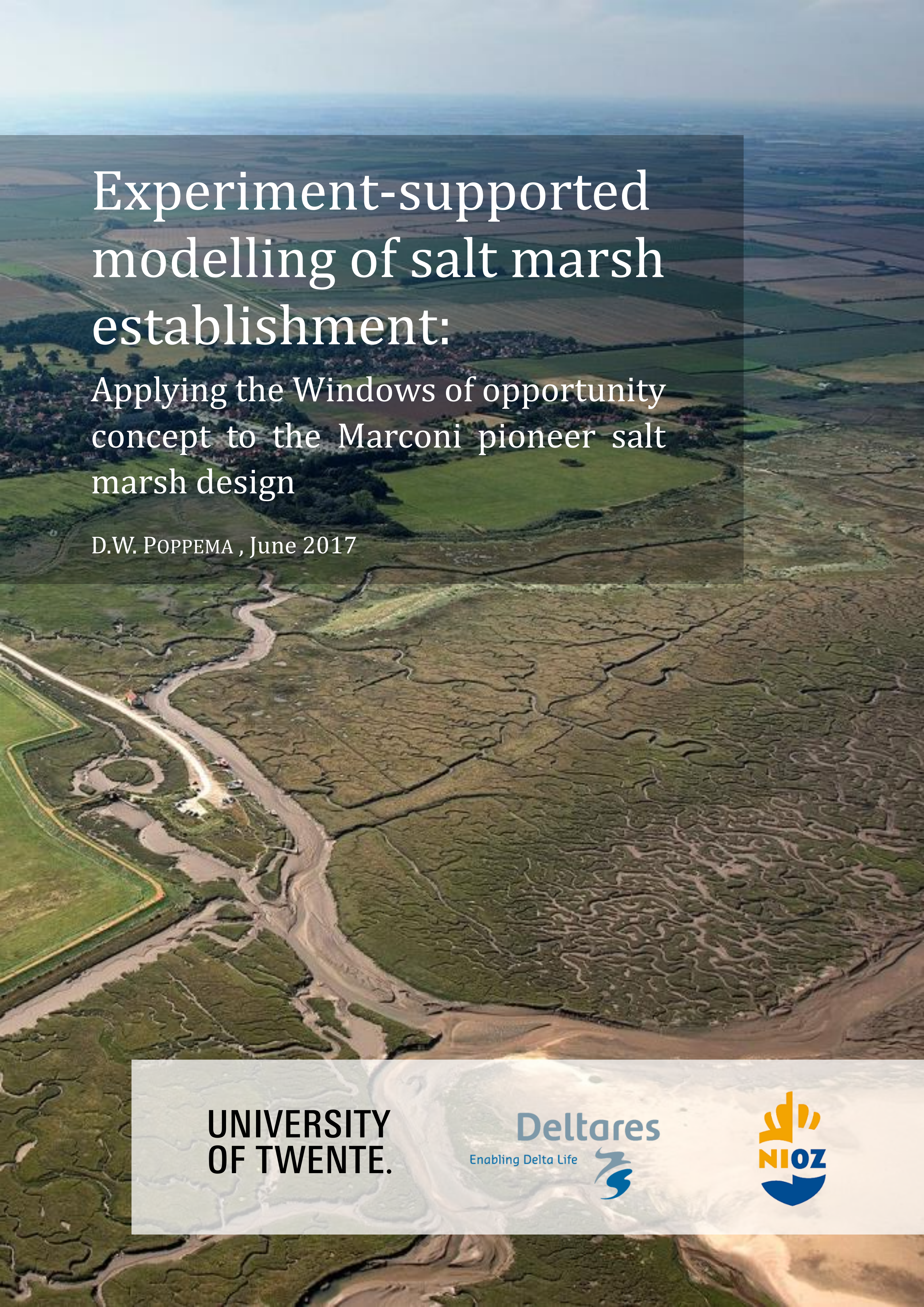

Experiment-supported modelling of salt marsh establishment:

Applying the Windows of opportunity concept to the Marconi pioneer salt marsh design

D.W. POPPEMA , June 2017

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Cover photo: The Thornham salt marsh (in Norfolk, UK) by J. Fielding

Experiment-supported modelling of salt marsh establishment

Applying the Windows of opportunity concept to the Marconi pioneer salt marsh design

By

D.W. (DAAN) POPPEMA

In partial fulfilment of the requirements for the degree of Master of Science

in Water Engineering and Management at the University of Twente

June 2017

Delft

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SUMMARY

Worldwide, many projects are trying to create and restore salt marshes because of their ecological functions and their benefits for flood protection and erosion control. One of these projects is the Marconi pilot project that is planned in Delfzijl, The Netherlands. Its aim is to create a pioneer salt marsh and to obtain generally applicable knowledge about salt marsh creation by experimenting with different measures and designs. This thesis, done as part of the Marconi project, has the objective to determine under which conditions pioneer salt marsh vegetation can establish and how this knowledge can be applied in the design of the Marconi pioneer salt marsh.

To determine if vegetation can establish, the Windows of opportunity (WoO) concept of Balke et al. (2011) is used. This theory states that plants require subsequently a short disturbance-free period to grow roots (WoO1); a period with calm hydrodynamic conditions (WoO2) in which the plants can grow stronger and a period in which the high-energy events do not exceed the vegetation limits (WoO3). Because plants are very sensitive to erosion and a large part of this erosion occurs during relatively moderate events, this study defines the limits of the windows in terms of the critical erosion depth (CED) of plants.

An experiment was used to determine the CED under varying environmental conditions. *Spartina anglica* and *Salicornia procumbens* plants were grown and subsequently tested in a wave flume to determine how much erosion they can handle before they topple over. This showed that the CED depends mostly on previous bed level change, supporting the choice to define the WoO framework in terms of bed level dynamics.

A Delft3D model of the situation at Marconi was set-up to predict the bed level dynamics and implement the WoO framework (see Figure 1). In this model erosion occurs, with a cliff forming around the high water line. As a result, vegetation establishment can only occur directly at the coast. The sensitivity analysis showed that the result is quite robust, with the expected establishment pattern being independent of the examined parameter values (durations and erosion limits of the WoO framework) and the sediment type and vegetation implementation in Delft3D. However, lower wave heights would reduce the erosion and improve the establishment chances. A wave height reduction of 50 percent prevents nearly all erosion and enables the successful establishment of a pioneer salt marsh.

In short, this study showed that it is essential for the stability of the Marconi pioneer salt marsh pilot that measures are taken to dampen the waves. For successful salt marsh establishment, a wave height reduction of 50 percent is probably sufficient. Furthermore, this study used the data from the experiment to calibrate and improve the WoO framework, thereby providing valuable information for future building with nature projects.

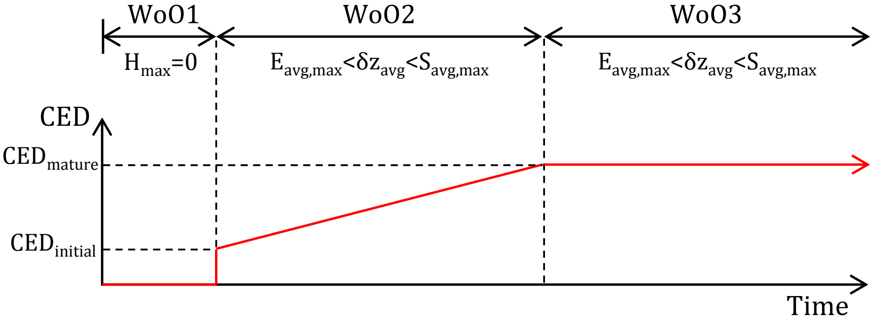

Figure 1: The Windows of opportunity framework as used in this study, with H indicating water depth, E erosion, δz_{avg} the average bed level change in a plant's life, S sedimentation and CED critical erosion depth.

PREFACE

This thesis forms the conclusion of my Master in Water Engineering and Management at the University of Twente. The research was carried out mainly at Deltares in Delft, with the experiment being done at the NIOZ in Yerseke.

This research project would not have been possible without the help of a number of people. First, I would like to thank my committee for their supervision and support throughout this project. I want to thank Mindert de Vries and Bas Borsje for giving me the opportunity to work on this project. Furthermore, I would like to thank Mindert for his creative ideas, his enthusiasm and his guidance during my work at Deltares and Bas for his help with modelling and his feedback on my report. I would like to thank Pim for his help with improving and interpreting the model and his help with the flume experiments. Furthermore, I want to express my gratitude to Zhenchang for his help with the design and execution of the experiment and to Suzanne for her critical views during our meetings.

For the experiment I also have a number of people I want to thank. First al all, I want to thank Tjeerd Bouma for giving me the opportunity to conduct the experiment at the NIOZ as part of the Be Safe program. Bert and Lennart, thank you for your help with the technical aspects of the experiment. And last but not least, I want to thank Yifei for all his help with the preparations of the experiment and the experiment itself!

Finally, I want to thank my fellow students at Deltares for all the lunches, coffee breaks and discussions we have had and my family and friends for their support during my thesis.

Daan Poppema,
Delft, June 08, 2017

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1

INTRODUCTION

Over the ages, the Dutch have reclaimed large areas of land from the sea, and in the process diminished the natural salt marsh area. However, nowadays the societal and scientific perception of salt marshes has changed and they are regarded as valuable ecosystems. They form a habitat and nursery ground for both rare and commercially important species, provide recreational opportunities and filter water (Vernberg, 1993; Roman, 2012). Their increased elevation and roughness attenuate waves, increasing coastal safety (Borsje et al., 2011; Vuik et al., 2016). And because they trap and stabilise sediment, they can – within limits – keep up with sea level rise (e.g. Temmerman et al., 2004; Kirwan & Megonigal, 2013). This combination gives them the potential to provide sustainable and cost-effective coastal protection.

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 (e.g. Wolters et al., 2005; Williams & Faber, 2001; Roman, 2012), and comparable projects for mangroves in the more tropical zones (e.g. Bosire et al., 2008; Primavera & Esteban, 2008). One of these projects is the Marconi pilot project that will be undertaken in the Eems, near Delfzijl, the Netherlands. Its aim is to examine the effect of different measures and designs on salt marsh establishment and development and thereby obtain generally applicable knowledge for future building with nature projects. This thesis, which is done at Deltares, forms a part of the Marconi project.

1.1 STATE OF THE ART

Salt marshes are coastal wetlands in the upper intertidal zone. The regular flooding by the tide in combination the impact by waves and storms makes them highly dynamic ecosystems, where tides cause an influx of sediment, plants trap this sediment and cause sedimentation and storms cause erosion (Temmerman et al., 2005a; Christiansen et al., 2000). Apart from the vertical sedimentation and erosion, the lateral seaward marsh expansion and landward marsh retreat play an important role in salt marsh dynamics. In general, retreat occurs when a salt marsh cliff forms and then erodes due to the wave attack upon this cliff. Expansion occurs when the conditions in front of the salt marsh cliff are calm enough for seedlings to establish. With the succession from mud flat to pioneer zone and eventually mature salt marsh, the marsh expands (Bouma et al., 2016; Silinski et al., 2016).

Like all plants, pioneer salt marsh vegetation can only establish when the conditions are sufficiently supportive. Important factors are the inundation time, elevation, wave climate, seed and nutrient availability, salinity and sediment characteristics (De Groot & Van Duin, 2013; Friess et al., 2012). Salt marsh vegetation, and especially pioneer vegetation, is adapted to the harsh environment of an intertidal mudflat. They can establish rapidly in saline, anoxic and frequently inundated conditions (Friess et al., 2012). However, if these stresses become too strong, establishment becomes impossible.

Several techniques exist to improve the conditions for salt marsh establishment. Amongst others, brushwood groynes and oyster reefs can decrease the hydrodynamic actions; sand and clay suppletions can increase the sediment supply; vegetation can be sown or planted directly and (experimental) techniques like nets and shell layers can decrease bioturbation (De Groot & Van Duin, 2013; Borsje et al., 2011; Storm, 1999; Van Oevelen et al., 2000; Suykerbuyk et al., 2012). However, with so many possible measures, it is important to choose those that fit the situation: solutions can only be successful if they specifically target the factors that are locally limiting salt marsh formation.

To determine if the hydrodynamic conditions permit salt marsh establishment, the Windows of opportunity (WoO) concept can be used. This concept, which Balke et al. (2011) developed for mangrove seedlings, states that seedlings can establish when the local conditions remain below the thresholds of the subsequent windows of opportunity. First, a disturbance-free period is required so that seeds can develop roots and withstand the stress of flooding. In the second window the stress that plants can withstand increases with increasing root length. During the third window, the erosion caused by high energy events should remain below what vegetation can withstand. Hu et al. (2015) applied this concept to salt marsh establishment and defined the limits of the second window in terms of bed shear stress (see Figure 1.1). Attema (2014) also implemented the third window to predict long-term salt marsh development, and defined both windows in terms of bed shear stress.

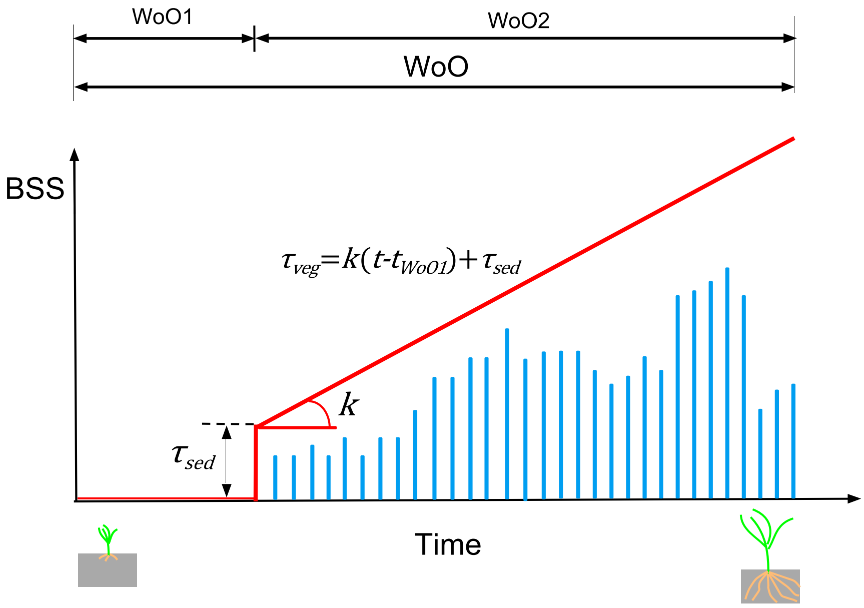

Figure 1.1: An illustration of the WoO framework, showing a situation with successful establishment: the bed shear stress [in blue] always remains under the time-dependent critical bed shear stress [the red line] (Hu et al., 2015)

1.2 Research gap

So far, the WoO framework has been defined in terms of critical bed shear stress. This implies that storms are normative, as the highest bed shear stresses are caused by the high waves during storms. However, according to Cao et al. (2017) seedlings are especially sensitive to bed level change, while Leonardi and Fagherazzi (2015) have found that most erosion occurs during moderate events instead of extreme events. Therefore, it might be better to define the windows of opportunity in terms of bed level change.

Such a change would make it possible to take the effects of both moderate conditions and extreme events into account, thereby making it possible to determine which conditions are limiting salt marsh formation and to decide upon the appropriate salt marsh restoration techniques. As this would be a novel approach, research into the application and implications of such a Windows of opportunity framework is needed.

To implement this Windows of opportunity framework, the strength of vegetation over time should be known. However, measurements of the erosion resistance of temperate salt marsh vegetation are limited. In addition, the research that exists (Bouma et al., 2016; Cao et al., 2017) focusses mostly on *Spartina* species and is based on experiments with only currents and no waves. Therefore, more data is needed on the strength of salt marsh vegetation, the effects of waves and the differences between different vegetation types.

Figure 1.2: A tussock of Spartina vegetation, surrounded by individual Salicornia plants, at a salt marsh near Moddergat, at the Dutch Wadden Sea (Braam, n.d.).

1.3 Research objective

This research aims to solve the identified research gaps. To do this, the following research objective is defined:

"To determine under which conditions pioneer salt marsh vegetation can establish and use this knowledge to reach new insights for the design of the Marconi pioneer salt marsh pilot."

In order to reach this objective, the following research questions should be answered:

1. *How do plant age, wave height and bed level change affect the critical erosion depth (CED) of pioneer salt marsh vegetation?*

   The goal of this question is to experimentally determine the critical erosion depth for seedlings, the differences between *Spartina anglica* (common cord grass) and *Salicornia procumbens* (Saltwort) species and the effects of age, wave height and bed level dynamics. In this, critical erosion depth is defined as the amount of erosion that has to occur before seedlings topple over.

2. *How can vegetation establishment at the Marconi pioneer salt marsh be predicted?*

   The goal of this question is to use the data from question 1 to define the WoO framework in terms of bed level change and use this framework in combination with a hydrodynamical Delft-3D model of the Marconi project site to predict salt marsh establishment. For establishment this research regards a period of a full year: the period in spring and summer to determine if seedlings can germinate and establish and the autumn and winter to determine if they can also survive the stronger winter storms.

3. *What are the implications of the experiment and model for the design of the Marconi pioneer salt marsh pilot?*

   The goal of this question is to use the results, sensitivities, uncertainties and conclusions of the previous questions to come to concrete recommendations for the Marconi project.

1.4 REPORT OUTLINE

Chapter 2 will present the methodology that is followed in this study. It describes the study area, the way in which the Windows of opportunity framework is used, the flume experiment and the Delft-3D model and its use for establishment modelling. Chapter 3 gives the results of this study. This starts with the results of the flume model, followed by the results of the establishment modelling. After presenting this baseline, it also details how these results depend on the choices made in the WoO schematization and the Delft3D model. Chapter 4 discusses the limitations, innovations and implications of this study, followed by the conclusions in chapter 5 and the recommendations in chapter 6.

2

METHODOLOGY

This chapter presents the methods used during this research. It starts with a description of the Marconi project site. Next, the definition and usage of the Windows of opportunity framework in this research are explained. The following section presents the experimental set-up and methods used to determine the critical erosion depth of salt marsh vegetation. And the last section describes the Delft3D model that is used to model vegetation establishment.

2.1 STUDY AREA

The Marconi pioneer salt marsh, which forms the reason for doing this research, will take place at Delfzijl, a coastal city in the north of the Netherlands. It is a part of a larger project to increase the coastal safety, spatial quality and quality of living in Delfzijl and improve its connection with the sea (De Groot & Van Duin, 2013; Municipality Delfzijl, 2016). Therefore, a pioneer salt marsh, salt marsh park and beach will be developed in front of the Schermdijk (see Figure 1). This Schermdijk is a four kilometre long harbour jetty that protects the harbour and coast behind it and houses a windmill park. (For more information on project Marconi, see the information brochure by the Municipality Delfzijl (2016) or the project report by Dankers et al. (2013).

Figure 2.1: An impression of the Marconi project at Delfzijl (view to the south-west, from Ecoshape, n.d.)

Delfzijl and the Marconi project are situated in the Eems Estuary (see Figure 2.2). The nearest (relatively small) salt marshes are 7 km away, while larger salt marshes can be bound at 15 km distance. The average tidal range is 3.0 m. Furthermore, the salinity is mostly saline at 23 ppt, but can vary due to the tide and freshwater from sluices and the river Eems. Suspended sediment concentrations are circa 100 mg/l (Van Maren et al., 2015a). The area in front of the Schermdijk consists of a combination of intertidal and subtidal flats. The mud contents of the sediment range from 25-50% to 75-100%. (De Groot & Van Duin, 2013)

Figure 2.2 (a) The location of the Marconi project within Europe. (b) A map of Delfzijl and its surroundings. The black box indicates the project area, circles indicate nearby salt marshes (based on De Groot & Van Duin, 2013)

2.2 WINDOWS OF OPPORTUNITY: PREDICTING ESTABLISHMENT

According to the Windows of opportunity concept, establishment is possible when the three subsequent windows are successfully finished. Window 1 should be disturbance-free, so that plants can develop roots to withstand stress of flooding. This is implemented as an inundation-free period (cf. Hu et al., 2015; Attema, 2014). In the second window, the stress that a seedling can withstand increases slowly with increasing root length, while this limit remains constant for the third window. In this study, the limits of window 2 and 3 are defined in terms of bed level dynamics. The definition of the WoO framework and subsequent modelling of establishment are only done for *Spartina* vegetation. This has two reasons. Firstly, more previous research exists for *Spartina* to base parameter values on and compare values with. Secondly, *Spartina* is used world-wide in salt marsh restoration projects, giving it a larger practical relevance. The resulting framework is displayed graphically in Figure 2.3 below and further explained in the following paragraphs. A mathematical description with the formulas used is given in Appendix A.

