Modelling climate change-related feedbacks between seagrasses and suspended sediment in the Rødsand lagoon (Denmark)

L.F.D. Akerboom









# Modelling climate change-related feedbacks between seagrasses and suspended sediment in the Rødsand lagoon (Denmark)

by

# L.F.D. Akerboom

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Cover: Walking in Eelgrass (Jamestown, Rhode Island, United States of America). Photography by Cory Janiak.



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Leonie Akerboom Delft, August 2018

# Summary

Seagrass meadows are essential and valuable to many shallow coastal ecosystems, due to the many important ecosystem services they provide. The interaction of feedbacks between hydrodynamics, sediment dynamics, and eelgrass can be described with a feedback loop. At locations where eelgrass is present, it favours its growth by modifying the local hydrodynamics (both waves and currents) and the sediment transport. Sediment resuspension is reduced by eelgrass presence, the light availability is subsequently increased, and growth is stimulated, i.e. further reducing the sediment resuspension. However, when eelgrass is absent, its growth is adversely affected. Sediment resuspension and, therefore, turbidity is enhanced, the available light is reduced, and eelgrass growth (or invasion) is hindered. Therefore, these systems are vulnerable and prone to external factors that influence the environmental conditions to become adverse. Especially hindered light penetration or changes in water temperature can push the system to an alternative ecological state, i.e. from dense eelgrass cover to a bare sediment state, with a little chance of return. Climate change effects, such as sea level rise, water temperature increase, and increased storminess, can increase these threats to the seagrass ecosystem and are, according to the literature, able to push the ecosystem into the bare seabed state. Because of its vulnerability and valuable benefits, conservation of and prevention of damage to the ecosystem are strongly demanded.

To this end, the shallow coastal (eco)system response to possible adverse conditions of a changing environment due to the mentioned climate change effects is assessed in this research. The Rødsand lagoon in Denmark was found to be an ideal study site, as it is characterised as a sheltered, shallow microtidal coastal system that accommodates eelgrass and that has been intact for many years. It is a good example of a thriving eelgrass ecosystem in a temperate climate, and a low-nutrient environment, where anthropogenic influences are limited. The environmental conditions of the study site could be assessed by means of the available literature and the data that was provided. In general, the hydrodynamic conditions are primarily dependent on wind, as this is the main forcing of both flow and waves. The flow- and wave conditions are, in general, relatively calm, which means that only for dynamic (storm) events sediment resuspension is induced.

In order to assess the interaction of feedbacks between hydrodynamics, sediment dynamics, and eelgrass, and the impact of climate change effects on the coastal system, a predictive tool in terms of a numerical model that includes these feedbacks was developed. This resulted in the coupled model: an interactive coupling between a physical model and a growth model was established. The physical model, developed as an online coupling of Delft3D-FLOW with Delft3D-WAVE, includes the effects of flow and waves on the sediment entrainment and therefore on the vegetation. The growth model simulates the eelgrass development over time based on the environmental conditions computed by the physical model and the subsequently calculated light climate. The simulated eelgrass development by the growth model was subsequently used as an input for the physical model for the next simulation period.

The developed coupled model was used as a predictive and pragmatic tool: simulations comprising idealised singular climate change effects of relative sea level rise, water temperature increase, and increased storminess were performed. The results of the coupled model and the provided data of DHI showed the same behaviour in terms of eelgrass development, hydrodynamic conditions, and sediment transport at most locations, except in the deepest depth zone (4-6 m). This indicates that the general performance of the coupled model is adequate. The environmental conditions in the coupled model are apparently more benign than in the model of DHI, i.e. more beneficial for the eelgrass growth, as the eelgrass biomass was far higher at the shallow depths than that the data of DHI showed. Two reasons can be given for these more beneficial conditions: 1) the sediment import from the offshore boundary and spreading into the domain is underestimated, resulting in more beneficial light conditions at the bottom and 2) the model only takes into account the forcings and, therefore, the hydrodynamic processes in the direction of the transect, whereas processes (related to hydrodynamics and sediment transport) acting perpendicular to the transect are omitted.

The results showed the impact of these climate change effects on the coastal system, especially on the eelgrass development. Decreased growth could be observed for all simulated climate change effects compared to the results of the baseline case with dense eelgrass cover. As the eelgrass at the deepest locations is the closest to its light-/depth-limit, it was found to be more susceptible to changes in the environment than eelgrass at shallower locations, leading to increased decay at larger depths. However, no indication or no clearly defined threshold of the system shifting to the alternate and undesired bare state due to the studied climate change forcings, i.e. relative sea level rise, water temperature increase, and increased storminess, could be derived for this specific study site. This means that a large-scale die-off of eelgrass in a shallow microtidal coastal system such as the Rødsand lagoon is unlikely to happen due to the studied forcings.

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# List of Symbols

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| Variable            | Description  | Unit                             |
|---------------------|--|----------------------------------|
| а                   | wave amplitude (=H/2)  | [m]                              |
| $A_{p}$             | horizontal cross-sectional area of a plant                   | [m <sup>2</sup> ]                |
| b                   | width of stem or leaves (plant diameter)                     | [m]                              |
| В                   | buoyancy parameter, the ratio of buoyancy to stiffness       | [-]                              |
| В                   | aboveground biomass  | $[gC m^{-2}]$                    |
| С                   | sediment mass concentration                                  | $[kg m^{-3}]$                    |
| Ca                  | group velocity   | $[m s^{-1}]$                     |
| у<br>С.,,           | wave celerity  | $[m s^{-1}]$                     |
| C                   | Chézy coefficient  | $[m^{1/2} s^{-1}]$               |
| Ca                  | Cauchy number, the ratio of drag to stiffness                | [-]                              |
| Cp                  | drag coefficient   | [-]                              |
| CDea                | equivalent drag coefficient                                  | [-]                              |
| $\tilde{C}_{\rm D}$ | bulk drag coefficient  | [-]                              |
| $d_s$               | suspended sediment diameter                                  | [m]                              |
| Ď                   | deposition rate  | $[kg m^{-2} s^{-1}]$             |
| Ε                   | erosion rate   | $[kg m^{-2} s^{-1}]$             |
| $E_{h}$             | Young's bending modulus (elasticity)                         | [Pa]                             |
| $\tilde{E_w}$       | wave energy  | [J m <sup>-2</sup> ]             |
| F                   | fetch  | [m]                              |
| $F_{drag}$          | drag force exerted on the plant                              | [N]                              |
| g                   | gravitational acceleration (= 9.81 m s <sup>-2</sup> )       | [m s <sup>-2</sup> ]             |
| $\bar{h}$           | water depth  | [m]                              |
| $h_{veg}$           | vegetation height  | [m]                              |
| н                   | wave height  | [m]                              |
| $H_{rms}$           | root-mean-square wave height                                 | [m]                              |
| i                   | gradient in water depth or bed elevation                     | [-]                              |
| Ι                   | second moment of area, $I = \frac{1}{2}bt^3$                 | [m <sup>4</sup> ]                |
| L                   | light intensity at the water surface                         | $[Fm^{-2}s^{-1}]$                |
|                     | compensation irradiance                                      | $[E m^{-2} s^{-1}]$              |
| Icanony             | light intensity at the top of the canopy                     | $[E m^{-2} s^{-1}]$              |
| $I_{k}$             | saturation irradiance  | $[E m^{-2} s^{-1}]$              |
| k                   | turbulent kinetic energy                                     | $[m^2 s^{-3}]$                   |
| k                   | wave number $\left(=\frac{2\pi}{2}\right)^{-1}$              | [m <sup>-1</sup> ]               |
| k                   | Nikuradse equivalent roughness height                        | [m]                              |
| $k_s$               | deflected vegetation height                                  | [m]                              |
| K veg               | light attenuation coefficient                                | [m <sup>-1</sup> ]               |
| l Ra                | length of leaves or plant                                    | [m]                              |
| l.                  | wave length  | [m]                              |
| <br>M               | erosion parameter  | $[\text{kg m}^2 \text{ s}^{-1}]$ |
| N                   | number of shoots or plants per unit area                     | [plants m <sup>-2</sup> ]        |
| Р                   | plant biomass  | [gC]                             |
| R                   | belowground biomass  | $[gC m^{-2}]$                    |
| $S_h$               | bed load transport   | $[kg m^{-1}s^{-1}]$              |
| $S_{s}$             | suspended sediment transport                                 | $[kg m^{-1}s^{-1}]$              |
| SSC                 | suspended sediment concentration                             | $[g  ^{-1}]$                     |
| t                   | thickness of leaves  | [m]                              |
| Т                   | wave period  | [s]                              |
| u                   | flow velocity in horizontal (x-)direction                    | [m s <sup>-1</sup> ]             |
| $u_0$               | (undisturbed) flow above the vegetation                      | [m s <sup>-1</sup> ]             |
| $u_*$               | friction – or shear velocity                                 | [m s⁻¹]                          |
| $u_{*,cw}$          | friction velocity due to wave and currents                   | [m s <sup>-1</sup> ]             |
| $u_{orb}$           | amplitude of the near-bed peak orbital velocity due to waves | [m s <sup>-1</sup> ]             |
| $u_v$               | flow through vegetation                                      | [m s <sup>-1</sup> ]             |
| V                   | flow velocity component in horizontal (y-)direction          | [m s <sup>-1</sup> ]             |
| W                   | flow velocity component in vertical (z-)direction            | [m s <sup>-1</sup> ]             |
| Ws                  | Fall- or settling velocity of sediment                       | [m s <sup>-1</sup> ]             |

| Variable  | Description   | Unit                                 |
|---|---|--------------------------------------|
| W   | wind velocity   | [m s <sup>-1</sup> ]                 |
| $Z_0$   | Roughness length  | [m]                                  |
| $Z_a$   | reference height above the bed                                  | [m]                                  |
| Z <sub>wave</sub>   | wave mixing depth   | [m]                                  |
| β   | Van Rijn coefficient (ratio of sediment and fluid mixing)       | [-]                                  |
| γ   | Vogel exponent  | [-]                                  |
| Δ   | relative density  | [-]                                  |
| ε   | turbulent kinetic energy dissipation                            | $[m^2 s^{-3}]$                       |
| Es  | sediment diffusion in the z-direction                           | [m <sup>2</sup> s <sup>-1</sup> ]    |
| $\mathcal{E}_{s,x}, \mathcal{E}_{s,y}, \mathcal{E}_{s,z}$ | sediment diffusion in the x-, y- and z-directions, respectively | [m <sup>2</sup> s <sup>-1</sup> ]    |
| $\mathcal{E}_{v}$   | wave energy dissipation rate by vegetation                      | [J m <sup>-2</sup> s <sup>-1</sup> ] |
| κ   | Von Kármán coefficient (= 0.41)                                 | [-]                                  |
| ν   | kinematic viscosity   | $[m^2 s^{-1}]$                       |
| ρ   | density of water  | [kg m <sup>-3</sup> ]                |
| $ ho_s$   | density of sediment   | [kg m <sup>-3</sup> ]                |
| $ ho_{v}$   | density of vegetation   | [kg m <sup>-3</sup> ]                |
| $	au_b$   | bed shear stress  | [N m <sup>-2</sup> ]                 |
| $	au_{cr}$  | critical bed shear stress                                       | [N m <sup>-2</sup> ]                 |
| $	au_{cr,d}$  | critical bed shear stress for deposition                        | [N m <sup>-2</sup> ]                 |
| $	au_{cr,e}$  | critical bed shear stress for erosion                           | [N m <sup>-2</sup> ]                 |
| $	au_{cw}$  | bed shear stress due to currents and waves                      | [N m <sup>-2</sup> ]                 |
| $	au_t$   | total bed shear stress  | [N m <sup>-2</sup> ]                 |
| $	au_{v}$   | shear stress due to vegetation drag                             | [N m <sup>-2</sup> ]                 |
| ω   | angular frequency $\left(=\frac{2\pi}{T}\right)$                | $[rad s^{-1}]$                       |

# 1 Introduction

This thesis is a scientific exploratory study, in which the current knowledge of seagrass ecosystems, the interaction of feedbacks, and the research on climate change forms the basis for the problem definition and the research objectives. Therefore, this chapter provides background information on the complexity of shallow coastal (eco)systems and climate change (section 1.1), and the related research problem is described in section 1.2. Subsequently, sections 1.3 and 1.4 give insight into what is already known of the interaction of feedbacks; the research objectives and research questions are established in section 1.5, and the study area is introduced in the final section of this chapter.

## 1.1 Background

### 1.1.1 Seagrass ecosystems

Seagrass meadows are essential and valuable to many shallow coastal ecosystems, providing numerous important ecosystem services (Barbier et al., 2011; Costanza et al., 1997). For instance, they create biological productivity and stimulate biodiversity by serving as habitats, nursery areas and food for fish and other marine organisms. Furthermore, the plants influence the water quality and the living environment, as they immobilise nutrients by uptake and store carbon in their biomass by means of photosynthesis. Many species and the functioning of the ecosystem depend therefore on seagrass. Coastal protection and erosion control are other important functions of seagrass. The seagrass induces hydrodynamic drag on the flow and shelters the seabed from hydrodynamic shear stresses, thereby reducing the flow velocities and attenuating wave energy. Additionally, the seagrasses stabilise the sediment with their root and rhizome system. This results in a reduction of sediment resuspension and an increase in sedimentation in the seagrass area.

However, seagrass is also vulnerable to adverse environmental conditions. Increased turbidity from suspended sediment or algae growth decreases the amount of light needed for photosynthesis, whereas changes in salinity or temperature can affect the resilience of the plants. Moreover, the plants can be damaged by strong currents, (large) waves, grazing by other organisms, or by anthropogenic influences (i.e. human impacts such as shipping and fishing industries, anchoring, etc.).

Typically, the seagrass ecosystem development and habitat suitability are determined by abiotic and biotic factors (Table 1.1 and Figure 1.1A). These factors together determine the species diversity, species abundancy, and productivity of the ecosystem. Abiotic factors can be divided into physical and chemical factors. Physical factors such as water movement by waves and currents, the composition of the substrate or sediment, the required light conditions, fluctuating water temperature, and forcings in terms of wind (or storm events) are the most basic factors. The other abiotic factors that are involved in the seagrass ecosystem are of chemical origin. Water quality is determined by the amount and composition of dissolved substances, like organic matter, inorganic nutrients or dissolved gasses. If one or more of these components is in deficit or abundantly available, seagrass development will be hampered. The same holds for soil composition and salinity levels, which need to be favourable for seagrass growth.



Figure 1.1 Feedbacks in seagrass ecosystems (Maxwell et al., 2016). Green symbols or "+" indicate positive effects, whereas red symbols or "-" indicate negative effects

| Table 1.1 Abiotic and biotic factors of the seagrass ecosystem |                                      |                                 |  |
|--|--------------------------------------|---------------------------------|--|
| Abioti   | <b>Biotic factors</b>                |                                 |  |
| Physical   | Chemical                             |                                 |  |
| <ul> <li>Water</li> </ul>                                      | <ul> <li>Dissolved gasses</li> </ul> | <ul> <li>Competition</li> </ul> |  |
| <ul> <li>Sediment</li> </ul>                                   | ■ pH                                 | <ul> <li>Predation</li> </ul>   |  |
| <ul> <li>Light</li> </ul>                                      | <ul> <li>Salinity</li> </ul>         | (grazing)                       |  |
| <ul> <li>Temperature</li> </ul>                                | <ul> <li>Inorganic</li> </ul>        | <ul> <li>Symbiosis</li> </ul>   |  |
| <ul> <li>Wind</li> </ul>                                       | nutrients (N, P)                     | <ul> <li>Disease</li> </ul>     |  |
| <ul> <li>Events (storm,</li> </ul>                             | <ul> <li>Soil composition</li> </ul> |                                 |  |
| flood)   | (minerals)                           |                                 |  |

#### Table 1.1 Abiotic and biotic factors of the seagrass ecosystem

Besides the effects of abiotic factors on the system, seagrass ecosystems are also vulnerable to impacts from biotic factors (Maxwell et al., 2016). Primary producers like phytoplankton and algae or epiphytes (organisms that grow on the seagrass) can compete for light and cause shading, leading to a decrease in available light for the seagrass plants, or compete for nutrients and oxygen. Benthic fauna (i.e. species that live in or on the seabed) inducing bioturbation, such as lugworms (*Arenicola marina*), compete with the seagrass both directly and indirectly. The lugworms rework the sediment, thereby causing burial of eelgrass shoots and seedlings and hinder eelgrass restoration directly (Valdemarsen et al., 2010). The indirect effect of sediment reworking is the enhancement of possible sediment resuspension and affecting the underwater light climate negatively. Either way, this prevents seagrass recolonisation in areas where bioturbators are dominant, with the consequence of a persistent unvegetated seabed (Figure 1.1B). Furthermore, predators (grazers) can have negative effects on seagrass, as they consume (parts of) the plants. Diseases are more uncommon but can also endanger seagrass ecosystems. The best-known example dates from the 1930s, when the wasting disease caused large-scale die-off of eelgrass in the North Atlantic region and thereby severely affected the remaining eelgrass populations (e.g. Frederiksen et al., 2004; Green & Short, 2003).

This thesis focusses on the feedbacks between the physical abiotic factors mentioned in Table 1.1 and the eelgrass ecosystem. The effects of biotic and chemical abiotic factors on the eelgrass ecosystem will be omitted for mainly two reasons. Firstly, modelling these effects would complicate the process (e.g. of model validation) and would make it more difficult to study the effects of the physical abiotic factors. Secondly, the eelgrass meadows that are present nowadays at the study test site (which will be introduced in section 1.6) have been present for multiple decades, indicating that none of the threats that chemical or biotic factors could pose to the seagrass development was present at the study site in a limiting way.

## 1.1.2 Eelgrass (Zostera marina)

Seagrasses are marine angiosperms (flowering aquatic plants) and they grow on every continent in the world, except in Antarctica (Green & Short, 2003). Eelgrass or *Zostera marina* L. is the most common seagrass species in temperate regions and is at the core of this study. The depth at which *Z. marina* typically grows is from 0 to -12m MSL (mean sea level) (Green & Short, 2003; Short et al., 2010), in both the intertidal and subtidal zones. Its presence has been recorded across the entire Northern Hemisphere in shallow coastal zones.

Eelgrass is a flexible, herbaceous plant with rhizomes (creeping rootstalks), roots, a leaf-sheath (or shoot) and relatively long, wide leaves (or blades), see Figure 1.2. The typical length of the plant and the width of the leaves are 80-110 cm and 3-12 mm, respectively (Den Hartog & Kuo, 2006; FNA, 2008). The leaf tip is generally rounded, the shoots are tubular and rupturing with age, causing the persistent old leaves to be stuck around the sheath and stay attached to the rhizome. The belowground part of the plant (i.e. the roots and rhizomes) anchors the plant, acts as nutrient storage, regulates the vegetative growth (Kuo & Den Hartog, 2006), and stabilises the substrate. The roots can live in an anoxic environment and are, together with the leaves, important in nutrient absorption.

Seagrass is well adapted to growth under relatively low nutrient conditions. When nutrient concentrations rise due to eutrophication, the (physiological) potential growth rate of seagrass is increased. However, in practice usually other species (phytoplankton, algae, epiphytes) will be competitively superior under these conditions and seagrass will eventually disappear due to the competition (e.g. for light, oxygen and nutrients). Overall, seagrass affects the carbon and nutrient levels, both locally (in the direct surroundings of the plant) and on a larger scale(e.g. in the coastal zones) by storage in the plant tissue (Mateo et al., 2006; Romero et al., 2006). Furthermore, the oxygen levels in both the water column (Larkum et al., 2006) and the substrate (Borum et al., 2006) are influenced by the seagrass to a large extent (release of excessive oxygen produced by photosynthesis).

New plants can develop from both vegetative reproduction - as they sprout from extending rhizomes - and sexual reproduction – as the plant can produce seeds, that disperse and germinate in a new location (FNA, 2008; Waycott et al., 2006). Regarding the study site in Denmark, flowering eelgrass is rare in this part of the world (Bach, 1993; Sand-Jensen, 1975), therefore reproduction is controlled by vegetative growth.



Figure 1.2 Eelgrass (Z. marina) plants: A) picture of an eelgrass plant during fieldwork August 2017, B) illustration of a vegetative eelgrass shoot, original drawing by Mark Fonseca (adapted from Gaeckle et al., 2006)

## 1.1.3 Seasonal and annual variability

Eelgrass ecosystem functioning depends to a large extent on the biomass and production of the meadows, which can fluctuate considerably over the year. In the research of Clausen et al. (2014), this seasonal and annual variability showed large differences across gradients in temperature and latitude (implicitly incorporating the combined effect of temperature and irradiance). Eelgrass populations in areas with higher summer temperatures showed stronger seasonal and annual variation in biomass, whereas cold-water eelgrass populations were found to be less dynamic. In these temperate climates, the annual mean biomass was larger and less variable over the year, suggesting that these eelgrass populations are able to maintain relatively high aboveground biomass during winter. Additionally, the annual variation in shoot density was smaller as well and the investment in belowground parts in terms of energy storage was larger than for warmer climates. The timing of the peak biomass was found to be earlier in warm areas at lower latitudes and later in cold areas at higher latitudes.

However, other parameters did not vary with temperature or latitude, e.g. magnitude of peak biomass, the length of the growing season, and mean annual shoot density. This indicated that other (local) factors can be more important, especially in shallow exposed areas. These local factors are for example hydrodynamic forcings by waves and currents or light attenuation in the water column by organic (phytoplankton, algae) and inorganic matter (sediment).

Clausen et al. (2014) found that temperature was a better indicator of population dynamics than latitude, meaning that global warming might affect eelgrass phenology noticeably and that as a consequence, eelgrass distribution might advance northwards.

For the study site, it was indeed mentioned by DHI in personal communication that the eelgrass plants are known to be present during the winter, i.e. that the aboveground biomass is not reduced to zero.

## 1.1.4 Alternative stable states

In seagrass ecosystems, a switch from a vegetated state to a bare seabed may be one from which it cannot recover (Carr et al., 2012a; van der Heide et al., 2007). Especially the shift from a dense seagrass meadow to a bare sediment bed is most undesirable and is based on positive feedback. Since the loss of seagrass meadow (or decreasing shoot density) generally leads to increased bed shear stress and corresponding enhanced resuspension of sediment and turbidity, increasing attenuation of the remaining light and thereby affecting the remaining seagrass meadow is imminent. Even when the disturbance is then removed, this new state will persist (Carr et al., 2012a).

Bistable behaviour in ecosystems can have severe consequences. The system response to environmental drivers is usually nonlinear, which can cause rapid shifts between two stable states. These shifts are induced by gradual or sudden (small) disturbances or stressors (e.g. changes in environmental drivers). Due to this uncertain behaviour, limited resilience is often one of the characteristics of these bistable systems (van der Heide et al., 2007). When the disturbance pushes the system over a certain threshold, the system switches easily to the alternate state (Scheffer et al., 2001). To induce a possible switch back to the original state, it is often required to further reduce the environmental conditions than before the switch, a phenomenon called hysteresis (Scheffer et al., 2001).

Figure 1.3 shows the alternative stable states of an ecosystem as presented and described by Scheffer et al. (2001). Three equilibria can exist: the dashed line indicates an unstable state, whereas the continuous lines indicate stable states. When the system is in the upper state but close to bifurcation point F2, a forward shift is easily induced, and the system will switch from the upper state to the lower state. Hysteresis is shown in the same figure, as the conditions for a backward shift (i.e. back to the original –upper– state) need to be severely reduced to reach bifurcation point F1, where it can shift back to the upper state.



