the marsh and is dependent on the overall bed level change throughout the site; the higher the bed level change in an area, the larger the impact of the sediment composition will be. When simulating the lowered marsh, the bed level change was found to change throughout the sections by an unequal amount. Out of sections E-G, section E's morphodynamics were revealed to be the most sensitive to changes in bed level, followed by section F. These dissimilarities could be related to the sediment compositions, since this sensitivity is in line with the differences in the clay/sand ratio of the sections.

The ratio of clay/sand of the bed affects the critical bed shear stress and erosion rate of the layer and therefore affects the morphodynamics and indirectly the development of *Salicornia* seedlings. The results of this thesis suggest that sections with a higher clay content have more erosion and are more sensitive to bed level change. This appears contradictory to previous results of literature as papers such as Houwing (1999) have shown that erosion rates of sand layers are higher than for clay layers. On the other hand, in the research of Van Rijn (2020), the critical bed shear stress for the sand fraction in a mud-sand bed mixture was found to be a factor 1.1-1.5 larger than the mud fraction. This, along with the fact that a low critical bed shear stress for clay was chosen for the area around the Marconi marsh, would suggest that the higher the clay content, the lower the overall critical bed shear stress for erosion would be.

During the comparison of the modelled stem density with the measured stem densities over sections E-G, a decreasing trend was noticed in the measured values which was absent in the model. This trend was also observed during the field excursion; Sparse sections of vegetation were found to be more frequent at sections F and G and plants were less developed than the ones found at section E. Variations in the modelled vegetation density between sections can only be caused by differences in the local hydro- and morphodynamics. Therefore, it could be that the trend is not visible due to the discrepancy between the modelled and actual morphodynamics. However, the simulations of the lowering of the marsh did not reveal a shift towards this trend either. Instead the vegetation at section E was found to disappear first, which is likely due to its lower elevation and higher clay content compared to sections F and G.

Another cause for the measured vegetation trend could be that an external factor influences the growth of the vegetation which is not accounted for in the model. Several papers point towards the effects of external factors such as nutrient availability (Pennings et al., 2002) or salinity, soil texture and water content (Moffett et al., 2010). This could also explain the difference in development found at the sections, since clay likely has more nutrients available than sand, resulting in better developed plants at section E because of its higher clay content.

6.5. Implications for Building with Nature

The model results have revealed potential advantages of sediment compositions based on the conditions of the marsh which should be considered when creating salt marshes and other intertidal ecosystems. Compositions with a high clay content had a low critical bed shear stress compared to sand, which was shown to result in erosion occurring faster and vegetation getting dislodged easier. Furthermore, clay compositions were also found to be more sensitive to changes in the elevation relative to the water level. On the other hand, field observations have revealed a potential positive effect of clay on the growth rate of vegetation. If this is the case, salt marshes at low-energy coasts could be made using compositions with a high clay content to promote plant growth, while compositions with a high sand content could be used at high energy coasts to increase the salt marsh's resistance to erosion and sea level rise.

Similar papers that have looked at the effects of sediment compositions on the growth of vegetation also point towards positive effects of clay on the vegetation's growth rate. First, a study by Liu et al. (2017) studied the impact of sediment type on the development of macrophyte communities. They concluded that the growth and biomass at these sediment compositions varied greatly between species, but that the highest growth rates and biomasses were found when using a 1:1 mixture of clay and sand. On the other hand, van Hulzen et al. (2007) found a strong correlation with the density of *Spartina* vegetation and the clay content as the muddy area in their study was found to have a significantly higher stem density than the sandy area. This suggests that, while the effects of clay content vary greatly between vegetation types, the clay content does indeed appear to have a positive impact on the stem density and growth rate of salt marsh vegetation.

Besides the sediment compositions, another interesting result for Building with Nature projects was the formulation of two requirements for a high stem density of *Salicornia Europaea* in the modelled marsh; early establishment such that there is plenty of time to grow and a location that is protected enough such that the vegetation does not experience significant bed shear stresses during the growth season.

Interestingly, the first requirement suggests that the seeds at the Marconi marsh should have been sown earlier, at the start of April instead of the end of May. Similarly, in their paper Davy et al. (2001) note that the performance of *Salicornia* is limited by the length of the growing season.

In cold climates with a growing season of effectively only 3 months, *Salicornia* was found to reach a height of 1-10 cm and have only a few branches from its main node. Meanwhile, in temperate latitudes with a growing season of around 7-8 months, the individuals could reach a height of up to 40 cm and had up to 4th-order branching at the nodes. Therefore, model results and Davy et al. (2001) both show that a longer time to grow does lead to significantly more developed and denser *Salicornia Europaea* vegetation.

The second requirement suggests that the design of salt marshes in Building with Nature should focus on preventing excessive erosion by reducing hydrodynamic energy in the area if necessary. Two papers that address the effect of bed level change on the establishment of salt marshes are Cousins et al. (2017) and Willemsen et al. (2018). The first paper looked at the establishment of salt marsh vegetation at 12 artificially placed clay terraces. Results showed that the terraces with the least change in surface height of sediment were the most favourable for plant colonisation. Willemsen et al. (2018) collected bed level change data from six salt marsh transects in the North Sea area and demonstrated that the location of the lower marsh edge was restricted by the inundation time and bed level change. For vegetation to withstand longer inundation stress, more stable bed levels were required. While for plants to withstand more dynamic bed levels, lower inundation stress was required. Furthermore, the paper also mentions the effect of inundation on the growth rate of vegetation, with longer inundation periods are also one of the requirements for a high stem density. Nevertheless, both papers indicate that bed level change is crucial for the establishment of salt marsh vegetation, which is in agreement with the results of this thesis.
7. Conclusion

The aim of this thesis was to investigate the impact of hydrodynamics and morphodynamics on the development of the pioneer vegetation *Salicornia Europaea* at a(n artificial) salt marsh by using a numerical modelling approach. To reach this goal, one main question and four sub questions were defined. The conclusions will be given per sub question. The main research question is:

"How do hydrodynamic and morphodynamic processes affect the numerically modelled development of Salicornia Europaea at an intra-annual time scale in a constructed salt marsh?"