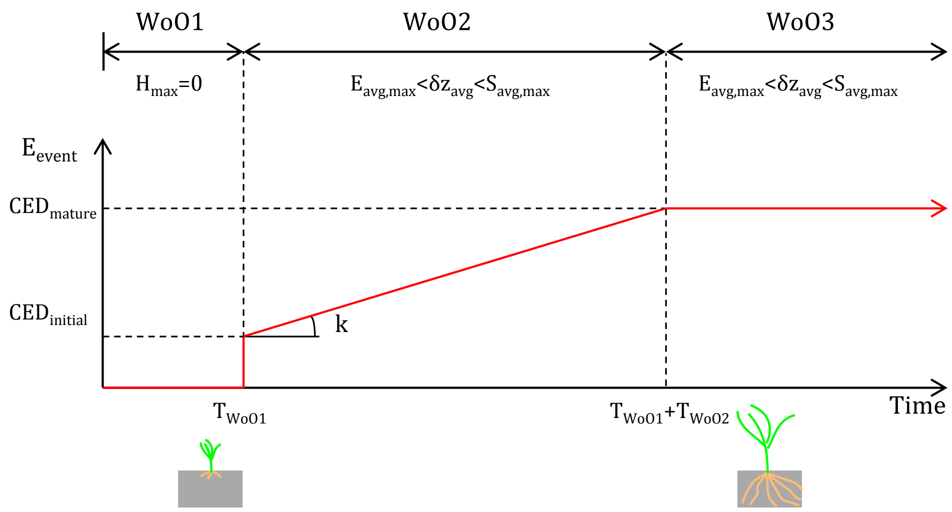

Figure 2.3: Graphical schematization of the Windows of opportunity framework as used in this study (figure adapted from Hu et al., 2015). In WoO1, the inundation depth should be zero. In WoO2 and WoO3, the average bed level change during a plants life should be between the erosion limit and sedimentation limit. Furthermore, the short-term erosion should be less than the CED. This CED depends on plant age for WoO2 and is constant for WoO3.

Window 2 and 3 are defined in terms of bed level dynamics. Bed level dynamics can hinder establishment in a number of ways. If the long-term sedimentation rate is higher than the growth rate of a plant, the plant will be buried and thereby fail. Conversely, if the long-term erosion rate is larger than the growth rate of the roots, the roots will be uncovered. In that case they cannot absorb nutrients or anchor the plant, also leading to failure. And lastly, short-term erosion events can uncover too much of the plant roots, also leading to insufficient nutrient intake and anchoring capacity and thereby failure.

The long-term erosion and sedimentation limits are governed by the growth rate of the plant. Given that the growth capacity of a plant is expected to be relatively constant, these limits can be defined as time-independent limits on the average erosion and sedimentation rate. In contrast, the short-term erosion limit is governed by the depth at which a seed is located and its root length. The root length increases over time, so this limit should also increase over time. This is supported by the work of Bouma et al. (2016), who found that the erosion limit increases significantly with age for *Spartina* seedlings of 20, 50 and 80 days. Apart from the influence of age, the short-term erosion limit is also affected by bed level dynamics. If more sediment is placed on top of the roots during a plant's life, more sediment can be eroded before the roots are uncovered and the plant fails. This sensitivity to bed level change is expressed by the parameter α in equation 2.1 and 2.2.

Window 2 ends when a plant reaches maturity and the CED stops increasing. This means window 1 and 2 should be finished before the end of the growing season, otherwise the plant is considered to have failed. Window 3 starts directly after window 2 and lasts until the end of the winter, to test if the plant can also withstand the erosion caused by storms. For this period the same three conditions are checked: short-term erosion; long-term erosion and long-term sedimentation. If a plant survives this entire period, the establishment is regarded as successful.

$$CED = CED_{initial} + \alpha * \delta z_{life} + \frac{t - T_{WoO1}}{T_{WoO2}} * (CED_{mature} - CED_{initial}) \qquad (2.1)$$

$$CED = CED_{mature} + \alpha * \delta z_{life} \qquad (2.2)$$

With:

CED	=	Short-term erosion limit (critical erosion depth)	[m]
$CED_{initial}$	=	Initial critical erosion 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]
T_{WoO1}	=	Duration of window 1	[day]
T_{WoO2}	=	Duration of window 2	[day]
CED_{mature}	=	Critical erosion depth of mature plant	[m]

An additional explanation should be given for the reasoning behind the dependency on plant age in equation 2.1. Hu et al. (2015) defined their limit (of bed shear stress) with an initial value and a growth rate k (also indicated in Figure 2.3). In my framework, CED_{mature} and the finished fraction of window 2 are used. Mathematically, both result in the same linear increase. However, if a growth rate k is used, the limit of window 3 depends on the duration of window 2. This is especially undesirable for a sensitivity analysis, where you want to be able to test the impact of different parameters independently. Therefore, the definition with CED_{mature} is used.

The parameter and parameter values that are used in the WoO framework are given in Table 2.1. The value for T_{WoO1} is based on the results that Hu et al. (2015) found when hindcasting salt marsh establishment in the Western Scheldt. T_{WoO2} is based on the fact that Bouma et al. (2016) found that the CED increases at least until an age of 80 days. The limits for sedimentation and erosion are based on the mortality that occurred when these values were exceeded in the experiments of Cao et al. (2017). T_{avg}, which is the period over which the short term erosion is calculated, is chosen such that longer storm events are captured in the period, while the amount of (compensatory) plant growth remains limited. The values for $CED_{initial}$, CED_{mature} and α will be based on the experiment. The values found for these parameters are given in section 3.1.7.

Table 2.1: The parameter values of Spartina that were used for the WoO framework. The first four values are based on literature, the last three will be based on the experiment

Parameter	**Meaning**	**Value**	**Source**
T_{WoO1}	Duration of window 1	2.5 days	Hu et al. (2015)
T_{WoO2}	Duration of window 2	77.5 days	Bouma et al. (2016)
$E_{avg,max}$	Max long-term erosion	5 mm/week	Cao et al. (2017)
$S_{avg,max}$	Max long-term sedimentation	15 mm/week	Cao et al. (2017)
T_{avg}	Averaging period for short-term erosion	7 days	
$CED_{initial}$	CED at start of window 2	Tbd	Experiment
CED_{mature}	CED of mature vegetation	Tbd	Experiment
α	Sensitivity to bed level change	Tbd	Experiment

2.3 FLUME EXPERIMENT: DETERMINING CRITICAL EROSION DEPTH (CED)

The goal of the experiment is to determine how the critical erosion depth of pioneer salt marsh vegetation depends on vegetation type, seedling age, wave conditions and bed level change. In order to test this, pioneer salt marsh plants were grown under conditions that are representative of the situation at Delfzijl and subsequently tested in wave flumes. The following variables were tested:

- Species: *Spartina anglica* and *Salicornia procumbens* (common cord grass and saltwort)
- Age: 10, 20 and 40 days;
- Wave height: 3, 6 and 9 cm
- Bed level change: -3; -1.5; 0; -1.5; -3 mm weekly.

More details can be found in the following paragraphs, which explain the set-up for the growing of plants, the sedimentation and erosion treatments and the wave flume tests.

2.3.1 SET-UP: GROWING PLANTS

Spartina seeds were collected at the Paulinapolder (in the Western Scheldt) in November 2015. They were stored in a fridge at 4 °C in seawater. *Salicornia* seeds were collected in 2015 at the Dortsman saltmarsh (near Tholen in the Eastern Scheldt). They were also stored at 4 °C until germination. To germinate the seeds, they were moved to a place with daylight and room temperature conditions. To increase the germination rate and obtain a sufficient number of seedlings, *Spartina* seeds were also germinated in an air drier at 30 °C. For both plants, germination took place in December and January. Seeds with a germ coming out of the seed were identified as seedling, and subsequently planted.

For planting cylindrical PVC pots of 12 x 16 cm (diameter x height) were used. The pots were lined with plastic (polyethylene) bags, punctured with holes to enable drainage of the pots without loss of sediment. Seedlings were planted at a depth of 20 mm, to facilitate comparison with earlier experiments that used the same burial depth (e.g. Bouma et al., 2016). With previous research (Zhu et al., 2017) indicating that sediment type has no strong effect on the CED, a commercially bought loamy sand was used for the experiment. The sand had a median grain size of 175 µm and contained approximately 10 percent silt.

Per species–age–bed-level-change combination, 17 pots with seedlings were prepared. In this way, five pots from every series can be tested per wave type, while still having a margin of two pots in case of unsuccessful growth or failed tests. Per pot, two to three seedlings (depending on the availability of germinated seeds) were planted, to increase the number of samples. And because *Salicornia* seedlings generally do not surface within 10 days, only the 20 and 40-day age groups were used for *Salicornia*. This leads to a total of 425[1] pots that are planted, with each 2 to 3 seedlings.

The plants were grown in a climate room, with a constant temperature of 18 °C (cf. Cao et al., 2017; Bouma et al., 2016). Artificial lighting was provided in the form of parallel fluorescent tubes above the tanks, with an intensity of 250 µmol m^{-2}s^{-1} for 18 hr day^{-1}. The relatively long lighting duration was chosen to compensate for the intensity that is lower than the average natural intensity. Tidal mesocosms were used to expose the plants to a semi-diurnal tide, with an inundation period of 2 hr/12hr. This period was chosen because it is comparable to the expected inundation duration of the pioneer zone at Marconi (De Groot & Van Duin, 2013; Rijkswaterstaat, 2016). The salinity of the tanks was 23 ppt, which is similar to the salinity at the Marconi site (De Groot & Van Duin, 2013). This salinity was obtained by mixing water from the Eastern Scheldt with fresh tap water.

Figure 2.4: A tidal mesocosm, with the lights above it

Figure 2.5: Plants growing in a tidal mesocosm

During the last two weeks of the experiment, the climate room had to be used for a different experiment. Therefore, the plants were moved to a greenhouse. In this greenhouse, the day temperature was approximately 18 °C, while the night temperature was approximately 12 °C. This light was the natural light of January, which means the intensity was higher than in the climate room, while the duration was lower.

[1] 3 Ages · 5 sediment treatments · 17 pots = 255 pots for *Spartina* and
2 Ages · 5 sediment treatments · 17 pots = 170 pots for *Salicornia*

2.3.2 SET-UP: EROSION AND SEDIMENTATION TREATMENTS

During their growth, the plants received weekly sedimentation and erosion treatments, to mimic long-term bed level changes occurring in the field (see Figure 2.6). The treatments had a magnitude of −3; −1.5; 0; +1.5 and +3 mm/week. Erosion treatments were applied by adding a disk at the bottom of a pot and carefully removing the sediment at the top. Conversely, sedimentation treatments were applied by removing a previously placed disk at the bottom of the pot and adding sediment on top (c.f. Balke et al., 2011; Bouma et al., 2016). Due to the polyethylene bags inside, the sediment could be lifted up and down without affecting the sediment or plants.

The first sediment treatments were done one week after planting the seedlings, after which they were repeated weekly. For planned erosion treatments on seedlings that had not surfaced yet, only the disk was added. No sediment was removed, to prevent accidentally harming the seedling. When the seedling had surfaced at a later treatment, the layer of sediment above the brim of the pot was removed and treatments were continued as normal.

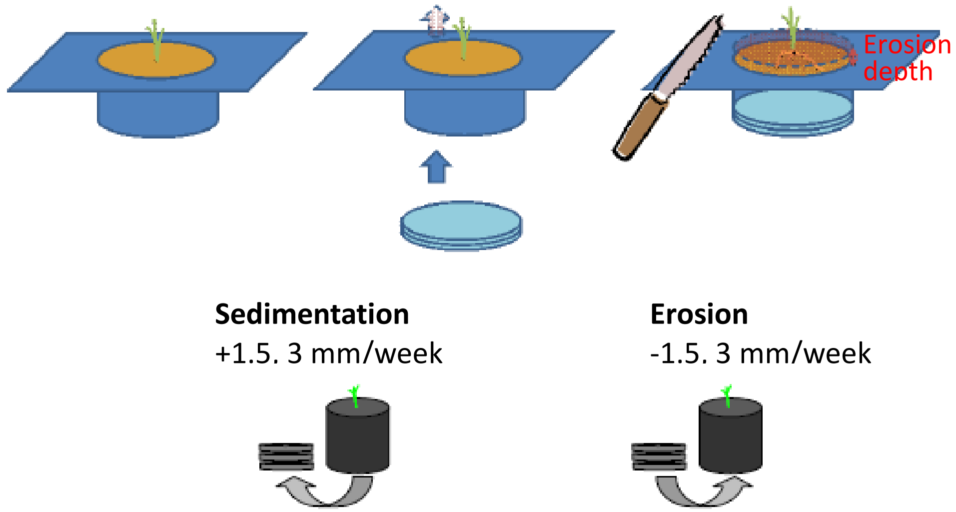

Figure 2.6: The methodology for applying accretion and erosion treatments (adapted from Bouma et al., 2016)

2.3.3 SET-UP: FLUME TESTS AND MEASUREMENTS

After being grown, the critical erosion depth of the plants was determined in a wave flume at the NIOZ in Yerseke (The Netherlands). The wave flume (see Figure 2.7 and Figure 2.8) has a length of 5 metres and a water depth of 13 to 30 cm. At one side waves are created by a horizontally moving wave paddle, and at the other side a wave dampening mat is applied to decrease reflection. The time between waves is approximately 15 seconds, to allow waves to dampen out fully before the next wave is created. The flumes were set-up to create three different waves: of 3, 6 and 9 cm high. For more information on the wave flume, see Rahman (2015).

The wave flume was used to test how much erosion plants can handle before they topple over. First, the pots were placed in the wave flume and exposed to five waves, to see if they toppled. If they did not topple over, a disk was inserted at the bottom of the pot and erosion was applied at the top, after which they were tested again. This procedure was repeated until a plant toppled over. The erosion needed to reach this point is defined as the critical erosion depth. The test duration of five waves was chosen to limit the erosion caused by waves. This assured that the effect of erosion (only caused by erosion treatments) and drag force on plants (caused by waves) could easily be distinguished. Although this distinction does not exist in the field, the resulting insight into the failure mechanism of plants is useful when vegetation failure is modelled.

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Figure 2.7: A photo of the test set-up in the wave flume

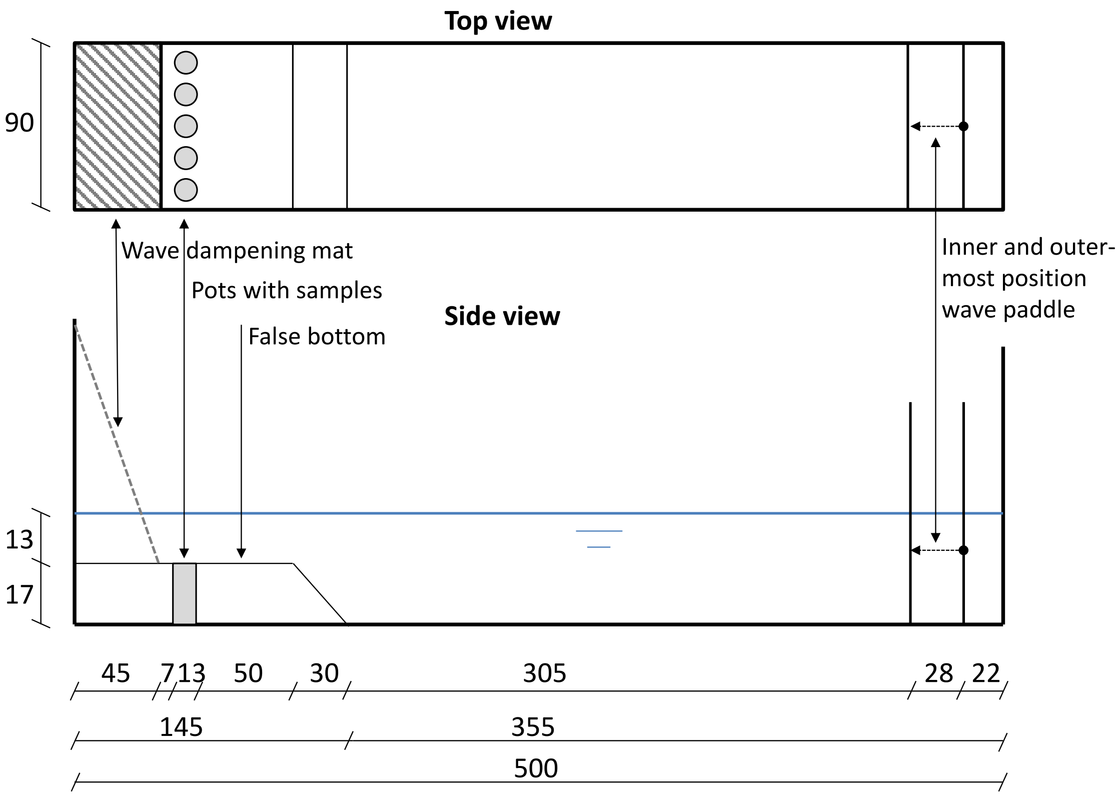

Figure 2.8: A sketch of the test set-up in the wave flume (distances are in cm)

After a plant toppled over, it was carefully removed from the pot. In case a pot contained multiple plants, the space from which the plant had been removed was refilled with sediment, after which the test continued for the remaining plant(s). And as a final step, the plant properties were measured. This means that the mass and length of the root, shoot, above-ground part and below-ground part were measured. In addition, the number of roots of *Spartina* seedlings was counted. For *Salicornia,* this is not possible because it has one main root with lateral roots continuously branching off.

For determining the below-ground and above-ground length, the burial depth and total treatment depth were used according to equation 2.3 and 2.4 (see also Figure 2.9). For determining the mass, the seeds were first air-dried at 60 °C and then weighted with a sensitive scale (with a sensitivity of 0.1 mg). The root mass of *Spartina* was weighted with and without the seed coat, given its high mass compared to actual roots. Furthermore, the mass of the underground part of the shoot was weighted to determine the above-ground and below-ground mass.

$$\begin{aligned} L_{above\ ground} &= L_{shoot} - burial\ depth - sedimentation\ depth \\ &= L_{shoot} - 2cm - sedimentation\ dept \end{aligned} \tag{2.3}$$

$$L_{below\ ground} = L_{root} + 2cm + sedimentation\ depth \tag{2.4}$$

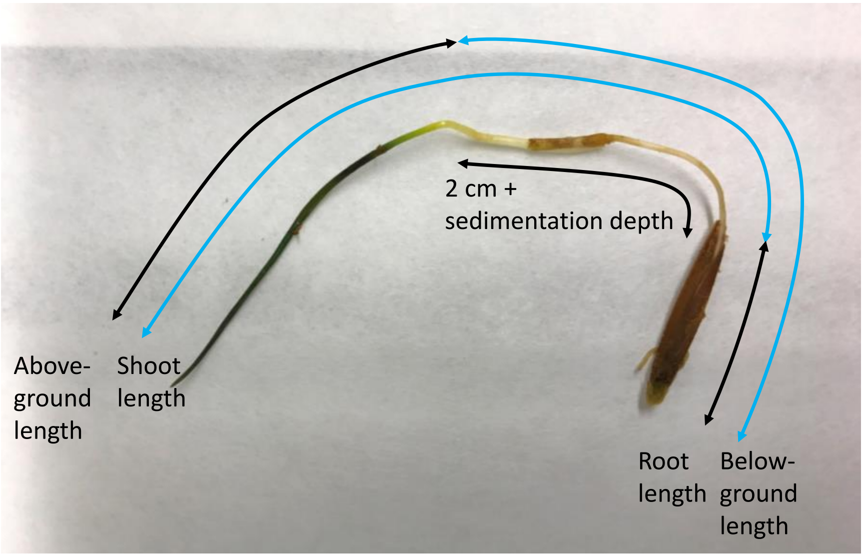

Figure 2.9: The root, shoot, above-ground and below-ground length of a seedling.

2.4 Delft3D: Modelling establishment

To model salt marsh establishment and test the redefined WoO framework, a hydro- and morphodynamic model of a salt marsh was made. The following sections describe the set-up of the model (section 2.4.1 to 2.4.4), its usage for the Windows of opportunity (2.4.5) and the sensitivity analysis (2.4.6 and 2.4.7).

2.4.1 Model description

Like previous studies modelling the development of salt marshes (e.g. Temmerman et al., 2005b; Schwarz et al., 2014), this study used a Delft3D model to describe the hydrodynamics, sediment transport and morphodynamics. Delft3D describes the hydrodynamics based on a finite-difference solution of the unsteady shallow-water equations in 2D (depth-averaged) or 3D (Lesser et al., 2004). The model applies the horizontal momentum equations, the hydrostatic pressure relation, the continuity equation, the advection-diffusion equation and a turbulence closure model. Wave propagation, refraction, dissipation and breaking are calculated with the Delft3D Wave module, which uses a third-generation SWAN model (see Booij et al., 1999).

The model is used to test the application and sensitivity of the Windows of opportunity framework. The model has an idealised set-up, with a simple grid, bathymetry and tidal forcing. Where possible, conditions have been based on the situation at the Marconi site. The model is run in a depth-averaged 2D mode. This significantly decreases computational times, while previous research indicates that this is a reasonable assumption for morphological studies of salt marshes, intertidal flats and mangroves (c.f. Schwarz et al., 2014; Van Leeuwen et al., 2010; Horstman et al., 2015). The parameter values used in the model are given in Table 2.2, and further explained in the following paragraphs.