Conditions Figure 1.3 Alternative stable states (Scheffer et al., 2001).

The sudden (and irreversible) transition in states is hard to recognise in advance, since the system can show little change in its state before a transition and as indicators for change may or may not be present (Scheffer et al., 2001). It is therefore important to not only determine the thresholds for the transition between the two alternative stable states, but also to be aware of these indicators for change. The first indicator for change can be "slowing down", as the recovery of the system to small disturbances takes longer as the system progresses towards the threshold (Scheffer et al., 2009; Van Nes & Scheffer, 2007). Another possible indicator is "flickering", strong environmental drivers may force the system to fluctuate between two states, i.e. frequently passing the threshold (Carr et al., 2012a; Scheffer et al., 2009).

It is often of major importance to prevent perturbations and shifting in ecosystem states, since restoration is usually difficult and requires expensive measures (Scheffer et al., 2001; van der Heide et al., 2007), e.g. due to the severe reduction needed in the environmental conditions to bring the system back to the original state. The indication for a system advancing to an alternative state may therefore help in ecosystem management and monitoring restoration efforts (Carr et al., 2012a).

## 1.1.5 Climate change effects

Besides the already mentioned numerous stressors that can have an impact on the eelgrass ecosystem, human impact endangers the eelgrass ecosystem on both the short term and the long term. Short-term anthropogenic influences are for example surface water pollution (e.g. excessive nutrient loading by agriculture), which enhances eutrophication and indirectly affects the light climate; dredging works, which increase turbidity directly or; shipping activities, causing physical damage to the plants or even uprooting by anchoring. However, changing environmental conditions due to these direct human impacts on the short term are excluded in this study. Solely the impacts of human activities on the long term are of interest here, captured in the effects of climate change.

Climate change is a comprehensive phenomenon, which has many different but severe consequences; not only in terms of direct environmental effects but also the socio-economic impacts. In general, the meteorological climate is affected by global warming (increase in temperature) due to greenhouse gasses. Extensive droughts, heat waves, extreme precipitation events, sea level rise, floods, changes in storminess and more powerful hurricanes, shifting of distribution areas of tropical plagues and diseases and changes in salinity are the main direct environmental consequences of climate change. The stressors on the eelgrass ecosystem considered in this thesis are related to the physical abiotic environment, mainly light- and temperature associated. Climate change affects the physical abiotic environment of the eelgrass at the study site - mainly by sea level rise, water temperature increase, and an increase in storminess, and these effects are studied in this thesis. As the study site is located in the southeast of Denmark (see section 1.6), changes in salinity could play a role (see Appendix A.2). It is known that the salinity gradient is omnipresent and salinity levels are constantly changing in the Danish Straits. Nevertheless, eelgrass populations have been recorded in the western Baltic Sea and the Rødsand lagoon over a very long time, therefore it is assumed that the effect of salinity differences on eelgrass is negligible for these populations. The same holds for possible but unknown changes in salinity due to climate change, which is omitted as well.

The effects of climate change related to the geographic location of the study site were examined and reported in the most recent downscaling assessment of climate change for the Baltic Sea, BACC II (The BACC II Author team, 2015, see Appendix A.2) and the Fehmarnbelt Environmental Impact Assessment (EIA) reports (FEHY, 2009, 2013b, 2013d; FEMA, 2013).

#### Sea level rise (SLR)

The assumed effect of sea level rise to this coastal system involving eelgrass is twofold and is based on the available light in the water column. On one hand, larger water depths will reduce the available light directly by increasing the water column. On the other hand, larger water depths decrease the influence of waves at the seabed: bed shear stresses caused by waves and subsequently suspended sediment concentrations are decreased, thereby favouring the light climate. The main hypothesis for sea level rise is a die-off of eelgrass growing at present depth limits, as the light climate is insufficient to sustain growth, but an extension of the eelgrass population towards shallower waters, i.e. shifting of the eelgrass habitat along the depth gradient.

BACC II assessed both a mid-range and a heuristic high-end sea level rise scenario using model projections. The mid-range SLR scenario predicts a global SLR of + 0.7 m ( $\pm$  0.3 m) at the end of the 21<sup>st</sup> century with respect to the end of the 20<sup>th</sup> century, leading to a relative SLR for the mid-range scenario of 0.5-0.6 m at the study site (Figure 1.4A). The high-end SLR scenario, computed from high estimates of the projected SLR in the Baltic Sea, reveals an expected SLR of +1.10 m, which is an additional 0.5 m of SLR (Figure 1.4B). The Fehmarnbelt EIA reports support the predicted SLR of the last high-end scenario, sea level rise of +1 m is expected for the years 2080-2100 at the study site.



Figure 1.4 Projected regional sea level rise in the Baltic Sea for A) the mid-range scenario and B) the high-end scenario (The BACC II Author team, 2015). The location of the study site is indicated with a black rectangle

#### Temperature

The known effect of temperature increase is that all processes are stimulated and happen faster, both growth and decay of eelgrass plants, as these processes are regulated by water temperature. The increase in water temperature has been derived for the study site from the BACC II Assessment (see Appendix A.2). A projected change in seasonal average sea surface temperature in the southern part of the Baltic Sea is expected for the years 2090-2099 with respect to the baseline years 1990-1999: in winter (December-January-February) the projected temperature increase is 2.4°C, in spring (March-April-May) the increase is 2.6°C, in summer (June-July-August) 1.8°C, and in autumn (September-October-November) 2.0°C. Another effect of temperature increase in the Baltic Sea region is the decreasing probability for sea ice, both the ice-covered area and the duration in which sea ice occurs are expected to decrease (FEHY, 2013d; FEMA, 2013).

#### Storminess

The effect of increasing magnitude, duration, or frequency of storm events is the enhancement of sediment resuspension and thereby affecting the underwater light climate. The storm magnitude is responsible for an initial larger sediment concentration in

the water column, storm duration retains the sediment in suspension and hinders the settlement, whereas storm frequency also affects the light climate and makes eelgrass recovery more difficult.

The BACC II Assessment argues that future changes in wind climate are highly uncertain. It is not possible to predict whether the wind speed magnitude will increase or decrease. Moreover, they claim that predictions of extreme wind speeds are even more uncertain than predictions for mean wind speeds. According to the Fehmarnbelt EIA reports, climate change will increase the extreme storm wind speed of 50-year return period by 3 m s<sup>-1</sup> or 10% by the year 2100. Furthermore, there are no indications of significant changes for more typical wind speeds. However, observations show a decrease of 5-15% of surface wind speeds in the Northern Hemisphere (Smits et al., 2005; Vautard et al., 2010). Also, the yearly strongest storm events show a decrease in power. This can be caused by climate change or by increasing surface roughness, associated with changes in vegetation distribution (forests and agriculture) and urbanisation, or by wind turbines (van Oldenborgh & de Vries, 2018).

No literature could be found that clearly states the changes in storm frequency or duration. Still, it is presumed that storm frequency and duration can be of importance considering adverse conditions to the eelgrass ecosystem.

#### Hypotheses on system behaviour under climate change

Climate change could affect (the intensity of) the feedbacks between the eelgrass ecosystem and its environment (Carr et al., 2012a; van der Heide et al., 2007). The research of Carr et al. (2012a) on modelling the effects of climate change on eelgrass ecosystems concludes that bistable dynamics indeed arise due to the increase in water temperature and sea level rise at their study site (Hog Island Bay, VA, USA).

The result of sea level rise in the research of Carr et al. (2012a) is that it pushes the eelgrass from an initial stable dense meadow state towards a bistable state where the resilience of the eelgrass is affected. However, this process takes place relatively slowly, as sea level rise acts on the long-term (several decades). The results, considering the effect of frequent disturbances (storm - and/or high-temperature related events), imply that eelgrass may be pushed into the bare sediment state. The rate at which this process takes place increases with increasing frequency and magnitude of the disturbance and at a faster pace than the impact of sea level rise. Overall, the initial meadow depth was found to be of major importance: eelgrass meadows in deeper water were found more susceptible to changes in the environment, as they are already living close to their depth limit.

## 1.2 Problem description

Shallow seagrass ecosystems are valuable due to the many ecosystem services they provide. Many species and the ecosystem functioning depend on the presence of seagrass. However, these shallow ecosystems are vulnerable and prone to external factors that influence the environmental conditions and can push the system from a vegetated to bare state, with little chance of return. These possible threats to the system and to seagrass development in particular, are hindered light penetration due to increased turbidity or a larger water depth, changes in water temperature, and human impacts e.g. climate change. Because of its vulnerability and valuable benefits, conservation and prevention of damage to the ecosystem are strongly demanded.

Managing the ecosystem is very important in assessing and predicting its development, in order to intervene in the early stages of decline. The problem is that there are no means (i.e. quantitative tools) available. The reason is that quantification of ecosystem sensitivity is difficult, and deep understanding of the feedbacks acting within the system is needed (i.e. to be able to implement these into a numerical model). However, all feedbacks between seagrass and suspended sediment interact with each other, further complicating the comprehensibility of the system. There are more intricate factors, although the following factors will not be taken into account in this thesis. Seagrass plants are for example able to adapt to their environment e.g. in terms of light and temperature requirements, but to which extent remains unknown. Another factor of uncertainty (and therefore difficulty) is climate change itself, since the rate of progress is unpredictable and the exact impact on the shallow (eco)system is undefined.

To develop a predictive tool for ecosystem management, one must be able to understand the ecosystem behaviour and to model eelgrass dynamics, i.e. the eelgrass development and the related eelgrass ecosystem feedbacks, under changing conditions. The synergy of feedbacks complicates the modelling of interactions and is not fully understood yet, although this is subject of many scientific studies. The next section elaborates on the current understanding of feedbacks by means of a literature review.

## 1.3 Feedbacks of hydrodynamics, sediment dynamics and vegetation

Coastal (eco)system behaviour primarily depends on feedbacks between three system drivers: hydrodynamics, sediment dynamics, and the submerged vegetation (eelgrass). Figure 1.5 illustrates the feedbacks that are of importance with numbered arrows, whereas the feedbacks that are considered as less important or irrelevant are depicted in grey. The subsections describing the feedbacks follow the same numbering as in Figure 1.5.



Figure 1.5 Important feedbacks between system components

The first feedback that is presumed to be less important and therefore excluded in this study is the effect of sediment dynamics on hydrodynamics. Possible consequences of high suspended sediment concentrations would be a local increase of the water density (only for extremely high concentrations) or severe changes in seabed morphology when sediment settling is enhanced (however, morphology changes are omitted in this study). The second omitted feedback consists of the direct effects of eelgrass on sediment dynamics, as these are assumed to be of minor importance compared to the indirect effects of vegetation (described in section 1.3.4). The direct effects are related to the actual presence of the plants. Firstly, the leaves of the plant filter the water and sediment particles are captured from the water column by direct particle trapping (Hendriks et al., 2008): collision with the leaves causes loss of momentum and therefore enhances the settlement of the particle. Secondly, the roots and rhizomes of the plant are responsible for soil stabilisation, thereby preventing the sediment from resuspension and increasing the critical bed shear stress needed for erosion.

## 1.3.1 The hydrodynamic effects on sediment dynamics

In general, hydrodynamic action (motion of water) is responsible for sediment transport. Waves stir up the sediment and bring it in suspension, whereas currents (flow) transport the sediment. Sediment can stay in suspension when the hydrodynamic action is sufficiently energetic, as settling generally occurs during low hydrodynamic actions (i.e. calm conditions).

The sediment transport formulations used in this study for bedload transport, suspended sediment transport, and exchange of sediment with the bed (erosion and deposition) are the same formulations as incorporated in the numerical computational program Delft3D-FLOW, which is used for modelling purposes. The formulations are the TRANSPOR2004 formulations (van Rijn et al., 2004) and are based on the principles of Van Rijn (1993). No adaptations have been made to these formulations; hence the detailed formulations and explanations are included in Appendix A.3.

## 1.3.2 The effect of sediment dynamics on vegetation

Sediment can have both direct and indirect effects on vegetation, of which the indirect effects are related to the light environment. Mainly bed level changes, the bed composition, and increased turbidity by suspended sediment are important. Substantial changes in height of the sediment bed, i.e. by accretion or erosion, can lead to severe changes in water depth, therefore indirectly influencing the light climate in a positive or negative way. As a direct effect of bed level changes, plants could be buried or covered with sand in case of accretion, or the sediment around and between the roots and rhizomes can be removed in case of erosion, leading to the possible uprooting of plants. Nevertheless, the effects of bed level changes are excluded from this study, as morphological calculations are omitted. The bed composition represents both the sediment grain size distribution and the chemical composition, such as the nutrient and oxygen content. In this context, only the sediment grain size is elaborated, as the chemical composition is omitted in this study.

When the sediment is fine-grained or contains a considerable amount of fine particles, these sediment particles are easily brought into suspension. As these fine particles have a low fall velocity, they will need a low energy environment with low flow velocities to settle. When they are suspended, these fine particles contribute to the turbidity of the water, thereby attenuating the light that eelgrass needs for growth and survival. For long-term and severe light reductions, the eelgrass will have a negative energy budget. It will use its energy reserves (stored in its rhizome system) and subsequently disappear. If the sediment is coarse i.e. the amount of fine particles is low, the effect of sediment on the underwater light climate will be minimal. The effects of light on the eelgrass development will be discussed in section 1.4, since suspended sediment is not the only factor determining the light climate.

## 1.3.3 The effects of vegetation on hydrodynamics

The hydrodynamics are influenced by the presence of submerged aquatic vegetation in terms of increased local turbulence, changes in the velocity profile i.e. decreased flow velocities in the canopy and wave attenuation, all mainly due to the hydrodynamic drag of eelgrass.

#### Attenuation of flow by submerged vegetation

Normally, the velocity profile over a rough bed is logarithmic, as derived by Prandtl and Von Kármán:

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \tag{1.1}$$

where  $\kappa$  is the von Kármán coefficient [-] and the roughness length  $z_0$  [m] is defined for hydraulically rough walls by Nikuradse as  $k_s/30$ , where  $k_s$  is the Nikuradse equivalent roughness height [m]. The corresponding Chézy coefficient C [m<sup>1/2</sup>s<sup>-1</sup>] can be calculated using the White-Colebrook formula:

$$C = 18\log\left(\frac{12h}{k_s}\right) \tag{1.2}$$

where *h* is the water depth [m]. Amongst others, Baptist et al. (2007) claim that when a single roughness is used, such as an adapted Chézy coefficient in case of vegetation presence, the vegetation is considered as a large bed structure with a logarithmic velocity profile above it. This is not a correct representation of reality, as water flows through and over the vegetation, thereby inducing turbulence, reducing flow velocities, and altering the flow velocity profile. The flow velocity profile deviates from the logarithmic profile; a typical flow velocity profile for submerged vegetation is given in Figure 1.6.



Figure 1.6 Schematised flow velocity profile for submerged vegetation (adapted from Baptist et al., 2007)

This flow velocity profile can be simplified (Baptist et al., 2007; Luhar & Nepf, 2013) to the undisturbed flow above the vegetation  $u_0$  and the flow through the vegetation  $u_v$ . At or just above the interface of the canopy with the water column, the flow velocity is severely reduced due to shear stresses. This flow transition is complex (Luhar & Nepf, 2013; Nepf, 2012a, 2012b), mainly due to the turbulent stresses partly penetrating into the patch, causing all kinds of flow phenomena (e.g. vortices). For simplicity, the flow velocities in this transitional region are not assessed in detail in this study.

The flow velocity profile is logarithmic sufficiently far above the canopy (Baptist et al., 2007; Luhar & Nepf, 2013):

$$u_0 = \frac{u_*}{\kappa} \ln\left(\frac{z - h_{veg}}{z_0}\right)$$
(1.3)

where  $u_* = \sqrt{g(h - h_{veg})i}$  is the friction velocity or shear velocity [m s<sup>-1</sup>] with  $h_{veg}$  the vegetation height [m] and i the gradient in water depth and bed elevation [-].

The flow through vegetation  $u_v$  [m s<sup>-1</sup>] can be approximated as uniform flow and can be analytically derived using the horizontal momentum balance for flow through submerged vegetation, where the vegetation is expressed as rigid cylinders. In the horizontal momentum balance is the total shear stress  $\tau_t$  [N m<sup>-2</sup>] equal to the sum of the bed shear stress  $\tau_b$  [N m<sup>-2</sup>] and the shear stress due to vegetation drag  $\tau_v$  [N m<sup>-2</sup>] ( $\tau_t = \tau_b + \tau_v$ ):

$$\tau_{t} = \rho ghi$$

$$\tau_{b} = \rho \frac{g}{C^{2}} u_{v}^{2}$$

$$\tau_{v} = \frac{1}{2} \rho C_{D} u_{v}^{2} Nbh_{veg}$$
(1.4)

where  $N \cdot b$  is the frontal plant area per unit volume, i.e. the number of shoots per area (N) times the width of the plant (b). This results in equation (1.5):

$$u_{v} = \sqrt{\frac{hi}{\frac{1}{C^{2}} + \frac{C_{D}Nbh_{veg}}{2g}}}$$
(1.5)

In case the bed resistance is much smaller than the drag force of the vegetation, equation (1.5) reduces to  $u_v = \sqrt{\frac{2ghi}{C_D Nbh_{veg}}}$ . As the flow velocity through vegetation is reduced compared to the undisturbed uniform velocity, the total bed shear stress is reduced accordingly.

#### Attenuation of waves by submerged vegetation

Wave attenuation by vegetation is caused by energy dissipation due to wave-vegetation interaction. The wave energy dissipation can be calculated as work carried out by the vegetation due to plant-induced forces acting on the fluid. The degree of wave attenuation depends mainly on the water depth at which the eelgrass grows (Hansen & Reidenbach, 2013), plant characteristics (e.g. geometry, buoyancy, shoot density (Chen et al., 2007), stiffness and spatial configuration, i.e. distance to the meadow edge (Bradley & Houser, 2009)), and wave parameters (e.g. wave height, wave period, and wave direction) (Mendez & Losada, 2004).

The most widely used formulation for wave attenuation is based on the rigid cylinder approach as derived by Dalrymple et al. (1984) and later modified by Mendez & Losada (2004). Assuming that linear wave theory is valid, waves are normally incident, and the bottom is locally flat, the conservation of wave energy includes a dissipation term solely due to interaction with vegetation:

$$\frac{\partial E_w c_g}{\partial x} = -\varepsilon_v$$

$$\varepsilon_v = \int_{-h}^{-h+h_{veg}} F_{drag} u dz$$
(1.6)

where  $E_w$  is the wave energy ( $E_w = \frac{1}{8}\rho g H^2$ ) with H the wave height [m],  $c_g$  is the group velocity [m s<sup>-1</sup>] =  $n \cdot c_w$  with  $n = \frac{1}{2}(1 + \frac{2kh}{\sinh(2kh)})$  and wave celerity  $c_w = \sqrt{\frac{g}{k} \tanh(kh)}$ ,  $k = \frac{2\pi}{L}$  is the wave number with L the wave length, h is the water depth, and  $\varepsilon_v$  is the time-averaged rate of energy dissipation per unit area induced by vegetation. Inertia and swaying motions are neglected for rigid cylinders; therefore the energy dissipation is only due to the horizontal drag force per unit volume  $F_{drag}$ :

$$F_{drag} = \frac{1}{2} \rho C_D b N u \left| u \right| \tag{1.7}$$

where the drag coefficient  $C_D$  [-] needs to account for the ignorance of plant motion in case of flexible plants (Dalrymple et al., 1984; Mendez & Losada, 2004) and u is the horizontal velocity in the vegetation due to wave motion [m s<sup>-1</sup>]. Using linear wave theory, Dalrymple et al. (1984) expressed  $\varepsilon_v$ , the time-averaged wave energy dissipation per unit area over the height of the vegetation for regular waves as given in equation (1.8).

$$\varepsilon_{\nu} = \frac{2}{3\pi} \rho C_D b N \left(\frac{gk}{2\omega}\right)^3 \frac{\sinh^3 kh_{\nu eg} + 3\sinh kh_{\nu eg}}{3k\cosh^3 kh} H^3$$
(1.8)

where  $\omega$  is the angular frequency [rad s<sup>-1</sup>]. Seasonal and spatial variability of the vegetation is taken into account by the plant parameters *b*, *N*, and  $h_{veg}$  (Paul & Amos, 2011). Mendez and Losada (2004) modified equation (1.8) for irregular waves, resulting in the mean rate of energy dissipation due to wave damping by vegetation  $\langle \varepsilon_v \rangle$ .

$$<\varepsilon_{v}>=\frac{1}{2\sqrt{\pi}}\rho\tilde{C}_{D}bN\left(\frac{gk}{2\omega}\right)^{3}\frac{\sinh^{3}kh_{veg}+3\sinh kh_{veg}}{3k\cosh^{3}kh}H_{rms}^{3}$$
(1.9)

where  $\tilde{C}_D$  is the bulk drag coefficient [-] that depends on the hydrodynamics (e.g. wave height) and plant type,  $H_{rms}$  is the rootmean-squared wave height [m]. Many different studies have been performed on the bulk drag coefficient  $\tilde{C}_D$  (e.g. Bradley & Houser, 2009; Kobayashi et al., 1993; Mendez & Losada, 2004; Paul & Amos, 2011). The widely varying results show that there is no generalised value or approach. For eelgrass, a value of 0.1 was assumed based on the studies of Bradley and Houser (2009) and Paul and Amos (2011), which were performed for two other types of seagrass (*Thalassia testudinum* and *Zostera noltii*, respectively).

#### 1.3.4 The indirect effects of vegetation on sediment dynamics via hydrodynamics

The sediment dynamics are indirectly affected by the vegetation via hydrodynamics in terms of turbulence generation and flow velocity reduction. By creating (additional) turbulence, vegetation initiates the development of local turbulent eddies. These can cause scour on a small scale (around the shoots) or on a large scale (around the patch of the seagrass), thereby enhancing the sediment resuspension. Furthermore, flow velocities and subsequently bed shear stresses induced by waves and currents are decreased in the eelgrass meadow. The reduction of shear stress largely depends on spatial density, i.e. the relative amount of open space within the meadow (De Boer, 2007).

The effect of the enhanced turbulence and decreased flow velocity on the sediment dynamics can be expressed by resuspension. As explained in section 1.3.2, enhanced sediment resuspension increases turbidity in the water column and adversely affects the light climate. However, a positive feedback for vegetation growth in terms of available light is created by reduced sediment resuspension rates and subsequently decreased turbidity (e.g. Adams et al., 2016; Carr et al., 2010; 2012a).

Decreased flow velocities influence the fluxes of deposition and erosion by means of the actual bed shear stress caused by flow and waves  $\tau_{cw}$ , as this parameter is proportional to the flow velocities close to the bed squared ( $\tau_{cw} \propto u^2$ ). Moreover, the physical presence of vegetation increases the critical bed shear stress for erosion  $\tau_{cr}$  as well, caused by the root stabilisation of the seabed. Both result in overall lower sediment mobility: sediment deposition is enhanced, as calm flow conditions within the meadow are favoured, whereas erosion is suppressed. What this precisely means for the sediment transport formulations and how these need to be adapted for flow through vegetation is explained in Appendix A.3.