7.1. Effects of the hydrodynamics on the Salicornia population

The first sub question is: "How do the hydrodynamics affect the establishment and population development of Salicornia Europaea?"

Hydrodynamic processes affect the establishment and population development of *Salicornia Europaea* negatively by inducing inundation and shear stress on the vegetation, which can cause these to dieoff. During the establishment of seeds, an area is required to be inundation-free in order to allow seeds to strand and develop roots so they can withstand the stress of flooding. Even though most of the modelled Marconi marsh was found to inundate regularly, vegetation was still able to establish due to the occurrence of low water levels during the growth season. Nonetheless, the difference in inundation frequency of the higher and lower marsh resulted in a vegetation pattern in which the high areas of the marsh, which are the areas above 1.4 m +NAP in every section of the Marconi marsh, had a more developed and spread out population of *Salicornia Europaea* than the lower areas, which are the areas below 1.4 m +NAP and are generally found in the first 50 metres of the salt marsh relative to the sea.

After seedlings develop into fully-grown *Salicornia Europaea* plants and form groups, they become much more resilient to hydrodynamic conditions. Model results indicate that inundation has a limited impact on the population development of *Salicornia Europaea* due to the extreme inundation required to cause these clusters of *Salicornia* to die-off (> 1 m). Since such high water levels never occurred in the modelled period at the Ems-Dollard estuary, inundation was unable to affect *Salicornia Europaea*.

Field observations revealed that vegetation was not present at areas seaward from the brushwood dams, despite model results indicating that the inundation is low enough for growth. The main difference between these areas is the lack of protection from hydrodynamic energy at these areas outside of the brushwood dams. Additionally, shear stress was found to significantly affect the modelled *Salicornia Europaea* clusters, although only during one time period with relatively high water levels and wave heights. While the shear stress threshold for plant mortality for these *Salicornia Europaea* clusters is quite high, the plant mortality rate itself is so large that the entire cluster would instantly die-off. This suggests that vegetation in these unprotected areas is affected by significant hydrodynamic energy and shows the importance of decreasing this energy for the development of vegetation at a salt marsh.

7.2. Impact of morphodynamics on the establishment of Salicornia

The second sub question is: "What morphodynamic factors affect the establishment of Salicornia Europaea?"

The model was unable to find significant impact from the bed level change as well as sediment composition at the marsh, both morphodynamic factors, on the establishment of *Salicornia Europaea*. This is likely due to the model being unable to reproduce the bed level change measured at the salt marsh and instead significantly underestimating the bed level change at the modelled marsh.

Nonetheless, results have indicated that *Salicornia Europaea* seedlings are sensitive to bed level change. During periods in the model with calm hydrodynamic and morphodynamic conditions, *Salicornia Europaea* seedlings were observed to die-off due to bed level change. Furthermore, *Salicornia Europaea* was observed to not be able to establish in areas outside of the brushwood dams of similar elevation due to the high hydrodynamic energy and bed level change at these areas compared to the protected sections behind the brushwood dams. This suggests that the negative effects of bed level change, such as burying or dislodging of vegetation, on *Salicornia Europaea* is actually quite significant.

Field observations have shown a clear difference in vegetation density at sections in the salt marsh with different sediment compositions. Layers with a high clay content were found to have denser vegetation than layers with a high sand content. This contrasts with the model results which suggest that sediment composition does not significantly affect the vegetation development at the current elevation. However, the model only considers the effect of the sediment composition on the morphodynamics in the area. This discrepancy between the model and reality suggests that there is another effect of the sediment composition, perhaps linked to the availability of nutrients in clay soil, on the development of vegetation which was not accounted for in the model.

7.3. Threshold for the limiting process of Salicornia's development

The third sub question is: "Is the vegetation development primarily limited by hydro- or morphodynamics and can we determine a threshold for the limiting processes?"

The model results along with field observations of the outer side of the salt marsh suggest that the morphodynamics are the most limiting factor for *Salicornia Europaea's* development. Despite the model's underestimation of the morphodynamics, bed level change was still found to have a clear negative impact on the development of *Salicornia Europaea*. A threshold for morphodynamic change in the model that causes die-off of vegetation at the sown sections of the salt marsh was determined for a measurement point outside of the marsh (G_{North}, Figure 2-5). When water levels and wave heights at this point exceeded 1.45 m and 0.4 m respectively, bed level change and die-off of *Salicornia Europaea* was indeed observed throughout the modelled marsh.

Furthermore, establishment of *Salicornia Europaea* seeds was found to be sensitive to hydrodynamics, with the model revealing a significant impact of the inundation frequency on the establishment of *Salicornia Europaea* and the resulting vegetation pattern found in the marsh. The threshold for impact on the vegetation development is merely the point at which water level exceeds the elevation and causes inundation of the area.