Table 2.2: Overview of the parameter values used in the Delft-3D model

Parameter	Value	Meaning	Source/remarks
Grid and bathymetry			
M	20 cells	# cells in x-direction	
N	40 cells	# cells in y-direction	
Δx	20 to 50 m	Grid resolution in x-direction	
Δy	7 to 25 m	Grid resolution in y-direction	
z_{min}	-5 m	Minimum elevation bed	
z_{max}	1.85 m	Maximum elevation bed	
i	1:100	(Initial) slope of bed	Applies until y=350m
Roughness and viscosity			
m	0.018 s/m$^{1/3}$	Manning coefficient	Van Maren et al. (2014)
ν	10 m^2/s	Horizontal eddy viscosity	Deltares (2016), Willemsen et al. (2016)
K	10 m^2/s	Horizontal eddy diffusivity	
Tide			
A_1	1.5m	Average amplitude semi-diurnal tide	Rijkswaterstaat (2013)
A_2	21 cm	Amplitude spring-neap cycle	Rijkswaterstaat (2013)
T_1	12 h	Duration semi-diurnal tide	
T_2	30 d	Duration spring-neap cycle	
v_{max}	0.7 m/s	Maximum flow velocity at channel	Van Maren et al. (2014)
Sediment dynamics			
ρ_{sed}	2650 kg/m^3	Specific density sediment	
P_{bed}	500 kg/m^3	Dry bed density	Van Rijn (1993)
w_s	0.5 mm/s	Settling velocity	Borsje et al. (2008)
$\tau_{cr,e}$	0.5 N/m^2	Critical bed shear stress erosion	Van Maren et al. (2015b)
$\tau_{cr,s}$	1000 N/m^2	Critical bed shear stress sedimentation	Winterwerp and Van Kesteren (2004)
M	0.1 $mg/m^2/s$	Erosion parameter	Borsje et al. (2008)
C	100 mg/L	Sediment concentration at boundary	Van Maren et al. (2015a)

2.4.2 Domain and time frame

The model domain consists of a rectangular grid of 20 by 40 cells. This is sketched in Figure 2.10. In the cross-shore direction, the resolution ranges from 7 metres at the coast to 25 metres towards the sea. In the alongshore direction, the resolution is 25 metres in the area of interest, which increases to 50 metres at the model boundaries. The location of the area of interest, in which vegetation establishment is modelled, is further explained in section 2.4.5. Because the predominant currents in the Eems are in alongshore direction, the eastern and western boundary are open. The water level is defined at the western boundary, while the flow velocity is defined at the eastern boundary. Waves are defined along all non-coastal boundaries.

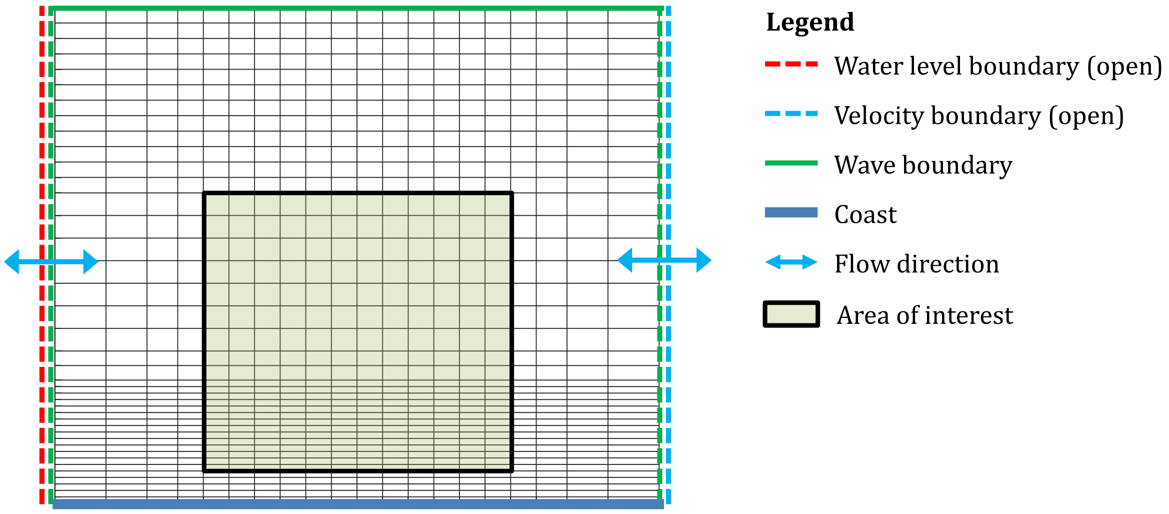

Figure 2.10: A sketch of the model grid, boundary definition and area of interest. Water levels and flow velocities are defined at the western and eastern boundary (left resp. right in this figure). The south (bottom) and north (top) boundary are closed w.r.t. water flow, but wave boundaries are supplied along the east, north and west boundary.

The bed level ranges from +1.85 to -5 metres (see Figure 2.11). The highest elevation of interest is +1.5 metres, as this is the highest planned elevation of the Marconi pioneer salt marsh. To prevent the occurrence of boundary effects at the coast, the model is extended to the point where the maximum elevation is higher than the maximum water level. From this point, the bed decreases with a slope of 1 percent in seaward[2] direction, based on the planned slope of the Marconi pioneer salt marsh (Rijkswaterstaat, 2015). At a depth of -2 m, the constant slope transitions into a cosinusoidally shaped channel, with a maximum depth of 5 metres. In the alongshore direction the (initial) bed level is uniform.

The roughness and viscosity are uniformly defined across the domain. For the roughness a manning coefficient of 0.018 ($s/m^{1/3}$) is used, based on earlier modelling work of Van Maren et al. (2014), who modelled sediment transport in the Eems and Dollard. For the horizontal eddy viscosity and diffusivity values of 10 m^2/s are used. This is a typical value for the grid cell size used (Deltares, 2016) and similar to what Willemsen et al. (2016) used for a model study of mangroves with a comparable grid size.

[2] Seaward is used in this report as the opposite of landwards, even if the Eems is strictly speaking no open sea.

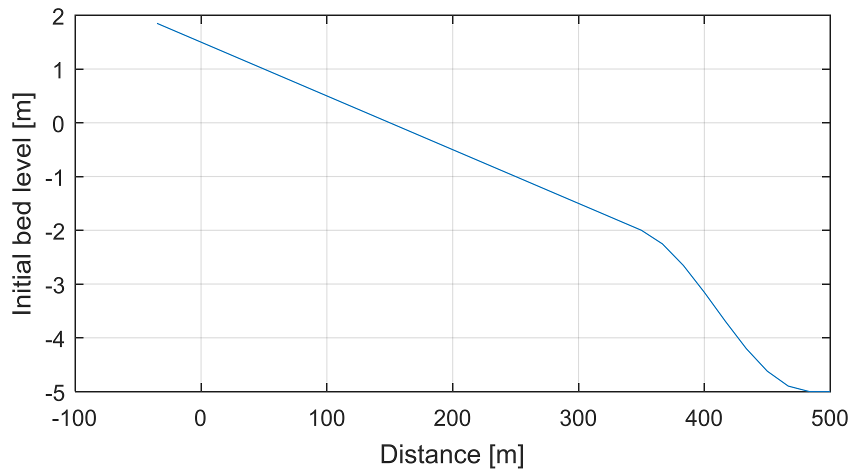

Figure 2.11: The initial bed level of the model in cross-shore direction. The area of interest stretches from 0 to 300 m and the initial profile is uniform in alongshore direction.

The model runs for a period of 1.5 years. The model is not in equilibrium at the start. To prevent the initial bed level change from impacting the results too much, the first half a year used as spin-up time. The last year is used to test vegetation establishment. During the spin-up time, winter conditions are applied, given that the highest bed level change is expected to occur in the winter. The period hereafter starts with summer conditions to test establishment, followed by winter conditions to test whether vegetation can also survive the winter storms.

2.4.3 HYDRODYNAMIC BOUNDARY CONDITIONS

The tidal dynamics of the Eems are represented in a simplified manner. Water levels (defined for the western boundary) are defined purely sinusoidally, with a period of 12 hours to represent the semi-diurnal tide and a period of 30 days to represent the spring-neap variation. Based on water level measurements at Delfzijl (Rijkswaterstaat, 2013) an average tidal range of three metres is used. Due to the spring-neap cycle, this varies from 2.58 metres at neap tide to 3.42 metres at spring tide.

Flow velocities, defined for the eastern boundary, are also defined sinusoidally. Due to the mass of water in the rest of the Eems and Dollard, the flow is best described as a standing wave, with a quarter period phase difference between the water level and flow velocity (Van Maren et al., 2014). The maximum (depth-averaged) flow velocity at the channel is set at 0.7 m/s: according to the model of Van Maren et al. this is a typical maximum flow velocity for such a depth at the Marconi location. The flow velocity along the boundary is scaled linearly to the water depth. This assures that no unrealistically high flow velocities occur in the shallow parts.

The wave conditions (see Figure 2.12) are defined uniformly along the boundaries. They are defined as a time series, based on the local wave conditions in the year 2012 as modelled by Van Maren et al. (2014). Because of the location of Delfzijl, in a bend of the Eems, waves coming from the east or north have the highest fetch length. Consequently, the majority of the waves and the highest waves come from these directions.

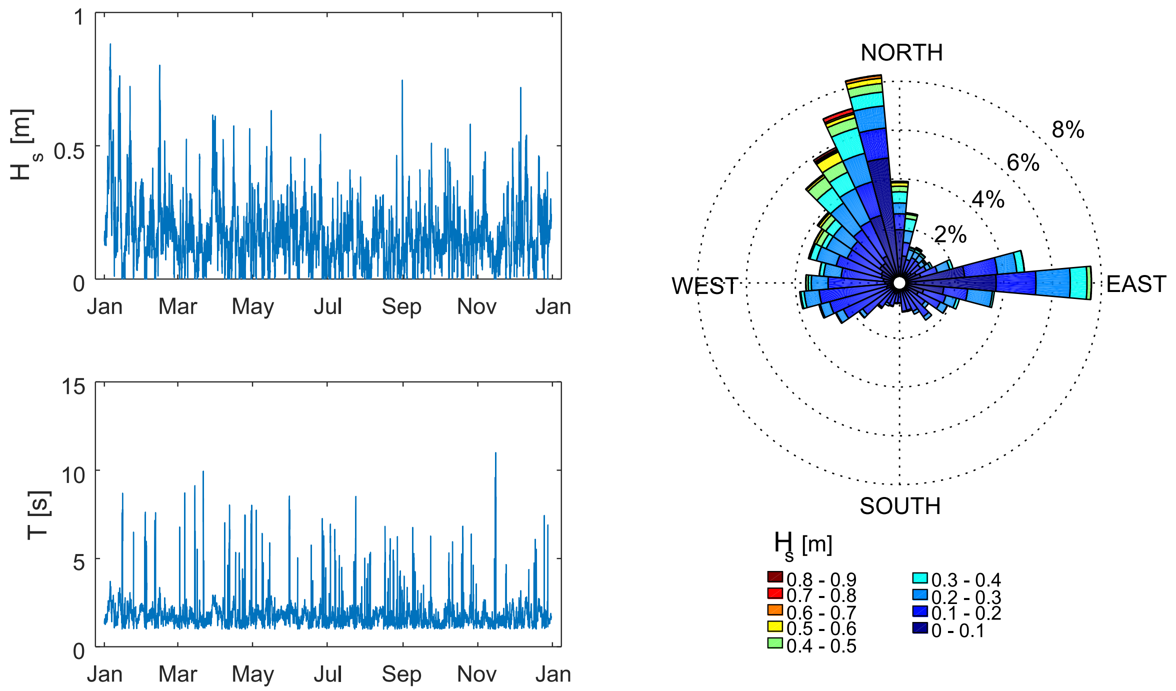

Figure 2.12: A plot of the wave height, wave period and direction (origin) of the waves

2.4.4 Sediment dynamics

For the sediment, a uniformly defined homogeneous cohesive sediment (mud) is used. Given the high mud content of the project location and the Eems in general (e.g. De Groot & Van Duin, 2013; Taal et al., 2015), only using mud is seen as a reasonable approximation. Erosion and sedimentation are calculated by Partheniades-Krone formulation (see Partheniades, 1965; Deltares, 2016), while sediment transport is calculated using the 2-dimensional advection-diffusion equations.

The density and dry bed density of the sediment are the default values of Delft3D: 2650 and 500 kg/m^3. For the dry bed density this is a fairly normal value for consolidated mud: Van Rijn (1993) gives a density of 300 kg/m^3 or more for consolidated mud. For the settling velocity a constant value of 0.5 mm/s is used, based on what Borsje et al. (2008) used for a model of the Dutch Wadden Sea. The value for critical bed shear stress for erosion is 0.5 N/m^2, the default value and equal to what earlier models of the Eems used (Van Maren et al., 2015b). The critical bed shear stress for erosion is 1 kN/m^2; the default value and high enough to comply with the findings of Winterwerp and Van Kesteren (2004) that a critical bed shear stress for sedimentation does not exist. The erosion parameter M is set so 0.1 mg/m^2/s, which is the default value and equal to the settings of Borsje et al. (2008).

The initial thickness of the sediment layer is 5 metres in the majority of the model area. Between y=300 and y=350 m (so bed levels of –1.5 and –2 metres), this decreases linearly to 0 metres. From this point onwards, it remains constant again. This is done to prevent the occurrence of strong erosion in the channel. The sediment concentration at the boundary is set to a constant and uniform value of 100 mg/L, based on long-term measurements and modelled values of the sediment concentration around Delfzijl (Van Maren et al., 2015a). Furthermore, the bed level at the boundaries is set to be constant. Physically, this can be explained by the fact that the Marconi project is located within a larger system (i.e. the Eems-Dollard), which remains mostly constant. And numerically, it has the advantage that it prevents the occurrence of instabilities.

2.4.5 VEGETATION MODELLING

The impact of vegetation on the hydrodynamics is not explicitly accounted for in the model. This is done because this study only aims to model vegetation establishment and no long-term morphological development. During the establishment phase, the density and height of the plants are so low, that vegetation has very little effect on the hydrodynamics. In addition, the expected width of the salt marsh is relatively limited with a maximum of 50 metres (De Groot & Van Duin, 2013). Moreover, vegetation has two conflicting effects at lower densities: at the plants flow velocities and erosion decrease, while between plants flow is concentrated, leading to increased erosion and channel incision (Temmerman et al., 2007). With the relatively large grid cells of this study, it is impossible to capture this behaviour.

So without online[3] vegetation dynamics, vegetation establishment is based purely on the output of Delft3D and the predictions of the Windows of opportunity framework. The big advantage of this set-up is that the effect of a different schematization of the WoO framework and different parameter values can be determined quickly, without having to run Delft3D again. This makes a thorough sensitivity analysis possible. In contrast, using online vegetation dynamics would mean that the effect of every parameter change would take three days to model, thereby severely limiting the possibilities for a sensitivity analysis.

The vegetation establishment is only predicted within the area of interest. To prevent boundary effects around the open boundaries from affecting the results, some space is needed around the eastern and western boundary. Towards the coast we limit the area of interest to an elevation of 1.5 metres, as this is the highest planned elevation of the pioneer salt marsh. And towards the channel we limit the area to the intertidal elevations. This leads to the area of interest as plotted in Figure 2.10, with a size of 12 by 24 cells.

The WoO model is run with the three-hourly output of Delft3D. With a tidal period of exactly 12 hours, this assures that the maximum water levels of each tide are captured properly. This is essential to test for the conditions of window 1, which needs a sufficiently long inundation-free period. The three-hourly output frequency is also more than sufficient to capture the bed level dynamics that are needed to test for WoO2 and WoO3.

2.4.6 SENSITIVITY ANALYSIS WOO PARAMETERS

Because the Windows of opportunity concept has been developed recently, there is a lack of data on the parameter values that should be used. To determine the impact of this uncertainty, a sensitivity analysis is used. For this analysis all parameters within the WoO framework are varied independently. The values used for this analysis are given in Table 2.3.

For most parameters a multiplication range from 1/3 to 3 is chosen. For the duration of the windows and the averaging period slightly different values are chosen, because they have to be an integer multiple of three hours (the chosen output frequency of Delft3D). For α a lower maximum value is chosen, as this is the upper limit of what is likely: the value of 1.1 (based on our experiment) is already significantly higher than what other research (Bouma et al., 2016; Cao et al., 2017) has found. For the duration of window 2 a maximum value of 120 days is used: if this window takes any longer, there is insufficient time for plants to reach the end of this window before the end of the summer.

[3] Online refers here to calculating the hydrodynamics and vegetation dynamics at the same time and including their mutual impacts

Table 2.3: Parameters used for sensitivity analysis

Parameter	Reference value	Unit	Minimum value	Maximum value
T_{Wo01}	2.5	days	0.875	7.5
T_{Wo02}	77.5	days	8.5	120
$E_{avg,max}$	-5	mm/wk	-1.67	-15
$S_{avg,max}$	15	mm/wk	5	45
α	1.1	-	0.37	1.5
$CED_{initial}$	16	mm	5.33	48
CED_{mature}	23	mm	16	67.5
T_{avg}	7	days	2.375	21

2.4.7 Sensitivity analysis Delft3D modelling

In the translation from reality to a Delft3D model, choices have to be made. The impact of three of these choices is addressed explicitly. The results with a different sediment type, with explicit vegetation modelling and with different wave heights are compared to the reference situation. In this section the reasoning behind the sensitivity analysis and the followed methodology are explained.

The sediment type has a strong impact on the model results. The reference model uses a single-graded uniform clay as sediment. However, in reality there are multiple grain sizes present. To examine the impact this could have, a run with two sediment fractions is used. Following the work of Van Maren et al. (2015b) for the Eems, settling velocities of 0.2 mm/s and 1 mm/s are used to represent unflocculated and flocculated sediment. For both sediment fractions a constant concentration of 50 mg/L is used at the boundaries – together adding up to the 100 mg/L used in the reference model. All other parameter values of both fractions are equal to values in the reference model.

In the reference model the impact of vegetation on hydrodynamics is not included: the establishment chances are only determined afterwards, based on the fact that young vegetation in low densities would have a limited impact on the hydrodynamics. To examine the effect of this choice, a model run with the impact of vegetation has also been made. Numerically, this is implemented by using the 3D rigid vegetation function of Delft3D. This model takes the impact of vegetation on turbulence and the momentum equation into account, based on the formulations of Winterwerp and Uittenbogaard (1997).

To confirm that the impact by vegetation is indeed negligible, settings with a maximum impact of vegetation are used. Therefore, vegetation is placed in the area where it would be expected to grow in the initial bathymetry: until an elevation of +1m NAP. This vegetation has a height of 0.4 m, a density of 400 stems/m^2 and a drag coefficient of 1, based on the values used by Temmerman et al. (2007) and the density plants can reach in 1 year in his model. The plants are present in this state from the start of the model.

The effect of wave height is studied, because wave-breaking measures can decrease the wave impact at Marconi and because salt marshes at other locations would experience a different wave climate. Runs are made with wave heights that are 50%, 75% and 90 of the reference height. The wave direction and period remain unchanged.

3

RESULTS

This chapter presents the results of this study. First, the results of the flume experiment are presented, followed by the results of the modelling of the Marconi environment and establishment chances and the results of the sensitivity analysis.

3.1 RESULTS OF FLUME EXPERIMENT

In this section the results of the experiment are discussed. It starts with the general plant properties and their impact on the critical erosion depth (CED). This is followed by the impact of seedling age, wave height and bed level disturbances on the CED. Finally, the relative importance of these three factors and the step from experimental results to WoO parameters are presented.

3.1.1 PLANT CHARACTERISTICS

Figure 3.1 displays the shoot and root size of the seedlings. This figure shows two important results. The first is that root size and shoot length are correlated for both *Spartina* and *Salicornia*. The second is that this correlation is mostly caused by the difference between the different age groups; within the separate age groups the lengths seem to be almost randomly distributed. A weak correlation still exists within the oldest age groups, but for the ages of 20 and 10 days, it is impossible to discern any meaningful relation.

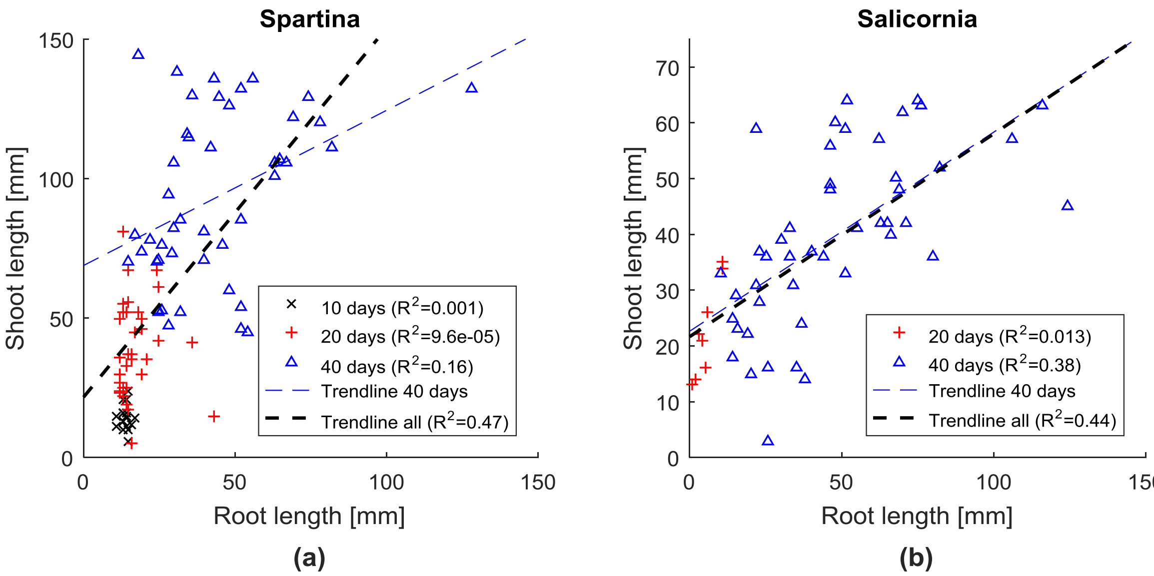

Figure 3.1: The relation between root length and shoot length for (a) Spartina and (b) Salicornia. Determination coefficients are shown for all sample groups, trend lines only for 40 days old seedlings and the combined sample groups (the younger age groups do not show any meaningful correlation to base trend lines on)

Especially the correlation between root and shoot length is relevant for the further interpretation of results. In general root and shoot lengths have opposite effects on the critical erosion depth: longer roots improve anchorage, increasing the CED, while longer shoots increase the drag force on plants, decreasing the CED. Therefore, results could be correlated with for instance root size, while it is actually the shoot size that is causing the effect.