#### 1.3.5 The hydrodynamic effects on vegetation

The hydrodynamic environment has mainly two effects on the submerged flexible vegetation. Firstly, the plant posture can be severely adjusted to the flow conditions and secondly, the hydrodynamic forces determine the tolerance limits of vegetation presence.



Figure 1.7 Schematisation of eelgrass reconfiguration (adapted from Luhar & Nepf, 2013). Left: reconfiguration is related to the flow velocity. Right: the flow velocity profile as induced by eelgrass presence

#### **Changes in plant posture**

Seagrass plants can be bent over by currents due to their flexibility, resulting in a change in morphology or **reconfiguration** (Vogel, 1994), as shown in Figure 1.7. Given a constant flow velocity, there will be a balance in the posture of the plant. In this case, there is an equilibrium between the hydrodynamic drag force, which causes the leaves or even the whole plant to bend over, and a restoring force. The restoring force can consist of the buoyancy (as the plant is lighter than water) and rigidity (or stiffness) of the blades. The total reconfiguration of the plant can therefore be described by two dimensionless parameters (Carr et al., 2016; Luhar & Nepf, 2011, 2013; Nepf, 2012b):

$$B = \frac{\left(\rho - \rho_{\nu}\right)gbtl^{3}}{E_{b}I} \tag{1.10}$$

$$Ca = \frac{1}{2} \frac{\rho C_{D} u^{2} b l^{3}}{E_{b} I}$$
(1.11)

where *B* is the buoyancy parameter, which is the ratio of buoyancy to stiffness as restoring force, *Ca* is the Cauchy number and the ratio of drag to stiffness,  $\rho$  and  $\rho_v$  are the specific densities of water and vegetation [kg m<sup>-3</sup>], *g* is the gravitational acceleration [m s<sup>-2</sup>]; *b* is the leaf width [m], *t* the leaf thickness [m] and *l* the leaf length [m]; *C<sub>D</sub>* is the drag coefficient [-], *E<sub>b</sub>* is Young's bending modulus (or elasticity) of the blade (Pa, see Appendix B.2.3) and  $I = \frac{1}{12}bt^3$  is the second moment of area of the leaf cross-section (assumed to be rectangular, [m<sup>4</sup>]). Using the classical quadratic law, the drag force acting on a rigid cylinder is typically expressed as  $F_{drag} = \frac{1}{2}\rho C_D u^2 bl$ , whereas the buoyancy is formulated as  $(\rho - \rho_v)gbtl$  and the rigidity as  $E_b I/l^2$ . Inter alia, Luhar & Nepf (2011) report typical parameter values for eelgrass (*Zostera marina*): the range of  $\rho_v$  lies between 700-900 kg m<sup>-3</sup>,  $E_b \approx 0.4$ -2.4 GPa, *l* varies between 0.15 and 2 m (with more typical values of 0.3-0.6 m), the range of *b* is 3-8 mm and the range of t is 0.2-0.5 mm with a mean value of 0.35 mm. The buoyancy parameter then ranges between  $B \approx 1$  and 170. If a typical velocity range of 0.05-0.5 m s<sup>-1</sup> is assumed, the value of the Cauchy number is approximately  $Ca \approx 10$ -40,000, where a large Cauchy number indicates that the plant posture is undisturbed by the flow.

The flow resistance is reduced in two ways: the frontal area of the plants is smaller and the shape of the plants tends to be more streamlined, thereby reducing the drag on the plant. Vogel (1994) proved that the relationship between the drag force and the flow velocity *u* is no longer quadratic, but is given by:

$$F_{drag} \propto u^{2+\gamma} \tag{1.12}$$

where  $\gamma$  is the Vogel-exponent and is always negative for submerged vegetation. The value of  $\gamma$  for flexible vegetation varies between 0 for nearly rigid vegetation and -2 for very flexible vegetation (e.g. Carr et al., 2016; Nepf, 2012b; Vogel, 1994).

As said, reconfiguration reduces drag on the vegetation by means of a reduced frontal area and a more streamlined shape. The deflected height of the vegetation  $k_{veg}$ , or the total plant area  $bk_{veg}$ , accounts for a reduced frontal area, but not for the streamlined shape of the vegetation. Nepf (2012b) therefore introduces an effective blade length  $l_{veg}$ , which resembles the total impact of reconfiguration on drag. It is the length of a rigid vertical blade that generates the same horizontal drag as the deflected blade of length l. The relationships proposed by Nepf (2012b) are given in equations (1.13) and (1.14).

$$\frac{l_{veg}}{l} = 1 - \frac{1 - 0.9Ca^{-1/3}}{1 + Ca^{-3/2}(8 + B^{3/2})}$$
(1.13)

$$\frac{k_{veg}}{l} = 1 - \frac{1 - Ca^{-1/4}}{1 + Ca^{-3/5}(4 + B^{3/5}) + Ca^{-2}(8 + B^2)}$$
(1.14)

#### **Tolerance limits for eelgrass presence**

Besides the light climate itself, which is of main importance to submerged aquatic vegetation growth, physical or chemical parameters are also part of the habitat requirements as they indirectly influence the light climate. Koch (2001) analysed these additional habitat requirements by means of a literature review and published a synthesis of these parameter thresholds, of which the physical hydrodynamic related findings are described here.

The hydrodynamic conditions (flow and waves) pose both minimum and maximum physical tolerance limits to the eelgrass presence and development. As explained in section 1.3.4 and mentioned by Koch (2001), the advantages of reduced flow velocities in the meadows are multiple: reduction of sediment resuspension by decreased bed shear stress, enhanced settlement, reduction of self-shading due to a more vertical plant position, and longer water residence times which increase nutrient absorption by the plant. Reduced flow velocities or even stagnant water can also have (phytotoxic) disadvantages, such as increased sulphide concentrations, increased accumulation of organic matter, or oxygen depletion. On the other hand, high flow velocities and corresponding bed shear stresses may prevent seedlings from establishment due to uprooting or cause rupture of the leaves of vegetative shoots. Therefore, the flow velocity range needed to support the growth and distribution of *Zostera marina* lies between approximately 0.05 and 1 m s<sup>-1</sup> (Koch, 2001). Logically, flow velocities outside this range may affect the feedback mechanisms and subsequently lead to eelgrass decline or die-off.

Koch (2001) also reviewed the effect of waves. Eelgrass growth seems to be limited by high wave energy only, as waves can erode the seabed and rupture or even remove eelgrass plants, in particular during storm events. Wave exposure mainly limits eelgrass growth and distribution and can force the vegetation to move to deeper waters, but can also have slightly positive effects such as reduction of epiphytes or self-shading. The minimum depth limit for eelgrass presence related to wave energy  $Z_{wave}$  [m] can be determined by the wave mixing depth (Chambers, 1987):

$$Z_{wave} = \frac{L}{2} \tag{1.15}$$

where L is the wave length for deep water [m] and T is the wave period [s] defined as

$$L = \frac{gT^2}{2\pi}, \ T = \left[\frac{0.46W}{g}\right] \cdot \left[\frac{gF}{W^2}\right]^{0.28}$$
(1.16)

where W is the wind velocity  $[m s^{-1}]$  and F is the fetch [m]. According to Koch (2001), these equations are valid for habitats with relatively deep waters (h > L/2) and with steep slopes; for gentle slopes or shallow depths it is more difficult to determine  $Z_{wave}$  as wave generation by wind and depth- and vegetation-induced dissipation act at the same time.

#### 1.3.6 Interaction of feedbacks

Reflecting on the feedbacks between hydrodynamics, sediment dynamics, and eelgrass as described in this section, the paper of Adams et al. (2016) refers to the interaction of these feedbacks as the seagrass-sediment-light (SSL) feedback. This SSL feedback loop, shown in Figure 1.8, contains all components that are of importance in this thesis. The current knowledge of feedbacks as described in this section is summarised here by using the SSL feedback loop of Adams et al. (2016) in Figure 1.8.

The essence of the feedback loop addressed by Adams et al. (2016) concerns the bistable behaviour that can be induced in eelgrass ecosystems (see subsection 1.1.4). At locations where eelgrass is present, it potentially favours its own growth. Seagrass modifies the local hydrodynamics (both waves and currents: indicated by (iii) and (iv) in Figure 1.8, see subsection 1.3.3) and the sediment transport (indicated by (v) and (vi), see subsection 1.3.4). Sediment resuspension is reduced by eelgrass presence (indicated by (vii)), the light availability is subsequently increased (indicated by (i), see subsection 1.3.2) and growth is stimulated (indicated by (ii)), i.e. further reducing the sediment resuspension. However, when eelgrass is absent, its growth is also adversely affected. Sediment resuspension and therefore turbidity is enhanced, the light availability is reduced, and eelgrass growth (or invasion) is hindered.



Figure 1.8 Simplified visualisation of the feedbacks in a seagrass ecosystem (Adams et al., 2016)

#### 1.4 Light in the water column

The crucial ingredient for photosynthesis is light. Eelgrass development and -survival are therefore determined by the amount of light that reaches the canopy. Since the light travels through the water column, the incident light is attenuated before it reaches the top of the canopy. The light attenuation over the water column is expressed by the Lambert-Beer law:

$$I_{canopy} = I_0 \exp(-K_d (h - h_{veg}))$$
(1.17)

where  $I_0$  is the light intensity at the water surface,  $I_{canopy}$  is the light intensity that reaches the top of the canopy, and  $K_d$  is the light attenuation coefficient. This means that an increase of  $K_d$  or depth leads to an exponential decrease in the light reaching the top of the canopy.

The water depth has a large influence on the amount of light available and is equally important as the light attenuation coefficient. As eelgrass needs light to survive, there is a limit to the depth at which the plants can grow. This depth limit is defined as the depth at which the light climate approaches the minimum light requirement. The less light scattering particles present in the water, the larger the depth limit. Typical profiles of light attenuation over the water column, based on equation (1.17) and for different values of  $K_d$ , are shown in Figure 1.9.



Figure 1.9 Light attenuation over the water column for clear and turbid water (adapted from Lake Access, 2006)

Particles in the water column cause absorption and scatter of light, therefore less light is available for the eelgrass. The more particles present in the water, the higher the light attenuation coefficient will be. The particle types that are included in the light attenuation coefficient are *chlorophyll a* particles (related to the amount of algae or phytoplankton in the water), coloured dissolved organic matter or CDOM (which filters out a special range of wavelengths) and suspended sediment particles. All particles contribute to both absorption and scatter, however absorption dominates in organic particles (*chl a* and CDOM), whereas scatter is dominant in inorganic particles (sediment).

$$K_d = c_1 \cdot SSC + c_2 \cdot chl \ a + c_3 \cdot CDOM \tag{1.18}$$

The coefficients  $c_1$ ,  $c_2$ , and  $c_3$  are site-specific (Carr et al., 2016) and need to be determined from light measurements, together with examined water samples determining the concentration of *chl a* and CDOM.

The light intensity at the water surface  $I_0$  varies throughout the year. In spring, the light intensity increases and the plants start to develop. During summer, the light intensity is largest; therefore the productivity of the plant increases until the growth limit is reached and the plant development stagnates. In autumn, the light intensity decreases again and the plants are dying off. The die-off process is not only due to the decrease in light availability, but can also be a result of temperature decrease and increase in storminess, causing hydrodynamic forcing and resuspension of sediment, further decreasing the light intensity.

The change in suspended sediment concentration (SSC) in time and space is the most relevant and interesting for this research, as the Rødsand lagoon is a low-nutrient environment: therefore, only the SSC will vary and the concentration of the other substances is kept constant and assumed as evenly distributed over the water column. The background light attenuation coefficient is then constant with depth, whereas the total light attenuation coefficient  $K_d$  varies with depth as the sediment concentration also varies with depth.

#### Minimum light requirement of eelgrass

The minimum light requirement (MLR) of eelgrass depends on multiple factors and can vary amongst different populations. This is likely due to plant adaptation to local light regimes, such as the local amount of surface irradiance (SI) and the water temperature (Lee et al., 2007). In temperate regions, surface irradiance is typically lower than for warmer climates, therefore the required light in terms of %SI will be higher. Therefore, it is difficult to apply the MLR of one eelgrass population to another population. The MLR is usually expressed in terms of percentage of surface irradiance (%SI), or in photosynthetically active radiation (PAR), which can be measured in energy or in the received number of photons per unit area per amount of time ([mol photons m<sup>-2</sup> s<sup>-1</sup>] or [E m<sup>-2</sup> s<sup>-1</sup>], where E is Einstein).

The minimum light requirement is subject of multiple studies (e.g. Borum, 1983; Dennison, 1987; Dennison et al., 1993; Duarte, 1991; Olesen & Sand-Jensen, 1993). Ochieng (2008) presents an overview of the reported estimates and concludes that, according to these multiple studies, eelgrass has an MLR range between 11% and 30% of surface irradiance (SI). Furthermore, Ochieng's study showed that 11% SI was not enough for long-term eelgrass growth and survival, as the mortality rate at this level of SI was about 80%. For 34% SI, eelgrass plants showed significant growth, however the resilience of these plants was affected. The conclusion of this research is that the MLR for eelgrass indeed varies between 11%-34% SI, with 34% being a sub-optimal condition for eelgrass growth.

The light requirements of the eelgrass population at the study site (see section 1.6) are on the low end of the range, due to the geographic location on the north side of the distribution area of *Zostera marina*. The MLR values were established by the Environmental Impact Assessment of the Fehmarnbelt tunnel (FEMA, 2013), as this construction site is in the proximity of the study site. Assuming a minimum light requirement of 15-20% SI (based on findings by Dennison et al., 1993), the minimum values for this eelgrass population are estimated to be 750-1000 E m<sup>-2</sup> cumulatively during the growth season (March-September). The compensation irradiance  $I_c$ , i.e. the (minimum) amount of irradiance needed to compensate for plant respiration, is estimated at 10-50 µmol photons m<sup>-2</sup> s<sup>-1</sup> (or 0.85-4.3 E m<sup>-2</sup> d<sup>-1</sup>). The saturation irradiance  $I_k$ , i.e. the (maximum) amount of irradiance needed for maximum photosynthesis, is estimated at 100 µmol photons m<sup>-2</sup> s<sup>-1</sup> (or 8.5 E m<sup>-2</sup> d<sup>-1</sup>).

## 1.5 Research objectives and research questions

This study aims to create a better understanding of shallow seagrass ecosystem behaviour (i.e. the interplay of feedbacks) and to improve the ability to predict the system response to possible adverse environmental conditions of a changing environment. Therefore, it is aimed to quantitatively assess the feedbacks between hydrodynamics, sediment dynamics, and eelgrass development and the impact of possible climate change effects on this kind of shallow coastal (eco)systems. The complexity and requested quantification of processes that determine the behaviour of this ecosystem demand the development and use of a numerical model. Therefore, two (secondary) objectives can be added to this project, that is, to develop a numerical model that includes the most important feedbacks of a shallow coastal (eco)system and to verify whether the model is capable of representing the general behaviour of such a coastal system.

The general research question is therefore formulated as follows:

To which extent can the climate change effects of sea level rise, temperature increase, and increased storminess lead to die-off of eelgrass in a shallow coastal system such as the Rødsand lagoon, by feedbacks of vegetation on hydrodynamics and sediment dynamics?

Corresponding sub-questions have been specified:

- 1. Can climate change lead to a different ecological (bare) state, as seagrass dies?
  - What can lead to a different ecological state of the system?
  - Is there a clearly defined tipping point/threshold?
- 2. How do different climate change forcings (sea level rise, temperature increase and increased storminess) affect seagrass presence?
  - Which factors determine seagrass presence?
  - What are the impacts of climate change forcings on the coastal system?
- 3. What are the environmental conditions of the study site?
- 4. How do the environmental conditions change by climate change forcings?
- 5. Which parameters are essential in defining the processes in the system and indicate the changes?

## 1.6 The study area

This section introduces the study area of this thesis and the rationale behind the choice of the study site.

The Rødsand lagoon is a shallow coastal system in the southeast of Denmark between the islands Lolland and Falster (Figure 1.10). The lagoon is about 30 km by 10 km in size; the depth range is 0 to 8 m and the area is considered as non-tidal, as the tidal range is small ( $\approx 0.1$  m). In the shallow and sheltered regions of the lagoon, mostly on the west side, seagrass of the type *Zostera marina* (eelgrass) is growing abundantly. The eelgrass is food for a large number of overwintering swans and the lagoon is part of a Natura 2000 site (Forsberg et al., 2017), i.e. anthropogenic influences are limited. The eelgrass populations in the Rødsand lagoon are perennial, which means that eelgrass plants are still present during the winter.



Figure 1.10 The Rødsand lagoon A) located in southeast Denmark (Femern.com) and B) a recent satellite image (Google Maps 2017)

This shallow coastal (eco)system has been chosen as a study site for various reasons. As it is located close to the Fehmarnbelt and the tunnel construction site (Figure 1.10A), the Rødsand lagoon was part of the Environmental Impact Assessment of the Fehmarnbelt connection. In the recent past, fieldwork and numerical modelling studies by DHI have quantified the turbidity-related impact of nearby construction works on the seagrass ecosystem in this lagoon. Currently, in the framework of the European Hydralab+ project, field studies, laboratory experiments, and numerical modelling (e.g. this thesis) are combined to assess the possible effects of climate change on seagrass development in this coastal system in relation to turbidity. Multiple parameters were surveyed in the field studies (see Appendix B) and the multiannual field measurements allow for assessment of seagrass development under different environmental conditions (e.g. calm and stormy weather) as the vegetation was monitored over a longer time period.

Moreover, the Rødsand lagoon is a good example of a thriving eelgrass ecosystem in a temperate climate; the area is not threatened by anthropogenic influences, is a low-nutrient environment and has been monitored for many years. Hence, this study area is suitable for the research purposes, i.e. assessing the eelgrass ecosystem behaviour in a changing environment by numerical modelling. It is not intended to perfectly model the study site in itself, but to use its (environmental) conditions for general assessment of this type of ecosystems.



Figure 1.11 Eelgrass in the Rødsand lagoon (Femern A/S)

# 2 Project approach and outlines

## 2.1 Project approach

In order to be able to answer the research questions as formulated in section 1.5, a project approach for this thesis has been developed. The framework of this project approach is presented in Figure 2.1, where the main pathway is laid out in the centre of the figure. Five components can be distinguished.

First, the data was collected from different sources: the fieldwork at the study site in August 2017, the model input and output obtained from DHI, and the available literature. The available literature consisted mainly of the Fehmarnbelt EIA reports, as the study site of this thesis is very close to the construction site of the Fehmarnbelt tunnel and the impact of the construction on the study site is described in these reports. At the same time, by using the input of the three data sources, the environmental conditions at the study site were assessed. The data analysis and the environmental conditions together formed the basis for the investigated system behaviour and the developed numerical model

Next, a physical numerical model has been developed that contains the physical processes of hydrodynamics and sediment dynamics. This model, hereafter referred to as physical model, has been tested with and without vegetation implemented, i.e. the growth dynamics of the vegetation has not been implemented yet.

The third component of this project was the development of a growth module, which describes and calculates the growth dynamics of the eelgrass. This growth model, as will be explained later on, is mainly based on the growth model of Carr et al. (2012a; 2012b) and was designed to be implemented in the model sequence.

Before moving to the next phase, separate tests have been carried out for the physical model and the growth model. The model sensitivity was analysed and the models were partially validated so that the outcomes of both models (e.g. the dynamics of eelgrass development, ranges of flow velocities, bed shear stresses) showed qualitatively the same behaviour as observed in the data. The models were coupled after this model reliability of the physical- and growth model was established, leading to the development of the final model. As this final model combines the action of the physical- and growth model by executing the coupling between the two models, this final or total model is also mentioned as the coupled model.

To assess the spatial (eco)system behaviour of the Rødsand lagoon in the present and in the future, year-round simulations have been carried out. These simulations were based on the present situation (with the present seagrass cover), a present situation with intended adverse environmental conditions (a bare seabed with only sparse vegetation) and future situations by including climate change effects (sea level rise, water temperature increase, and storminess). This final application of the coupled model led to the results that have been analysed and which provided the answers to the research questions as described in section 1.5.

# 2.2 Thesis outline

Chapters 3 and 4 elaborate on the examined and established environmental conditions of the Rødsand lagoon by means of literature research and the data collection and analysis, respectively. The fieldwork data consisted of short-term data acquired from the Hydralab+ fieldwork of August 2017. Year-round data sets for a representative year were made available by DHI by means of a time series of all the requested parameters from their numerical model. Other long-term data that could be examined was data from the literature, such as the Environmental Impact Assessment (EIA) reports from the Fehmarnbelt tunnel project.

The setup of the coupled model and the preceding development of the coupled model components (i.e. the physical model and the growth model), the model validation, and model application are described in chapter 5. Chapter 6 shows the results of the model simulations and contains the analysis of the model results. A critical reflection on this scientific study and discussion of the assumptions made during the process are provided in chapter 7. Lastly, the conclusions of this study and recommendations for further research or different model applications are given in chapter 8.



Figure 2.1 Project approach

# 3 Environmental conditions of the Rødsand lagoon

The Rødsand lagoon is a shallow coastal lagoon and the main study location of this thesis. Therefore, its characteristics, dynamics, and long-term behaviour have been studied by use of available literature. In assessing the environmental risks of the construction of the Fehmarnbelt tunnel, Environmental Impact Assessment reports have been written. As the Rødsand lagoon is located in the direct vicinity of the tunnel, this site has also been assessed and reported in these EIA reports. They were also the most important source for the compilation of this chapter.

## 3.1 Sheltered location

The features that protect the Rødsand lagoon from offshore influences, such as waves and currents, are two spits and a submerged sandbank in between. As the satellite images in Figure 3.1 show, these features have been in place for more than 30 years and even migrate and "curl" inwards. This could indicate a sediment import into the lagoon, however there are no records of sediment transport available to verify this presumption.



Figure 3.1 Satellite images of the Rødsand lagoon of A) year 1984 and B) year 2016 (Google Inc., 2018)

The opening between the eastern spit and the sandbank allows for the exchange of water with the adjacent Baltic Sea. The other opening between the western spit and the sandbank is too shallow, most of the time, and therefore blocks water exchange. However, with a south-westerly wind, the wind setup together with the offshore waves cause overwash into the lagoon.

## 3.2 Depth variation

One of the characteristics of the coastal lagoon is that it is very shallow: the depth variation is from 0 to -7.5 m. In Figure 3.2, the bathymetry of the lagoon is plotted; the data is obtained from the Digital Bathymetry Model of the European Marine Observation and Data Network (EMODnet) and has an accuracy of 1/8·1/8 arc minute (134x231.5 m). It can be seen that in the eastern part of the bay, the depth is the largest and there is a depth gradient sloping upwards to the west (the shallow part). The western spit is even emerged and therefore no depth showing on the map. To a lesser degree, there is a second depth gradient from south to north.



Figure 3.2 Depth variation (EMODnet Bathymetry Consortium, 2016)

## 3.3 Eelgrass distribution and seabed composition

When the bathymetry of the lagoon is compared with the eelgrass distribution map of Figure 3.3, it can be observed that the eelgrass predominantly grows in the shallow parts of the lagoon. The hypothesis is that due to the light requirements of the eelgrass to perform photosynthesis, the light penetration in the deeper parts of the lagoon is insufficient and therefore hinders the growth of eelgrass. Consequently, the seabed in these deeper locations is bare. This phenomenon is also reflected in the vertical eelgrass distribution bar chart of Figure 3.4, where it can be seen that at larger depths the eelgrass cover is often sparse. The cover percentage in this bar chart has a typical bell-shaped vertical distribution pattern and resulted from diver observations along different transects of the Rødsand lagoon in the summer of 2009. Low covers were found between 0.5-1 m and 4-6 m, medium cover between 2-4 m, and maximum cover between 1-2 m. The deepest observations with 10% cover were recorded at 5.2 m and the average depth limit was at 4.6 m in the eastern part of the lagoon.