The formed groups of fully developed *Salicornia Europaea*, on the other hand, were found to be much more resilient to hydrodynamic factors such as the inundation and shear stress in the model. Only during one rough hydrodynamic time period, relative to the hydrodynamic climate found inside the Ems-Dollard estuary, did the amount of *Salicornia Europaea* clusters decrease somewhat. Since the *Salicornia Europaea* clusters were unhindered by the hydrodynamic climate, high-density groups were observed throughout the site at the end of the growing season. These high-density clusters appear to form when two requirements are met; an early establishment to give *Salicornia Europaea* plenty of time to grow into fully-developed vegetation and a location that is protected well-enough from hydrodynamic energy to prevent excessive erosion or plant mortality due to shear stresses.

7.4. Sensitivity of Salicornia population to the elevation and brushwood dams

The fourth sub question is: "What are the effects of the elevation of the constructed salt marsh and brushwood dams on the vegetation?"

While the field observations indicated that the brushwood dams protect the vegetation from high hydrodynamic energy and bed level change, the model results showed that the brushwood dams at the Marconi marsh had little effect on the modelled vegetation development. Removing the brushwood dams, which are supposed to protect the area from high shear stress and erosion, from the model did not create a significant increase of erosion or die-off of vegetation inside the sections of the marsh. This discrepancy is likely caused by the dissimilarity between the modelled and actual bed level change at the salt marsh. Based on the field observations of the lack of vegetation outside of the sections, we would conclude that the brushwood dams have significantly reduced the wave energy entering the sections of the salt marsh.

The development of *Salicornia Europaea* was found to be affected by the elevation of the marsh in three stages. The first stage is of well-established *Salicornia* vegetation throughout the marsh and occurred when the elevation was above the mean high water at Delfzijl (1.4 m +NAP). Lowering the marsh to below this mean high water level, changed the relatively well-established *Salicornia Europaea* vegetation towards sparse vegetation as found in the pioneer zone. Lastly, when the elevation was reduced to 1 metre below the mean high water, the sparse *Salicornia Europaea* vegetation of the pioneer zone transitioned to no establishment of *Salicornia* whatsoever.

Interestingly, the model results show that slight reductions in bed level can increase the sedimentation and vegetation density in the area, while large reductions will likely result in a significant increase of erosion and decrease in vegetation density. The morphodynamics and vegetation development during these changes in elevation appear to be correlated; with presumably the increase in sedimentation strengthening against dislodging and the increase in erosion causing the dislodging of *Salicornia Europaea* seedlings.

Finally, while the sediment composition had a limited effect on the modelled morphodynamics and vegetation dynamics at the current elevation of the Marconi marsh, the impact increased when lowering the marsh elevation. During the simulations in which the marsh was lowered, bed level change was found to adjust throughout the sections by an unequal amount. The morphodynamics of areas with high clay content appear to be the most sensitive to changes in elevation while areas with high sand content are found to be less sensitive. This difference is in line with the lower critical bed shear stress of clay compared to sand. In other words, the impact of sediment composition on the morphodynamics and consequently the vegetation dynamics increases the higher the total bed level change is.

8. Recommendations

Based on the results, a few recommendations can be made for future research. These concern the used model, artificial marshes and research on salt marsh vegetation.

Regarding the current model, it is recommended to fix the mentioned limitations of this study. Most importantly, the artificial inundation threshold for sediment dynamics should be lowered as much as possible without affecting the stability of the model. Wind and water level data should be used of the same year. The domain's grid and bathymetry are both simplified and should be refined to increase the accuracy and stability of the model. The current Ems-Dollard boundary uses a basic constant discharge due to the lack of data and the complexity of the water level fluctuations due to the tides. A good option might be to extend the boundary until the start of the Ems river or a similar location where water level measurements have been performed.

At the Marconi marsh, new measurements should be performed at the brushwood dams to improve the dimensions in the model. Additionally, more vegetation measurements should be performed at the sections to increase the sample size. This would increase the accuracy of the used average stem densities for the sections. Preferably, data could also be gathered of the low-lying areas at Marconi which could not be reached during the field excursion.

Due to model instabilities, the diffraction factor in the wave model could not be used. The absence of diffraction negatively affects the accuracy of the flow around the jetties, meaning that the hydro- and morphodynamics around section A have likely been negatively affected as well. The problems with the diffraction factor from the wave model should be investigated. Furthermore, factors such as the critical inundation depth for window 1 of the WoO and critical shear stress and inundation for plant mortality of the population dynamics should be calibrated instead of using constant values. Results have shown that the model is sensitive to the critical inundation depth while perhaps not sensitive enough to the population dynamics factors. Finally, it is also recommended to perform a sensitivity analysis on the parameter settings to test the robustness of the results and see which parameters have a large impact on the model results.

After addressing the current limitations of the model, the model could be extended to simulate for multiple years. Such a run time could be used to investigate the effects of the sowing strategy and development of *Salicornia Europaea* during the first year on the development during the subsequent years. Furthermore, it could be used to predict the vegetation dynamics and morphodynamics at Marconi over the long-term. It should be noted that for longer simulations, the limitations with the usage of the Morphological factor (Morfac) also need to be addressed. In this study we used a timestep of 12 hours for the vegetation development. Combined with the short time window of the WoO's window 1 (2.5 days), this means that any Morfac larger than 4 would create larger timesteps than this window's duration. This would enable establishment every timestep with ebb tide, creating substantial overestimation of the establishment phase of *Salicornia*. Indeed, overestimation was already observed when comparing the regular model with a Morfac of 4 with a model with no Morfac (Figure 6-5). By changing the usage of Morfac from every timestep to after every cycle of window 1, this effect could potentially be circumvented.