3.1.2 IMPACT SEEDLING SIZE ON CED

With the results on the root and shoot size known, the relation between seedling size and critical erosion depth can be examined. This is done in Figure 3.2 below. On average the critical erosion depth of *Spartina* increases with increasing above- and below-ground length, while the CED of *Salicornia* decreases with increasing above-ground length. Figure 3.1 showed that root and shoot size are correlated. Therefore, the effect found for *Spartina* should in all likelihood be attributed to the higher anchorage strength and depth caused by longer roots, with the apparent positive effect of the above-ground length just being the effect of the correlation between root and shoot length.

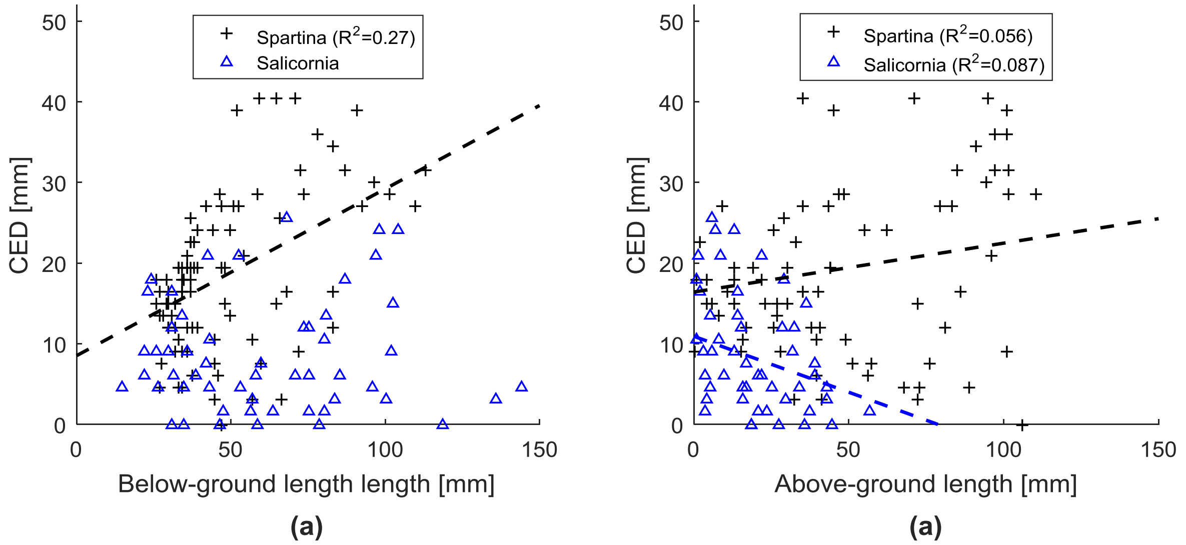

Figure 3.2: The above-ground length (a) and below-ground length (b) of Spartina and Salicornia plotted against the CED, with trend lines indicating the average relation. No trend line is plotted for the impact of below-ground length on CED for Salicornia, because of the lack of correlation (R^2=0.0008).

When examining the impact of the below- and above-ground mass, comparable relations can be found. However, for *Salicornia* the correlation becomes significantly stronger when plotting the ratio of the above-ground mass to the below-ground mass. This is plotted in Figure 3.3. This figure shows that the CED of *Salicornia* seedlings becomes smaller when the relative above-ground mass becomes larger. For *Spartina* this trend cannot be found.

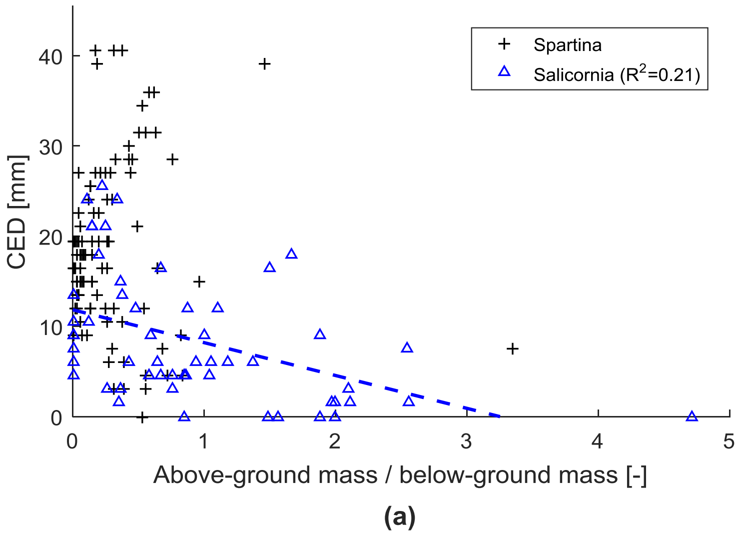

Figure 3.3: The ratio of the above-ground mass to the below-ground mass plotted against CED. For Salicornia, there is a significant negative relationship (R^2=0.21). For Spartina there is no correlation (R^2=0.0001), so no trend line is plotted.

3.1.3 Impact age on CED

Paragraph 3.1.1 showed that both the root and shoot size increase with seedling age. Therefore, it is interesting to see how the critical erosion depth changes over time. The effects of seedling age are shown in Figure 3.4 below. In order to plot the data of seedlings that are exposed to different amounts of bed level change in the same figure, the total depth of the sedimentation treatments is subtracted from the critical erosion depth. This is called CED compensated. The figure shows that for *Spartina* the critical erosion depth increases on average with seedling age. For *Salicornia*, the critical erosion depth decreases on average with seedling age. In both cases this only explains a small part of the variation, with coefficients of determination between 0.05 and 0.1.

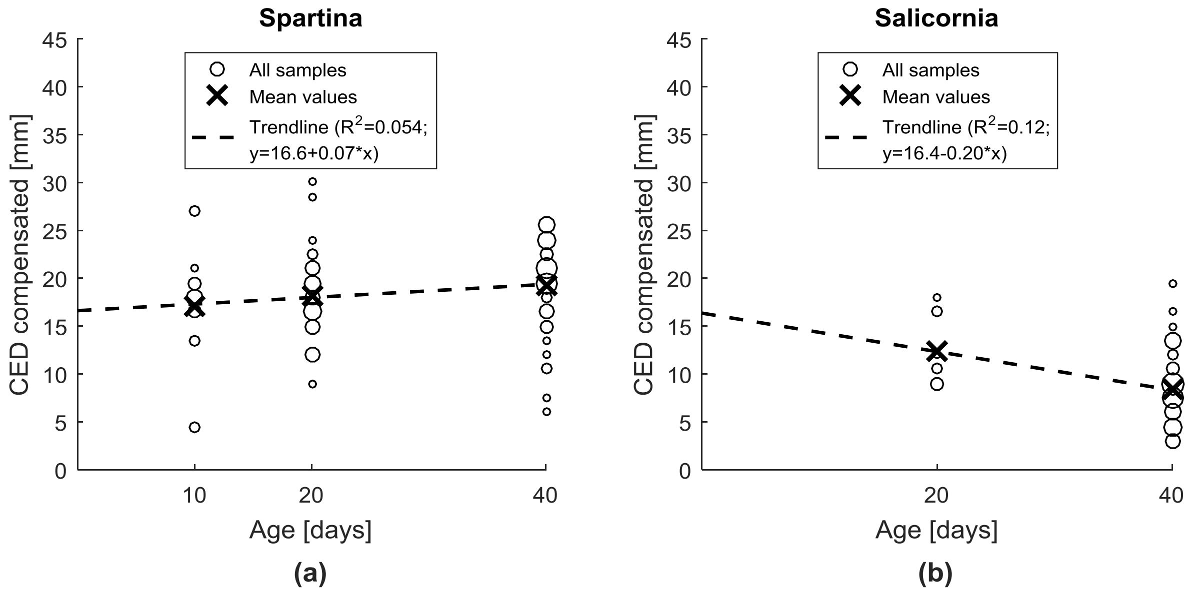

Figure 3.4: The impact of seedling age on CED compensated for Spartina (a) and Salicornia (b) seedlings, with circles indicating the samples, crosses indicating mean values per age group and the dotted lines indicating trend lines. The size of the circles indicates the number of samples per value (ranging from 1 to 11)

3.1.4 Impact wave height on CED

The impact of wave height on the critical erosion depth is visible in Figure 3.5. These results show that for the plants and wave heights of the experiment the wave height has a negligible impact on the CED. Increasing the wave height with 1 centimetre lowers the critical erosion depth on average with only 0.25 mm. The variation explained by this relation is less than 2 percent of the total variation in critical erosion depth. Furthermore, the relation remains weak when looking at the average CED values. For *Spartina* the average CED with waves of 6 and 9 cm is practically equal, while for *Salicornia* there is very little difference between the 3 and 6 cm waves.

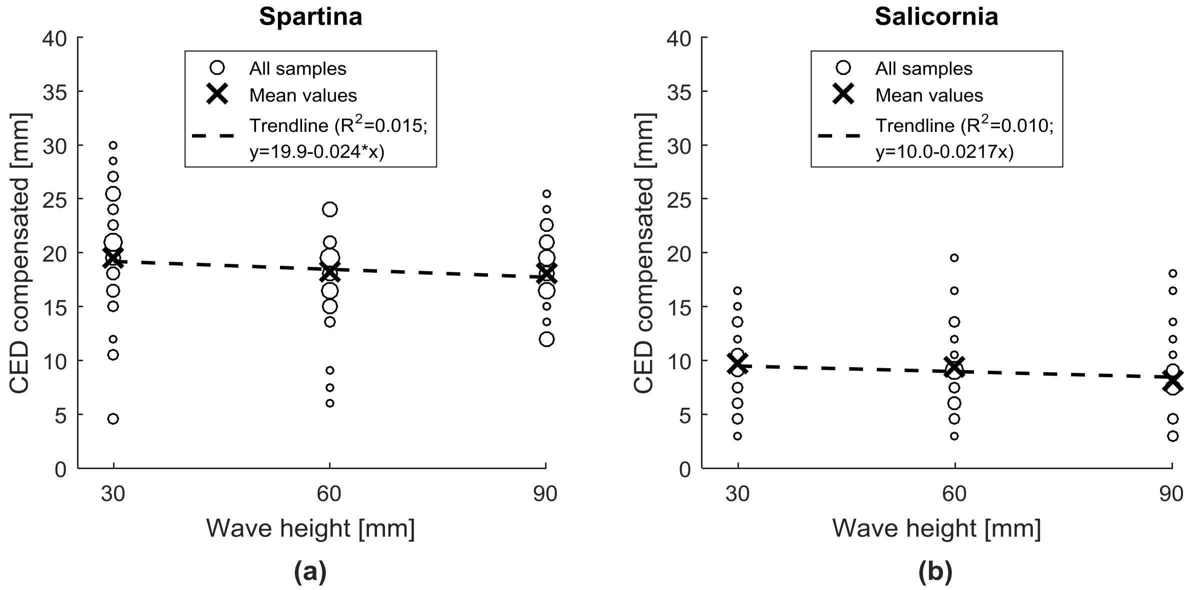

Figure 3.5: The impact of wave heights on CED compensated, with samples, mean values per age group and trend lines shown and the size of the circles indicating the number of samples per value (ranging from 1 to 8 samples)

3.1.5 Impact bed level disturbance on CED

The impact of bed level disturbances on the critical erosion depth is shown in Figure 3.6. Given that the bed level change is plotted explicitly now, it is no longer necessary to compensate for it using CED compensated. Therefore, the normal critical erosion depth is plotted on the y-axis. The graphs show that there is a strong relation between bed level change and critical erosion depth. With a correlation of 0.81 and 0.70 respectively, the majority of the variation in the experiment can be explained by this variable. *Spartina* shows a high sensitivity to bed level disturbances: every mm of sedimentation results on average in a CED that is 1.12 mm higher. *Salicornia* shows a lower sensitivity: on average every mm of sedimentation increases the CED with 0.77 mm.

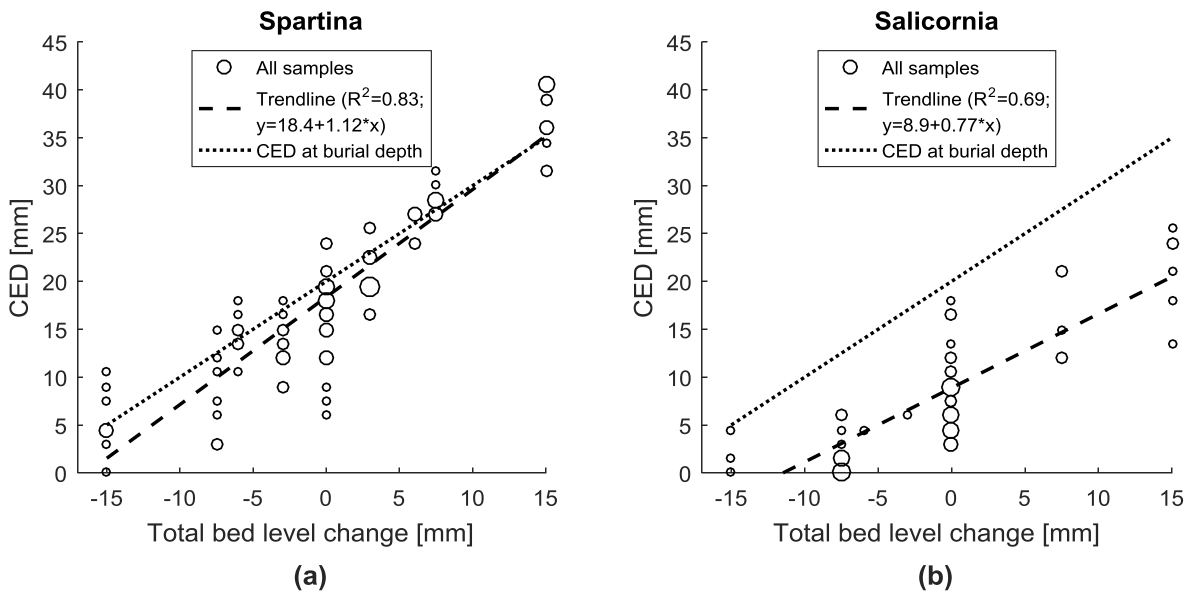

Figure 3.6: The impact of bed level disturbances on CED for Spartina (a) and Salicornia (b), with the size of the circles indicating the number of samples per value of CED (ranging from 1 to 6 samples). The dotted line indicates when the CED equals the burial depth (20 mm), corrected for accretion and erosion treatments. The dashed trend line lies below this line. For Spartina (a), the trend line has a slope higher than 1, indicating a high sensitivity to bed level change. For Salicornia (b), the slope is lower than 1, indicating a lower sensitivity to bed level change.

3.1.6 The relative importance of plant properties, waves and bed level disturbance

The previous subsections show the impact of the seedling size, age, wave heights and bed level disturbance separately. Here, their combined impact and relative importance are examined. Regarding the size, the below-ground length (L_{BG}) is used for *Spartina* and the above-ground length (L_{AG}) is used for *Salicornia*. Furthermore, the impact and significance of bed level disturbance (δz) and wave height (H_{wave}) are determined.

The previous results showed that bed level disturbances have by far the most impact on the critical erosion depth. Therefore the (linear univariate) model with only bed level change is used as a reference to which the performance of models with additional variables is compared. Equation 3.1 describes the models that were fitted to the data. The results this gives for *Spartina* and *Salicornia* are shown in the following paragraphs.

$$CED = \alpha_1 + \alpha_2 * \delta z + \alpha_3 * variable\ X \qquad (3.1)$$

3.1.6.1 Spartina

As Table 3.1 shows, bed level disturbances explain already 83 percent of the variation in CED for *Spartina*. It has little value to also use the below-ground length, seedling age or wave height: this increases R^2 with less than 0.01. Looking at the significance, the impact of none of the additional variables meets the 95-percent confidence limit. This means that the results of this experiment alone form no reason to confidently reject the null hypothesis (that they do not impact CED). Given the small additional value and significance of these variables, the results of multivariate models with more than two variables are not presented here.

In comparison with the univariate results in the previous paragraphs, the below-ground length of the seedlings has significantly less impact now. This shows that the predictive value of the below-ground length arrives largely from its correlation with the bed level change[4], which is now also explicitly accounted for in the model. As an additional variable – next to the bed level change – its value is slightly lower than the value of the seedling age.

Table 3.1: A comparison of the model performance and statistical significance of models using different variables to predict the CED of Spartina. The determination coefficient R^2 indicates the fraction of the variation that is explained by the model; the additional variation indicates how much additional variation is explained by also using L_{BG}, age, or H_{wave}; the parameter values are the values of α in the equation "$CED = \alpha_1 + \alpha_2 * \delta z + \alpha_3 * variable\ X$" and $P(\alpha 3 = 0)$ shows the probability that the null hypothesis that the additional variable has no impact is correct (so a two-sided test is used).

Model	R^2	Additional variation explained [%-points]	Parameter values			$P(\alpha_3 = 0)$ [%]
			α_1 [mm]	α_2 [-]	α_3	
Only δz	0.830		18.4	1.11		
δz and L_{BG}	0.836	0.55	16.7	1.06	0.03 [-]	6.92
δz and age	0.836	0.60	16.3	1.10	0.079 mm/day	5.78
δz and H_{wave}	0.833	0.30	19.7	1.11	-0.022 [-]	17.80

[4] The below-ground length is the root length + the accretion depth + 20 mm (the burial depth)

3.1.6.2 SALICORNIA

The results for *Salicornia* are visible in Table 3.2. In this case, the bed level disturbances explain 70 percent of the variation in CED for *Spartina*. It has relatively little value to also use the above-ground shoot length or seedling age, as this increases R^2 with less than 0.05. The impact of also using wave height is negligible, with an improvement of less than 0.01. Looking at the significance, the impact of shoot length and seedling age is significant at the 99-percent confidence limit. Based on this experiment, the null hypothesis for wave height (that it does not impact CED) cannot be confidently rejected. Given the relatively small additional value and significance of these variables, the results of multivariate models with more than two variables are not presented here.

Compared to *Spartina*, the model performance of *Salicornia* is a bit lower. Especially the bed level disturbances explain less variation: 70 instead 83 percent. It is now more useful to add below-ground length or age as a model predictor. However, it remains useless to add wave heights as a predictive factor: it barely increases the variation that can be explained and the probability that it has indeed an impact is even lower than for *Spartina*.

Table 3.2: A comparison of the model performance and statistical significance of models using different variables to predict the CED of Salicornia. The determination coefficient R^2 indicates the fraction of the variation that is explained by the model; the additional variation indicates how much additional variation is explained by also using L_{AG}, age, or H_{wave}; the parameter values are the values of α in the equation "$CED = \alpha_1 + \alpha_2 * \delta z + \alpha_3 * variable\ X$" and $P(\alpha 3 = 0)$ shows the probability that the null hypothesis that the additional variable has no impact is correct (so a two-sided test is used).

Model	R^2	Additional variation explained [%-points]	Parameter values			$P(\alpha_3 = 0)$ [%]
			α_1 [mm]	α_2 [-]	α_3	
Only δz	0.699		9.1	0.77		
δz and L_{AG}	0.747	4.80	10.8	0.74	-0.11 [-]	0.10
δz and age	0.737	3.73	20.9	0.77	-0.286 mm/day	0.40
δz and H_{wave}	0.707	0.78	10.7	0.77	-0.027 [-]	19.92

3.1.7 CALIBRATING WOO FRAMEWORK ON EXPERIMENTAL DATA

The Windows of opportunity framework will use bed level change and age to predict the critical erosion depth of *Spartina* seedlings. Although the impact of age in this experiment is relatively weak, the combination with previous results by Bouma et al. (2016) justifies the usage of age to predict the CED. Equation 3.2 shows with which values the best agreement with the experimental results can be obtained (this is the same as in Table 3.1). In this section, the translation to WoO parameters and the uncertainty in the prediction is further examined.

$$\begin{aligned} CED &= \alpha_1 + \alpha_2 * \delta z + \alpha_3 * age \\ &= 16.3 + 1.1 * \delta z + 0.079 * age \end{aligned} \quad (3.2)$$

The values of α_1 and α_2 are used directly in the WoO framework, for the initial CED and the sensitivity to bed level change. However, instead of a growth to CED (α_3), a maximum CED is used. The value for CED_{max} is determined from the growth rate using the expected duration of WoO1 and WoO2. This leads to a value of $CED_{max} = 16.3 + 0.079 * (2.5 + 77.5) = 23\ mm$.