Although Figure 3.3 shows the eelgrass distribution of 2009, it is known that this eelgrass population has been present in the Rødsand lagoon for decades. The eelgrass plants in the shallow part of the lagoon are remarkably persistent in their presence although sparse covers are most commonly found, probably due to the hydrodynamic forcings that are unfavourable for the growth of the eelgrass. The forcings that are acting on the system are treated in the next section.





Figure 3.3 Eelgrass distribution and coverage (adapted from FEMA, 2013). Dark green colours indicate dense cover of eelgrass (50-100%), whereas lighter green colours indicate sparser cover

Figure 3.4 Vertical distribution of eelgrass in the Rødsand lagoon in summer 2009 (FEMA, 2013). Cover estimated by divers along transects

Eelgrass plants need sand to anchor their roots and rhizomes. According to the EIA of the Fehmarnbelt construction (Brøker, Hansen, & Middelboe, 2014), the seabed is formed by glacial deposits. However, the nearshore seabed is covered with layers of sand, creating the right conditions for the eelgrass to be present. The exact composition of the seabed of the Rødsand lagoon remains largely unknown. The only indication for a composition that could be found was the grain size distribution of suspended sediment that was accumulated at mid-water level in the western part of the lagoon during one month's period (November to December 2009). This distribution is shown in Figure 3.5.



Figure 3.5 Grain size distribution of suspended sediment (November-December 2009) (FEHY, 2013c)

## 3.4 Hydrodynamic forcings

The two forcing mechanisms that are important at this study site are wave motions and wind-induced flow. Tidal influence on this coastal system is minimal, as the Danish straits further reduce the amplitude of the tidal waves travelling from the North Sea

through the Skagerrak and the Kattegat. The tidal amplitude in the Baltic Sea is very small (in the Rødsand lagoon, it is less than 10 cm) and tidal influence is therefore neglected in this study.

Meteorological conditions are of great importance, as wind-waves and wind setup dominate during storm conditions. The waves that may occur are solely locally wind-generated waves since the lagoon is sheltered and intrusion of offshore waves is blocked. Besides inducing waves, winds with a large fetch (coming from the east or west) can create wind setup, see Figure 3.6. This results in a tilted water level and complex 3D return flow mechanisms in both horizontal and vertical direction.



Figure 3.6 Schematic principle of wind setup inducing a return flow in the vertical direction

Apart from the flow, which is known for its sediment transport capacity or entrainment, waves also act on the system by bringing sediment in suspension. The sediment is stirred up most easily at bare sediment beds, since eelgrass acts as a retention mechanism due to the anchoring of the root system and creates additional resistance to the flow, causing the flow velocities to decrease and attenuate the energy of the waves (see subsections 1.3.3 and 1.3.4).

Since the seabed in the eastern part of the lagoon is bare, but also the spits and sandbank consist of loose sand that can easily be transported, sediment is stirred up locally in these regions by the waves and transported with the wind-driven flow. Therefore, the wind directions that influence the coastal eelgrass system the most are winds with directions in the range of 45° (from the northeast or NE) to 247.5° (from the west-southwest or WSW). These winds have a relatively large fetch and the suspended sediment is transported inwards, thereby directed towards the eelgrass beds.

Winds from other directions (outside this particular range) certainly have an impact on the coastal system, although the fetch is limited, and for low wind velocities, the bed shear stress does not exceed the critical shear stress, meaning it is not high enough to entrain the sediment from the bed.



Figure 3.7 A) SSC at NS04 and NS05 B) wind speed and wind direction (October 2009) (FEHY, 2013c)

The time series of Figure 3.7 (FEHY, 2013c) show that the suspended sediment concentrations for the nearshore measuring stations NS04 and NS05 vary significantly. The measuring station NS04 is a sheltered location, situated behind the western spit

barrier. The other station NS05 is more exposed, since it is situated in the deeper part and at the exchange opening of the lagoon. See Figure 4.1 for the locations of the measurement stations. The report of the Fehmarnbelt impact assessment on suspended sediments (FEHY, 2013c) draws the conclusion that for a wind speed larger than 8 m s<sup>-1</sup>, the SSC in the Rødsand lagoon increases and sediment suspension events arise.

## 3.5 Conclusion

So far, the following assumptions of the lagoon behaviour result from this chapter: in the eastern part of the lagoon, the depth is too large to accommodate eelgrass. With a storm coming from the east, the sediment is locally resuspended and dispersed towards the existing eelgrass beds in the (more shallow) western part of the lagoon. Therefore, a spatial turbidity gradient can occur. As explained in section 3.2, there is a depth gradient from east to west (deep to shallow), but also from south to north.

An important conclusion that can be drawn is that the conditions in the Rødsand lagoon - the sheltered location, depth variation, and eelgrass distribution - did not vary to a large extent and can even be considered as (fairly) constant over the last decades.

# 4 Data

This chapter describes the data that were collected and that were made available and elaborates on the analysis and the subsequent use of the data to set up the numerical model. The overview of data that was needed for the development of the numerical model and data that has been provided by the other parties involved in the Hydralab+ project is added in Appendix B.1. This overview consists of three tables, each focussed on another system driver: hydrodynamics, sediment dynamics, and eelgrass. The analysis of the fieldwork data can also be found in Appendix B.

## 4.1 Fieldwork August 2017

During the fieldwork in the last week of August 2017, multiple participants from the Hydralab+ project were involved in the data collection. The participants are affiliated with the University of Hull, University of Loughborough, Forschungszentrum Küste Hannover and DHI. The data was collected by different measurement equipment, which is described in Appendix B. The collected data, the analysis and the results are also included in this appendix.

The overall conclusion that could be drawn from the obtained data of the fieldwork was that no significant effect of eelgrass feedback on the coastal system was observed under these conditions, i.e. there were no conclusive differences between sites with and without eelgrass. The conditions during this measurement campaign in summer were absolutely calm. Moreover, the spatial scale that has been examined during this measurement campaign is in fact relatively small, in the order of 100x100 meter, therefore the measurements can be considered as local measurements. However, to reflect on the behaviour of the complete coastal system, spatial specific data is also needed for both calm and dynamic conditions.

These data only provided insight in the local ecosystem behaviour for calm conditions, instead of the desired variability in space and in the environmental conditions i.e. including dynamic conditions. However, it is still an important feature of the system behaviour. It is now known that for (extremely) calm conditions, no feedback of the eelgrass on the system behaviour can be observed.

# 4.2 Model data DHI

After analysing the fieldwork data and concluding that the effect of eelgrass on the coastal system could not be interpreted over time, i.e. under dynamic conditions varying during the year, additional data was requested from DHI. This data was used as input for or generated as output from the environmental model that DHI used in the Fehmarnbelt Environmental Impact Assessment (EIA). The time series of data for each parameter was provided for the year 2005, which is according to DHI a representative year in terms of hydrodynamic forcings (wind, currents and waves) (FEHY, 2013a).

## 4.2.1 Discretisation of the coastal system

Modelling the lagoon in 3D or analysing the data of the whole lagoon would become too complex and time-consuming, apart from the fact that the required data to do so is unavailable. To be able to relate model results to the behaviour of the lagoon and to process all the data in an efficient and useful manner, the lagoon behaviour has been discretised. With this discretisation, the assumption is made that certain locations represent the full spectrum of system behaviour.

A limited amount of locations was appointed that are assumed to cover the essence of the system behaviour. The selection for locations is based on the different depth ranges (Figure 3.2) combined with a difference in eelgrass cover derived from the only spatial vegetation distribution available (Figure 3.3, FEMA (2013)). Together, these locations cover the same vertical distribution of eelgrass that was introduced in Figure 3.4 and therefore the system behaviour of the lagoon.

In total, 20 locations were appointed, see Figure 4.1. Most of the locations are part of single or multiple transects, based on the expected behaviour of spatial gradients (depth and/or turbidity gradients), however at some locations (i.e. 4, 5, 6 and 13), the expected behaviour is somewhat different. Locations 4 and 5 are situated at the opening between the western spit and the sandbank; overwash and flow and associated sediment transport and –deposition during highly dynamic conditions is the likely cause of the seabed to be bare (Table 4.1). Location 6 is situated in a derived eelgrass cover of 25-50%, whereas the surrounding areas with approximately the same depth are characterised by an eelgrass cover of 50-100%. The last distinctive location is number 13: besides the fact that it is part of a deep trench stretching from the deepest part of the lagoon and again a bare seabed is to be expected, the depth gradient towards the shore is significantly large.



Figure 4.1 Discretised locations for system behaviour

As explained, all these locations together should represent the behaviour of the coastal system accurately enough. Table 4.1 shows the intended representation of the vertical eelgrass distribution of the Rødsand lagoon that can be compared to the actual measured vertical distribution of eelgrass (Figure 3.4).

|           | Eelgrass Cover [%] |         |           |
|-----------|--------------------|---------|-----------|
| Depth [m] | 0                  | 25-50   | 50-100    |
| 0.5-1.0   | 4                  | 7       | 3,8       |
| 1.0-2.0   | 5                  | 17      | 1,9,11,18 |
| 2.0-4.0   |                    | 6,10,12 | 2         |
| 4.0-6.0   | 13,15,16,19        | 14      |           |
| > 6.0     | 20                 |         |           |

The local prevailing conditions at these 20 locations were requested to and have been provided by DHI, as they developed a numerical model of a large part of the Baltic Sea, including the Rødsand lagoon, and calibrated the model to field data. The model input and output of DHI is used to force the developed model in this thesis and to verify these model results. The parameters that have been requested and subsequently provided, the conclusions that could be drawn from the data analysis and the data that was exactly used for what purpose in the continuation of the research, is described in the remaining part of this section.

## 4.2.2 Requested and provided data

#### General

The parameters that were requested were almost all exactly the same as the provided parameters; although some of them were not. The requested parameters were actual (seasonal) eelgrass cover, actual depth, flow velocity over the water column, SSC over the water column, significant wave heights and corresponding wave periods, bottom shear stress, wind speed and direction, and surface light. However, the model of DHI is a 2DH model, thereby excluding the variation of parameters in the vertical direction. Hence, the vertical varying values of some parameters (SSC, flow velocity and direction) were not provided, but the depth-averaged values were provided instead.
Additionally, the time steps between parameters varied. Data from the ecological module has a time step of 12 hours, e.g. the eelgrass biomass, the average light in the water column, and the NTU. The data from the hydrodynamic module, e.g. flow velocity and direction, and water depth, has a time step of 30 minutes. The provided wind data (speed and direction) has hourly values. The model output, such as the bed shear stress, wave data (height and period) has time steps of 2 hours. Finally, the temperature data was provided with a time step of 3 hours.

Lastly, the model of DHI did not include explicit modelling of (natural resuspension of) fine sediments. The effect of suspended sediment on the environment was modelled implicitly by taking into account turbidity in the form of turbidity units (NTU, Nephelometric Turbidity Units). The assumptions for modelling the NTU were based on environmental conditions (wind velocity, water depth, waves, and bed shear stress). As NTU is a measure of scatter in the water column and is dependent on the particle size of the suspended material, DHI assumed that there is a higher fraction of particles in the water column due to rougher weather conditions in autumn and winter, resulting in a higher NTU. For the same reason, it was assumed that the amount of suspended particles is lower during calm conditions in spring and summer, resulting in a lower NTU.

#### Aboveground eelgrass biomass

The only provided data on eelgrass presence was the aboveground eelgrass biomass of the year 2005 at all 20 locations in gCm<sup>-2</sup>.

#### Wind speed and direction

The wind data provided was exactly what was needed for this study: the wind speed in m s<sup>-1</sup> and wind direction relative to the North for the representative year 2005. As expected, the wind data is the same for the whole area.

#### Depth

The actual water depth of the 20 locations was provided for the year 2005.

#### Flow velocity and direction

The model calculated the hydrodynamics explicitly in the horizontal direction, but only depth-averaged. The available flow velocity and flow direction were therefore provided: depth-averaged values for every location.

#### Light

Different data sets of light were made available by DHI. First, the surface light was provided in  $\mu$ E m<sup>-2</sup> s<sup>-1</sup>, which is constant over the lagoon. Furthermore, the average light in the water column is a vertical average over the whole water column (surface to bottom), but it is not averaged over time: it is an instantaneous output for night (0.00h) and day values (12.00h). Two sets of bottom lights were made available. The first bottom light is the instantaneous output for night and day values, i.e. in the same format as the averaged light in the water column. The other bottom light data set contained smoothed values obtained by exponential smoothing.

The light attenuation coefficient  $K_d$  from the Lambert-Beer equation (1.17) was not saved during the modelling study of DHI and could therefore not be provided. DHI did recommend estimating the light attenuation coefficient using surface and bottom light along the water depth from the provided data sets. Eventually, this provided bottom light was not needed, as the bottom light is calculated by the model itself; see section 5.4. The other recommendation related to the calculation of the light attenuation coefficient that DHI gave was to calculate the light attenuation coefficient of suspended sediment by using the absorption and scattering of the sediment particles involved:

$$K_{SSC} = \sqrt{a^2 + 0.256ab} \cdot SSC \tag{4.1}$$

with the values of absorption  $a \ [m^2 g^{-1}]$  and scatter  $b \ [m^2 g^{-1}]$  for different grain sizes as used in the (ecological) model of DHI and the mass-specific light attenuation calculated as in equation (4.1), see Table 4.2. These values could also be found in one of the Fehmarnbelt EIA reports (FEMA, 2013). The scatter for the largest grain size (b = 0.05 for 170 µm) was estimated by extrapolating the given values related to the increasing grain sizes and the mass-specific light attenuation was calculated accordingly.

Table 4.2 Absorption, scattering and resulting mass specific light attenuation coefficients

| Grain size | Absorption                        | Scatter                           | Mass specific light                           |  |
|------------|-----------------------------------|-----------------------------------|---|--|
| [mm]       | [m <sup>2</sup> g <sup>-1</sup> ] | [m <sup>2</sup> g <sup>-1</sup> ] | attenuation [m <sup>2</sup> g <sup>-1</sup> ] |  |
| 0.0065     | 0.0278                            | 2.714                             | 0.142   |  |
| 0.010      | 0.0278                            | 1.814                             | 0.117   |  |
| 0.028      | 0.0278                            | 0.756                             | 0.078   |  |
| 0.064      | 0.0278                            | 0.354                             | 0.057   |  |
| 0.170      | 0.0278                            | 0.05                              | 0.034   |  |

#### Wave height and wave period

The wave parameters were provided; however the wave direction was not included. The assumption of wave direction being the same as the wind direction was made, since only wind-generated waves are present in the lagoon due to its sheltered position. Moreover, some gaps were found in the data for locations 1, 3, 5, 6 and 7.

#### **Bed shear stress**

The data set of the bed shear stress was also provided for the representative year 2005. As in case of the wave parameters, some gaps were found in the data at the same locations.

#### Water temperature

The water temperature of the lagoon was provided for every location during the year 2005.

#### Turbidity units (NTU)

The NTU (Nephelometric Turbidity Unit) data, as provided, are model-predicted estimations of turbidity and, like other previous parameters, depth-averaged. These data were provided because it is the best proxy that was available for the suspended matter in the water column. The original NTU calculated by DHI's model consists of two parts: one part is the NTU caused by organic matter (e.g. detritus and phytoplankton), the other part is the NTU of inorganic matter (suspended sediment, e.g. silt or sand). Both contribute to the light climate in the water column by scatter and absorption, see section 1.4.

#### 4.2.3 Data analysis

This subsection discusses the analysis of the provided data per parameter.

#### Aboveground eelgrass biomass



Figure 4.2 Eelgrass presence for 20 locations in Rødsand lagoon (Model results DHI)

The model output of DHI of aboveground biomass during the year 2005 at the 20 predefined locations is shown in Figure 4.2. Clearly visible at all locations is the realistic seasonal variability of aboveground biomass over the year. By looking at the biomass at the start of the year compared to the biomass at the end of the year, a decrease in aboveground biomass can be observed. Moreover, the locations with the largest aboveground biomass also show the largest decrease in biomass (up to 25%). At the locations with the smallest aboveground biomass, the decrease in biomass is also relatively smaller (5-10%). One of the explanations for this large decrease could be that the light conditions were unfavourable for this year, since it is unknown whether these were representative of the area or not. Nevertheless, the light conditions of 2005 were used in all model simulations assuming 2005 was a representative year considering meteorological conditions (FEHY, 2013a).

#### Wind speed and direction

The wind data of 2005 was compared to the long-term wind data of 1947-2010 by means of comparing wind roses, see Figure 4.3.

From these wind data, it can be concluded that the prevailing winds are directed in an east-west direction and that the wind conditions of 2005 (Figure 4.3A) are similar to the long-term wind conditions (Figure 4.3B). Noticeable is that the peak of eastern wind (including storms) is absent for the year of 2005 and that there is somewhat more spreading towards east-northeast and southeast direction.



measurements, 1947-2010. (FEHY, 2013a)

Analysing the wind data of 2005 also led to the evaluation of extreme or dynamic conditions in terms of storms. Only one storm was present that can actually be called a storm; this is the case if class 9 on the Beaufort scale, comparable to a wind speed of 20.8 m s<sup>-1</sup> or higher, is reached. This single storm was recorded on 8 January 2005 from 14:00 to 18:00. During the rest of the year, the number of events found was low, with only four events of class 8 on the Beaufort scale (wind speed larger than 17.2 m s<sup>-1</sup>).

### Depth

The water depth at all locations is not only different than that was derived from EMODnet, but also fluctuates over time. In Figure 4.4, the water depth for all locations is shown for a short time period (from 7 until 25 February). The small fluctuations with a frequency of 12 hours are caused by the tidal forcings (with a tidal amplitude of about 0.1 m), whereas the large fluctuations are caused by the exchange with the Baltic Sea. This is possible due to the modelled domain of the DHI model, as this domain contains a large part of the southern Baltic Sea. The water depth in the Rødsand lagoon is influenced (and forced) by fluctuations of the southern Baltic Sea water level, by exchange of water through the inlets (see section 3.1). The main trend in these fluctuations included lower water levels during winter and higher water levels during summer. These higher water levels during summer are presumably due to the expansion of water by increasing water temperatures.



Figure 4.4 Water depth for all 20 locations in the Rødsand lagoon including tidal signals and large-scale fluctuations

#### Flow velocity and direction

An important question was whether the horizontal flow in the Rødsand lagoon is directed in the direction of the forcings or whether circular flow can be observed. The data analysis of flow velocity and direction showed no indication of circular flow during dynamic conditions (Figure 4.5). During a westerly storm, i.e. strong winds coming from the west, the flow in the lagoon was mainly directed from west to east, see Figure 4.5A. For the opposite direction, the same conclusion could be drawn: in case

of an easterly storm, with strong winds coming from the east, the flow was directed from east to west, see Figure 4.5B. In general, it could be concluded that circular flow in the horizontal direction was absent during these dynamic conditions.

In case horizontal circular flow would be observed during meteorological forcing conditions, the 2DV model approach would not be the best approach and may even be insufficient, as this model only comprises processes acting in the same direction as the model. However, as no circular flow patterns were observed, the 2DV model approach is still applicable to the Rødsand lagoon study site.



Figure 4.5 A) Western and B) eastern wind events with depth-averaged flow: flow patterns within the lagoon are east-west directed.

Another observation was that, in general, the flow velocity magnitudes were considerably low, in the range of 0.01-0.5 m s<sup>-1</sup>, even under dynamic conditions such as storms. This could be because the provided flow velocities were depth-averaged, meaning that the absolute magnitude of velocities over the water column can be higher.

#### Light

The provided hourly surface irradiance for the year 2005 could not be compared to the reference data to examine its representativeness in the long-term. It was assumed that, like for all other meteorological parameters, the year 2005 was also representative in terms of the surface irradiance, as no other data was available either.

#### Wave height and wave period

The wave heights and periods showed no remarkable results. As the wave direction was not provided by DHI, it was assumed that the wave direction is the same as the wind direction, since only wind waves are assumed to be present at the study site due to its sheltered location.

#### **Bed shear stress**

In general, the bed shear stress was found to be remarkably high, i.e. almost 10 times higher than it would have been in case of calculating the bed shear stress from the other provided parameters (wave height, wave length, water depth, and flow velocity). The results of the comparison between the provided and the calculated bed shear stress from DHI are given in Figure 4.6. As the provided bed shear stresses are far higher than one would expect, and the calculated bed shear stress show more reliable results, these calculated bed shear stresses are used subsequently in the model verification, see section 6.6.



Figure 4.6 The provided bed shear stress by DHI versus the calculated bed shear stress from other parameters provided by DHI

#### Water temperature

Figure 4.7 shows the water temperature for all locations for a limited time period, i.e. from 1 until 13 April, in order to show the fluctuations more clearly. The daily fluctuations in water temperature are typical for shallow systems: fast warming and cooling is possible due to the shallow water depth. The daily range of these fluctuations is about 1°C for the whole year, but in winter the fluctuations are observed to be larger. Differences between locations are caused by the exchange of water at the inlets located in the west (location 5) and in the east (location 20). For the shallowest locations, the heating and cooling rate of the water is fastest, and the daily fluctuation is largest. The latter two features can be observed best at location 7, see Figure 4.7. As a result, the fluctuations are milder at the deepest locations (i.e. locations 15, 16, and 20) due to the larger water depth. The black line in Figure 4.7 is the spatial and temporal average that will be used as input for the growth model, see also the next subsection (4.2.4).



Figure 4.7 The water temperature for all 20 locations as provided by DHI and in black the spatial and temporal average

## Turbidity units (NTU)

The NTU data could be used to compare the results of the suspended sediment concentration (SSC) from the coupled model with the approximated suspended sediment concentration from the NTU data in the model of DHI. The correlation between turbidity and suspended sediment was examined for the Rødsand lagoon by the Fehmarnbelt EIA (FEHY, 2013c) using sediment traps mounted in the middle of the water column for a period of one month (November - December 2009). The relation between measured turbidity (NTU) and SSC in mg  $\Gamma^1$  can be described as:  $SSC = 3.4 \cdot NTU$ . The conversion factor of 3.4 is related to on the composition of the suspended material for grain sizes smaller than 0.063 mm (silt, clay, and mud particles): the larger the factor, the coarser the suspended sediment. This can be explained by the shallow water depth of the lagoon, because in case of dynamic conditions larger (bed) material is easily brought into suspension as waves interact with the bottom and stir up the sediment.



Figure 4.8 Suspended sediment concentrations as converted from NTU for all 20 locations

The converted SSC values from the provided NTU data for 20 locations are given in Figure 4.8, again for a limited time span of four weeks (30 January - 27 February) for clarity. It can be seen that at the deepest locations (locations 15, 16, and 20) the turbidity and the subsequent SSC are always highest, presumably due to the sparser spatial density of eelgrass at these deeper locations (see 4.2.3 Data analysis of aboveground eelgrass biomass). A few peculiarities can be mentioned. First of all, all peaks in SSC occur at the same time at all locations and are relatively of the same height, indicating that both advection and diffusion of high sediment concentrations would be absent in the lagoon. It is presumed that the model predictions are fallible regarding suspended sediment concentrations (converted NTU values), as advection and diffusion are expected to arise in this system. Furthermore, there is a distinct winter threshold value of NTU (visible in Figure 4.8 at 3 - 5 February), and the peaks are added or subtracted from this winter value. Especially the subtraction for the shallow locations is surprising.