Next, regarding research of artificial salt marshes, such as Marconi, it would be interesting to investigate the effects of nutrient availability and other external factors on the development of vegetation in the area. As was discussed in this thesis, these factors, while absent from our model, likely have an impact on the population dynamics of the vegetation. By determining the impact of such

external factors, the accuracy of models could be increased, and one could determine the preferable sediment composition, as well as other factors, to create a successful artificial marsh.

Studies could be performed on the combination of multiple vegetation species in a marsh. A greater understanding of the competition in establishment of plant species as well as the modelling aspects of accounting for multiple plant types would be beneficial for our ability to predict salt marsh development.

Lastly, the various research into the characteristics of *Spartina* and its impact on its surroundings should be used as a basis for future research on different salt marsh vegetation. The effects of important pioneer vegetation, such as *Salicornia*, on the hydrodynamic flow could be investigated. Results could then be compared to the significant impact of the dense *Spartina*. Furthermore, to improve the modelling of vegetation, flume experiments regarding erosion and sedimentation sensitivity of salt marsh vegetation should be performed. Field research on the population dynamics of such species, could also be used to determine the growth patterns and rates and determine important parameters such as the vegetation's maximum density of plants and stems over the year.

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Appendix A: Bed level data points



Figure A-1: Data points of the measurements at the Marconi marsh. Blue indicates a relatively high elevation while red is a relatively low elevation. Note that in section X no data was collected. This is because the section contains a large heap of sand and will therefore not be considered due to the resulting disturbance.

Appendix B: Vegetation parameter plots

In this section some interesting results of the simplified simulation of *Salicornia Europaea* are shown. The simulations show that for an intra-annual plant such as *Salicornia Europaea*, diffusion is not an important parameter. Furthermore, it explains why the establishment probability had to be lowered compared to Schwarz et al.'s (2018) 8%.

Die-off and diffusion Scenarios

In this section, the effects of a slow and instant vegetation die-off along with the diffusion term were investigated. The latter was set at 0 for Salicornia because of a lack of clonal growth (Schwarz et al., 2018). Would the diffusion have any effect on a plant with such a short life cycle? Figure B-1 shows the development of the total stems in the area over five years of; Spartina (with an EP of 0.1% but no dieoff in winter), Salicornia with instant death at the start of winter, Salicornia of which the maximum density dies off after 1.5 months and the same but with an addition of a diffusion term (D=0.2). The difference between the three Salicornia runs is difficult to notice. In particular, the diffusion does not seem to have a significant effect on the development of Salicornia. This is likely because of the intraannual life cycle of Salicornia, while diffusion only really takes effect over multiple years. The slow death scenario did not have the effect that was hoped for. Stems are only present slightly longer compared to the instant death (also see Figure B-2 and Figure B-3). This is due to the overall low stem densities which were used in this model version (Figure B-2 and Figure B-3), since the longer die-off scenario was based on the maximum possible density. With a low stem density, the type of death is unimportant. However, the impact should become noticeable with a higher stem density. The model used for the growing season simulations of Chapter 0 used a maximum stem density (K) of 600 stems/ m^2 . This was based on field measurements performed at the Marconi site (4.4).



Figure B-1: The total stems in the area for the four model tests over five years with measurements made every 400 hours (4hr*100 Morfac=400 hours).



Figure B-2: The bed level (left bar, in m) and the stem density (right bar, stems/m2) over the area (with x and y in metres) of the test with instant death of Salicornia just at the end of summer 1 (a, t=10) and the start of the winter (b, t=11).



Figure B-3: The bed level (left bar, in m) and the stem density (right bar, stems/m2) over the area (with x and y in metres) of the test with slow death of Salicornia (2 months for 200 stems to disappear) just at the end of summer 1 (a, t=10) and the start of the winter (b, t=11).

New Window 2 setup with high establishment probabilities

In this test, 5 years were run with planted vegetation in the 1st year and the usage of vegetation densities and stem heights during window 2. In year 1, the EP was 100% in the planted areas, year 2 had a general EP of 4% and year 3-5 had a general EP of 8%. Results can be found in Figure B-4. No correlation between the location of the vegetation in year 1 and year 2-5 can be found. Furthermore, with the stem density of 10 stems/m² during window 2 and 20 stems/m² after window 2, the process in each cell can clearly be seen. One thing that should be mentioned is the significant increase in vegetated cells compared to the previous tests (such as Figure B-2 & Figure B-3), even though the establishment probability is lower than what was used in most runs.

The original code uses the EP at the end of a successful 2nd window and, in case of failure, resets the windows to zero. In essence, for the entire process an 8% chance is given that during this time a seed was actually present in the cell. However, when including vegetation characteristics during window 2, the presence of a seed needs to be determined before the process starts instead of afterwards. Therefore, the code was changed to where the EP was checked every timestep, giving an unnatural establishment of vegetation. In order to create a somewhat realistic model with the inclusion of window 2, the EP needs to be lowered to a realistic value. This was done via calibration based on the field measurements in Chapter 4.4.