With these values, the average error in the CED prediction is 0 mm, indicating that no systematic underestimation or overestimation occurs. The average absolute error is 3 mm, which is quite acceptable given the variability of the plants and the resolution of the measuring technique. However, larger errors up to 15 mm do occur as well. The distribution of the errors is plotted in Figure 3.7. To provide a better sense of how big the errors are, the relative errors are examined as well. 75 Percent of the errors is smaller than a quarter of the measured CED.

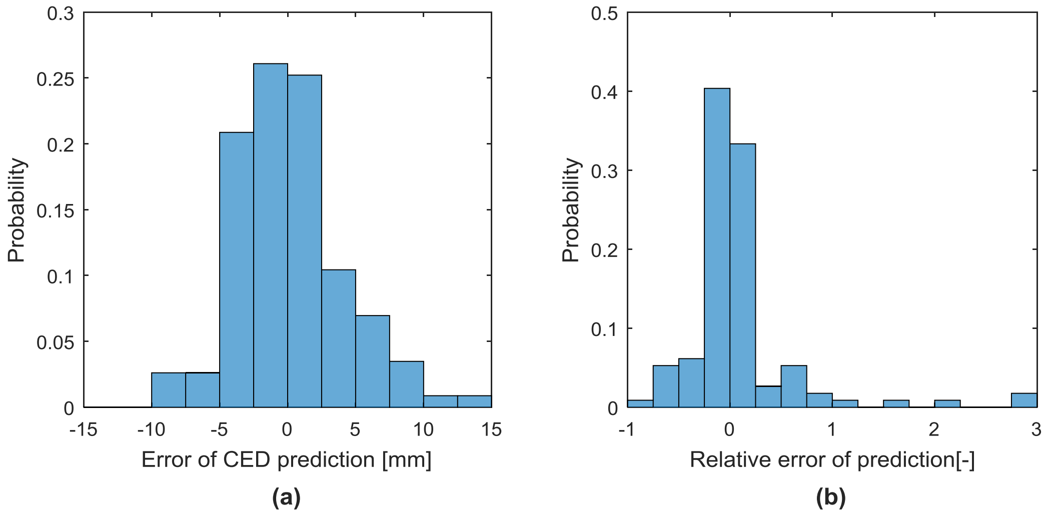

Figure 3.7: The distribution of the errors in the prediction of the CED of Spartina. Relative errors in (b) are expressed as fraction of the experimentally determined CED

3.1.7.1 SENSITIVITY ANALYSIS CALIBRATION

Given the variability of the experimental results and of plants in general, it is important to examine how the model performance changes with different parameter settings. This is done with a sensitivity analysis. Again solely the impact of the initial CED, CED growth rate and sensitivity to bed level change are examined. Table 3.3 shows the parameter values that were used for this analysis.

Table 3.3: The parameter ranges used for the sensitivity analysis of the calibration values

Parameter	Meaning	Initial value	Lowest value	Highest value
α_1	Initial CED	16 mm	5 mm	25 mm
α_2	growth rate CED	0.08 mm/day	0.04 mm/day	0.4 mm/day
α_3	Sensitivity δz	1.1 [-]	0.4	1.25

The initial CED depends mostly on the burial depth of the seeds. Given the fact that seedling emergence becomes less successful with increasing burial depth, its possible range is relatively limited. For the growth rate the uncertainty is larger: in the experiments of Bouma et al. (2016), the CED increased with approximately 0.35 mm/day, while we found a growth rate of approximately 0.08 mm/day. Lastly, the sensitivity to bed level disturbances is examined. The value in our experiment is higher than what was previously found by Bouma et al. (2016) and by Cao et al. (2017). Therefore the focus of the sensitivity analysis lies on lower values. Figure 3.8 shows the results of the sensitivity analysis. Both the average error and the sum of squared errors (SSE) are given

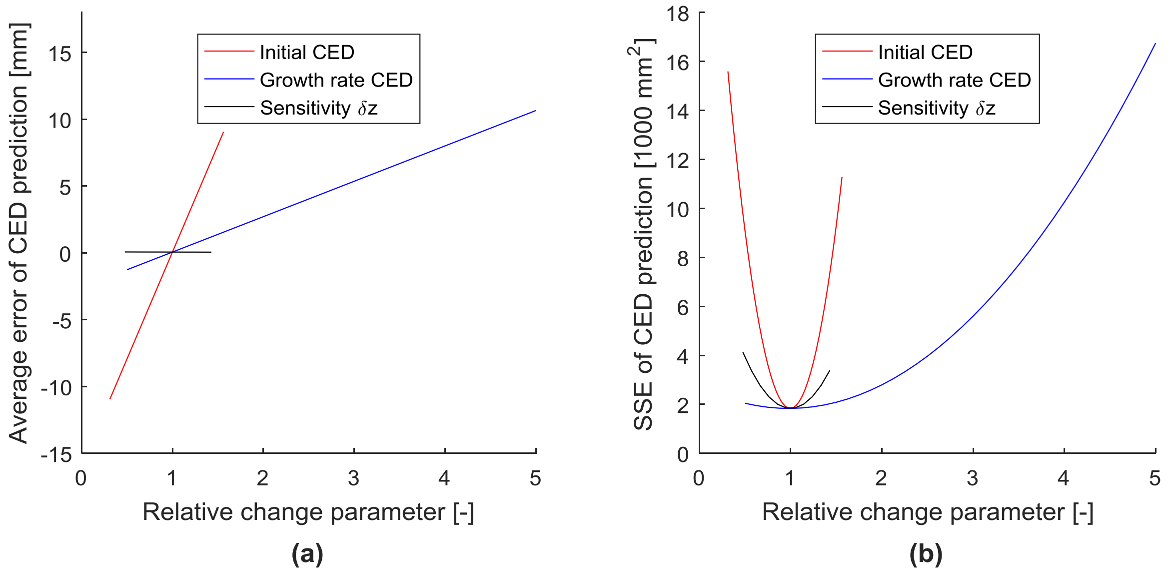

Figure 3.8: The impact of different parameter values on the average prediction error and sum of squared errors of the CED of Spartina. This shows that the growth rate of the CED (the blue line) and the initial CED (in red) have significantly more impact than the sensitivity to bed level change (the black line).

Figure 3.8 shows that the sensitivity to bed level change has no impact on the average error – because of its opposite effect for sedimentation and erosion – and only a limited impact on the SSE. The initial critical erosion depth and growth rate of the CED have a stronger impact on the model results: the initial depth because of the high sensitivity to changes (visible as a steep line) and the growth rate because of the large range of possible values.

3.2 Results modelling

In this section, the results of the modelling are presented. First, the predicted bed level change in Delft3D is presented, because this forms the main input for the Windows of opportunity model. Secondly, the predicted establishment of the Windows of opportunity model is presented. Section 3.3 will contain a sensitivity analysis, to analyse the uncertainty of these results.

3.2.1 Delft3D: bed level change

The most important factor for the Windows of opportunity framework is the bed level. The survival of window 2 and WoO3 depend directly on the bed level change. Window 1 is defined in terms of water depth, which in turn depends on the bed level. Therefore this paragraph presents the bed level change. Figure 3.9 present the bed level after the spin-up time. It shows that within the area of interest quite some erosion occurs, with maxima of 25 centimetres. Figure 3.10 presents the bed level and bed level change in a full year (from April to March). This is the period that is used to predict vegetation establishment. This figure shows that the erosion and sedimentation continue. In the area of interest this leads to a cliff, between +0.85 m and +1.5 m (mean high water).

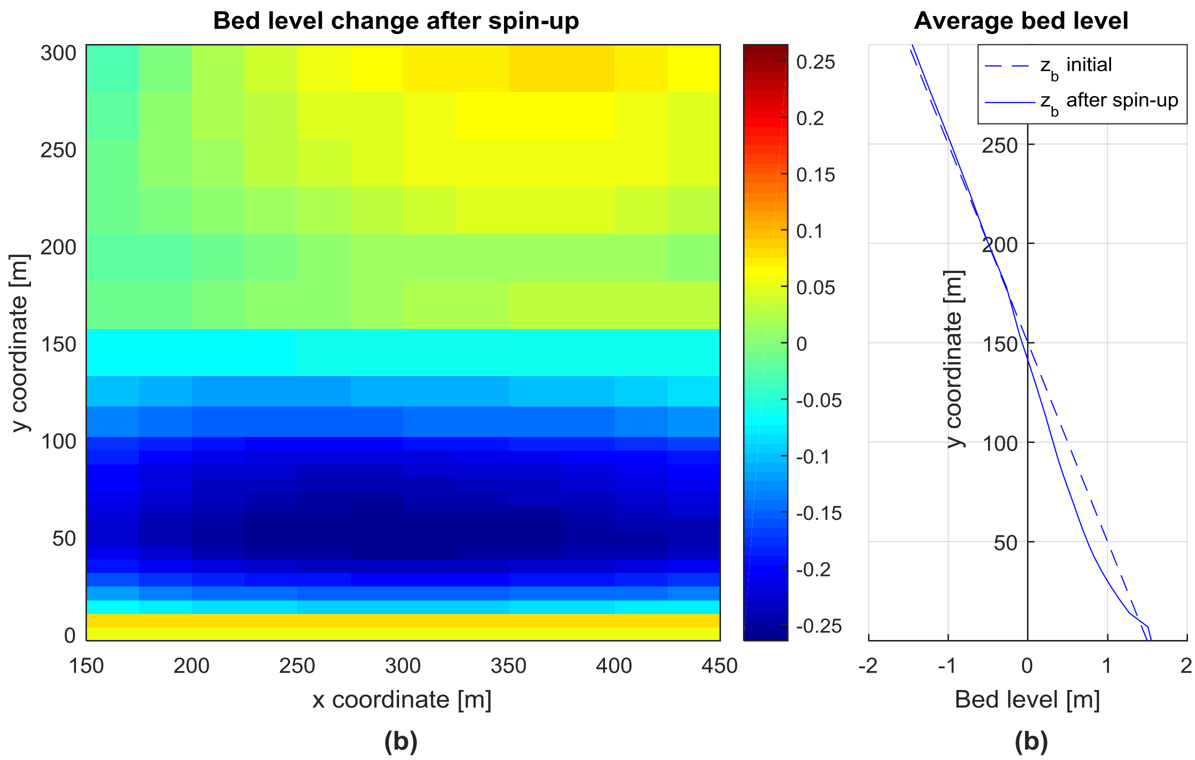

Figure 3.9: The average bed level and bed level change in the area of interest. Panel (a) shows the bed level change during the spin-up period in m. Panel (b) shows the average bed level profile in the area of interest.

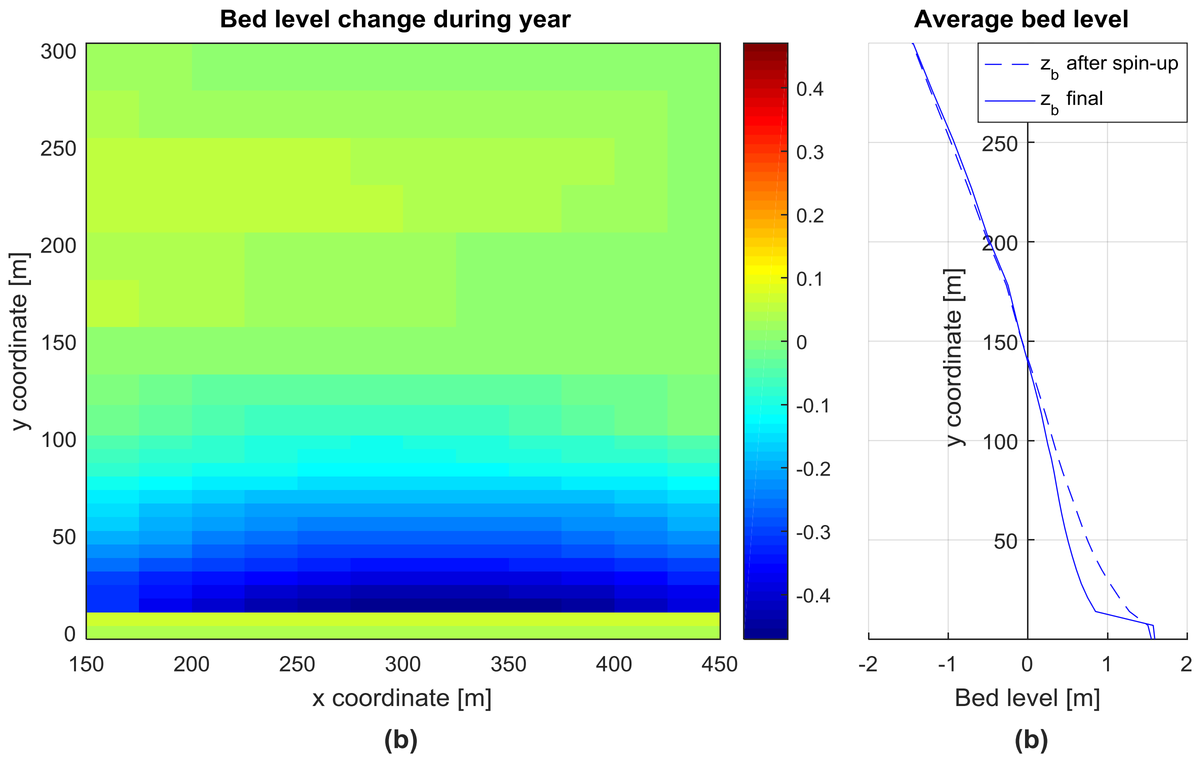

Figure 3.10: The average bed level and bed level change in the area of interest. Panel (a) shows the bed level change over the year in m. Panel (b) shows the average bed level profile at the start and end of the year in the area of interest.

3.2.2 WINDOWS OF OPPORTUNITY: ESTABLISHMENT

Based on the predicted bed level change in Delft3D, the establishment opportunities for *Spartina* vegetation can be determined. The results this gives are visible in Figure 3.11. This figure shows the locations where establishment is possible according to the separate conditions and the overall result.

As shown in the bottom right panel of Figure 3.11, establishment is only possible in the two rows near the coast (of 7 metres each): north of these rows establishment is not possible. This has a number of reasons. Due to the erosion that occurs in the spin-up period, a cliff arises. North of this cliff, the bed level becomes lower than mean high water at spring tide (MHWS), which means that it does not remain dry long enough for window 1 to occur. Furthermore, the erosion continues after the spin-up period, during the establishment phase. As a consequence, the limits for the average long-term erosion and the short-term storm erosion are exceeded for both window 2 and window 3.

The third row near the coast forms an exception to this result: at the start of the establishment period, its elevation sufficiently high for a successful WoO1. However, the continuing erosion still prevents a successful establishment: the short-term and long-term erosion limits are exceeded in both window 2 and window 3.

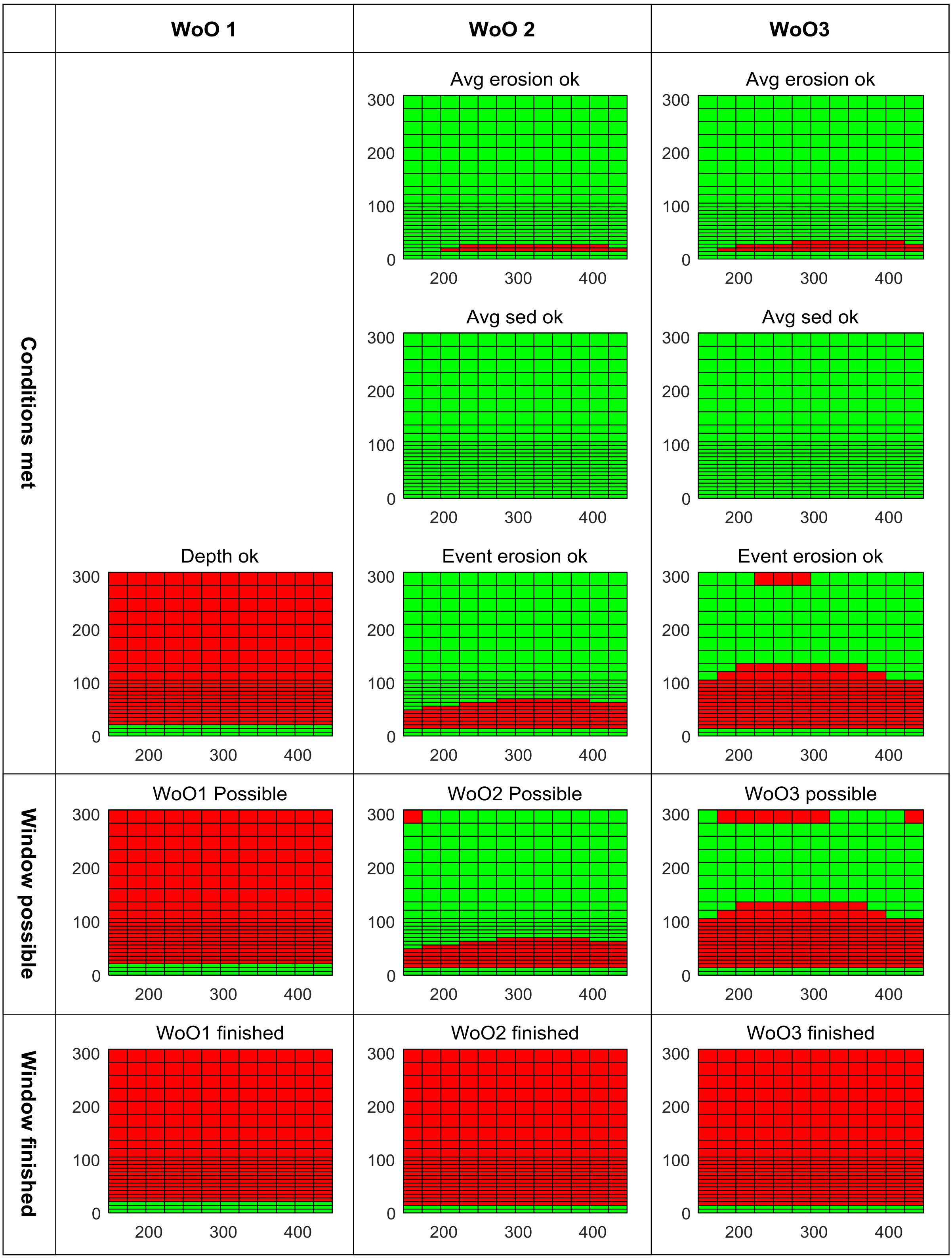

Figure 3.11: The results of the Windows of opportunity model. Every grid shows a top view of the area of interest, with the coast located at y=0 and the deepest part at y=300. Column 1, 2 and 3 show the results for resp. window 1, 2 and 3. Row 1-3 show if the separate conditions are met for the duration of a window. Row 4 shows if a window is possible, so if these conditions are all met at the same time. (So red square in the top left corner of 'WoO2 possible' indicates for instance that the average sedimentation, average erosion and event erosion are not met simultaneously, even if the rows above indicate that individually they are met at least once.) Row 5 shows if a window can be finished, so if at the same time both the previous window is finished and the new window is possible. The bottom right panel shows in which cells establishment can be successful.

3.3 Sensitivity analysis

A sensitivity analysis is used to determine the impact of modelling choices and parameter values. First, the sensitivity of the establishment to the parameters in the WoO framework is examined, followed by the sensitivity of the Delft3D model in section 3.3.2.

3.3.1 Sensitivity analysis WoO parameters

Because the Windows of opportunity concept has been developed recently, there is a lack of data on the parameter values that should be used. To determine how much impact this uncertainty has, the results with different parameter values are examined. To present the results, the establishment patterns are aggregated into the number of cells within the area of interest where a window is possible or finished (i.e. cells where the conditions of a specific window are met, and cells where simultaneously also the previous window is finished.) All parameter values are varied independently. The values used are given in section 2.4.6, the result is plotted in Figure 3.12.

This analysis shows that the result is quite robust. As explained in the previous section, multiple criteria are simultaneously limiting establishment. Consequently, the end result (i.e. the prediction if establishment is successful, in the lower-right panel of Figure 3.11 and Figure 3.12) does not change, even if the new parameter set allows one of the conditions to be met. Nonetheless, the intermediate results do show some variation.

Whether window 1 would be possible (so the left panel of the fourth row of Figure 3.11) depends on the duration of this window (T_{WoO1}). Figure 3.12 shows that durations longer than 4 days decrease the number of successful cells, up to the point that window 1 is no longer possible at the third row near the coast. At this point, the cells where window 1 and window 2 are finished coincide exactly (see the bottom row of Figure 3.11). Shorter durations do not increase the number of successful cells: as long as the duration remains more than a tidal cycle (12 hours), window 1 is unsuccessful outside the three rows at the coast.

Whether window 2 would be possible (so the mid panel of the fourth row of Figure 3.11) depends quite strongly on its duration (T_{WoO2}). Figure 3.12 shows that lower durations increase the number of successful cells, longer durations decrease the success rate. Furthermore, the potential success rate of window 2 also depends on the value for CED_{mature}, with higher values increasing the success rate. However, this increase or reduction in establishment would not occur directly seaward of the already successful cells, but further away from the coast, where window 1 is not successful (not plotted). Consequently, the number of finished cells – which also depends on window 1 – does not change.