The NTU value in calm (summer) conditions was used to derive the background light attenuation coefficient  $K_{back}$  and to separate the NTU data between NTU of organic matter and NTU of inorganic matter (sediment). Hereby it was assumed that the increase in winter NTU was due to the larger SSC in the water column, as organic matter will be nearly absent (phytoplankton and algae will be present in spring and summer). Moreover, the converted NTU to SSC values were used in the optimisation procedure and validation of the physical model, although it is now known that this data set is inadequate for its actual purpose.

## 4.2.4 Conclusions and continuation of research

The data could be used in the continuation of this study as either input for the physical model (and the physical model part of the coupled model), input for the growth model (and the growth model part of the coupled model), or as verification to compare with the model results.

**Wind speed and direction** was used as input for the physical model as hydrodynamic forcing, and implemented without any processing, i.e. in the same way as obtained by DHI. Also, the **wave height and wave period**, together with assuming the wave direction being equal to the wind direction, were used as input for the boundary conditions of the physical model-wave part. As the time step of the wave data was 2 hours and the input for the model was defined every hour, linear interpolation was used to fill the data gaps.

The **surface light** obtained from DHI was used as input for the growth model, as was the **water temperature**. The surface light was converted from  $\mu$ E m<sup>-2</sup> s<sup>-1</sup> to E m<sup>-2</sup> day<sup>-1</sup> in order to calculate the light during the day, but otherwise left intact. The water temperature was provided per location with an original time step of 3 hours, but the required hourly input for the growth model was defined using spline interpolation. Furthermore, the hourly temperature data for the whole year 2005 was averaged both spatially (one value for the whole lagoon) and over time (as the black line shown in Figure 4.7). The time-averaging was performed by calculating the moving mean of the hourly data, using a sliding window of a week's time across neighbouring elements. By using both the spatial and temporal average, only the temperature trend is preserved and used, instead of the observed and instantaneous temperature. This is more relevant for the calculation of eelgrass development over the whole day, as daily temperature fluctuations are averaged out.

The year-round eelgrass biomass, water depth, flow velocity and flow direction, the calculated bed shear stress from the other parameters provided by DHI and the converted SSC values were subsequently used as verification of the model results, i.e. to verify whether the model simulations result in the same values for these control parameters (see chapter 6). Hereby the difference in model approach needs to be taken into account, i.e. the differences between the 2DH model of DHI and the 2DV coupled model (see chapter 7).

# 5 Model setup

This chapter presents the rationale behind the physical model approach, outlines of the model setup of the physical model, and the growth model, and subsequently the coupled model that have been developed. The data that has been provided by DHI has been used as input for the different models as well as verification data sets to assess whether the developed model(s) provided the same results.

## 5.1 Rationale behind the physical model approach

At the start of this thesis project, it was suggested to build a 3D physical model of the whole lagoon. It turned out that this would be a bridge too far, mainly for two reasons. First, extensive data sets would be needed, however these were unavailable. Second, the involved processes and feedbacks would introduce large complexity; this would neither be beneficial to the understanding of the model performance nor to the analysis of the model results. Hence, the physical model was restricted to a 2DV model, where processes in the vertical are still included, but only the spatial gradients in one horizontal direction are assessed.

A significant and probably obvious disadvantage of the 2DV model is that there is always information "lost" by going from 3D modelling to 2D modelling. In a 2DV model, the system behaviour is examined in one horizontal direction only, which is the direction of the forcings, and the processes in perpendicular directions are excluded. Therefore, the fundamental assumption needed to be assessed: is it true that all important transport and forcing mechanisms act in the same direction as the 2DV model? The answer to this question was found in the analysis of the flow velocities and directions provided by DHI of the 20 locations (see subsection 4.2.3, Figure 4.5). In general, it could be concluded that circular flow in the horizontal direction was absent during these dynamic conditions. This conclusion was critical, as it supported the underlying requirements for a 2DV model. Furthermore, from these main wind directions (east-west) it was decided to place the 2DV transect in the same direction, i.e. east-west orientated.

In the vertical direction, the return flow induced by the wind will play an important role in the vertical velocity profile, especially in the shallowest parts of the transect. Furthermore, the eelgrass development is highly dependent on the spatial distribution, as in nature it is possible to close up a bare seabed or uprooted patch by horizontal extension of the rhizomes and vegetative growth of shoots. Eventually, this horizontal eelgrass development was not taken into account in the model approach explicitly as the growth for each grid cell was evaluated and calculated separately, i.e. independently from neighbouring grid cells. To always allow and sustain growth, some sparse but viable plants remain in every grid cell for an otherwise bare seabed, meaning that the model contains a lower threshold for the state variables.

The developed numerical model is process-based, which means that physical relations between hydrodynamics, sediment dynamics, the eelgrass, and the environment are implemented. The choice for developing a process-based model instead of an empirical model is based on the required applicability: the model is intended for climate change modelling; in other words, for extrapolation of the present situation with additional conditions accounting for climate change. Process-based models are more reliable in this case: physical relations stay the same over time, whereas the conditions in an empirical sense may change extensively. An empirical model would be much less reliable and even undesirable for this application.

## 5.2 Physical model

The physical model that has been developed during this study makes use of the numerical simulation program Delft3D, developed by Deltares. Delft3D is composed of several modules, including the FLOW and the WAVE module. The physical model uses an online coupling between the modules Delft3D-FLOW and -WAVE. The composition of the physical model is described in this section, of both the Delft3D-FLOW module and the Delft3D-WAVE module separately.

## 5.2.1 Delft3D-FLOW

Delft3D-FLOW is a multi-dimensional (3D) hydro- and morphodynamic simulation program which calculates non-steady flow and transport phenomena that result from meteorological forcings on a boundary-fitted grid (Deltares, 2017), for instance. This physical model calculates for example wind-driven flow, sediment transport, and wave-driven currents and includes for example an advanced turbulence model to account for vertical turbulent viscosity and diffusivity (k-ɛ turbulence model).

## Bathymetry and grid parameters

The physical 2DV model uses a realistic transect from location 16 to the west coast of the lagoon, with a total length of approximately 19 km, considering the actual bathymetry and therefore the depth gradient that is present in the lagoon. This actual bathymetry is derived from EMODnet (EMODnet Bathymetry Consortium, 2016) and is depicted in Figure 5.1. The accuracy of the bathymetry map is 1/8 arcminute x 1/8 arcminute, which is the same as 134 m in the longitudinal direction and 231.5 m in latitudinal direction. The grid size of the physical model in x- and y-direction (i.e.  $\Delta x$  and  $\Delta y$ ) is based on this accuracy of the EMODnet bathymetry. The number of grid cells in the transect (142 in m- or x-direction, 1 in n- or y-direction) is based on

the distance between the offshore and onshore location (x-direction) and the application as a 2DV-model (y-direction), where only 1 grid cell is needed. As Delft3D needs one extra "virtual" grid point in both directions, the total number of grid points was set on 144x3.



Figure 5.1 Bathymetry of the modelled transect

Table 5.1 shows the model location, the actual depth, and the corresponding depth zone of the chosen observation points, which are the discretised locations that lie within the vicinity or in the transect (see Figure 4.1 and Appendix C). In this way, the model results can be compared to the data of DHI.

| Location | Depth [m] | Depth zone | Grid point [-] |
|----------|-----------|------------|----------------|
| 16       | 5.30      | 4-6 m      | 1              |
| 15       | 5.91      | 4-6 m      | 13             |
| 14       | 5.27      | 4-6 m      | 22             |
| 12       | 4.10      | 2-4 m      | 47             |
| 9        | 1.77      | 1-2 m      | 60             |
| 6        | 3.33      | 2-4 m      | 78             |
| 4        | 0.57      | 0.5-1 m    | 125            |
| 3        | 1.32      | 1-2 m      | 110            |
| 2        | 1.62      | 1-2 m      | 104            |

#### Table 5.1 Locations (observation points) that are contained in the modelled transect

#### **Vertical layering**

As this 2DV-model is defined in both the x-direction and z-direction, vertical ( $\sigma$ -)layers have been assigned to the model. The layer thickness of the physical model is therefore defined as a percentage of the (possibly time-varying) water depth. The layering was based on the largest water depth, the inclusion of wind at the surface and vegetation at the bottom of the transect: to resolve both wind and vegetation accurately, these layers should be small. Furthermore, the variations between the layers should not be large, i.e. the layer distribution must be smooth. The process of determining the dimensions of vertical layers was iterative, as the velocity profile over the water column was investigated to check whether the accuracy was the same as for 100 layers of all 1% (see Appendix C).

| Layer   | Thickness [%] | Layer       | Thickness [%] |
|---------|---------------|-------------|---------------|
| 1 (top) | 2             | 12          | 7             |
| 2       | 2             | 13          | 5             |
| 3       | 3             | 14          | 3.5           |
| 4       | 5             | 15          | 2.5           |
| 5       | 7             | 16          | 1             |
| 6       | 7             | 17          | 1             |
| 7       | 8             | 18          | 2             |
| 8       | 8             | 19          | 2             |
| 9       | 10            | 20          | 2             |
| 10      | 10            | 21          | 2             |
| 11      | 8             | 22 (bottom) | 2             |

| Table 5.2 Vertical lave | ering of the physica | l model (σ-lavers)   |
|-------------------------|----------------------|----------------------|
|                         | sing of the physica  | 111100001 (0-107013) |

#### Numerical settings

The time step of the physical model was chosen based on the propagation of disturbances (waves and flow) through the domain related to the CFL-criterion. The small time step of 0.2 min is used for the accuracy of the results, as stability is not an issue in this case. The output interval of the physical model parameters was set at 1 hour, as both the provided wind data and the surface light are hourly values as well.

#### Meteorological forcing: wind

The data of DHI comprised hourly wind data for the year 2005. This data set was implemented in the physical model in both the FLOW and WAVE module. Surface flow is therefore computed by the model, as a result of the wind shear stresses on the water surface.

With an easterly wind, the flow velocity is directed towards the left at the surface, flowing into the domain. This surface flow is induced by the wind. The influence of the wind on the flow velocity decreases with increasing depth, therefore the velocity magnitude reduces. However, a return current is induced lower in the water column, meaning that the flow is directed to the right close to the seabed. Also wind set-up is taken into account by the physical model. When there is an easterly wind, the water level builds up at the closed end of the transect, but when a westerly wind prevails, the water is pushed away from the closed end towards the offshore boundary.

#### Initial and boundary conditions (Water level boundary East, other boundaries are closed)

The only boundary condition applied is at the offshore side of the domain (at location 16), since all other boundaries are closed. The offshore boundary ensures that there is a balance between water inflow and outflow. The open boundary condition is defined by a constant water level (0 m MSL) to force the model to compute the inflow and outflow and flow velocities itself.

The initial conditions can be applied in Delft3D using a cold start, where a user-defined input is applied, or a hot start where the results of a previous simulation are used as input. The former is used for the tests of week 1, whereas the latter is used for long-term simulations comprising multiple weeks.

#### Sediment transport

The sediment transport of two fractions is computed in this physical model. The smallest fraction, comparable to the d<sub>10</sub> that was given in the accumulated grain size distribution (Figure 3.5), is modelled as a cohesive fraction with a grain size of 10  $\mu$ m. This smallest fraction represents all the fines that are present in the seabed of the study site and have the largest impact on the light attenuation. A larger sediment fraction, d<sub>50</sub> of the given accumulated grain size distribution with a grain size of 170  $\mu$ m, was modelled as a sand fraction (i.e. non-cohesive sediment). The bed composition was unknown, but the initial thickness of both layers was adjusted to the suspended sediment concentration that resulted from both fractions. Also, all other sediment parameters, such as the dry bed density, the fall velocity  $w_s$ , the erosion parameter *M*, and the critical bed shear stress for erosion  $\tau_{cr}$  were investigated and adjusted according to an optimisation procedure.

Many different combinations of sediment parameters were simulated for three different locations, see Appendix C.2. During these test simulations, vegetation was excluded but the effect of both flow and waves on the bed shear stress was simulated with the coupling of Delft3D-FLOW-WAVE. The vegetation was excluded to be able to compare the sediment simulation results (with different sediment parameter settings) with the data of DHI, as their model also excludes the effect of vegetation on the bed shear stress.

The optimal settings of the sediment parameters derived from the sediment simulations are summarised in Table 5.3. The model simulation (test 30, see Appendix C.2) with these settings showed the largest resemblance to the converted NTU to SSC data of DHI. Hereby it was aimed to model the dynamic behaviour of the sediment resuspension (i.e. in terms of erosion- and deposition rates), similar to the rates of the converted SSC data.

| Sediment d <sub>50</sub>                          |        |        | Sediment d <sub>10</sub>                                   |       |                                    |
|---|--------|--------|--|-------|------------------------------------|
| Parameters  | Value  | Unit   | Parameters   | Value | Unit                               |
| Sediment type (SedTyp)                            | sand   | -      | Sediment type (SedTyp)                                     | mud   | -                                  |
| Specific density $\rho_s$ (RhoSol)                | 2650   | kg m⁻³ | Specific density $\rho_s$ (RhoSol)                         | 2650  | kg m⁻³                             |
| Median sediment diameter d <sub>50</sub> (SedDia) | 1.7e-4 | m      | Settling velocity w <sub>s</sub> (WS0=WSM)                 | 8e-5  | m s <sup>-1</sup>                  |
| Dry bed density (CDryB)                           | 1600   | kg m⁻³ | Dry bed density (CDryB)                                    | 500   | kg m⁻³                             |
| Sediment layer thickness (IniSedThick)            | 5      | m      | Sediment layer thickness (IniSedThick)                     | 0.1   | m                                  |
|   |        |        | Critical bed shear stress for erosion $\tau_{cr}$ (TcrEro) | 0.03  | Nm <sup>-2</sup>                   |
|   |        |        | Erosion parameter M (EroPar)                               | 2e-5  | kg m <sup>-2</sup> s <sup>-1</sup> |

Table 5.3 Optimised parameters for both sediment fractions

To kick-start the import of sediment from the offshore boundary into the domain and thereby increasing the sediment concentrations at the deep locations, some additional tests were performed with use of the results of test 30. First, a varying water level at the offshore boundary was implemented as provided by DHI, with the intention of pushing the water into the domain with a high water level at the boundary and draining the system with a low water level at the offshore boundary. The results showed no significant increase in sediment concentrations at the deep locations, but the sediment concentration did increase at the shallower locations. As this was not the intention, the water level was subsequently kept constant again. Secondly, a higher sediment concentration imposed over the water column at some distance from the boundary was forced to flow in the domain at all times with a small discharge. Also, this intervention did not give the desired results of higher sediment concentrations at the deep locations, as the sediment did not really flow into the domain. Without any progress in resolving the suspended sediment inflow, as proven by these short-term tests, it was decided to continue the simulations with the original settings (boundary conditions: constant water level and time-varying sediment concentration imposed over the water column).

#### Vegetation

There are more methods to implement vegetation in Delft3D, see Appendix C for detailed descriptions. The first method is based on the assumption that the vegetation could be represented by a modified bed roughness, i.e. the vegetation is represented as a large bed structure. However, this would give incorrect results, as the vertical flow velocity profile cannot be represented correctly. Also, the imposed bed shear stresses would become higher instead of lower, of which the latter is correct when vegetation is present. Sediment transports would be severely overestimated compared to the actual sediment transports when vegetation is present. Therefore, another method needs to be applied.

The effect of eelgrass is implemented in Delft3D-FLOW by means of the rigid (3D) vegetation module. For a detailed explanation, see Appendix C. The essence of this rigid vegetation module is that vegetation is represented as rigid cylinders with the dimensions of the plants (vegetation height  $h_{veg}$ , stem diameter *b*), and by their presence adding extra source terms to the turbulent kinetic energy (*k*) and dissipation ( $\varepsilon$ ) equations. These extra source terms describe the amount of work spent by the vegetation on the fluid, hence introducing increased turbulence where vegetation is located.

Furthermore, the vegetation is made dynamic, as the growth development of the (eelgrass) vegetation over time, as well as the spatial variation in both height and stem density, are included in the physical model by means of the coupling with the growth model (see sections 5.3 and 5.4). The diagram in Figure 5.2 shows how the outcomes of the growth model and the coupling are used as input for Delft3D-FLOW. As plant heights are confined to height classes, only a limited number of "different" plants need to be assigned in the plant input (\*.inp) file to the Delft3D-FLOW module. Subsequently, for every height class, the number of shoots per m<sup>2</sup> is defined for every grid cell in separate \*.dep-files, related to the model grid. Delft3D-FLOW uses both the \*.inp- and \*.dep-files to take into account the spatial varying vegetation. As the coupling between the growth model and the physical model is performed every week, the vegetation in Delft3D-FLOW is also updated weekly.

#### **Excluded model parameters**

Salinity has not been taken into account and is therefore set to zero. The specific density of water  $\rho_w$  is therefore set to 1000 kg m<sup>-3</sup>. Temperature has been excluded in the physical model as there is little effect on the hydrodynamics and sediment dynamics, but it is included in the growth model. The same holds for light, this is implemented in the coupled model and the growth model, but not explicitly calculated in the physical model.

#### 5.2.2 Delft3D-WAVE

This module of Delft3D, Delft3D-WAVE, can use the SWAN model (an acronym for Simulating WAves Nearshore) to compute the evolution of random, short-crested wind-generated waves in coastal regions and inland waters. This SWAN model was developed at the Delft University of Technology and integrated into the Delft3D model suite. For detailed information about SWAN, one is referred to its homepage (The SWAN team, 2018). Here, only the main features of SWAN that are used in this study and that require explanation are highlighted.

Essentially, six physical processes of generation, dissipation, and nonlinear wave-wave interactions are implemented in SWAN: wave growth or energy input by wind, non-linear transfer of wave energy through three-wave and four-wave interactions and wave decay due to white capping, bottom friction, and depth-induced wave breaking. The main forcing mechanism in this wave model is wave generation by wind, as offshore waves are not of interest at this study site due to its sheltered condition (and therefore offshore waves were excluded in the model).

#### Bathymetry

The bathymetry in Delft3D-WAVE was based on the transect already developed for Delft3D-FLOW. However, as SWAN needs both horizontal directions to compute the waves in the domain, and for the energy leakage at the boundary of the wave domain

not to influence the flow transect, the bathymetry of the transect was duplicated in the y-direction. The final number of grid points in both x- and y-direction (m- and n-direction) is therefore 144x65 (142x63 grid cells).

#### **Boundary conditions**

The boundary conditions that were implemented at the offshore boundary are derived from the wave data of DHI at location 16 and were assumed constant in the y-direction. These wave data consisted of the wave height, wave period, wave direction (assumed to be the same as the wind direction), and the directional spreading, assumed as a cosine power of 4 ([-], see (Deltares, 2018)).

#### Vegetation

A seventh physical process can be added to the above-mentioned six essential processes in SWAN: wave dissipation by vegetation. The method that is used by SWAN is the cylinder approach as suggested by Dalrymple et al. (1984) and extended by Mendez and Losada (2004), as described in subsection 1.3.3. This method of implementing vegetation in Delft3D-WAVE is of the same sort as the method described for Delft3D-FLOW. In SWAN, vegetation motions such as swaying and reconfiguration are (also) neglected, as the plants are modelled as cylinders. The mean rate of energy dissipation per m<sup>2</sup> due to wave damping by vegetation is given by equation (1.9) in subsection 1.3.3.

The only parameter that is further required is the bulk drag coefficient  $\tilde{C}_D$ , depending on the hydrodynamics and the plant type. As said in subsection 1.3.3, the bulk drag coefficient of eelgrass was found to be 0.1, based on the studies of Bradley and Houser (2009) and Paul and Amos (2011) which were performed for two other types of seagrass (*Thalassia testudinum* and *Zostera noltii*, respectively). In the physical model, a value of 0.1 was subsequently used.

The spatial density of the vegetation can be varied in SWAN, however implementing spatially varying height is excluded. A fixed value of 0.25 m was used for the vegetation height in SWAN for all simulations; a practical value that takes implicitly into account the flexibility of the vegetation (by bending of the vegetation, the effective height is reduced).

### 5.2.3 Coupling Delft3D-FLOW-WAVE

The online coupling between DELFT3D-FLOW and -WAVE involves a dynamic interaction in two ways. Through this coupling, both the effect of waves on the flow and the effect of the flow on waves are accounted for by means of wave-driven currents, enhanced turbulence, and bed shear stress. Data is exchanged between both modules using a communication file, which contains the most recent data of the flow and wave computations. Essential is the interval at which the communication file is stored: this is related to the computational time of the model and the needed accuracy for the modelling purpose. It was found that a coupling interval of 3 hours was efficient enough in terms of computational time and accurate enough for the model results (see Appendix C).

The effect of flow on waves (by the set-up, current refraction, and enhanced bottom friction) and the effect of waves on flow (by forcing, enhanced turbulence, and enhanced bed shear stress) are accounted for in the coupling of Delft3D-FLOW-WAVE.



Figure 5.2 Modelling dynamic vegetation in Delft3D-FLOW

## 5.3 Growth model

#### 5.3.1 Introduction

The purpose of the growth model in this study is to examine the annual and interannual morphology and condition of eelgrass meadows under environmental stressors, e.g. hydrodynamic forcings and climate change effects. As different and more difficult physical phenomena (such as deviation of the flow, scour around the stems of the plants, etc.) act on the meadow edge, this model only assesses the development of eelgrass plants at sufficient distance from the meadow edge, where these phenomena can be omitted.

Multiple eelgrass growth models have been studied: Bach (1993), Verhagen & Nienhuis (1983), Zharova et al. (2001) and Carr et al. (2012a, 2012b). All four of these models describe seasonal variations in both above- and belowground production and biomass and the models are used as a predictive tool, e.g. for lake management. However, the four models have a different focus. Verhagen & Nienhuis created a complex mathematical model that requires a lot of data, incorporating the effect of ageing of the eelgrass population. Bach's eelgrass model is used as a submodel for a eutrophication model, therefore paying attention to the nutrient limitation of eelgrass growth. Moreover, here the belowground biomass is not explicitly modelled (only modelled as a percentage of aboveground biomass). Zharova et al. used their model for analysis of the Venice lagoon: they assessed the importance of individual factors (light, temperature, etc.) for the overall eelgrass dynamics. Finally, the model of Carr et al. was used (together with a 1DV hydrodynamic model) in assessing the complex interactions between hydrodynamics, sediment dynamics and (inter-)annual cycles of eelgrass development and altered conditions in case of climate change. Furthermore, the main difference between the multiple growth models is the climate: both Bach and Verhagen & Nienhuis modelled eelgrass development in temperate climates (Denmark and the Netherlands respectively), whereas Zharova et al. and Carr et al. modelled eelgrass development in a much warmer climate (Venice, Italy and Hog Island Bay, VA, USA, respectively).