Figure B-4: On the left: The total stems in the area for the Win2 stem height and density test over five years with data collected every 400 hours (4hr*100 Morfac=400 hours). In year 1, the EP was 100% in the planted areas, year 2 had a general EP of 4% and year 3-5 had a general EP of 8%. On the right: The bed level (left bar, in m) and the stem density (right bar, stems/m2) over the area (with x and y in metres) at the end of summer year 2 with 4% EP



Figure B-5: The bed level (left bar, in m) and the stem density (right bar, stems/m2) over the area (with x and y in metres) over time during the growing season of year 2 (EP=4%). The difference in vegetation that has completed the second window and the plants that are still in it can clearly be seen.

Appendix C: Python code of the vegetation dynamics

```
import numpy as np
import bmi.wrapper
import ctypes
import matplotlib.pyplot as plt
import matplotlib.tri as tri
import os
import datetime
from scipy import integrate
import faulthandler
faulthandler.enable()
## Specify paths of dll-files and input-files
D3D_HOME = r'E:\Data Delft3D
model\Deltversion\Marconiv2\MarconiModel\MarconiModel\Marconi_v02\Code1709\windows\oss
_artifacts_x64_63721\x64'
dimr path = os.path.join(D3D HOME, 'dimr', 'bin', 'dimr dll.dll')
dflowfm_path = os.path.join(D3D_HOME, 'dflowfm', 'bin', 'dflowfm.dll')
workdir
         = r"E:\Data Delft3D
model\Deltversion\Marconiv2\MarconiModel\MarconiModel\Marconi v02"
config file = os.path.join(workdir, 'dimr config.xml')
mdu file = os.path.join(workdir, 'fm', 'Marconi v02.mdu')
grid_file = os.path.join(workdir, 'fm', 'grid_marconi_v07_net.nc')
figsavefolder= r"E:\Data Delft3D
model\Deltversion\Marconiv2\MarconiModel\MarconiModel\Marconi v02\figs"
print("D3D_HOME :" + D3D_HOME)
print("dimr_path :" + dimr_path)
print("config_file:" + config_file)
## Add corrects locations to environment variable PATH
os.environ['PATH'] = os.path.join(D3D HOME, 'share', 'bin') \
+ ";" + os.path.join(D3D HOME, 'dflowfm', 'bin') \
+ ";" + os.path.join(D3D HOME, 'dimr', 'bin') \
+ ";" + os.path.join(D3D_HOME, 'dwaves', 'bin') \
+ ";" + os.path.join(D3D_HOME, 'esmf', 'scripts') \
+ ";" + os.path.join(D3D_HOME, 'swan', 'scripts')
## Define DFM wrapper
model_dfm = bmi.wrapper.BMIWrapper(engine=dflowfm_path, configfile=mdu_file)
## Define and initialise DIMR wrapper
model dimr = bmi.wrapper.BMIWrapper(engine=dimr path, configfile=config file)
model dimr.initialize()
print ('model initialized')
## Get the pointers to important model variables of FlowFM, list of accessible parameters and
meaning can be found
at:https://svn.oss.deltares.nl/repos/delft3d/trunk/src/engines_gpl/dflowfm/packages/dflowfm_lib/i
nclude/bmi_get_var.inc
```

ndx=model dfm.get var('ndx') ndxi=model_dfm.get_var('ndxi') xzw=model_dfm.get_var('xzw') yzw=model_dfm.get_var('yzw') Inx=model dfm.get var('Inx') Inxi=model_dfm.get_var('Inxi') In=model_dfm.get_var('ln') dx=model_dfm.get_var('dx') wu=model dfm.get var('wu') ba=model dfm.get var('ba') bedlevel=model_dfm.get_var('bl') ## initialisation of vegetation variables rnveg=model dfm.get var('rnveg') stemdia=model_dfm.get_var('diaveg') stemheight=model_dfm.get_var('stemheight') ## settings # define number of timesteps (nt) and duration of time steps (tstep) in [s] mtpervt=12*3600 #model run time (s) between vegetation updates/checks daysecs=3600*24 MF=4.0 tstep_season = int(180/(mtpervt*MF/(daysecs))) #43 # length of a season is 180 days / 4.16666 days = 43 days nt=tstep season #or 1 for a test model days = nt*mtpervt / (3600*24)model_months = nt*mtpervt / (86400*30) ncells = len(rnveg)print ('models spans', model_days, 'days, or', model_months, 'months') print ('# of vegetation timesteps ', nt) print ('timestep length ', mtpervt ,' seconds') ## WoO parameters WoO T = np.zeros(shape=(len(bedlevel),)) # WoO progression tracking array: how far is each grid cells into the WoO W2steps = np.zeros(shape=(len(bedlevel),)) # How many timesteps in second window completed hcrit = 0.01 # critical inundation depth [m] CED1 = 8e-03 # initial critical erosion depth single timestep [m] CED2 = 27e-03 # mature critical erosion depth single timestep [m] Savg = 15*((1.0)/(MF*7*24))*1.0e-03 #originally /by morfac!# critical average sedimentation over plant life in [m/s] (15 mm / week) Smin = 1*60*60 # minimum age for average sedimentation chekc in [s] $Eavg = 5^{((1.0)/(MF^{*}7^{*}24))^{1.0e-03}}$ #originally /by morfac!# critical average erosion over plant life [m/s] (5 mm / week) Emin = 1*60*60# minimum age for average erosion check in [s] alpha = 1.50 height_W2=0.02 PW2=20 #Stem density at the start of W2

import array as arr EP = arr.array('d', [0.0075, 0.0075, 0.0075, 0.0075, 0.0075]) #Schwarz: 0.92, 0.92, 0.84, 0.76, 0.76, 0.76