Whether the window 3 is possible (so the right panel of the fourth row of Figure 3.11), depends mostly on the CED of mature vegetation, the sensitivity to bed level change and the duration of the event (i.e. the period for which a maximum erosion is defined). However, like before, there is no effect on whether window 3 can be finished. Directly seaward of the cliff strong erosion occurs, so any additional cells where WoO3 would become possible are located further seaward. In those cells Window 1 is already limiting establishment, so the overall establishment pattern does not change. This means the pattern bottom right panel of Figure 3.11 remains the same, leading to the straight lines for WoO3 finished in Figure 3.12.

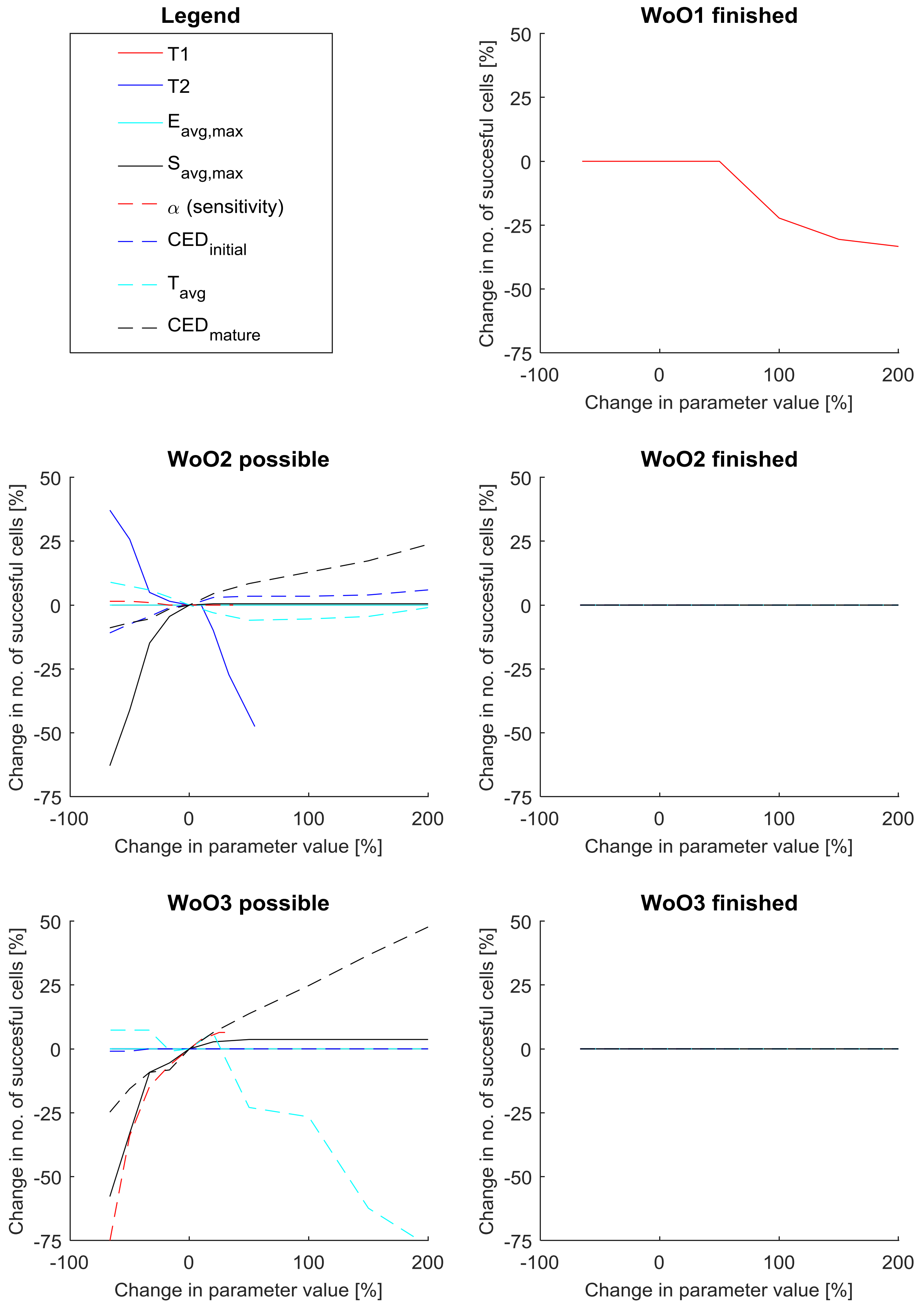

Figure 3.12: A sensitivity analysis of the Windows of opportunity parameters. The left column shows if a window is possible, so if all conditions of that window are met at the same time. The right column shows if a window can be finished so if at the same time the previous window is finished and all conditions of the new window are met. (WoO1 possible is not plotted: without the existence of previous windows, this is the same as WoO1 finished). Establishment is possible when window 3 is finished, so the bottom right panel shows the (in)sensitivity of establishment.

3.3.2 Sensitivity analysis Delft3D model

The establishment chances are determined by the combination of the WoO framework and the results from Delft3D. The previous section examined the impact of changes in the WoO framework, this section looks at the impact the model set-up in Delft3D. Three different factors are examined: the sediment type, the impact of vegetation and the wave forcing. The results are described in this section. For some of the figures, the reader is referred to the appendices.

3.3.2.1 Sediment type

Because of the direct dependency of establishment on sediment dynamics, the sediment is very important. This section describes how the results would change when a different sediment type is used. Instead of the single-graded sediment of the reference model, two types of clay with different settling velocities are used (for information on the exact settings, see section 2.4.7). With this sediment, the amount of erosion increases, leading to a slightly higher cliff. This is plotted in Figure B.1 and Figure B.2 in Appendix B**.**

The differences in the bed level dynamics also affect the establishment chances of the different windows (for details see Figure B.3). With the stronger erosion, window 1 becomes impossible at the third row near the coast, while further seawards window 2 and 3 become possible less often. However, because other conditions were already limiting establishment at these locations, the predicted establishment (i.e. the successful completion of window 3) does not change.

3.3.2.2 Impact of vegetation

The impact of vegetation modelling is studied to determine how the results would change if the model includes the impact of vegetation on the hydrodynamics. This has very little impact on the bed level change and supports the choice to not include the impact of vegetation on hydrodynamics in the reference model. The erosion during the spin-up period is up to 1 cm smaller than in the reference model, so very small compared to the total erosion of up to 25 cm. After the entire model run, the maximum decrease in erosion is 3 cm, so also very small compared to the maximum erosion of 70 cm. Both results are plotted in Appendix C. The slight decrease in erosion has no effect on where the erosion is acceptable. Consequently, the predicted establishment remains the same.

3.3.2.3 Wave forcing

The impact of wave forcing is important because Marconi will use wave-dampening measures to make the area more suitable for salt marsh vegetation. Therefore, this section looks at the change in the results when the waves at the model boundary become up to 50% lower. As shown in Appendix D, the erosion would decrease significantly when the waves become lower (Figure D.1 and Figure D.2). The cliff, which is approximately 70 centimetres high at the end of the reference model run, decreases to 50 cm and 25 cm with when the waves are 25% and 50% lower respectively.

When the waves become 25 percent lower, the overall establishment does not change (see the green line in Figure 3.13). The number of cells where window 2 and 3 would be possible changes strongly, as shown by the red and purple lines. However, this change occurs further seawards, where window 1 is already limiting establishment. (For the detailed results with spatial patterns, see Figure D.3 in the appendix).

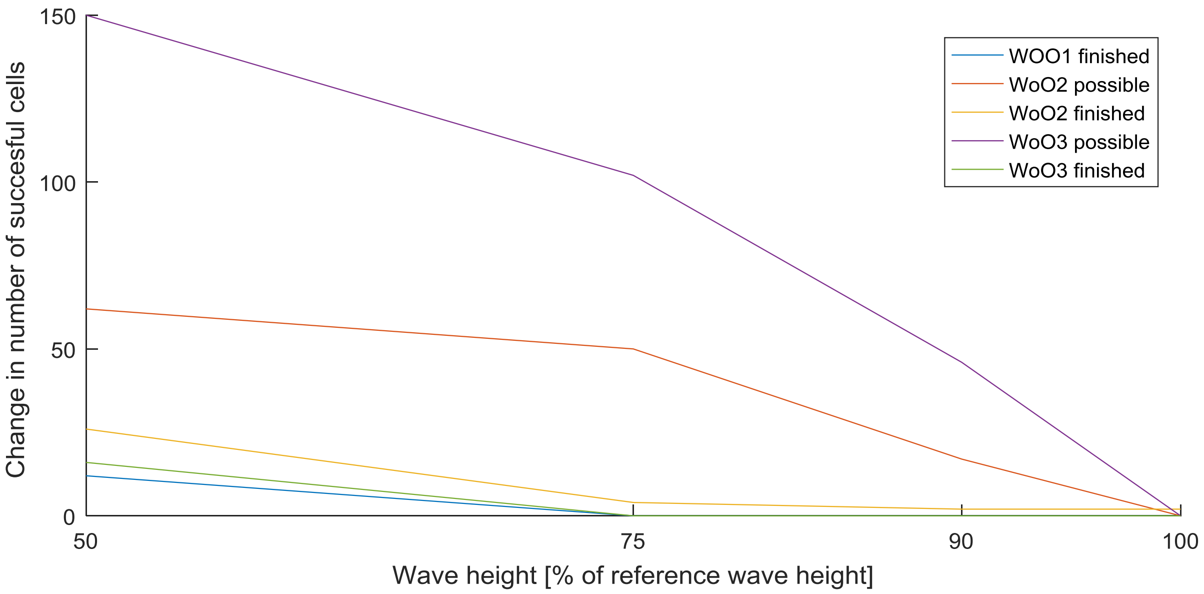

Figure 3.13: The dependency of establishment on wave height (wave heights are measured at the boundary, wave direction does not change)

When the waves become 50 percent lower, the overall establishment does change. At this point the establishment generally becomes possible at two more rows, as visible in the bottom right panel of Figure 3.14. Furthermore, the success per cells depends almost fully on window 1: the conditions for window 2 and 3 are met almost everywhere. This means that the water depth instead of erosion is limiting establishment. Another effect is that the sedimentation becomes so strong at the seaward end of the domain, that window 2 and 3 cannot occur anymore. These results show that the Marconi project needs wave-dampening measures to make the area suitable for a pioneer salt marsh.

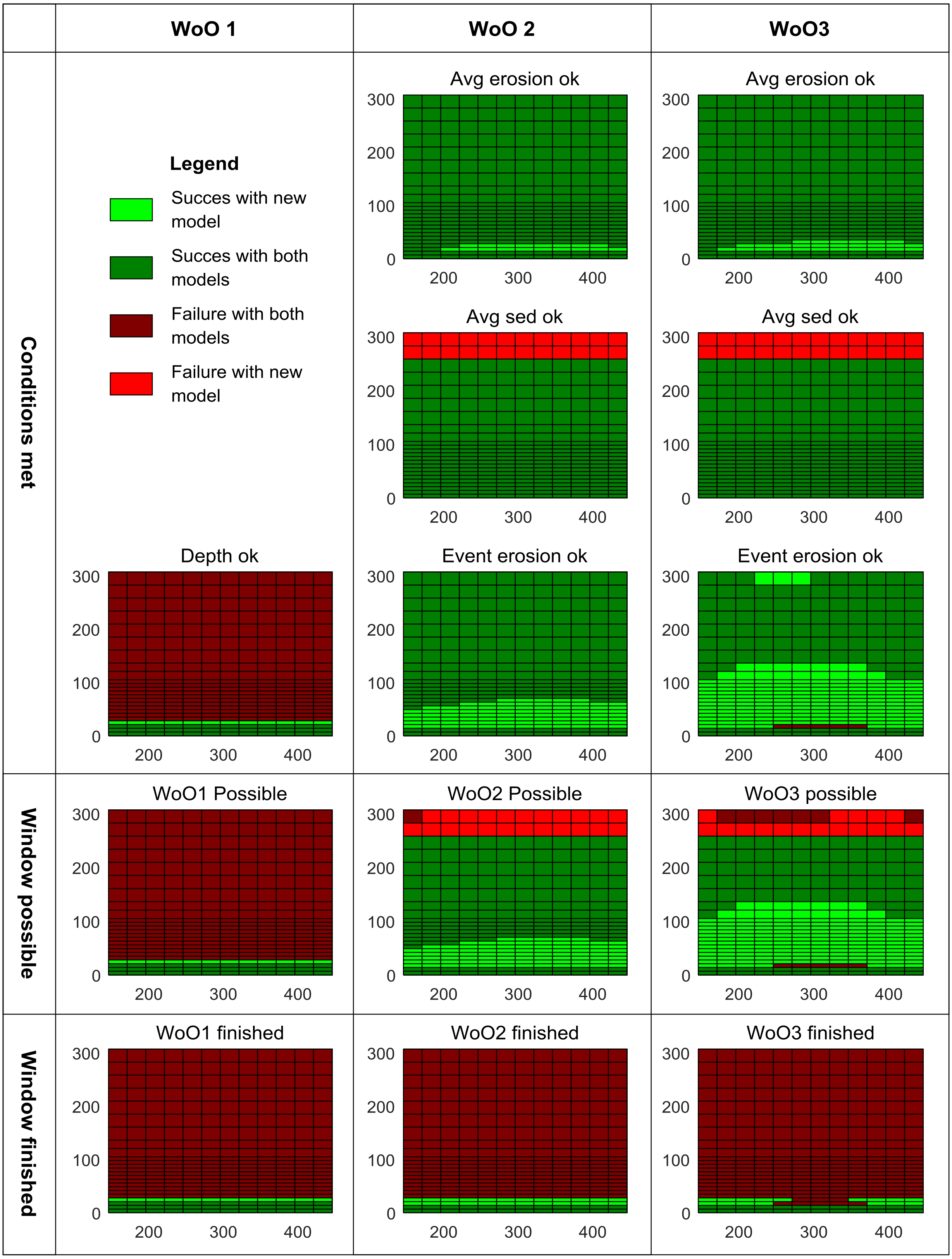

Figure 3.14: The results of the Windows of opportunity model with 50% lower waves. Every grid shows a top view of the area of interest, with the coast located at y=0 and the deepest part at y=300. Row 1-3 show if the separate conditions are met, row 4 shows if a window is possible, so if these conditions are all met at the same time. Row 5 shows if a window can be finished, so if at the same time both the previous window is finished and the new window is possible. This means the bottom right panel shows in which cells establishment can be successful. Dark colours indicate results equal to the reference wave height, bright colours indicate a difference.

4

DISCUSSION

In this study the windows of opportunity for salt marsh establishment were defined in terms of bed level dynamics, an experiment was run to determine these limits and a Delft3D model was used to test the usability and implications of the model. This chapter starts with describing the limitations and innovations of the experiment. This is followed by the implications the experiment has for the WoO framework and general comments about the framework. In the third section, the set-up and results of the modelling are discussed. And finally, the implications of this study for Marconi are examined.

4.1 DISCUSSION FLUME EXPERIMENT

4.1.1 METHODS OF FLUME EXPERIMENT

The goal of the flume experiment was to determine the critical erosion depth of salt marsh vegetation. The first point of discussion lies in the definition of this critical erosion depth: the erosion depth at which a plant topples over. Although toppling quickly leads to failure – especially when it occurs because erosion has uncovered the roots – plants can potentially re-erect themselves. In that case toppling does not equal failure. However, in pioneer salt marshes the stresses from the tide and waves are quite high, making this less likely. Furthermore, a practical argument for using the erosion depth of toppling instead of dislodgement is that plants can be broken or lost at dislodgement, making it impossible to measure root and shoot lengths.

Another limitation is the one that applies to all laboratory studies: its applicability to the real world. In this case, plants are for example grown in a climate room. Although the tidal cycle, the day-night (light) cycle and the salinity are mimicked, they are not equal to the field conditions. Furthermore, waves, currents and wind are absent during vegetation growth. If they would be present, plants might react by adapting to this kind of stresses, similar to how trees have been found to react to wind by increasing the size of their root base (Stokes et al., 1995). Furthermore, the sediment used is not exactly the same was what is found in salt marshes. All in all, differences exist between the experiment and field conditions and they can affect the results.

A further point of attention lies in irregular shape and limited height of the waves in the experiment. The waves are asymmetrical, due to the way the waves are created and the presence of a false bottom (which creates a depth difference). Furthermore, wave dampening is imperfect, leading to wave reflection. However, waves in the field are also not perfectly sinusoidal, due to for instance shoaling. And more importantly: given the conclusion that the CED is more important than the wave height, the wave definition is of lesser importance in this study. Nonetheless, the fact remains that the maximum wave height of the experiment of 9 centimetres is significantly lower than what is found in the field.

Regarding the execution of the experiment, some remarks have to be made as well. The seeds in the experiment were relatively old (approximately 1 year) and were forced to germinate out of their natural growing season. Furthermore, near the end of the test, plants were moved from the climate rooms to a colder greenhouse because the climate room was needed for other experiments. In addition, the salinity was relatively high in comparison with earlier experiments, to mimic the salinity of the Eems. All in all, the results of the experiment could be regarded as the minimum limits of what a plant should be able to resist.

4.1.2 Results of flume experiment

In the experiment, the bed level change was found to have a far larger effect than the wave height. However, this is under the condition that waves do not cause erosion (which was experimentally achieved by limiting the number of waves per run). Consequently, this result should not be interpreted to mean that wave heights do not matter. Rather, it means that the erosion the waves cause is more important than their drag force on the vegetation.

Based on this conclusion, the induced erosion instead of the bed shear stress should be used to account for the effect of waves. With this approach, the limited wave heights of the experiment become less relevant: the effect of higher waves is still accounted for, only in a different manner. This approach has two advantages. In the first place, it allows taking into account the previous bed level dynamics, which are shown by the experiment to be very important. Secondly, it allows taking into account more moderate conditions, which over time can cause even more erosion than the relatively extreme events that are tested for with bed-shear-stress-dependent limits (Leonardi & Fagherazzi, 2015).

When comparing the results for *Spartina* to previous literature, there are some remarkable differences. An important difference is that the CED in this experiment is relativity low. The CED was on average slightly below the burial depth and increased with less than 0.1 mm/day. Cao et al. (2017) found CED values that were approximately 5 mm higher. Bouma et al. (2016) found CED values that are 5 to 10 mm higher (for resp. 20 and 50 days old plants) and growth rates that are approximately 3 times higher. Furthermore, the seedling mortality is higher than in the experiment of Cao et al. (2017).

There are multiple explanations for these differences. A first explanation is that we determined the CED in a wave flume, while previous studies only applied currents. It is possible that plants topple more quickly under the alternating forces and currents caused by waves, than under unidirectional forces and currents. However, a second explanation is that the plants grew less well in our experiment, due to the aforementioned seed age, salinity and movement to the greenhouse.

A second difference with previous results lies in the sensitivity to bed level change. In this study, a sensitivity of 1.1 was found, meaning that every mm of sedimentation increased the CED with (an average of) 1.1 mm. In contrast, previous studies (Bouma et al., 2016; Cao et al., 2017) found values of less than 1, meaning plants partially compensated for bed level disturbances. Partially, this can be caused by the presence of lower vegetation ages in our study: it costs time for plants to adapt to their environment. Another reason might be that plants grew less well in this study, and were consequently unable to adapt to bed level change.

A novel aspect of this experiment is the comparison of *Spartina* and *Salicornia*. The results show large differences between both species. The critical erosion depth of *Spartina* is approximately 1 cm larger than for *Salicornia*, which agrees with the fact that *Spartina* can establish at lower elevations than *Salicornia* (Doody, 2008). Furthermore, the CED of *Spartina* increases with increasing root length, while the CED of *Spartina* increases with decreasing shoot length. As shoot length increases with age, this also causes the CED of *Salicornia* to decrease with age.

The opposite effects of root and shoot length can be explained by the toppling mechanism of both species. For *Spartina*, erosion uncovers the roots and/or seed at a certain moment, at which point they cannot support the plant anymore and the plant topples over. For *Salicornia*, the stem loses support with increasing erosion, until it bends completely. At this point the roots are still stable. This is caused by the physical differences between the plants: *Salicornia* has thicker and heavier shoots. Consequently, waves exert more force, shoots are more top-heavy and toppling occurs more quickly.

4.2 Discussion WoO Framework

In this study, three different windows are implemented to model the establishment of *Spartina*. Following previous research (e.g. Attema, 2014; Hu et al., 2015), the first window is defined as an inundation-free period. Balke et al. (2014) have, as a proof of concept, shown that a framework with only this inundation-free period can be used to predict the establishment of a pioneer salt marsh. However, the absence of inundation should actually be regarded as a proxy for the necessary disturbance-free conditions: even under temporarily inundated conditions seeds can germinate and establish. Therefore, the framework might underestimate the success rate of window 1.

For the second and third window, the limits were defined in terms of bed level change, instead of bed shear stress. The experiment showed that bed level change indeed has a larger impact than bed shear stress (tested through wave heights) and supports this choice. However, there are some limitations and consequences to the exact implementation that is followed.

For the second and third window, the limits were defined in terms of bed level change, based on the desire to allow for the erosion that moderate events can cause over time and on the results of the flume experiment. In Window 2, the critical erosion depth depends on the vegetation age (see also Figure 2.3). In the experiment, the dependency of CED on age was relatively weak for *Spartina* plants. However, given that other research (e.g. Bouma et al., 2016) has found a stronger dependency on age and that the lower growth rates of this experiment can partially be explained by the experimental conditions, the inclusion of the age-dependency remains justified for *Spartina*. However, if one would apply the framework to *Salicornia* plants, it might better to exclude the seedling age or even introduce a negative dependency: in the experiment the CED of *Salicornia* plants decreased with increasing age and shoot length.