The model of Carr et al., hereafter also referred to as "Carr's model" for simplicity, is used in this research, as it is the most recent version and builds upon prior efforts to model seagrass growth dynamics. It was originally used for research with the same purpose as the research of this thesis: modelling eelgrass development on longer timescales (related to climate change) taking into account water-sediment-vegetation interactions. By using this validated and well-documented model, model consistency is guaranteed. Replicating and assessing the functioning of the growth model and the implications of the outcomes are therefore relatively transparent. Developing a new growth model has never been the main focus of this research: the coupling of an eelgrass growth model with the physical Delft3D-model and the feedback loops between these two models is the key objective. Also, validation of a new growth model would not be possible, as suitable and complete datasets to perform these validations are lacking. The only consequence of direct implementation of Carr's model for the Rødsand lagoon study site was the climate: the temperate eelgrass population studied here has other light and temperature requirements than eelgrass in a warm climate, such as Carr's study site. Ultimately, some adaptations to Carr's model have been made to represent the conditions in the Rødsand lagoon best.

## 5.3.2 Model framework

The complete eelgrass growth model equations for calculation of the state variables N (total number of shoots per area), P (biomass per shoot [gC]), R (belowground biomass [gC m<sup>-2</sup>]), and  $h_{veg}$  (vegetation height [m]) of Carr et al. (2012a, 2012b) with the applied adaptations and detailed explanations are included in Appendix D.

In general, the growth model is based on the following relations. The aboveground biomass per m<sup>2</sup> B [gC m<sup>-2</sup>] is the product of the total number of shoots N and the biomass per shoot P:  $B = N \cdot P$ . New shoot recruitment and biomass production are direct functions of daily available irradiance (related to the suspended sediment concentration in the water column) and average water temperature. Respiration is scaled only as a function of daily average water temperature. A fraction of the aboveground production is transferred to a combined rhizome biomass R. The growth model uses belowground (or rhizome) biomass as energy storage for vegetative growth, i.e. to form a new shoot, thereby supporting shoot recruitment. Mortality of an individual shoot in turn affects both the associated aboveground biomass and some small fraction of the belowground biomass through uprooting. Not included in the growth model are the energy translocation to the rhizomes prior to leaf and shoot senescence and biomass allocation into flowering and seed components for sexual reproduction.

Carr's original model allocates and tracks the biomass by accounting for the distinct structural components (individual leaves and stems) for each shoot. In this study, these leaf and stem components are not simulated explicitly, mainly to simplify the modelling procedure. Instead, one shoot biomass (*P*) and one vegetation height ( $h_{veg}$ ) are used. The shoot is simulated as a bundle of a predefined number of leaves and the biomass is the same for all individual shoots. The vegetation height is scaled directly to the shoot biomass:

$$h_{veg} = \frac{P}{\rho_{veg} \cdot \# leaves}$$
(5.1)

Using this equation for vegetation height implies that all shoots and all leaves of the plants in the modelled 1 m<sup>2</sup> have the same length.

Another difference with the original Carr model is the leaf age limitation function. Carr et al. modelled all individual shoots and leaves and could therefore indicate the age of each component. As growth development data (e.g. ages) of these components at the study site is not available, one shoot morphology is used, and age of the plants is omitted. The leaf age limitation function  $F_{age}$  is adapted: the leaf age is averaged for the reference case of Carr and omitted for the Rødsand study case ( $F_{age} = 1$ ) and both assumed constant over time. As a consequence, there is no change in shoot biomass caused by loss or regrowth of leaves: the plant always has the same amount of leaves.

#### **Limitation functions**

As plants need light for photosynthesis, it is one of the main growth requirements together with temperature. The light limitation function used in the growth model is based on the photosynthesis-irradiance (P-I) curve, see Figure 5.3. The P-I curve consists of an initial slope  $\alpha$ , the compensation irradiance  $I_{o}$  and the maximum photosynthetic rate  $P_{max}$  at saturation irradiance  $I_{k}$ . According to Bulthuis (1987), it is proven that water temperature in temperate climates has no effect on the initial slope  $\alpha$  of the P-I curve, as this slope is fully determined by irradiance [µmol photons m<sup>-2</sup> s<sup>-1</sup> or µE m<sup>-2</sup> s<sup>-1</sup>]. However, as respiration increases with increasing temperature, the temperature does have an effect on the compensation irradiance  $I_{c}$  and saturation irradiance  $I_{k}$ . This means that for increasing temperatures, the plant needs a higher irradiance to produce the same amount of biomass.



Figure 5.3 Photosynthesis vs. irradiance (light intensity) curve

Attenuation of light in the water column is due to particles present in the water column, causing absorption and scatter of light, see section 1.4. Those particles can be organic (e.g. chlorophyll a and CDOM) or inorganic (suspended sediment). In this growth model, the total light attenuation coefficient  $K_d$  is represented as the sum of the background value  $K_{back}$  and light attenuation caused by suspended sediment  $K_{ssc}$ . The background light attenuation  $K_{back}$  consists of the light extinction due to absorption and scattering by organic particles and the water itself and is assumed constant in time and space. The suspended sediment light attenuation coefficient  $K_{ssc}$  is space- and time-varying, as is the suspended sediment concentration, and depends on the grain size of the suspended sediment. The absorption of light  $a [m^2g^{-1}]$  by sediment is constant, is not depending on grain size and is relatively small compared to the scattering of light  $b [m^2g^{-1}]$ , which is grain size dependent. For b holds: the smaller the sediment particles, the larger the scattering of light.

$$K_d = K_{back} + K_{SSC} \tag{5.2}$$

$$K_{SSC} = \sqrt{a^2 + 0.256ab} \cdot SSC \tag{5.3}$$

The values used for the light attenuation coefficients in the modelling procedure are mentioned later in this chapter, in the section 'Model implementation'.

Similarly, the temperature can limit growth as the eelgrass plants have a range of optimum temperatures in which photosynthesis can be performed. In warm climates, often higher temperatures are limiting, whereas in temperate climates the lower temperatures will limit eelgrass productivity. The multiple growth models mentioned earlier are either developed for a

warm climate or for assessing eelgrass growth in a temperate climate. Hence, the multiple growth models use different temperature photosynthesis limitation functions (see Figure 5.4). The temperate climate models of Bach (1993) and Verhagen & Nienhuis (1983) use the temperature photosynthesis limitation function as indicated by 'ft1' in Figure 5.4, whereas the warm climate models of Zharova et al. (2001) and Carr et al. (2012a, 2012b) use the photosynthesis temperature limitation function as indicated by 'ft2'.



Figure 5.4 Temperature limitation functions (adapted from Zharova et al., 2001)

For the temperature respiration function, all of the multiple growth models use the function indicated by 'ft1'. The used limitation functions for the growth model in this study, their descriptions, and sources are given in Appendix D, Table 13.

### 5.3.3 Model implementation and verification

To determine whether the growth model is working and implemented correctly in the numerical computation program MATLAB, the case of Carr et al. (2012a) with those specific environmental conditions has been replicated first. The plant parameters were optimised (see Appendix D.2) and when the reliability of the growth model was established, i.e. when the model showed sufficient resemblance to empirical observations and the results of Carr's case, the growth model as used for replication of the Carr's case was used for the Rødsand lagoon case. As the climates are very different, some minor adaptations had to be made to make Carr's model suitable for the Rødsand lagoon case.

#### Reference case: Carr et al (2012a)

Carr et al. used their growth model to investigate the dynamics of eelgrass in Hog Island Bay, a shallow coastal bay in Virginia, USA. The year 2000 has been used as a reference case, as the eelgrass showed stable growth during this year according to Carr et al (2012a). The number of days with eelgrass growth was the largest of the examined nine years and the number of days exhibiting a loss (above 28°C or below 5°C) was the smallest. Furthermore, the temperature never exceeded 30°C (which is the identified threshold for summer die-offs) and the number of sediment transport events during the year 2000 was the lowest. Besides these favourable conditions, the data needed to perform the Carr reference case were practically available and complete for the year 2000, contrary to the other years exhibiting favourable conditions and stable growth. The required data consisted of temperature and irradiance. Hourly water temperature data were obtained from the NOAA Wachapreague station in Virginia, USA (WAHV2, 37°36'N, 75°41'W). Hourly measurements of photosynthetically active radiation (PAR) of incident radiation were obtained from the VCR-LTER station Hog Island (37°27'N, 75°40'W).

The initial conditions (for 1 January 2000) of the state variables were not given by Carr, hence they were approximated from the published figures and varied during the optimisation of the growth model. The initial aboveground biomass  $B_0$  and belowground biomass  $R_0$  were given by Carr (63 and 32.8 gC respectively),  $N_0$  was varied during the optimisation and  $P_0$  and  $h_{veg0}$  were calculated based on  $B_0$  and  $N_0$ . The depth of 1.6m MSL was the same as used in the original research and here considered constant over time (although the location experiences a tidal range of 1 m). The light attenuation coefficient  $K_d$  was implemented as determined by Lawson et al (2007) and used by Carr et al.:  $K_d = 0.2784 + 0.052 \cdot SSC$  (the background light attenuation  $K_{back}$  was set to 0.2784 and the suspended sediment light attenuation  $K_{ssc}$  was given as 0.052 · SSC). However, data of the SSC (variation over the year, number of resuspension events, average and extreme values) were lacking. Two constant values for the SSC, i.e. in spring/summer and in autumn/winter, have been taken and have been used in the optimisation procedure. For the model simulations and exact details on the optimisation procedure, see Appendix D.2.

#### **Results Reference case**

The results of the reference case as explained above are promising. The original figure made by Carr et al., displaying the ratio and interannual variation in above- and belowground biomass for the year 2000 is shown in Figure 5.5A. In Figure 5.5B, the best replicate simulation of Carr's model is shown, the graphs in this figure represent also above- and belowground biomass for the year 2000.



Figure 5.5 A) Original growth model simulation by Carr et al. for the year 2000 and B) the best simulation of the replicate model case (run 4).

As can be seen in Figure 5.5A and Figure 5.5B, all year-round dynamics are reasonably well-replicated. Also the reaction of the model to long-term and short-term disturbances is visible. Due to the warm climate and the corresponding high water temperatures, the eelgrass is unable to sustain growth between July and October. The aboveground biomass growth in the replicate model (3B) is overestimated, although the graph has a similar shape to the original simulation. One of the reasons for this overestimation could be the unknown hydrodynamic conditions, e.g. the wave-current conditions, and the corresponding varying SSC that Carr et al. have taken into account, but could not be reproduced with the replicate model. The belowground biomass of the replicate model also shows a similar shape to the original model. However, due to the overestimated aboveground biomass, the ratio of above- and belowground biomass in Figure 5.5B could be misleading.

These results establish the general performance of the model; hence the model has been used for the Rødsand lagoon case.

#### Research case: Rødsand lagoon (2005)

The growth model formulations are the same as for the reference case of Carr et al., with the exception that the temperaturerelated limitation functions  $F_{phot}$  and  $F_{T}$  are adapted to a temperate climate using the related functions of Bach (1993).

DHI provided all year-round eelgrass development by means of aboveground biomass (see Figure 4.2), of which location 9 has been replicated by the growth model: this location is part of the modelled transect with the coupled model.

As the model simulation was performed stand-alone for the moment, i.e. not coupled with the hydro-morphodynamic computations of Delft3D, subsequently the water depth and the SSC calculated from the DHI (model) data were used here. The data of DHI showed that the daily average water temperature in the Rødsand lagoon is approximately the same everywhere. The background light attenuation coefficient  $K_{back}$  was calculated based on the provided surface- and bottom light model data of DHI and was established at 0.24 for location 9. The initial state variables  $B_0 = 18.23$ ,  $R_0 = \frac{1}{2}B_0$  and  $P_0 = \frac{1}{2}B_0/N_0$  were used. Again, an optimisation of the model has been performed for the current situation, where different values for the parameters *#leaves*,  $maxN_{grow}$ ,  $P_{cc}$  and  $K_{back}$  have been tested.  $N_0$ , the initial number of shoots per m<sup>2</sup> has also been varied. For details on this optimisation procedure, see Appendix D.

#### Results study case: Rødsand lagoon, location 9

The result of simulation 13, shown in Figure 5.6, was found to be the most representative, as the results show the largest resemblance to the model data of DHI (smallest RMSE between the data and the model simulation). Also, the maximum height of the vegetation showed correspondence to the values measured during the fieldwork.

The calculated aboveground biomass (in magenta) can follow the original data of DHI (in black) relatively well, but the model calculations clearly deviate from the original DHI data. During the optimisation procedure, the lagging behaviour of the growth model has been investigated. Unfortunately, there is no indication that any of the implemented parameters or limitation functions can be adapted in such a way that this behaviour can be mitigated. Nevertheless, during the year, the short-term and long-term trends are visible, just like they are present in the DHI data. This indicates that the growth model can be used in the continuation of this research. Hence, the growth model is implemented into the coupled model with the settings of run 13.



## 5.4 Coupled model

The coupled model will be described in this section for the baseline case, the present situation with present eelgrass cover, as all other model simulations contain only minor adaptations. These minor adaptations per simulation are described in section 5.5 Model application.



Figure 5.7 Flow diagram of the coupled model

The functioning of the coupled model and the sequence, in which both the physical and growth models are used, is visualised in Figure 5.7. The coupled model is developed as a MATLAB script and basically consists of three phases: the initialisation phase, where all simulation – and plant parameters are given; phase 1, in which the first simulation of the physical model is executed with the initial plant heights and spatial densities, and phase 2, in which the actual (longer term) simulation is executed.

Phase 2 uses the conditions of the physical model simulation of the previous week to calculate the light environment and runs the growth model to calculate the plant development (per day) of the last week. Then plants in the physical model are updated

by taking the output of the growth model for the last day of the past week, in terms of the spatial plant density N and the vegetation height  $h_{veg}$ . The spatial plant density N is then described in the updated plant density input file (for both Delft3D-FLOW and -WAVE) and the calculated values for  $h_{veg}$  are grouped into height classes. A height class matrix divides the individual heights of the plants into height classes of 10 cm. It was therefore assumed that the influence of the plants on the hydrodynamics does not differ substantially between e.g. vegetation heights of 20 and 30 cm respectively, as both will be assigned to the height class of 25 cm. Subsequently, the master definition file (\*.mdf) of Delft3D-FLOW is updated for the new week (start- and stop time of the simulation, the output files of the last week are used as restart files, etc.). Lastly, the physical model will start computing the next week with updated plants. Overall, this means that all Delft3D simulations are performed for the vegetation state at the beginning of the week. Here, it was assumed that the influence and the growth/decay rate of eelgrass only differ substantially over the timescale of one week, considering the relatively slow growth/decay rate of eelgrass plants.

What is implemented besides just using the physical model (Delft3D-FLOW-WAVE-Veg, taking care of the feedbacks between hydrodynamics, sediment dynamics, and eelgrass), and the growth model (resembling the growth dynamics of the eelgrass) is the essential coupling between both models: the calculation of light available for eelgrass development. This light calculation in the coupled model uses the hydrodynamic and sediment conditions of the previous week, e.g. the SSC over the water column and the water depth (calculated by the physical model), as input for the growth model. The calculation itself is based on the background light attenuation  $K_{back}$  (caused by anything else than suspended sediment) and the effect of changing sediment concentration over the water column (i.e. in the vertical direction, over the different model layers). The coupled model uses the hourly instantaneous values of the surface irradiance and the sediment concentrations of the two sediment fractions in every layer of the water column (from the physical model). Then the attenuation of light over every layer of the water column (including the available light at the bottom  $I_{bottom}$ ) is calculated per hour, see Figure 5.8. Hence, the Lambert-Beer equation (equation(1.17) in section 1.4) and the equations for the light attenuation coefficient  $K_d$  (equations (5.2) and (5.3) in subsection 5.3.2) are used. As the timescale of the growth model is one day (i.e. 24 hours), the hourly values of bottom light are integrated over the day. This is a different and more practical "civil engineering-based" approach than used by the ecological model of DHI, in which turbidity units were used and the light was smoothed over the day.



Figure 5.8 Schematisation of the light calculation implemented in the coupled model

By performing the light calculation as described in this section, the incident light is calculated at the bottom, i.e. the seabed. This means that the actual incident light at the leaves is slightly underestimated, as the leaves find themselves at some distance from the bottom (related to the vegetation height). On the other hand, self-shading and shading of the bottom light by the leaves have been excluded, resulting in a slight overestimation of the incident irradiance at the bottom. Overall, the order of magnitude of incident light at the bottom is assumed to be reasonable as both the vegetation height and shading cancel each other out.

The coupling interval between the physical and the growth model is one week: after one week of hydro- and morphodynamic simulations with the physical model, the plant development during the past week is calculated using the growth model. The time step of the growth model itself is one day, but the coupling interval has been set to one week. It is assumed that the growth of the eelgrass plants only differs significantly on this weekly timescale. Hence, the computational time is reduced compared to using a coupling interval of a day.

## 5.5 Model application

The coupled model is used as a conceptual model to explore the possible effects of climate change on the eelgrass development for one year. The simple question that is supposed to be answered while assessing each climate change effect is: "What happens if...?" The magnitude of the climate change effects has been based largely on the BACC II, the most recent downscaling study of climate change for the Baltic Sea. However, since this model study explores the conceptual effects of climate change, more severe effects have also been simulated to see whether the tipping point of the system (going from a vegetated state to a bare seabed) could be observed.

## 5.5.1 Baseline cases

#### Baseline case 1: Present situation with present eelgrass cover

The present situation with the "known" eelgrass cover serves as the reference case for all other simulations. The conditions for the year 2005 have been implemented as described in section 5.4 Coupled model.

The initial eelgrass cover has been derived from the aboveground biomass data of DHI at locations that are within or close to the modelled transect. The used locations are mentioned from east to west (in onshore direction): location 16-15-14-12-9-6-2-3-4. Location 5 was excluded, as the data showed that this eelgrass cover is under influence of the inflow opening at the southwest of the lagoon. Subsequently, for the grid cells that are situated between locations, linear interpolation of the aboveground biomass was performed. As explained before, the aboveground biomass is the product of the number of shoots and the biomass per shoot. To reduce the number of variables to be adapted, it was assumed that the spatial density N is less uniform than the vegetation height  $h_{veg}$  (or biomass per shoot P), therefore the vegetation height (and the biomass per shoot) was initially kept constant over the whole transect and the number of shoots per m<sup>2</sup> is varied according to the varying aboveground biomass.

With this baseline case, the basic model performance and accuracy are examined. Moreover, it is possible to quantify the relative effects of the climate change-related simulations by comparing those simulation results with this baseline case.

#### Baseline case 2: Present situation with the bare seabed

This case is based on Baseline case 1; however, in this case almost no eelgrass is present from the start of the simulation. Unfortunately, the model is incapable of growing eelgrass from an absolutely bare seabed, as flowering plants or dispersion of seeds is excluded. Therefore, some initial vegetation in the form of seedlings, viable plants that can sustain the growth of new plants, is included in every grid cell of the model. This sparse vegetation can be the start of new eelgrass populations and eelgrass restoration can be assessed in this way. Nevertheless, the sparse eelgrass population may be the reason for the environmental conditions to become adverse. As there is almost no vegetation, both the flow and waves will not be attenuated, causing the bed shear stress to be higher than with eelgrass presence, therefore sediment resuspension will increase, and the light environment will subsequently become unfavourable, possibly resulting in decay of the sparse eelgrass vegetation.

The goals of this simulation are 1) to investigate whether the environmental conditions have become too adverse (in absence of a dense eelgrass cover) for the sparse vegetation to grow back to the original eelgrass cover and 2) to examine in which areas it is possible for the plants to grow back when the environmental conditions are found to be still favourable.

All model input parameters, boundary conditions and forcings are the same as for Baseline case 1. The initial vegetation is the only difference: in this case it is as if the eelgrass in the transect has been removed, except for some viable seedlings that are left behind. In the model, this has been implemented at the beginning of the year as if 5 plants per  $m^2$  for each 0.3 m length in every grid cell are present.

## 5.5.2 Cases with climate change effects

The effects of climate change on shallow coastal systems with eelgrass populations are imminent and possibly threatening to eelgrass development. The year-round simulations that have been performed by the coupled model are focussing on a single climate change effect at a time: either it concerns sea level rise or temperature increase or increase in storminess.

#### Climate change effect 1: Sea level rise (SLR1 and SLR2)

The effect of sea level rise on the study site has been investigated using two simulations. SLR1 was the first simulation that comprised a water level elevation of 1 m on top of the modelled water level of 2005. According to the downscaling study of the Baltic Sea (BACCII), this is a reasonable but at the high-end prediction. After the observed effects of simulation SLR1, a second simulation, SLR2, was performed with a higher water level increase of +1.5 meter on top of the modelled water level of 2005. This increased water level is higher than the high-end prediction of the BACC II, however this increase is not unrealistic. As the sea level continues to increase non-linearly over time, mainly depending on the emission of greenhouse gasses and the self-

enhancing effect of climate change, it is possible that the resulting sea level rise is higher than the high-end predictions made in the past. Therefore, the effect of this high sea level rise of +1.5 meter on the study site has been explored.

The underlying hypothesis of the effect of sea level rise on the coastal system with eelgrass is twofold. Raising the water level causes the water depth to increase; therefore the light needs to travel a longer way and is attenuated to a larger extent. This higher light attenuation increases exponentially with increasing depth, related to the Lambert-Beer equation (equation (1.17)). On the other hand, the influence of the waves on the seabed (i.e. by means of the orbital velocity inducing bed shear stress, thereby bringing sediment in suspension) decreases hyperbolically with increasing water depth (see Appendix A.3, equation (A.11)). Less sediment is brought into suspension, resulting in a possibly positive feedback to the light environment. To summarise, the sea level rise affects the light climate in two ways, both positively and negatively.

The model input parameters, the forcings, and the (initial) plant parameters are the same as for Baseline case 1. Sea level rise is included in the model by defining different conditions for the offshore boundary: the water level is still kept constant over the whole year, but now the water level is raised from 0 m MSL to +1 or +1.5 meter MSL, depending on the simulation. Also, the initial water level over the whole transect has been adapted to +1 or +1.5 meter MSL to match the initial boundary conditions.

#### Climate change effect 2: Temperature increase (TEMP1)

The increase in water temperature for this specific study site (Rødsand lagoon) has been derived from the BACC II, see section 1.1.5. A projected change in seasonal average sea surface temperature has led to the following values: in winter (December-January-February) the projected temperature increase is 2.4°C, in spring (March-April-May) the increase is 2.6°C, in summer (June-July-August) 1.8°C, and in autumn (September-October-November) 2.0°C.

The expected effect of an increase in water temperature is the growth- and decay rate, i.e. the eelgrass development, as implemented in the growth model (section 5.3.2 and Appendix D). As a result of higher temperatures, the demand for irradiance will also become higher to produce the same amount of biomass, related to the temperature limitation functions for photosynthesis and respiration. As long as the required irradiance is available, both growth and decay will take place at a much faster rate for higher water temperatures.

To examine whether water temperature increase in itself has a noticeable effect on the eelgrass development, a high-end water temperature increase of on yearly average 4°C has been simulated. Given the original temperature time series, the spatially and time-averaged temperature was calculated from the DHI data (see section 4.2.4, the blue graph in Figure 5.9). This temperature time series has been altered accordingly to the seasonal variations projected by the BACC II (red graph in Figure 5.9), but then for an annual mean increase of 4°C. This means that the seasonal variations were preserved, but on top of these variations, 2°C has been added. Hence, the temperature sequence that is implemented in this simulation is shown with the yellow graph in Figure 5.9.



Figure 5.9 Projected increase of water temperature with the annual means of 2°C and 4°C

#### Climate change effect 3: Increase in storminess (STORM1)

Increase in storminess can be expressed as the increase in duration, magnitude, and frequency of storms during a certain time period. As there is only one storm present in the original wind series of 2005, the choice has been made to investigate the assumed increase in storminess by means of increasing frequency (i.e. more storms during the year) caused by climate change.