W1 = (2.5*daysecs)/MF	#Divided by morfac length of Window 1 in [s] (2.5
days default)	
wdcrit = 0.01	<pre># critical inundation depth [m]</pre>
W2 = (90*daysecs)/MF	<pre>#Divided by morfac length of Window 2 in [s];</pre>
days*daylength (90 days default)	

preallocating the matrix used for saving historic bed level values and vegetation density values blh = np.zeros(shape=(len(bedlevel),3)) rnveg_historic = np.zeros(shape=(10553,((nt)))) bl_historic = np.zeros(shape=(len(bedlevel),((nt)))) stemheight_historic=np.zeros(shape=(len(bedlevel),((nt)))) EPSuc=np.zeros(shape=(len(bedlevel))) Veghist = np.zeros(shape=(len(xzw),1)) Plantonce=np.zeros(shape=(len(bedlevel))) c=np.zeros(shape=(len(bedlevel)))

```
## population dynamics parameters
yearsec=24*60*60*365
P0=60.0
                       # Plant density of seedlings after W2 (stems/m2)
r=20.0/(365*2)
                               # intrinsic growth rate of plant density (per year)
K=600.0
                               # carrying capacity of plant density (stems/m2)
Ctau=(30.0/(365*24))*yearsec
                                       # plant erosion coefficient due to bed shear stress (m^-2 s^1)
tau_crp=0.25
                          # critical bed shear stress for plant erosion (N/m2)
Cinund=3000/(365*24)
                                       # plant erosion coefficient due to inundation stress (m^-3 y^-
1)
inund crp=1.0
                           # critical inundation height at high tide for plant erosion (m)
diam_def=0.005
                            # default diameter stems
height_def=0.28
                           # default height stems
                               # diffusion coefficient [m^2 y^-1]
D=0
```

```
stemdia[:]=diam_def
model_dfm.set_var('diaveg',stemdia)
print ('stemdia set: ',stemdia)
stemheight[:]=height_def
model_dfm.set_var('stemheight',stemheight)
print ('stemheight set: ',stemheight)
Vegsectionsnodes=np.loadtxt("E:\Data Delft3D
model\Deltversion\Marconiv2\MarconiModel\MarconiModel\Marconi_v02\CellsSectionsv2.txt",dty
pe=int) #The sown seeds at Sections E, F and G
rnveg[:]=0
model_dfm.set_var('rnveg',rnveg)
print ('rnveg set: ' + str(rnveg))
```