The experiment showed an equally strong impact on the CED for seedling age and the root and shoot size (see section 3.1.6). However, the usability of the model gives a further argument to use the seedling age in the model. The seedling age can be determined within the framework, while root and shoot sizes would have to be modelled separately, based on at the very least seedling age and possibly also season, nutrient availability, hydrodynamics, salinity or other factors. This would add more parameters, more complexity and more uncertainty.

To keep the WoO framework simple and the number of parameters limited, it uses linear and deterministic relations. However, this is a simplification of reality. Furthermore, it leads to discontinuities in the framework, for instance between the increasing erosion resistance of window 2 and the suddenly constant erosion resistance after window 2. So the natural behaviour might be captured more accurately using different functions (e.g. logarithmic, quadratic or sinusoidal). However, lacking the knowledge which function and parameters should be used, the linear equations remain most appropriate for the moment.

Another limitation of the current framework is that it cannot be used to predict the survival over longer periods. The long-term sedimentation and erosion limits are currently defined over the entire life of the plant (see Figure 2.3 or equation A.2). However, alternating periods of strong sedimentation and erosion can lead to plant failure, while the average bed level change remains acceptable. This becomes especially relevant when modelling even longer periods, but it could already introduce an overestimation of the area with acceptable long-term bed level dynamics in the current application. Therefore, a maximum period over which the average bed level change is calculated could form a valuable addition to the framework.

In a similar manner, the short-term erosion limit currently depends on the total net bed level change during a plant's life (see equation A.4). However, given that plants adapt their growth rate to compensate for bed level change (Bouma et al., 2016), not all previous bed level change should be taken into account. So the model could be improved by using a limit to which previous bed level changes are used or a weighting function to gradually decrease the impact of older bed level changes. However, given the desire to keep the model simple, the relatively limited period for which survival is tested in this study and the lack of knowledge of exactly how older bed level changes should be discarded, this is not implemented. As a result, the model could underestimate establishment in areas with continuous erosion.

A last remark is that the WoO model only evaluates the suitability of the hydrodynamic and morphodynamic conditions. It assumes that the necessary seed bank and biochemical and climatological conditions are present. So in order to make a general prediction about establishment chances, these conditions have to be taken into account separately.

4.3 Discussion modelling

4.3.1 Methods of modelling

The establishment of salt marsh vegetation is predicted using a combination of a Delft3D model and the WoO framework. Because of the direct dependency of the WoO framework on sediment dynamics, the first remarks pertain to the modelling of sediment dynamics. The sediment in the model is a uniform single-graded clay. In a natural system, multiple gradations occur simultaneously, with the exact mixture depending on the local conditions. Without the stabilising effect that this can have, sediment dynamics can become stronger and unrealistic effects can occur. Furthermore, the sediment concentration at the boundaries was set to a uniform and constant concentration of 100 mg/L. However, in reality the concentration varies over space and time.

For the establishment at Marconi, the simplifications in the Delft3D model can also have an impact. The model is defined as a simple square with a constant slope, while the local situation and bathymetry are more complex. They affect the flow and wave patterns and could provide additional shielding to the salt marsh. Partly this is solved by using wave conditions out of a model of the Eems and Dollard that includes the larger system more accurately. The wave conditions show indeed the expected bimodal distribution, with waves from directions with lower fetch lengths indeed being lower and less common (see section 2.4.3). Nonetheless, the model set-up might underestimate the current dampening of these waves. Furthermore, additional wave dampening measures are planned in Marconi. These are not included in the model, nor in the wave boundary conditions.

Likewise, the simplifications in the tidal definition have an impact on the predicted establishment. The water level is important for the success of WoO1. In the model, the water level (tide) is defined as the superposition of two sinuses, for the semidiurnal tide and the spring-neap variation. In reality, the variation in the water levels is larger, due to the other tidal components and wind set-up. This means cells (elevations) where the model says that WoO1 is impossible, might in reality have a sufficiently long inundation-free period. Consequently, the model might underestimate the number of cells where WoO1 is possible. Furthermore, the increased cyclicity of the tide can cause inaccuracies in the model to add up (more strongly) over time.

A last remark is about the usage of the Delft3D model for the windows of opportunity. A successful establishment depends on the combination of low water levels (i.e. neap tide) for WoO1 and benign hydrodynamic conditions for window 2 and 3. This makes it a rare event. Hu et al. (2015) have shown that this does not occur every year. Given the duration of this model, care should be taken in the interpretation of results. If for a certain location the separate windows are possible, but the combination of windows is not, then the relative timing of the windows might be limiting establishment. With the timing depending completely on chance, this means that the deterministic representation of a stochastic process can lead to an underestimation of the establishment opportunities.

4.3.2 RESULTS OF MODELLING

A Delft3D model was used to predict vegetation establishment. Ideally, this model is in morphodynamic equilibrium. This is also the reason a spin-up period was used. In this spin-up period erosion occurs in the intertidal area. This leads to a cliff around the elevation of high tide. After the spin-up period this erosion continues – although at a lower speed**.** This has two effects. The erosion that occurs in the spin-up period and establishment period decreases the occurrence and duration of inundation-free periods, thereby limiting in which cells WoO1 is possible. And the erosion in the establishment period limits the success of window 2 and 3.

There are different explanations for the strong erosion and the occurrence of the cliff. Partly it can be the numerical effect of the model set-up, with a uniform homogeneous sediment, constant and uniform sediment concentrations at the boundaries and a very regular tidal forcing. On the other hand, the current situation in the Eems is also that the bed level is low until the coast (dike), without the broad gentle-sloped beaches of the Wadden Sea. If for Marconi only the local bed level would be changed, without introducing any wave-breaking measures (which is basically what has happened in the model), then the system would try to restore the old equilibrium. In that sense, it is logical that the model predicts a return to the old situation with lower bed levels.

As a result of the cliff, a bimodal distribution of establishment chances occurs. At the two rows near the coast, disturbance-free periods are abundant and erosion is virtually absent. Consequently, all windows can be finished and establishment is successful. Below the cliff, the elevation is too low, and sufficiently long disturbance-free periods do not occur. Consequently, window 1 cannot succeed (apart from the row directly below the cliff, where the elevation at the start of the growing season is still sufficient for window 1). Furthermore, the erosion is quite strong in this area, prohibiting the success of window 2 and window 3.

The predicted establishment is quite stable, because multiple conditions are simultaneously limiting the establishment seawards of the cliff. The sensitivity analysis of the WoO parameters consistently shows the same result: establishment is only expected at the two rows near the coast. The sensitivity analysis with the sediment type shows the same pattern. However, for the possibilities of the separate windows the sensitivity analysis does show an effect. In this sensitivity analysis one factor was changed at the time, while all of them are uncertain in reality. So if they would change simultaneously, the predicted establishment can change. Furthermore, the sensitivity analysis with the wave heights shows that lower wave heights do increase the establishment chances.

With the possibilities of the separate windows, the sensitivity of the different parameters can be compared. This shows that, of the WoO parameters, the sensitivity to the duration of window 2, the duration of the event and the CED of mature vegetation is the highest. The sensitivity analysis of the Delft3D model showed that the sediment type has some effect on where the separate windows would be possible. Therefore, additional research into the values of these factors would be valuable to decrease the uncertainty of the framework. Furthermore, the sensitivity analysis with the wave heights demonstrated that the Marconi project needs wave-dampening measures to make the area suitable for vegetation.

Considering the uncertainties in the WoO framework and the Delft3D model, the real-life establishment could certainly be more wide-spread than predicted. However, the consequent prediction of erosion indicates that this is (partly) the natural reaction of the Eems trying to revert to its equilibrium situation. Therefore, the deviation from the model results is expected to be relatively small.

4.4 Discussion implications for Marconi

The Delft3D model predicts erosion to occur, thereby indicating that the situation and bathymetry as planned for Marconi are not stable without additional measures. So, in order to facilitate the pioneer salt marsh, some form of wave breaking measures will be necessary. This is further substantiated by the sensitivity analysis of the wave heights. This showed that erosion decreases with lower waves and that establishment becomes more successful at a wave height reduction of 50 percent.

In addition, the experiment showed that the erosion limits for *Salicornia* are quite a bit lower than for *Spartina*. This difference exists for all ages, but becomes especially apparent for older *Salicornia* plants. One of the goals of the Marconi project is to have a diverse pioneer salt marsh that includes *Salicornia* vegetation (Buro Bakker, 2015). The higher erosion limits suggest that this is only likely to succeed at the highest parts of the pioneer salt marsh.

Lastly, the model and methodology of this study can be used in the further design of the Marconi salt marsh. The model and methodology that were developed can be used to predict the effects of concrete measures on the erosion and establishment chances. Furthermore, they can be used to predict which conditions limit establishment. Based on this expectation, you can predict whether planting vegetation would be useful (if WoO1 is limiting) or not (if window 2 or 3 is limiting).

5

CONCLUSIONS

The goal of this study is "To determine under which conditions pioneer salt marsh vegetation can establish and use this knowledge to reach new insights for the design of the Marconi pioneer salt marsh pilot." To achieve this goal, three research questions were defined. The conclusions will be given per research question.

5.1 THE CED OF SALT MARSH VEGETATION

The first research question is: "*How do plant age, wave height and bed level change affect the critical erosion depth (CED) of pioneer salt marsh vegetation?*"

The experiment showed that critical erosion depth depends strongly on the bed level change during a plant's life. The wave height mainly has an effect through the erosion it causes; in the experiment the additional drag force of higher waves was of lesser importance. Furthermore, age and root length have on average a weak positive impact on the CED of *Spartina*. For *Salicornia* age and shoot length have instead on average a negative impact on the CED.

The difference between both plants is caused by the difference in their failure mechanism. In the experiment, *Spartina* seedlings generally toppled when their seed or roots were uncovered. As root length increases with age, the critical erosion depth increases as well. In contrast, *Salicornia* toppled because of shoots completely (and plastically) bending over under the wave forces. As the shoot length increases with age, they become more top-heavy and the drag force they experience increases. Consequently, the CED of *Salicornia* decreased with age. Because they topple before their roots are uncovered, their CED is also lower than the CED of *Spartina*.

5.2 MODELLING SALT MARSH ESTABLISHMENT

The second research question is: "*How can salt marsh establishment at the Marconi pioneer salt marsh be predicted?*"

Salt marsh establishment can be predicted using the Windows of opportunity theory. The predictions of this theory can be improved when the vegetation limits are defined in terms of bed level dynamics instead of bed shear stress. This forms an improvement because A) plants are shown to be especially sensitivity to bed level change and B) because this enables taking into account the effect of the more frequent and less extreme events that can cause major bed level change. However, at the same time such a definition makes the application of the framework more difficult, because it requires reliable information on bed level change, which is more difficult to model than bed shear stress. For Marconi, this bed level change was predicted with a Delft3D model of the area.

5.3 IMPLICATIONS FOR MARCONI

The third research question is: "*What are the implications of the experiment and model for the design of the Marconi pioneer salt marsh pilot?*"

Additional wave-breaking measures are needed to protect the pioneer salt marsh. Without these measures, significant erosion will occur and the vegetation limits of the water depth, short-term erosion and long-term erosion will be exceeded. The model predicts that a wave height reduction of 50 percent is sufficient to nearly stop the erosion. At this point bed level dynamics are no longer limiting the establishment of vegetation. Therefore the establishment increases, up to the point where the elevation becomes too low for pioneer vegetation.

Furthermore, the experiment showed that the critical erosion depth is lower for *Salicornia* than for *Spartina*. Bed level dynamics decrease with elevation, so this means that *Salicornia* will grow at slightly higher elevations than *Spartina*. Existing literature already indicates that *Salicornia* generally grows slightly higher in the marsh than *Spartina*, but this study supports that knowledge and adds some mechanistic insight into why this is the case.

6

RECOMMENDATIONS

This study results in a number of recommendations. These recommendations are shown below, and concern future experiments, modelling applications and the Marconi project.

6.1 RECOMMENDATIONS FOR FLUME EXPERIMENTS

- Examine the impact of waves and currents on the CED. The CED values of this study are significantly lower than in previous studies. This can be caused by the fact that this study used waves in the flume tests, while most previous studies only used currents. However, another explanation is that the plants did not grow as well in this study. To determine the effect of waves – and thereby the validity of previous results - plants that are grown under exactly the same conditions should be tested with both waves and currents.

- Research the CED of mature vegetation and the time needed to reach this value. The sensitivity analysis showed that the model is quite sensitive to these values. Therefore, it would be wise to perform experiments with older salt marsh plants and see how the CED develops over time.

6.2 RECOMMENDATIONS FOR MODELLING

- Examine how the WoO framework can take the timing of bed level dynamics into account. Currently, the WoO framework treats erosion that occurred two weeks ago the same as erosion that occurred two months ago. However, in reality plants slowly adapt to changes in their environment. So the framework would be improved if it can somehow incorporate this reaction time.

- Include biogeomorphologic feedbacks in the Delft3D model. The sensitivity analysis demonstrated that in the current Delft3D model including the effect of *Spartina* seedlings on the hydrodynamics barely impact the results. However, vegetation also affects the strength of the bed (i.e. the critical bed shear stress). Furthermore, algae, worms, birds and other organisms also positively and negatively affect the sediment dynamics (e.g. Widdows & Brinsley, 2002; Paalberg et al., 2005; Temmerman et al., 2007). Together, they certainly have an impact bed level dynamics and vegetation establishment.

- Use longer time series for hydrodynamic conditions. Earlier research by Hu et al. (2015) showed that the establishment of salt marsh vegetation is a rare event, depending on the relative timing of the tide and wave conditions. Therefore, it would be better to use longer time series of the water levels and wave conditions.

6.3 Recommendations for the Marconi project

- Use wave-dampening measures for the pioneer salt marsh to reduce the wave heights by at least 50 percent. The current wave climate results in strong erosion at the location of the pioneer salt marsh. This erosion makes it impossible for a salt marsh to develop. The results show that a wave height reduction of 50 percent prevents nearly all erosion and enables the salt marsh to establish.

- Use the WoO framework and the developed Delft3D model to evaluate the effect of measures. When designing the Marconi salt marsh, this model can be used to predict the effect of measures. This can help in choosing which measures should be used and which configurations would work best.

- Use the monitoring program of the Marconi project to calibrate and improve the WoO framework. Because the pioneer salt marsh is part of a pilot project, an extensive monitoring program is planned. It would increase the usability of the collected data if a high temporal resolution is used for the measurements of the vegetation and bed level dynamics. This data can be used to calibrate the parameters of the WoO framework, in a similar way as Hu et al. (2015) did when hindcasting vegetation development at the Western Scheldt.

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Appendices

Appendix A. THE WOO FORMULATION

This appendix gives a mathematical description of how the Windows of opportunity framework is defined in this research. The equations are indicated per window.

Window 1: $t \leq T_{WoO1}$
Plants are not inundated, allowing a seed to grow roots and anchor itself. This is described by equation A.1.

$$H = 0m^{5} \tag{A.1}$$

With:

t	=	Time since establishment (age)	[day]
T_{WoO1}	=	Duration of window 1	[day]
H	=	Water depth	[m]

Window 2: $T_{WoO1} < t \leq T_{WoO1} + T_{WoO2}$
Conditions are calm, allowing the plant to grow stronger. This is described by equation A.2 until A.5 (eq. A.4 is equal to eq. 2.1 in the main report).

$$-E_{avg,max} < \delta z_{avg} < S_{avg,\max} \tag{A.2}$$

$$-CED < \delta z_{event} \tag{A.3}$$

With

$$CED = CED_{initial} + \alpha * \delta z_{life} + \frac{t - T_{WoO1}}{T_{WoO2}} * (CED_{mature} - CED_{initial}) \tag{A.4}$$

$$\delta z_{event} = z_b(t) - z_b * (t - T_{event}) \tag{A.5}$$

And

T_{WoO2}	=	Duration of window 2	[day]
H	=	Water depth	[m]
T_{WoO2}	=	Duration window 2	[day]
$E_{avg,max}$	=	Long-term erosion limit (defined positive)	[m/day]
δz_{avg}	=	Average bed level change during life of plant	[m/day]
$S_{avg,max}$	=	Long-term sedimentation limit	[m/day]
CED	=	Short-term erosion limit (critical erosion depth)	[m]
E_{event}	=	Short-term erosion	[m]
T_{event}	=	Duration over which E_{event} is calculated	[day]
$CED_{initial}$	=	Initial critical erosion depth	[m]
α	=	Sensitivity to bed level change	[-]

[5] Conceptually, the condition is that plants should not be inundated, so $H = 0m$. However, in Delft3D cells are dry when the depth is less than the flooding depth (the parameter that determines at which depth Delft3D considers a cell to be flooded). So this becomes $H < H_{flooding}$

δz_{life}	=	Bed level change during life plant (up to start event, so $t - T_{event}$)	[m]
CED_{mature}	=	Critical erosion depth of mature plant	[m]
z_b	=	Bed level (positive upwards)	[m]

Rest of life: $t > T_{WoO1} + T_{WoO2}$
The conditions remain below the maximum of what a mature plant can handle. This is described by equation A.6 until A.8. (Equation A.6 and A.7 are the same as eq. A.2 and A.3 for WoO2, eq. A.8 is the same as eq. 2.2 in the main report.)

$$-E_{avg,max} < \delta z_{avg} < S_{avg,\max} \tag{A.6}$$

$$-CED < \delta z_{event} \tag{A.7}$$

With

$$CED = CED_{mature} + \alpha * \delta z_{life} \tag{A.8}$$

Appendix B. THE IMPACT OF THE SEDIMENT TYPE

This appendix shows how the results would change when a combination of two clays with different settling velocities (0.2 mm/s and 1 mm/s) is used, instead of the single-graded sediment used in the reference model. This appendix supports the results in paragraph 3.3.2.1 of the sensitivity analysis.

B.1 BED LEVEL CHANGE

The figures below compare the bed level and bed level change that occur in the area of interest.

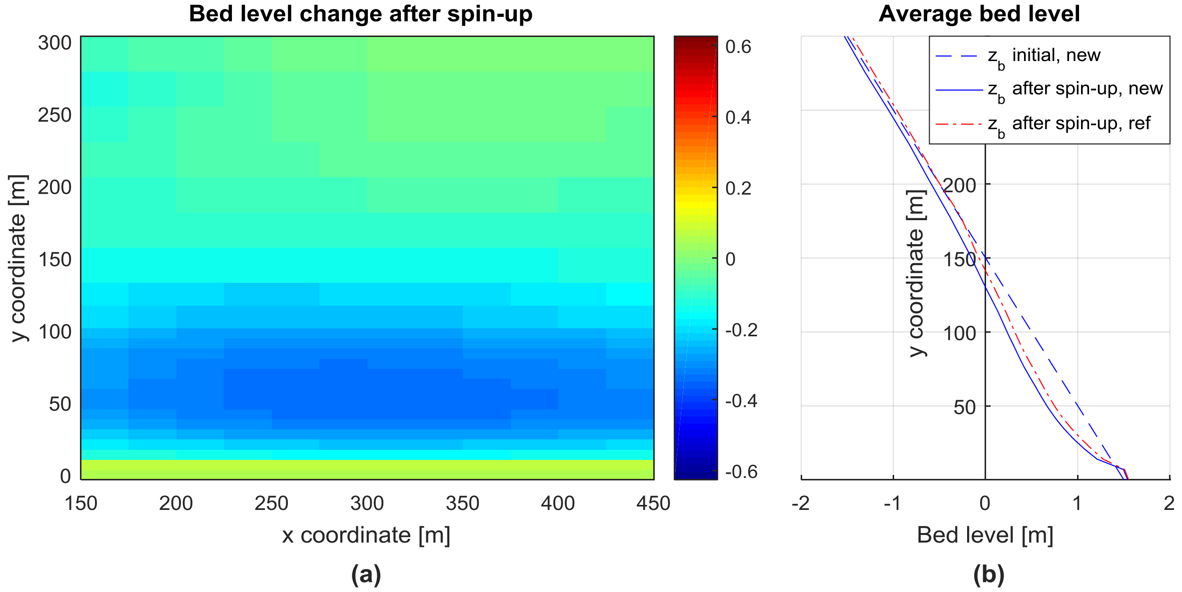

Figure B.1: The bed level and bed level change in the area of interest when a combination of two clays is used. (a) Shows the bed level change after spin-up in m and (b) shows the average bed level profiles before and after spin-up. The red line indicates the reference model (one type of clay), the blue lines indicate the new model with two clay gradations.