The presumed effect of more storms on the eelgrass development lies in the effect of storms on the hydrodynamic forcings. A storm typically creates wind set-up, resulting in local decreases and increases in water depth, thereby affecting the light climate. Furthermore, a storm enhances the formation of wind-generated waves, creating waves with larger amplitudes. These waves, in turn, will work the seabed with larger orbital velocities and larger bed shear stresses, causing more sediment resuspension and negatively affecting the light climate.

To investigate the effect of more storms, the wind- ,wave- and SSC conditions from 6 January 2005 0:00 to 10 January 0:00 (the January storm) have been replicated and implemented in the corresponding time series during different stages of the eelgrass development under which the eelgrass could be affected. The first extra storm was implemented when the eelgrass is growing: during spring, from 16 May 2005 to 20 May, this storm will be referred to as the May storm. The second additional storm was implemented when the eelgrass biomass is the largest at the end of the summer, from 27 September to 1 October. This storm will be referred to as the September storm. The third and final storm has been added at the end of the year, when aboveground biomass is already declining, from 5 November to 9 November, and it will be mentioned as the November storm.

For this simulation, adaptations were made to the wind conditions, the wave conditions, and the sediment conditions to include the three extra storms in the model forcings. The wind conditions, both the wind speed and wind direction of the pre-existing January storm, were "copied" and replaced the wind conditions during 16-20 May, 27 September-1 October, and 5-9 November. The same procedure was applied to offshore boundary conditions: the wave height, wave period, and SSC were "copied" from the January storm and fit into the wave- and SSC conditions at these specific times. It applies for all adaptations that a smooth transition between original and fitted storm conditions was made using linear interpolation over the first and the last eight hours of the implemented storm.



Figure 5.10 Example of the altered time series of wind- and wave conditions for the May storm

## 6 Results

As explained in section 5.5, the coupled model has been used to simulate the system behaviour under different conditions. Two baseline cases have been simulated: the present situation with the known seagrass cover in the current state and the present situation with a mainly bare seabed. The effects of climate change, i.e. sea level rise, water temperature increase, and increased storminess, have been simulated separately. In this chapter, only the most important results are shown and examined per simulation, the other results and detailed observations have been included in Appendix E.

The results of the simulations are examined in sections 6.1 to 6.5 by means of the eelgrass development over the year, as this parameter clearly indicates the impact of (changes in) environmental conditions. In section 6.6, the interaction of feedbacks related to the environmental conditions (i.e. flow and wave conditions, bed shear stresses, SSC, and light) is assessed and described.

Eelgrass development can be expressed best in terms of the aboveground biomass ( $B \text{ [gC m}^{-2}\text{]}$ ), as the shoot density and the vegetation height (related to the biomass per shoot) together determine this spatial biomass density. Less important is the belowground biomass, as this merely has a supportive function to the plant growth. Therefore, the eelgrass development will mainly be discussed in this chapter by referring to the aboveground biomass, or simply mentioned as biomass. However, for the results of the other state variables, one is referred to Appendix E.

## 6.1 Baseline case 1: Present situation with present eelgrass cover

At the depth zones 0.5-1 m and 1-2 m, the aboveground biomass was found to be increasing over the whole year (Figure 6.1A and B). The summer fluctuations are more distinctive at the locations with the largest biomass, indicating that the eelgrass adapts more easily to the environmental conditions. This can be explained using the growth formulations: the increase or decrease of eelgrass biomass is related to the total present eelgrass biomass, i.e. causing larger fluctuations for larger biomass. Also, the growth rate is larger at the locations with the largest amount of eelgrass (location 2 and 9) than for less densely covered locations, visible as the steeper gradient of the curves from the beginning of April until approximately mid-July. The shallowest locations 3 and 4, with depths of 1 m and 0.5 m, show more flattened curves, presumably due to higher bed shear stresses and the adverse wave conditions at these locations.



Location 6 and location 12 (Figure 6.1C) are considered as the more intermediate locations, as the depth is about 3 m and about 4 m, respectively. This depth difference of 1 m results in a relatively large difference in biomass between the two locations. Moreover, the eelgrass development is approximately stable (slightly decreasing) in this depth zone (2-4 m).

The biomass at the deep locations is shown in Figure 6.1D. At the two deepest locations, 15 and 16, the biomass is small at the beginning of the year and further decreases during the year. This means that the environmental conditions are unfavourable to sustain the sparse eelgrass growth at these locations and for these depths (5.3 m and 5.91 m). Location 14 is within the same depth range (5.27 m), but has a larger biomass at the start of the year and shows some development over the year (yet net decay). From the results for location 14, it can be concluded that at the deep locations, close to the depth limit of eelgrass, it is apparently possible for eelgrass to grow, but then the initial biomass possibly needs to be higher than that is assumed and simulated here.

The yearly development shows the same seasonal variability as the data of DHI, and is in accordance with the literature (see section 1.1.3). However, it was found that DHI predicted a decline in biomass at all locations for the year 2005, whereas the simulations of Baseline case 1 show biomass growth and stable behaviour at the depth zones 0.5-1 m, 1-2 m, and 2-4 m. For the deepest locations in depth zone 4-6 m, the Baseline case 1 simulation calculates much lower biomass than the data of DHI, as the latter also showed eelgrass development at these locations.

## 6.2 Baseline case 2: Present situation with bare seabed

The same trends as for Baseline case 1 could be observed for Baseline case 2 regarding the eelgrass aboveground biomass. At the deepest depth zone (4-6 m) the sparse vegetation was decaying over the whole year, whereas at the depth zone of 2-4 m some stabilisation of growth was observed (neither net growth nor decay over the year). In the two shallowest depth zones (0.5-1 m and 1-2 m), the sparse vegetation experienced net growth over the year.



The analysis of the results of Baseline case 2 (in terms of the aboveground eelgrass biomass) shows that the environmental conditions for a bare seabed have not become too adverse for the sparse vegetation to grow back to its original dense state. It is therefore presumed that eelgrass in the depth zones of 0.5-1 m, 1-2 m, and 2-4 m is able to grow back to its original spatial cover.

Furthermore, it was attempted to examine the interaction of feedbacks and to show the difference in system behaviour and environmental conditions between the presence of a dense eelgrass cover and the absence of eelgrass by using the results of both baseline cases. To assess these differences in environmental conditions, it is best to use a dynamic (storm) event, combined with abundantly present eelgrass. However, these conditions do not occur simultaneously in the original data sets of the meteorological representative year 2005. Hence, this assessment was made by using STORM1 simulations for both vegetation presence and vegetation absence. The assessment of environmental conditions and the interaction of feedbacks is therefore described in section 6.6.

## 6.3 Climate change effect 1: Sea level rise

The effect of sea level rise was investigated with two simulations: SLR1, with an instantaneous water level increase of 1 m, and SLR2, with an increase of 1.5 m. The overall results of both simulations show the same trends; therefore, both simulations are examined at the same time and compared to each other, as well as to Baseline case 1.

All locations in the four depth zones showed approximately the same trend. This trend can be described as slower growth rates and also slower decay rates. Moreover, the eelgrass biomass over the whole year was in general lower compared to Baseline case 1. This is for the shallower locations in depth zones 0.5-1 m and 1-2 m mostly not a problem, as still net yearly growth can be observed for both simulations SLR1 and SLR2. For the intermediate (2-4 m) depth zone, the net development over the year turned from slight growth into slight decay. The locations in this depth zone are the most interesting, as here a tipping point could be observed, i.e. switching from slight net yearly growth to slight net yearly decay (see Figure 6.3C). Even more decay was observed for SLR1 and SLR2 in depth zone of 4-6 m than was already the case for Baseline case 1.



Figure 6.3 Eelgrass development at the locations in the four depth zones for SLR1 and SLR2 compared to Baseline case 1

As explained in subsection 5.5.2, all conditions were the same as for Baseline case 1 except for the increase of water depth, however the eelgrass development turned out to be negative for both SLR cases. Thereby it is proven that the positive effect of wave reduction (and thereby bed shear stress reduction and SSC reduction) does not outweigh the far more negative effect of available light reduction due to the larger water column and direct increase in light attenuation.

## 6.4 Climate change effect 2: Temperature increase

The main hypothesised effect of temperature increase is the faster growth and decay rates of biomass. This could indeed be observed in the results of the TEMP1 simulation (Figure 6.4). Especially, the graphs of locations in the shallowest depth zones (0.5-1 m and 1-2 m) showed the steepest gradients for growth and decay. Furthermore, the summer biomass was higher than for Baseline case 1 and at most shallow locations approximately constant (a flattened top of the graph could be observed). Summer fluctuations, possibly due to environmental disturbances e.g. less/more light or lower/higher water temperatures during a few days, were largest for the depth zone 1-2 m, e.g. location 2 (Figure 6.4B).



Figure 6.4 Eelgrass development in the four depth zones for TEMP1 compared to Baseline case 1

In depth zones 2-4 m and 4-6 m, the summer biomass was even less than that of Baseline case 1. This is presumably due to the fact that for higher temperatures the plants require more light to grow, i.e. the plant growth efficiency decreases with increasing temperatures. Respiration is enhanced for higher temperatures; therefore, more light is required to sustain biomass growth. If the available irradiance at these deep locations was not enough to sustain growth in Baseline case 1, then the irradiance in case of higher temperatures is certainly not enough to sustain growth here. The final result is net (enhanced) biomass decay over the year; see Figure 6.4C and Figure 6.4D.

## 6.5 Climate change effect 3: Increase in storminess

In this simulation (STORM1), the original storm in January was replicated and subsequently added to the original wind series at different stages of eelgrass development: when the eelgrass is starting to grow (mid-May), when the eelgrass biomass is the largest (end-September), and when the eelgrass biomass is already declining (begin-November). These storms have been given the names of the months in which they act, i.e. the May storm, the September storm, and the November storm.

It was found that the May storm hinders the eelgrass development to a large extent, such that not only temporary decay is visible, but also long-term eelgrass development is affected. The effect of the storm is substantial and stays present until late summer or during the rest of the year, especially at the locations in depth zones 1-2 m (Figure 6.5B) and 2-4 m (Figure 6.5C).

The temporary consequence of the September storm is, at most locations, expressed as increased decay during and shortly after the storm when the SSC is increased. The November storm occurs when the eelgrass is already returning to its winter state, i.e. both temperature and light conditions are unfavourable for eelgrass growth. The impact of the November storm is not noticeable at any location, as no change in the gradient of the curve can be observed. Overall, it can be concluded that the effect of the same storm (i.e. with the same intensity) is different during different stages in the eelgrass development.

Besides these added storms, it was found that the original January storm did not cause any increased decay of the eelgrass plants, as there is no additional decline in the gradient of the aboveground biomass visible during this period. The plausible reason is that the plants are in their winter state and therefore relatively short and sparse during winter; hence storm impact is less in this stage of eelgrass development.



## 6.6 Interaction of feedbacks in the shallow coastal (eco)system

As explained at the end of section 6.2, the interaction of feedbacks was assessed with the results of the simulations STORM1 and STORM1-NoVeg. This latter simulation had the same environmental conditions, i.e. the implemented wind conditions as given in Figure 6.6, but only sparse initial vegetation was implemented (like for Baseline case 2). The examined time period here ranges from 16 to 20 May, as the May storm acts on the system when normally eelgrass is growing. During the May storm, which is a westerly storm, location 4 ran frequently dry due to the wind set-down and the shallow depth of the lagoon. Only the most striking results are described in this section. The results of all parameters at the locations are added in Appendix E.2.



Figure 6.6 Wind conditions in the STORM1 simulations with and without eelgrass (16-20 May), the dashed line is the SSC threshold of 8 ms<sup>-1</sup>

#### Hydrodynamic conditions (flow and waves)

At all locations, both the velocity profile over the water column at a specific moment in time and the wave heights during the May storm event have been assessed. Unlike the expected reduction in wave height, at least for the shallow locations where vegetation occupies a large part of the water column and the wave energy should be attenuated significantly, no considerable decrease in wave height could be observed. In case of vegetation presence, wave heights are only slightly reduced (in the order of a few centimetres) compared to the results of vegetation absence. See Appendix E.2 for the corresponding figures.

The flow profiles at the three remaining depth zones did show a substantial difference between vegetation presence and absence, see Figure 6.7. When vegetation was present, the flow velocities were largely reduced, i.e. in the order of 0.02 to even 0.15 m s<sup>-1</sup>. The flow velocities during the storm were still relatively low and ranged between 0.2 m s<sup>-1</sup> in the offshore direction (at the water surface due to the westerly wind, indicated with a minus sign) and 0.25 m s<sup>-1</sup> in the onshore direction. The change in the flow velocity magnitude is therefore considerably large and can be fully attributed to the presence of vegetation. For every depth zone, the velocity profile of one location is depicted in Figure 6.7.



Figure 6.7 Flow profiles of STORM1 simulations with and without eelgrass for 18 May 21.00hr in depth zones A) 1-2 m, B) 2-4 m and C) 4-6 m

#### Bed shear stress and suspended sediment

The bed shear stresses generated by both flow and waves during the May storm were also reduced substantially due to vegetation presence. Again, for every depth zone, the resulting bed shear stresses are depicted in Figure 6.8 for one location only. Clearly visible in Figure 6.8A are the periods in which location 4 experiences drying and flooding. The bathymetry at location 9 experiences the largest shear stresses and there is almost no shear stress reduction at location 15 due to the water depth.

An interesting question could be whether the flow or the waves are dominant in the reduction of bed shear stress. As it was observed that wave heights were almost unaffected in case of vegetation presence compared to vegetation absence, and the shear stress due to waves is related to the wave height by the orbital velocity, it is presumed that the flow conditions impose the largest reduction to the bed shear stresses. However, the wave energy dissipation by vegetation and the increased turbulence levels should be investigated in more detail to be certain of this dominance of flow over waves in bed shear stress reduction.

Furthermore, the shape of the bed shear stress graphs of locations 9, 6, and 15 (Figure 6.8A, B, and C) and the shape of the corresponding SSC graphs in Figure 6.9 show large correspondence to the shape of the wind graph (Figure 6.6). One of the Fehmarnbelt EIA reports concluded that sediment suspension events arise at the study site for wind speeds larger than 8 m s<sup>-1</sup> (see section 3.4 and FEHY (2013c)). This phenomenon can also be observed in the results of these STORM1 simulations; in terms of the wind-driven bed shear stresses and the subsequently enhanced sediment concentrations. As a result, it is hereby demonstrated that the model is able to reproduce that physical (hydrodynamic) behaviour, irrespective of the provided data.



Figure 6.8 Bed shear stresses of STORM1 simulations with and without eelgrass for 16-20 May in depth zones A) 0.5-1 m, B) 1-2 m, C) 2-4 m and D) 4-6 m

As explained before, directly related to the bed shear stress is the resuspension of (fine) sediment. Figure 6.9 shows the corresponding depth-averaged suspended sediment concentrations for the same locations as used before in this section. Although a substantial reduction in suspended sediment was expected in case of vegetation presence, these graphs show, surprisingly enough, that the depth-averaged SSC is roughly of the same order for vegetation presence as for vegetation absence, at least during storm conditions.



Figure 6.9 SSC of STORM1 simulations with and without eelgrass for 16-20 May in depth zones A) 0.5-1 m, B) 1-2 m, C) 2-4 m and D) 4-6 m

#### **Light climate**

Due to the higher levels of resuspension during storm conditions, e.g. in the period of 16-20 May and also for 21 May as the sediment takes time to settle, the light attenuation in the water column is higher. Figure 6.10 shows the daily irradiance at the seabed during the May storm compared to the available light in Baseline case 1, for the four locations in the different depth zones. As the black graphs of Baseline case 1 already show: the deeper the location, the larger the water column, and the larger the light attenuation, the less light is available at the bottom. The light attenuation is further increased by the suspended sediment concentrations during the storm event, and the available light for the eelgrass is even reduced to zero at almost all locations. The resulting effect of little to no available light for eelgrass growth due to storm conditions was clearly visible in the graphs of aboveground biomass of the STORM1 simulation with vegetation (see section 6.5, Figure 6.5) as disturbances in eelgrass growth or even temporary decline of aboveground biomass.



Figure 6.10 Daily available bottom light of STORM1 simulations compared to Baseline case 1 for 12-24 May in depth zones A) 0.5-1 m, B) 1-2 m, C) 2-4 m and D) 4-6 m

Moreover, the results considering the modelled light climate in Baseline case 1 shows other features that are interesting to mention. The minimum light requirement in terms of yearly cumulative irradiance as established by the Fehmarnbelt EIA reports (750-1000  $\text{Em}^{-2}$ , see section 1.4) is not met at the deep locations (14, 15, and 16), see Figure 6.11. The value of this specific parameter is largely responsible for the permanently declining aboveground eelgrass biomass at these locations: the plants simply do not obtain enough light during the year. For some of the locations, this minimum light requirement is already obtained in May-June, i.e. in the middle of the growth season (March-September).



Figure 6.11 Cumulative available bottom light of Baseline case 1 for the year 2005 at all locations

# Discussion

Before establishing the main conclusions and answering the research questions, a critical reflection on the conducted research is required. In this chapter, the model results, the technical model aspects and model approach, its limitations, the model applications (in terms of assessing climate change and for other purposes), and the provided data are discussed. Subsequently, the last section of this chapter reflects on the research objectives and -questions.

#### **Model results** 7.1

In the previous chapter, the results of the model simulations were presented and described. This section reflects once more on the model results by means of providing the concluding figure of the spatial distribution of eelgrass in the modelled shallow coastal (eco)system and by comparison with the references (e.g. data and literature).



Figure 7.1 Spatial distribution of eelgrass biomass over the modelled transect (Baseline case 1)

The spatial (and therefore vertical) distribution of the aboveground eelgrass biomass over the transect as resulted from Baseline case 1 is reflected in Figure 7.1. The initial biomass is indicated with the black dotted line and shows the distribution at the start of the simulated year. This parameter was the only one imposed on the model and was based on the provided eelgrass data by DHI; the other biomasses (yearly mean, minimum and maximum, and the final biomass at the end of the year) were calculated in the Baseline case 1 model simulation. The depth contours of the transect (i.e. the bathymetry) are clearly reflected in this calculated spatial distribution, especially since the initial biomass did not really contribute to this particular shape of the graph. It can therefore be concluded that the eelgrass development is directly dependent on the water depth and the related environmental conditions, e.g. the light climate and the indirect impact by the flow and waves in terms of sediment resuspension.

Moreover, this spatial distribution can be compared to the eelgrass distribution as established by DHI in section 3.3. If one were to draw a line in Figure 3.3 where the transect is located, one would find the same kind of spatial distribution as reflected in Figure 7.1. The vertical distribution of Figure 3.4 in terms of eelgrass can also be implicitly compared to Figure 7.1 by bringing the depth zones back to attention (see the bathymetry in Figure 5.1 and Appendix C.1). And overall, the ranges of biomasses in Figure 7.1 in the different depth zones show a striking resemblance to the bell-shaped vertical distribution of Figure 3.4, apart from the deepest locations, where the range in biomass is presumably underestimated.

The interaction of feedbacks was elaborated in section 6.6. The interplay between hydrodynamic conditions (flow and waves), bed shear stresses, sediment resuspension, and light in the water column showed the effect on the eelgrass development. The model has proven to include the feedbacks in a correct manner and to show adequate results. However, before an exact quantitative value can be given to the importance of the feedbacks, and to determine to how long and to which extent these feedbacks are acting on the system under which conditions, more extensive research is demanded. A more thorough data analysis (including long-term and dynamic conditions) is recommended, subsequent model validation to the knowledge obtained from this analysis is suggested, and additional model simulations need to be performed.

Eelgrass biomass was used as a direct indicator of the system sensitivity to environmental conditions in the analysis of the model results. The plants respond to all the forces implied by the hydrodynamics and sediment dynamics and plant development is therefore considered as the most accurate indicator. Also, short-term disturbances (i.e. storm events) are reflected in the eelgrass development, whereas the yearly averaged SSC and hydrodynamic conditions remain the same.

## 7.2 Technical (model) aspects

#### **Model performance**

The model results show decent and reliable eelgrass development in the first three depth zones (0.5-1 m, 1-2 m, 2-4 m). At larger depths, it appears that the model accuracy and reliability is less than for the shallower depth zones and presumably the eelgrass presence is underestimated. This means that for the first three depth zones the model will presumably predict eelgrass revival for consecutive years. However, in the deepest zone (4-6 m), the predicted eelgrass development will remain structurally zero, which is not in agreement with the available data. Although the diver observations were conducted in summer 2009 and the bar chart (Figure 3.4) shows the instantaneous vertical distribution at that moment, it is known that at least a sparse (<10%) eelgrass cover can be present up to an approximate depth of 5 m (see section 3.3). Moreover, the model data of DHI shows eelgrass development at this deepest depth zone, albeit the aboveground biomass remains small (1.5-7 gC m<sup>-2</sup> for location 14 and 0.5-1.1 gC m<sup>-2</sup> for locations 15 and 16).

The deepest zone of the model requires more attention and should be examined thoroughly before application in further research (e.g. at other study sites). The implications of model application in its current state, with less apparent accuracy and reliability in the deepest parts of the model, is that in case one is interested in exploring the depth limit of eelgrass growth or when the water depth is increased by e.g. climate change, one uses the more unreliable part of the model.

Although the model already shows adequate and credible results in terms of hydrodynamic forcings, sediment transport and the eelgrass development, still a detailed model validation needs to be performed (e.g. for the sediment- and the growth model parameters) by using additional data. For the sediment- and growth model parameters, data containing the bed composition, time series of sediment concentrations over the water column and long-term plant parameters are needed. These data was unavailable for this study (see section 7.6), hence the model performance could be improved.

#### Comparison DHI model versus coupled model, 2DH versus 2DV

The hydrodynamic model of DHI, of which the input and output is used in this study, takes into account the hydrodynamic processes (flow and waves, turbulence, etc.) in both horizontal directions and is depth-averaged over the vertical, hence it is a 2DH model. The effect of vegetation on the hydrodynamic processes is omitted in the DHI model and the effect of sediment dynamics on light availability are only implicitly taken into account by means of turbidity (NTU, related to environmental conditions and linked to bed shear stresses). The coupled model developed in this study contains all feedback processes (hydrodynamics, sediment dynamics, and eelgrass development) acting in one horizontal direction and in the vertical direction (2DV model). These models have therefore a different approach. If one would compare both models and their results, i.e. the provided data by DHI and the coupled model results, one would find that the processes perpendicular to the transect (hydrodynamics and sediment transport) are underestimated in the coupled model. However, this is always the case for 2DV models. Two benefits of the coupled model compared to the model of DHI can be identified. The first benefit lies in the vertical processes, which are fully taken into account in the coupled model and are more detailed (e.g. in terms of sediment transport modelling, containing two sediment fractions) than in the model of DHI. The second benefit is the implementation of the feedbacks between the hydrodynamics (flow and waves), the sediment dynamics, and the vegetation, which were proved to be included and perform reliable results.