locating indices of possible vegetated gridcells used for the WOO loop (it is unnecessary to check for windows in grid cell located below -1m, no vegetation can grow there) count=0 veg_area = np.zeros(shape=(10553,)) for j in range(0,10553):

```
if bedlevel[j]>=-1 and bedlevel[j]<3: #NB not exact numbers, just an approximation
    veg_area[count]=int(j)
    count=count+1
veg_area=veg_area[:count]
def makeinirandfield (P):
  P[range(ndxi)]=0
  return(P)
def erosveg(P,tau_max):
  dptau=-P*Ctau*(tau max-tau crp)
  dptau[dptau>0.0]=0.0
  return(dptau)
def inundveg(P,wd_mn):
  dpinund=-P*Cinund*(wd_mn-inund_crp)
  dpinund[dpinund>0.0]=0.0
  return(dpinund)
def vegRoC (P,t0):
  dPdt=np.zeros(ndxi)
  # logistic growth
  dPdt=dPdt+r*P*(1-P/K)
  # Diffusion
  dPdt=dPdt+0
  # erostau
  dPdt=dPdt+erosveg(P,tau_mn)
  # inundation stress
  dPdt=(dPdt+inundveg(P,wd_mn))*MF
  # return rate of change
  return(dPdt)
  # population dynamics equation in winter season
def vegWinter (P,t0):
  dPdt=np.zeros(ndxi)
  # erostau
  dPdt=dPdt+erosveg(P,tau_mn)
  # inundation stress
  dPdt=dPdt+inundveg(P,wd_mn)
  # return rate of change
  dPdt=dPdt
  return(dPdt)
##set initial vegetation field
rnveg=makeinirandfield(rnveg[range(ndxi)])
                                                  # random seeding of plants
## model update and WoO loop
realtime=0
tdata=1
tt = 0
summersteps=0
wintersteps=0
```

```
year=0
t=np.array([0.0,1.0])
for i in range(1,nt+1):
  model dimr.update(mtpervt)
                                      #update the model
  is_dtint=model_dfm.get_var('is_dtint')
                                              #timespan over which statistics are kept, needs to be
reset after each vt (otherwise accumulative)
  print(is dtint)
  realtime=realtime+is dtint
  print('real time is ' + str(realtime) + ' s, or ' + str(realtime/daysecs) + ' days')
  print('step ' + str(i) + ' of ' + str(nt))
  bl=model dfm.get var('bl')
  hs=model_dfm.get_var('hs')
                                      #load in the water level
  blh[:,2]=bl
                                      #store the bed level in a matrix so it can be checked against
previous bed levels in the WoO model
  ## summer time step calculations
  if summersteps < tstep_season:
    # population dynamic (growth, decay tau, decay wd) model every timestep
    is_maxvalsnd=model_dfm.get_var('is_maxvalsnd')
    is sumvalsnd=model dfm.get var('is sumvalsnd')
    bedlvl=model dfm.get var('bl')
    tau mn=is sumvalsnd[range(ndxi),0]/is dtint
    vel mn=is sumvalsnd[range(ndxi),1]/is dtint
    wd mn=is sumvalsnd[range(ndxi),2]/is dtint
    tau max=is maxvalsnd[range(ndxi),0]
    vel_max=is_maxvalsnd[range(ndxi),1]
    wd_max=is_maxvalsnd[range(ndxi),2]
    # run plant growth model
    rslt=integrate.odeint(vegRoC, rnveg[range(ndxi)], t,h0=.05,hmax=.1)
    rslt=integrate.odeint(vegRoC, rnveg[range(ndxi)], t)
    for veg in range(ndxi):
      if WoO T[veg]==-1:
                                                                                     #decay due to
        if rnveg[veg]>0.1:
bed shear stress
           rnveg[veg]=rslt[1,[veg]]
         if rnveg[veg]<=0.1 and WoO_T[veg]==-1 and rnveg[veg]!=0: #if established vegetation has
vanished, WOO opens and is checked again
           rnveg[veg]=0.0
           WoO_T[veg]=0
        elif rnveg[veg]<=0.1 and rnveg[veg]!=0: #decay of diffused vegetation
           rnveg[veg]=0.0
    if year==0:
      for j in veg_area:
        k=int(i)
        c[k]=EP[year]
        a=np.random.rand(1)
        if Vegsectionsnodes[k]==1 and Plantonce[k]==0:
           Plantonce[k]=1
           c[k]=0.55;
```

```
if a \geq (1-c[k]) or EPSuc[k]==1:
          EPSuc[k]=1
          if WoO_T[k] == -1:
             continue
          elif WoO T[k] \le W1:
             if hs[k] < hcrit:
               WoO_T[k]=WoO_T[k]+mtpervt
             else:
               WoO_T[k]=0
               EPSuc[k]=0
          elif WoO_T[k]> W1 and WoO_T[k] <= W1+W2:
             if W2steps[k]==0:
               blh[k,0]=blh[k,2]
               blh[k,1]=blh[k,2]
               rnveg[k]=PW2
               stemheight[k]=height_W2
               W2steps[k]=1
             if (-blh[k,1] + blh[k,2]) > -(CED1 + ((WoO_T[k]-W1)/W2) * (CED2 - CED1) + (alpha * (-
blh[k,0]+blh[k,2]))) and (-blh[k,0] + blh[k,2])/max((WoO_T[k]-W1),Emin) > -Eavg and (-blh[k,0] +
blh[k,2])/max((WoO_T[k]-W1),Smin) < Savg:
               WoO_T[k]=WoO_T[k]+mtpervt
               blh[k,1]=blh[k,2]
               stemheight[k]=height_W2 + (WoO_T[k]-W1) * (height_def-height_W2)/W2
             else:
               WoO T[k]=0
               W2steps[k]=0
               stemheight[k]=0
               rnveg[k]=0
               EPSuc[k]=0
          elif WoO_T[k] > W1+W2:
             rnveg[k]=P0
             WoO T[k] = -1
             W2steps[k]=0
    elif year!=0:
      for j in veg_area:
        k=int(j)
        a=np.random.rand(1)
        if a >=(1-(EP[year])) or EPSuc[k]==1:
          EPSuc[k]=1
          if WoO_T[k] == -1:
             continue
          elif WoO T[k] \le W1:
             if hs[k] < hcrit:
               WoO_T[k]=WoO_T[k]+mtpervt
             else:
               WoO T[k]=0
               EPSuc[k]=0
          elif WoO_T[k]> W1 and WoO_T[k] <= W1+W2:
             if W2steps[k]==0:
               blh[k,0]=blh[k,2]
               blh[k,1]=blh[k,2]
```

```
rnveg[k]=PW2
               stemheight[k]=height_W2
               W2steps[k]=1
             if (-blh[k,1] + blh[k,2]) > -(CED1 + ((WoO_T[k]-W1)/W2) * (CED2 - CED1) + (alpha * (-
blh[k,0]+blh[k,2])) and (-blh[k,0] + blh[k,2])/max((WoO_T[k]-W1),Emin) > -Eavg and (-<math>blh[k,0] + blh[k,2])
blh[k,2])/max((WoO_T[k]-W1),Smin) < Savg:
               WoO_T[k]=WoO_T[k]+mtpervt
               blh[k,1]=blh[k,2]
               stemheight[k]=height_W2 + (WoO_T[k]-W1) * (height_def-height_W2)/W2
             else:
               WoO_T[k]=0
               W2steps[k]=0
               stemheight[k]=0
               rnveg[k]=0
               EPSuc[k]=0
          elif WoO_T[k] > W1+W2:
             rnveg[k]=P0
             WoO_T[k] = -1
             W2steps[k]=0
    ## print information on current timestep
    currentDT = datetime.datetime.now()
    print ('Summer Timestep ', str(summersteps),' completed at --> ', str(currentDT),' \n')
    ## Update summer season counter
    summersteps=summersteps+1
      ## switch between summer and winter season
  if summersteps == tstep_season and wintersteps == 0:
    WoO T[WoO T>1]=0
                                             # re-set progress of WoO in every grid cell
    W2steps[WoO_T>1]=0
                                             # re-set number of timesteps in window 2
  ## winter time step calculations
  if summersteps == tstep season and wintersteps < tstep season: # boundary between end
summer-begin winter, vegetation will be adjusted
    is_maxvalsnd=model_dfm.get_var('is_maxvalsnd')
                                                                    # [-] Integral values on flow
nodes
    is sumvalsnd=model dfm.get var('is sumvalsnd')
    is_dtint=model_dfm.get_var('is_dtint')
    wd_max=is_maxvalsnd[range(ndx),2]
                                                    #maximum water level and maximum bed
shear stress during the last time step
    tau_max=is_maxvalsnd[range(ndx),0]
    rslt=integrate.odeint(vegWinter, rnveg[range(ndxi)], t,h0=.05,hmax=.1)
    rslt=integrate.odeint(vegWinter, rnveg[range(ndxi)], t)
    for veg in range(ndxi):
      if rnveg[veg]>0.1:
                                                                    #decay due to bed shear
stress
        rnveg[veg]=(rslt[1,[veg]])-(200/(15.0))
                                                    #New integration of cell and slow die-off due
to winter: Takes 15 tsteps for max stems to disappear: 15*8/2=60 days --> Oct-Nov
      if rnveg[veg]<=0.1 and WoO_T[veg]==-1 and rnveg[veg]!=0: #if established vegetation has
vanished, WOO opens and is checked again
        rnveg[veg]=0.0
```

```
WoO T[veg]=0
         EPSuc[veg]=0
      elif rnveg[veg]<=0.1 and rnveg[veg]!=0:
                                                    #decay of diffused vegetation
         rnveg[veg]=0.0
    ## print information on current timestep
    currentDT = datetime.datetime.now()
    print ('Winter Timestep ', str(wintersteps),' completed at --> ', str(currentDT),' \n')
    ## Update winter season counter
    wintersteps=wintersteps+1
  ## switch between winter and summer; reset season counters
  elif summersteps == 43 and wintersteps == 43:
    summersteps = 0
    wintersteps =0
    model_dfm.set_var('stemheight',stemheight)
    ## print information on current timestep
    print ('Year ', str(year),' completed \n')
    year=year+1
  if (i) % (1) == 0:
    rnveg historic[:,tt]=rnveg
    bl historic[:,tt]=bl
    stemheight_historic[:,tt]=stemheight
    tt=tt+1
                             #export the latest bed level and vegetation values to check the output
  np.savetxt('blout.txt',bl)
whilst running the model
  np.savetxt('rnvegout.txt',rnveg)
  ## feed back the updated vegetation field to the FM model
  vegupdate=np.copy(rnveg)
  vegupdate[vegupdate<2]=0
                                        #only vegetation with densities greater than 2 stems/square
meter are fed back into the DFM model
  model_dfm.set_var('rnveg',vegupdate)
  #reset the maximum bss and inundation height value counter
  is_sumvalsnd.fill(0.0)
  is maxvalsnd.fill(0.0)
  is dtint.fill(0.0)
  model_dfm.set_var('is_sumvalsnd',is_sumvalsnd)
  model_dfm.set_var('is_maxvalsnd', is_maxvalsnd)
  model_dfm.set_var('is_dtint',is_dtint)
model_dimr.finalize()
```

```
print ('model finished')
## end of script
```