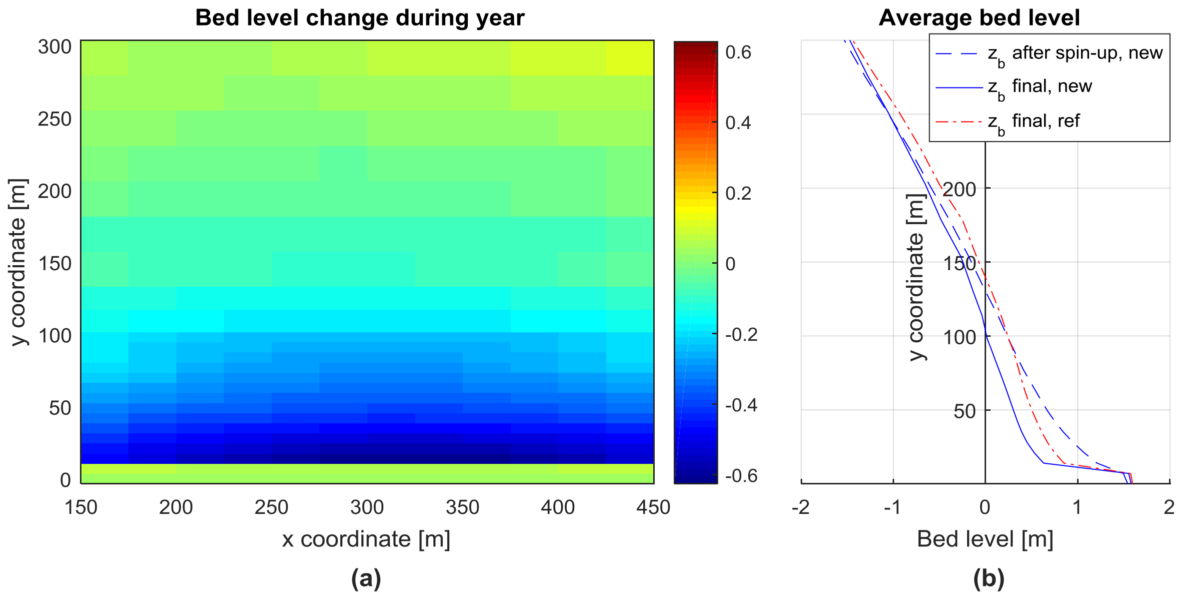

Figure B.2: The bed level and bed level change in the area of interest when a combination of two clays is used. (a) Shows the bed level change during the year in m and (b) shows the average bed level profiles before and after this year. The red line indicates the reference model (one type of clay), the blue lines indicate the new model with two clay gradations.

B.2 Establishment chances

The figure below shows the establishment chances when a sediment with two clay gradations is used.

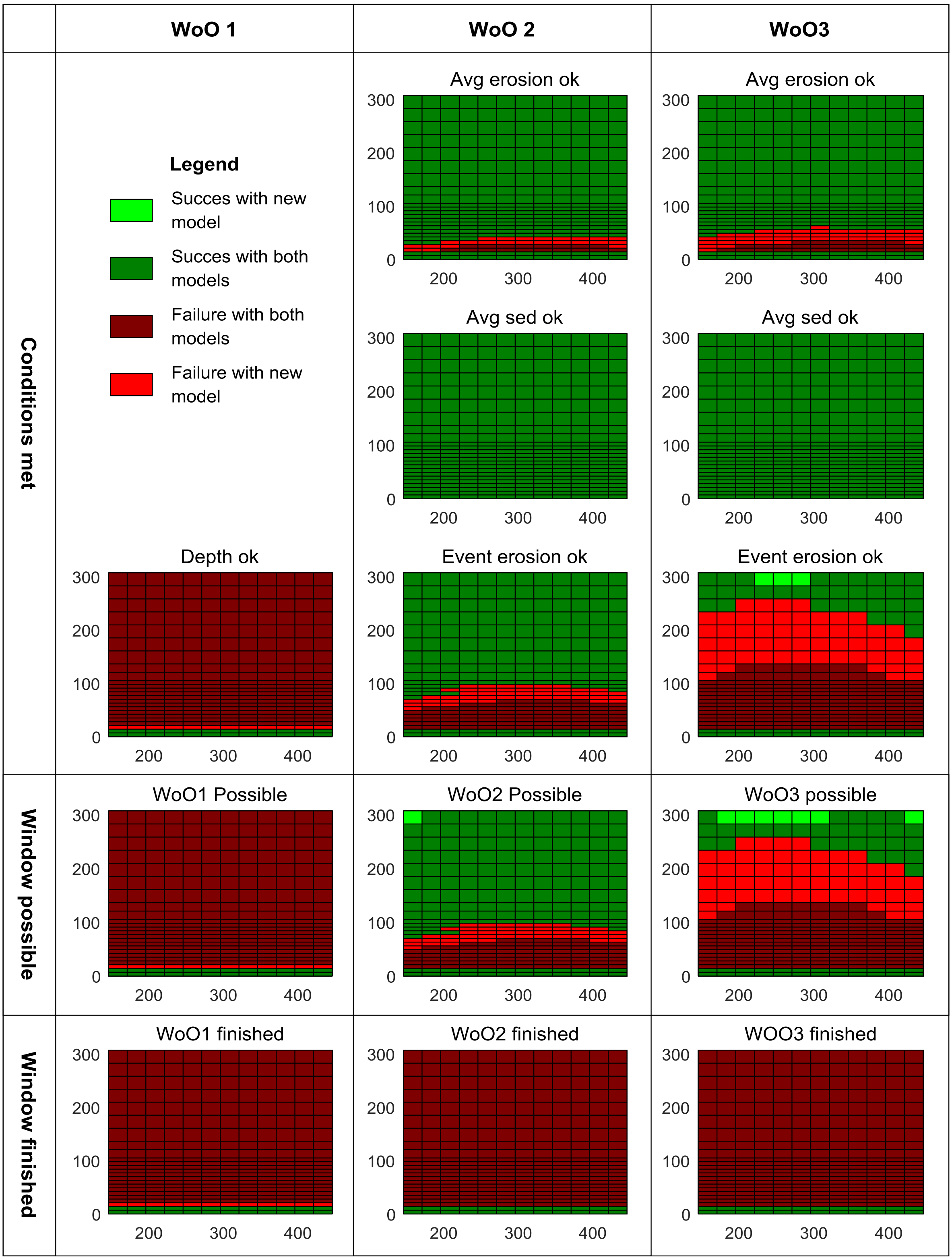

Figure B.3: The results of the Windows of opportunity model with two clay gradations. Every grid shows a top view of the area of interest, with the coast located at y=0 and the deepest part at y=300. Row 1-3 show if the separate conditions are met. Row 4 shows if a window is possible, so if these conditions are all met at the same time. Row 5 shows if a window can be finished, so if at the same time both the previous window is finished and the new window is possible. Dark colours indicate results equal to the reference model, bright colours indicate a difference.

Appendix C. THE IMPACT OF VEGETATION

The impact of vegetation on the bed level dynamics is plotted in the figures below. These figures show how much the bed level change would change, if the impact of vegetation on the hydrodynamics is included in the Delft3D model according to the methods of section 2.4.7. The figures support the results in paragraph 3.3.2.2 of the sensitivity analysis.

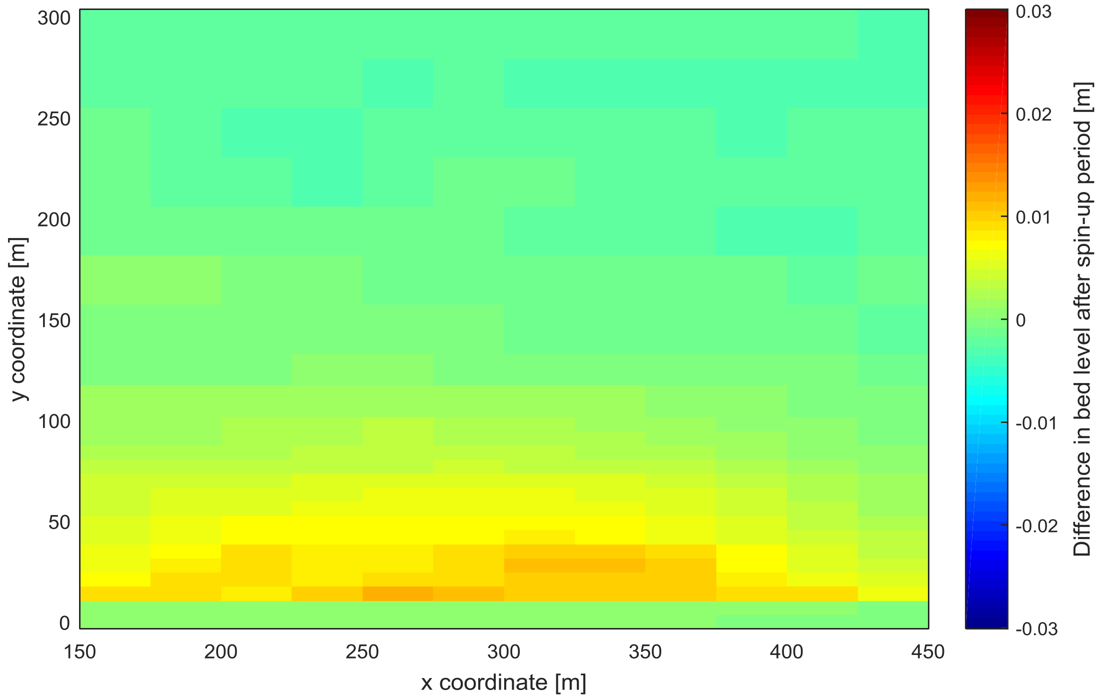

Figure C.1: The difference in bed level change after the spin-up period when the impact of vegetation is included. Positive numbers indicate the bed level becomes higher when the impact of vegetation is included.

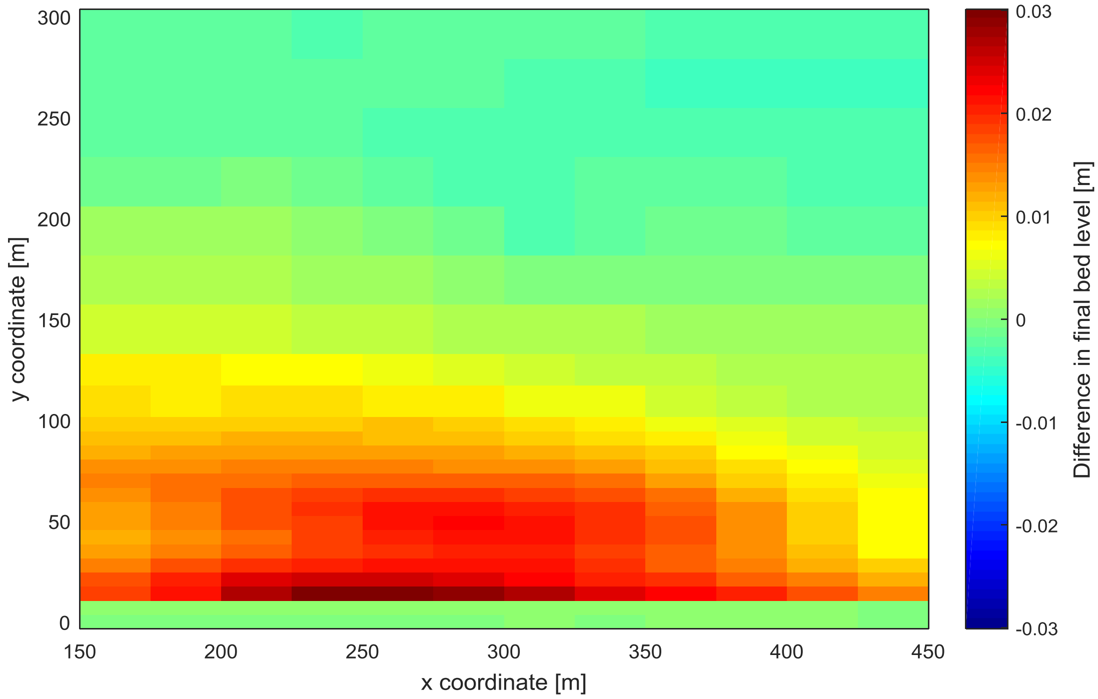

Figure C.2: The difference in bed level change at the end of the model run when the impact of vegetation is included. Positive numbers indicate the bed level becomes higher when the impact of vegetation is included.

Appendix D. THE IMPACT OF WAVE HEIGHT

D.1 BED LEVEL CHANGE

The figures below show the impact of the wave height on the bed level. They support the results in paragraph 3.3.2.3 of the sensitivity analysis. Figure D.1 shows the average bed level profiles in the area of interest after the spin-up period. Figure D.2 shows the average profiles at the end of the model. These figures show that the height of the cliff and the equilibrium slope decrease with decreasing wave height.

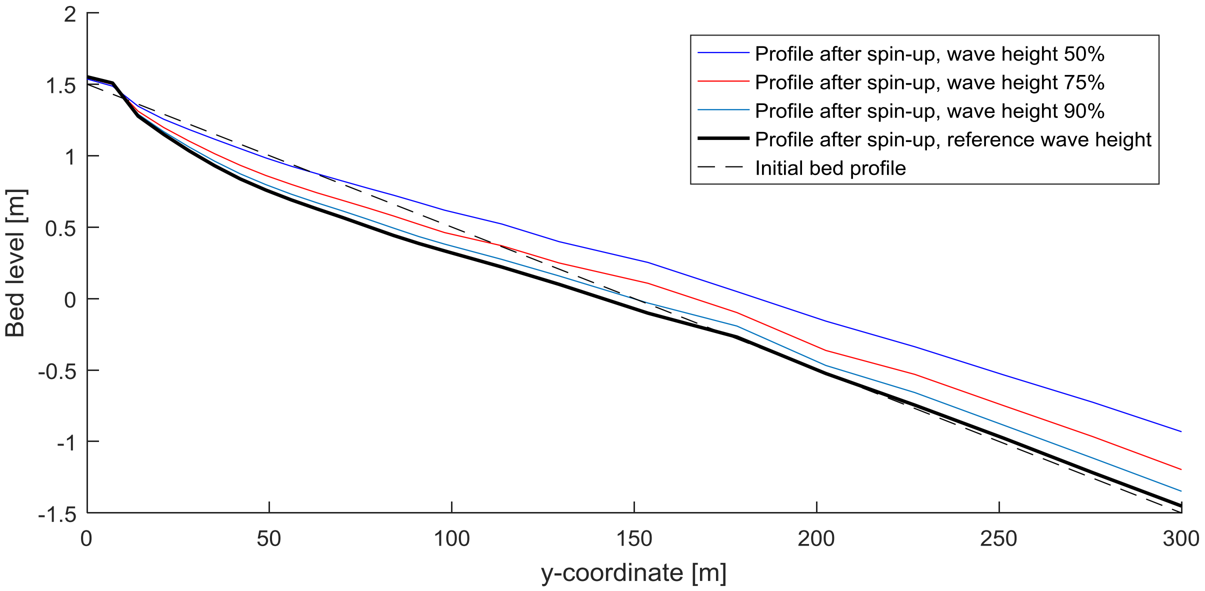

Figure D.1: The average bed level profiles in the area of interest for different wave heights, after the spin-up period

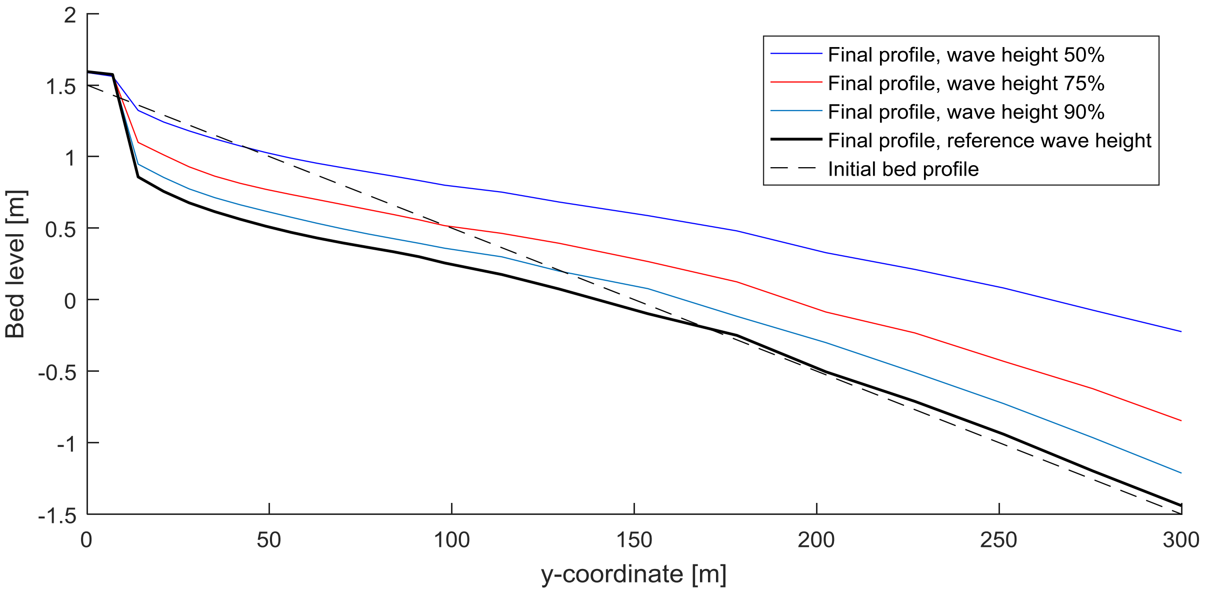

Figure D.2: The average bed level profiles in the area of interest for different wave heights, at the end of the model

D.2 Establishment chances

The figure below shows the establishment patterns when the wave height decreases with 25%.

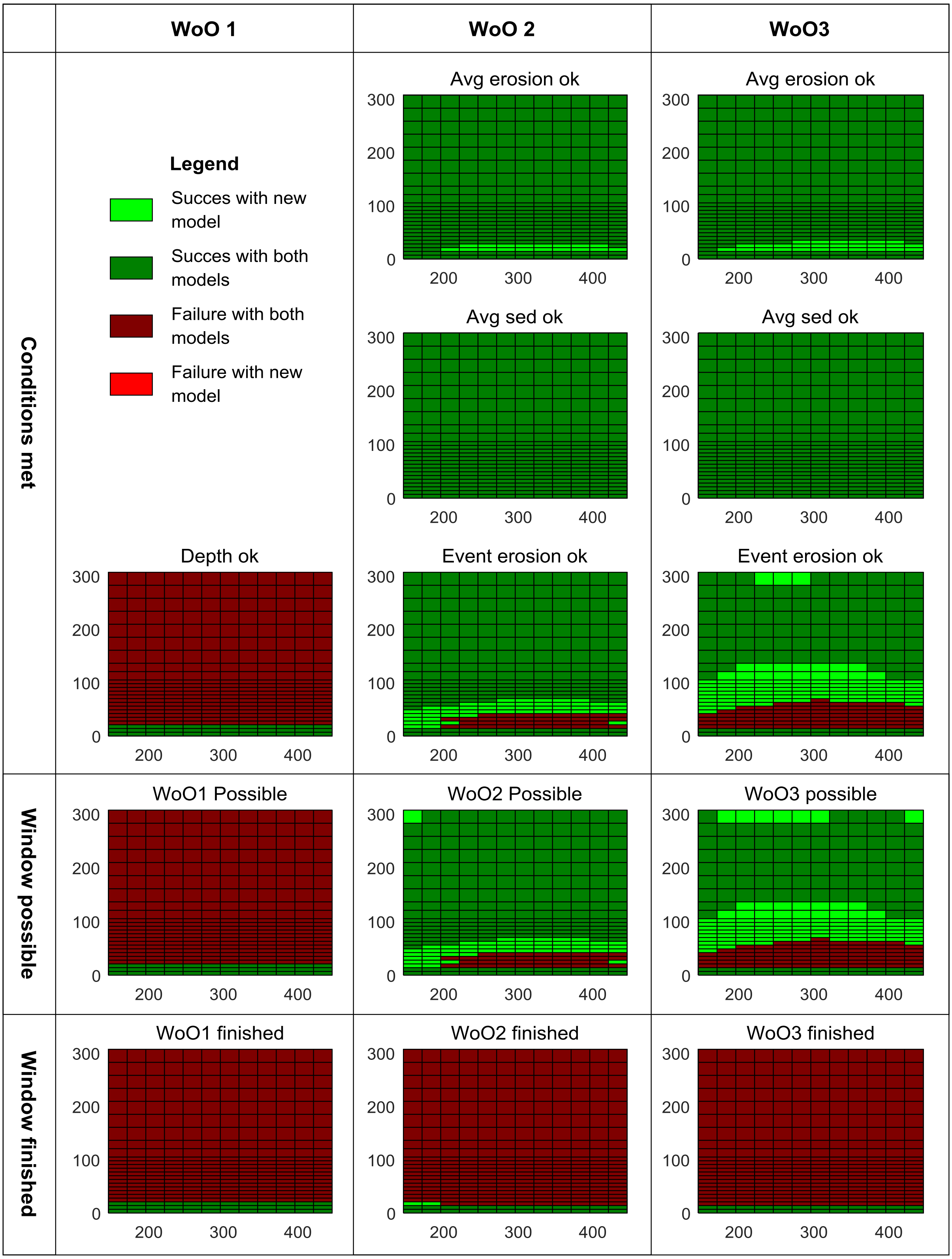

Figure D.3: The results of the Windows of opportunity model with 25% lower waves. Every grid shows a top view of the area of interest, with the coast located at y=0 and the deepest part at y=300. Row 1-3 show if the separate conditions are met. Row 4 shows if a window is possible, so if these conditions are all met at the same time. Row 5 shows if a window can be finished, so if at the same time both the previous window is finished and the new window is possible. Dark colours indicate results equal to the reference wave height, bright colours indicate a difference.