Appendix D: 2D bed level change plots of the lowered Marconi marsh simulations

Below four figures of the bed level change (m) over the Marconi site can be found which were made during the lowered Marconi marsh simulations.



Figure D-1: The bed level change (m) at Marconi when it is lowered by 0.25 m over half a year on the right axis plotted along with the lowered bed level (m) on the left axis. Bed level changes of under 0.5 mm were cut, revealing the bed level underneath.



Figure D-2: The bed level change (m) at Marconi when it is lowered by 0.5 m over half a year on the right axis plotted along with the lowered bed level (m) on the left axis. Bed level changes of under 0.5 mm were cut, revealing the bed level underneath.

Appendix D: 2D bed level change plots of the lowered Marconi marsh simulations



Figure D-3: The bed level change (m) at Marconi when it is lowered by 0.75 m over half a year on the right axis plotted along with the lowered bed level (m) on the left axis. Bed level changes of under 0.5 mm were cut, revealing the bed level underneath.



Figure D-4: The bed level change (m) at Marconi when it is lowered by 1.0 m over half a year on the right axis plotted along with the lowered bed level (m) on the left axis. Bed level changes of under 0.5 mm were cut, revealing the bed level underneath.

Appendix E: 2D vegetation plots of the lowered Marconi marsh simulations

Below four figures of the stem density (stems/m²) over the Marconi site can be found which were made during the lowered Marconi marsh simulations.



Figure E-1: The stem density (stems/m2) per cell at the Marconi marsh when lowered by 0.25 m on the right y-axis along with the lowered bed level (m) on the left y-axis. The black lines indicate the dikes separating the sections.



Figure E-2: The stem density (stems/m2) per cell at the Marconi marsh when lowered by 0.5 m on the right y-axis along with the lowered bed level (m) on the left y-axis. The black lines indicate the dikes separating the sections.

Appendix E: 2D vegetation plots of the lowered Marconi marsh simulations



Figure E-3: The stem density (stems/m2) per cell at the Marconi marsh when lowered by 0.75 m on the right y-axis along with the lowered bed level (m) on the left y-axis. The black lines indicate the dikes separating the sections.



Figure E-4: The stem density (stems/m2) per cell at the Marconi marsh when lowered by 1.0 m on the right y-axis along with the lowered bed level (m) on the left y-axis. The black lines indicate the dikes separating the sections.