On the other hand, DHI determines the impacts on eelgrass by the dynamic ecological model (FEMA, 2013). This ecological model was calibrated and validated, and includes detailed, but yet unidentified, descriptions of growth and decay processes. These processes are based on plant dependencies of light and temperature, like the developed growth model, and nutrients, which are not included in the growth model. Unlike in the developed growth model, the ecological model of DHI takes into account sediment quality, oxygen levels, and especially nutrients explicitly. This means that in the ecological model of DHI, eelgrass growth could only sustain where sediment conditions (e.g. low H<sub>2</sub>S in sediments, adequate nutrient concentrations in pore water) and light conditions were appropriate. The possible consequence for the results of the coupled model is an overestimation of eelgrass presence, as these limiting factors (i.e. nutrient availability and sediment conditions) were not included.

#### Model approach

A 2DV model was used for this study for mainly two reasons. Firstly, spatial processes were found to be important (i.e. hydrodynamics and sediment transport): a simplified 1DV model would not have been able to incorporate these processes correctly and would therefore have been inadequate. Secondly, 3D effects were ruled out for this specific study site beforehand. Processes in horizontal directions other than the transect e.g. circular flow and corresponding sediment transport were excluded at this study site (see section 4.2.3) and therefore a 2DV model could be used. The advantages of modelling in 2DV over 3D modelling are the reduced model complexity and therefore its increased comprehensibility (i.e. of the interaction of the

feedbacks and the impact on the model results). The model purpose and the research objective of contributing to a better understanding of the interaction of feedbacks required insight into the model functioning, hence developing a 2DV model and understanding the results was sufficiently challenging.

However, by using a 2DV model, some information is always lost compared to reality. Due to the modelling of one horizontal direction only, the horizontal flow velocities were lower than the data indicated. Also, the sediment supply was lower compared to the data of turbidity as provided by DHI. Moreover, the wind is, in reality, responsible for initiating horizontal and vertical circulation, which is not taken into account in this model.

By modelling only one transect instead of the whole lagoon, the exact spatial distribution of eelgrass and local processes were neglected. However, it was not the intention of this study to create an exact replica of the Rødsand lagoon, but merely to assess its behaviour and the interaction of feedbacks in a shallow coastal (eco)system in general. The approach of modelling one transect, comprising an idealised representation of the conditions at the study site, is accepted.

In case of development of a 3D coupled model, the framework developed in this study can form the base and can be extended for 3D purposes, but must also be improved for the deeper locations near the depth limit of eelgrass (imposed by light). A full 3D model can have some benefits, especially when an assessment is needed at other locations with a difficult bathymetry or spatially non-uniform behaviour (where both horizontal directions are needed, i.e. flow and waves are less unidirectional), e.g. in shallow estuaries or tidal inlets. The disadvantage of a 3D model is that it could be complex to fully understand the consequences, i.e. the impact of the environmental forcings on the interaction of feedbacks. Also, the required computational time will be substantially longer than for 2D modelling, especially for assessing the long-term behaviour, which was unavailable within this study. Developing a reduced climate of meteorological conditions (that have the same impact on the coastal system and the eelgrass development) could help to speed up the computational time, especially in the long-term. More accurate data over the long-term would be needed for these simulations, comprising wind, wave, light, temperature, and eelgrass development related time series.

## 7.3 Model limitations

#### Limitations of the numerical model

Currently, it is not possible to implement horizontally varying plant height in SWAN. Therefore, a spatially uniform (effective) plant height of 0.25 m was assumed in Delft3D-WAVE, based on the fact that plants will deflect due to wave action. On the contrary, Delft3D-FLOW allowed for the inclusion of the horizontally varying plant height by means of coupling with the growth model. This horizontally varying plant height was implemented as the full length of the plant, thereby excluding reconfiguration. This presumably results in an overestimation of plant height and an underestimation of flow velocities through vegetation, especially in case of large waves or storm conditions: then the eelgrass is expected to reconfigure, and the effective plant height will reduce substantially. Also, swaying motions are not taken into account in the model, neither in the FLOW-module nor the WAVE-module, however, according to Bradley & Houser (2009), the rigid cylinder approach is a good first approximation. Further research and development are required to be able to implement swaying vegetation in the numerical model.

The drag coefficient for Delft3D-FLOW was taken as  $C_D \approx 1$  by assuming the rigid cylinder approach, however according to calculations with Dynveg (see Appendix C.3.3)  $C_D$  should be taken as approximately 2. The result is that plants are modelled too "smooth", meaning that the plants in reality obstruct flow to a larger extent (larger drag force), thereby the turbulence and the dissipation are somewhat underestimated here. Furthermore, reconfiguration is not taken into account, as the full length of the plant was used as input for the model. This should again have consequences for the drag force: in reality the drag force is smaller, as the plants have a reduced frontal area and a more streamlined shape. Here, the consequences for the results are minor, as in general the flow velocities are low, the wave heights are small, and the Dynveg calculations showed that the deflected height  $k_{veg}$  is almost the same as the full height  $h_{veg}$  (see Appendix C.3.3). However, when the environmental conditions become dynamic, e.g. in case of storms, it would be better to model the effective blade length  $l_{veg}$ , which resembles the total impact of reconfiguration on drag (see subsection 1.3.5 and equations (1.13) - (1.14)).

Direct implementation of the effect of bed shear stress on eelgrass presence (e.g. as tolerance limit) was not included in the growth model, as the flow- and wave conditions at the study site are relatively mild and are not likely to cause large-scale uprooting. However, the effect of bed shear stress was taken into account implicitly in the coupled model by incorporating the effect of sediment resuspension on the light attenuation in the light calculations.

#### Missing or excluded processes

Several processes were omitted in the coupled model during this study. Eelgrass plants are able to adapt to their environment to some (yet unknown) extent, e.g. to the light- and temperature conditions, however the study site is located at the northern

boundary of the eelgrass distribution area and the daily light requirements are already on the low end of the range. After all, the plants would not survive in much lower light concentrations. Direct physical impact by waves was neglected, but can cause rupture of leaves or plants, and direct implementation of the bed shear stress as a tolerance limit was excluded. Furthermore, tidal influences and salinity are neglected. Also, the processes of possible eelgrass deterioration like (increased) uprooting due to e.g. storm conditions or wave impact, grazing by other organisms, and diseases were left out. Processes that could benefit eelgrass revival other than vegetative growth, like extensive and explicit horizontal expansion of vegetative shoots or sexual reproduction by seed dispersion and subsequent eelgrass invasion by seedlings, were excluded as well. Lastly, the impact of nutrients and other organisms on eelgrass development, both that sustain and hinder growth, was left out completely.

All these processes were not taken into account in the growth model (hence excluded in this study) for mainly two reasons. Firstly, the above-mentioned processes are of minor importance in the case of the test study site. The shallow non-tidal coastal ecosystem in the Rødsand lagoon has been present for many years and can be considered a pristine environment (i.e. with little human impact and low-nutrient levels) with relatively mild environmental conditions (e.g. low flow velocities, small wave heights), see section 1.6 and chapter 3. Secondly, as the growth model formulations were adopted from Carr et al. (2012a, 2012b), in which these processes are also neglected, and no indications on how to implement these additional processes could be found in literature, these processes were excluded.

In other (shallow) coastal ecosystems these above-mentioned processes could play a substantial role, and omitting these processes can have a large impact. For instance, these ecosystems could be located in a highly (hydro)dynamic or eutrophic environment. Hence, it is advised to explore whether these processes need to be taken into account at the specific study site and if so, to conduct further research on how to implement these processes in the growth model formulations, e.g. by means of an extensive literature study.

## 7.4 Climate change effects

This study provides insight into what might happen to the shallow coastal system under the singular effects of climate change. The different effects of climate change (sea level rise, increase in temperature, and storminess) were investigated separately, thereby increasing the understanding of the influence of each climate change effect on the coastal system. Essentially, this study has focussed on the assessment of feedbacks between hydrodynamics, sediment dynamics, and submerged vegetation i.e. eelgrass by means of pragmatic scenario testing. All simulations were conducted for one year with a representative year of forcings at the base and additional singular climate change-related forcings. It could be questioned how representative these tested scenarios and their results are, compared to climate change in reality, as climate change acts on the timescale of decades, its progress is highly uncertain (e.g. might be accelerating over time) and the effects of climate change all happen at the same time (i.e. have a mutual impact on the coastal (eco)system). It might be possible for the system and eelgrass plants to adapt to the changing climate to some extent. The system could, with help of the present eelgrass population, be able to import sediment and might therefore be able to keep up with the pace of sea level rise by raising the bathymetry. Also, the eelgrass plants might be resilient enough to adapt themselves to the more unfavourable conditions due to climate change. As these long-term processes and climate change are very uncertain in itself, the exact development in the long term is difficult to assess.

The assessed climate change effects, which were used as forcings on the coastal system in the model simulations, were assumed to consist of (relative) sea level rise, increase in water temperature, and the increase in storminess. It could be possible that other climate change effects, such as extensive droughts, precipitation events, or changes in salinity, also have their effect on the shallow coastal (eco)system. These effects were not assessed during this study as their impact was assumed to be of less importance, based on the primary conditions that are needed for the eelgrass to grow (light and temperature, see sections 1.4 and 5.3). In the context of changing light and temperature conditions due to climate change, other primary producers such as algae will also be affected. They are assumed to grow faster in warmer water and will compete for light with the eelgrass; however, these secondary implications of climate change were also neglected, as the study site is a low-nutrient environment. Yet these shifts in abundance of other organisms and the effect on the eelgrass presence could be of importance and should be considered in further research, e.g. at other locations.

#### (Relative) Sea level rise

In this study, the sensitivity of the variability in aboveground eelgrass biomass development to the effect of depth variations has been assessed by means of an instantaneous increase of the water level. The research questions are focussed on the ecological perspective of the effects of climate change: is the eelgrass able to survive (and possibly adapt to) relative sea level rise? In case the water depth is increased, what happens to the balance between eelgrass survival versus the impact of morphology and hydrodynamics based on the model formulations? Due to the larger water column, the sediment resuspension by waves is reduced, which would favour eelgrass growth, yet light penetration at the bottom is hindered to a larger extent. Since the latter process is crucial for eelgrass growth (and therefore survival) and despite the positive effect of SSC reduction, the aboveground biomass was reduced in all depth zones in case of a water level increase (see section 6.3). At this study site, eelgrass presence is considered to be more essential than the morphology of the lagoon, therefore this study emphasised on the effects on eelgrass development.

The morphological feedback, which is important to the long-term development of the lagoon and to the possible change in system behaviour due to sedimentation, was not included here. Of course, climate change also has an effect on the morphology. The lagoon could start importing sediment and the question remains whether the shallow coastal bay can keep up with the sea level rise by adapting its seabed morphology. In case the morphology is able to keep pace with the sea level rise, then the water depth in the lagoon will remain constant and Baseline case 1 gives answers to all the questions. It could also be that the eelgrass population is able to translate towards the shallower depths of the lagoon, although the horizontal expansion rate of vegetative shoots was found to be relatively slow (in the order of 12.5-16 cm per year, (FEMA, 2013)). In that case, the distribution of biomass over the transect will be exactly the same as for Baseline case 1, unless during the morphological processes the bed slope changes.

Technically, it has not been investigated how climate change in reality can change the lagoon. In fact, it is assumed here that the water level rises faster than the seabed morphology is adapting, therefore relative sea level rise has been assessed. Whether this is legitimate or appropriate in reality remains an open question. The effect of instantaneous relative sea level rise and the translation to the erosion of sediment and decreased light availability and the feedback on the eelgrass development was made as a first step. Of course, to be able to completely and precisely determine the impact climate change imposes on the coastal system, the combined effect of changes in seabed morphology and actual sea level rise should be examined simultaneously. Within the limited available time and together with the development of the components of the coupled model, this proved to be a step too far to be included in this study. Therefore, the assessment made here comprises the relative water level increase in case the seabed morphology falls behind with the sea level rise.

#### Water temperature increase

The simulated water temperature increase of a yearly average of 4 °C, yet taking into account the seasonal differences as predicted by BACC II (see subsections 1.1.5 and 5.5.2), was the high-end scenario for temperature increase. This high-end scenario was used to examine whether the temperature increase in itself would have a noticeable effect on the eelgrass development. The results showed an increased growth- and decay rate during the year, together with a longer period during the summer of maximum biomass (see section 6.4). However, as the temperature increase of 4°C is excessive compared to the actual predicted temperature increase of on average 2°C, the effect of temperature increase due to climate change will in reality also be to a minor extent.

Furthermore, as was also the case for sea level rise, the temperature increase was imposed as an instantaneous modification to the system. In contrast to sea level rise, the coastal system will not adapt to temperature increase over time with respect to the hydro- and morphodynamics and only the eelgrass plants are affected. The implications of the instantaneous temperature increase are therefore assumed to be small. It may be possible that the plants are able to adapt to warmer water temperatures, given that the light conditions are favourable as well; however, plant adaptation was excluded in this study (see section 7.3 Missing or excluded processes).

Also, the temperature data was smoothened to only show the long-term trend over the year. This means that daily fluctuations are not taken into account, and that eelgrass could be vulnerable for these fluctuations as these are also affected by temperature increase.

#### **Increased storminess**

In this study, it was assumed that the underwater light climate could be affected by an increase in storminess, i.e. increasing storm magnitude, storm duration, or the frequency of storm events. Although no literature could be found that predicts changes in storm frequency or duration, and the increase in storm magnitude is rather uncertain (see subsection 1.1.5), simulations with assumed increase in storm frequency were conducted. It was assumed that storm frequency would have a substantial impact on the shallow coastal (eco)system, and this impact was also shown in the results of the STORM1 simulation. Although it was presumed that storm frequency would increase over the upcoming decades due to climate change, this is quite unpredictable (see subsection 1.1.5). Unfortunately, the effect of an increase of storm magnitude and an increase in storm duration on the shallow coastal (eco)system could not be assessed due to the limited time available for this study. These latter two effects could be of importance to the system and are recommended to be simulated and analysed in the light of further research.

Regarding the increased storminess scenario STORM1, it is possible that the conditions of a January storm might be too intense to represent a storm in other seasons during the year. However, the January storm was the most severe storm during 2005 and hence used for replication in the storm sequence. With these extra storm events, the behaviour of the shallow coastal (eco)system during and directly after the storm events was assessed at different stages of eelgrass development, to see when

the impact was largest of the short-term storm conditions. It was found that a storm event during spring (i.e. in May), when the growth rate of eelgrass is fastest, had the largest impact (see section 6.5).

#### **Representativeness of climate change scenarios**

The evaluation of the possible climate change effects of (relative) sea level rise, water temperature increase, and increased storminess was made for every singular effect. It was attempted to force the system and to find the threshold for shifting to the alternative (bare or at least declining) state by pragmatic scenario testing of possible adverse environmental adaptations. It was not attempted to represent realistic effects on the coastal system behaviour and eelgrass development perfectly: the effects of somewhat exaggerated and idealised singular climate change forcings on the interaction of feedbacks within the coastal system were assessed. Instead of taking into account changes in seabed morphology, only the impact of relative increase of the water level was assessed; the water temperature scenario was increased compared to what is projected by real climate change studies and multiple intense storms were forced on the system in May, September, and November, even when these storms in reality are rarely present at those times of year.

Furthermore, the progress of climate change remains uncertain, primarily due to its complexity. All climate change effects act at the same time; however, this was not assessed during this study due to the intricacy of interactions. The aim of this study was to contribute to the understanding of the interaction of feedbacks and the consequences for eelgrass development by assessing one (singular) climate change effect at the time. In this respect this study was successful, and the validity of the results was unaffected, yet only the first step in understanding the possible effects of climate change has been taken.

#### Implications

In terms of all the processes involved in climate change and the timescale at which they evolve (i.e. decades), the used period of one year for all simulations is technically not long enough to represent the long-term effects of real climate change. Still, it was decided to abandon the idea of modelling multiple years, and to use one year in all the "long-term" simulations instead, for several reasons. The computational time is far less compared to simulation periods of multiple years (or even decades), only data for one year (2005) was available, and the duration of one year is the minimum simulation period that was needed to reflect on the seasonal variability of the eelgrass. The consequences of using a shorter simulation period than actually desired are related to the limited insights into the long-term development of the system behaviour, such as the supposed changes in lagoon morphology on the long-term and the possible adaptations of the eelgrass population to climate change (e.g. translation of the eelgrass over the depth gradient towards the shallower parts of the lagoon).

## 7.5 Upscaling or model application for different studies

In this study, it was not attempted to exactly model the behaviour of the study site, but to examine a shallow coastal (eco)system in general. The environmental conditions of the Rødsand lagoon were merely used to provide a basis for the research. This allows for model application also at other (geographic) locations, for which the environmental conditions of that particular site are then needed. The minimum required (preferably long-term) data would consist of an accurate bathymetry and corresponding water depth of the study area, sediment data of bed composition and sediment resuspension, meteorological conditions such as wind-, light-, and water temperature data, (offshore) wave conditions and detailed measurements of eelgrass presence and -characteristics. Before application of the developed coupled model at another geographic location i.e. in another shallow coastal ecosystem, an assessment needs to be made of which processes further need to be included in the model, as some processes were omitted in this study that could be relevant or of major importance for the newly examined location (see section 7.3).

In one of the simulations, the choice has been made to simulate a "bare" seabed, with the possibility for the eelgrass to grow back (by implementing seedlings in the model). It is a variant that requires both little explanation and no additional simulations/iterations. The results of this Baseline case 2 have shown that when only a few plants per m<sup>2</sup> are present, the conditions are still favourable (especially in the shallow depth zones) to sustain eelgrass development and here it seems possible for the eelgrass population to grow back to a stable situation, albeit over many years. It could be that for a more favourable eelgrass cover, the plants would return to their stable state more rapidly, thereby decreasing the vulnerability of the sparse vegetation. This could provide an interesting insight into the possibility of eelgrass restoration at bare seabeds and could give an indication which environmental conditions are needed for the eelgrass to grow to the dense eelgrass cover state.

Also, artificial interventions might help improve restoration efforts, as they can give a kick-start to the positive feedback of eelgrass development and therefore natural eelgrass restoration. Artificial eelgrass meadows provide suitable hydrodynamic and light conditions and stabilise the sediment to allow natural eelgrass to grow from seeds, take root after transplantation, or expand from existing meadows (The SeaArt Project, 2018). Research can be conducted by means of flume experiments, which are being performed while writing this report in the light of the SeaArt Project, but the developed (numerical) coupled model in this study can be the second step in further research. By implementing the characteristics of these artificial eelgrass plants (drag
coefficients, plant density, plant parameters, etc.) the timescale of degradation of the temporal biodegradable structures and the newly cultivated natural eelgrass plants, the effects of restoration efforts could be explored and quantitatively assessed. A pilot study on eelgrass restoration at a suitable location can be considered as the last step in further research of this topic, of which the location is analysed and selected beforehand by using the developed coupled model. Logically, the local environmental conditions of the pilot study location need to be implemented, and an extension of the growth model may be required, e.g. in terms of seed dispersion and direct implementation of bed shear stresses.

# 7.6 Data

Two datasets were made available and were both used in the assessment of conditions at the study site: the fieldwork data collected in August 2017 as part of the Hydralab+ framework, and the provided model input and output data by DHI. As mentioned in section 4.1, the fieldwork data did not lead to conclusive answers about the effect of the interaction of feedbacks in the coastal (eco)system, as the data were collected during calm (summer) conditions and were very local. The provided model data were obtained from the calibrated hydrodynamic- and ecological model by DHI, for which collected field data of previous years were used. These model data were therefore considered to be representative of the conditions at the study site and assumed to show little deviations from reality. However, as described in section 4.2.3, the provided bed shear stress data showed unrealistic large values compared to the calculated bed shear stress from the other provided parameters. Therefore, it has been decided to continue with the calculated bed shear stress values. Also, the SSC values converted from the NTU data showed peculiar behaviour (see subsection 4.2.3), and as there were no other sets of sediment data available, this data set needed to be used, although it was known that this data set was, in fact, inadequate for its ultimate purpose (sediment parameter optimisation and model validation).

Still, data from dynamic conditions, e.g. due to severe meteorological (storm) events, was unavailable. Furthermore, DHI did not model the sediment transport explicitly; therefore, representative sediment concentrations were also unavailable. This lack of sediment data was compensated by the provision of NTU and the conversion of NTU to SSC, yet real (measured) sediment data were absent. Also, the bed composition was not provided, but needed to be included in the model: this data gap has been overcome by an iterative optimisation procedure of model validation of the sediment parameters and the bed composition to the limited (from NTU-converted) depth-averaged sediment concentration in the water column.

Like the data of dynamic conditions and sediment concentrations, data of multiple years was also unavailable. The year 2005 was proven to be a representative year in terms of meteorological and corresponding hydrodynamic conditions (FEHY, 2013a) and it was therefore assumed that the surface light was also representative. For long-term assessment, i.e. a simulation period of multiple years, a decent (field) data collection of multiple years is required, also regarding the perennial eelgrass conditions. Moreover, the eelgrass conditions and plant parameters used in this study could only be derived from a spatial distribution map of summer 2009 (Figure 3.3), the aboveground eelgrass biomass of 2005 as modelled by DHI (model output, see Figure 4.2), and the field experiments of August 2017 (see Appendix B.2.3). In particular, the model data output of DHI has been extensively used and was considered as a directive. However, all three sources consider eelgrass conditions and eelgrass parameters at different times: no consistency could be guaranteed.

Another interesting thing is the difference in model approaches between the DHI model (2DH) and the developed coupled model (2DV). As these approaches are fundamentally different, the results of both models (the provided model input and output data by DHI and the model results as presented in this study) are also different. The hydrodynamic- and ecological model of DHI only modelled depth-averaged conditions, thereby losing information in the vertical direction, yet processes in the horizontal directions are more detailed than in the coupled model. This was necessary to bear in mind while assessing and comparing both models.

# 7.7 Research objectives and research questions

This section discusses the research objectives and research questions posed at the start of this study. It was aimed to create a better understanding of shallow coastal (eco)system behaviour and the interaction of feedbacks. This study provided an insight into these subjects by means of a literature study and the development of a numerical 2DV model in which the interaction of feedbacks was taken into account. The feedbacks of hydrodynamics, sediment dynamics, and vegetation were implemented in the coupled model by means of using different modules. In the coupled model, both the physical model and the growth model were combined to assess the interaction of feedbacks. With this numerical model (also referred to as the coupled model), the ability to predict the system response to possible adverse environmental conditions of a changing environment was improved. The quantitative assessment of feedbacks and the impact of possible climate change effects on this kind of shallow coastal (eco)systems was made by analysing the simulation results, performed with the coupled model. It was proven that the numerical model includes the most important feedbacks in a shallow coastal (eco)system and the capabilities of the model were shown in

terms of representing the general behaviour of this kind of coastal systems. Moreover, this developed coupled model is the first step in providing means for early assessment of seagrass ecosystems.

Most of the research questions were answered during this study. Mainly three sources of information were used to assemble these desired answers. Firstly, the performed literature study on both the shallow coastal ecosystem behaviour and the interaction of feedbacks, as well as on the environmental conditions described in the Fehmarnbelt EIA reports, provided the means for answering the research questions 1 to 3. The two sets of data, both obtained from the fieldwork and the provided input and output of the DHI model, also contributed to the knowledge of seagrass ecosystem behaviour and gave additional insight into the environmental conditions at the study site (research question 3). The results of the model simulations provided parts of the answers to the questions about climate change (research questions 3 and 4); that is, in terms of order of magnitude, not by giving an exact value. Furthermore, the model results provided a clear answer to the question about which indicators were essential and could be used best for assessing the system behaviour (research question 5).

As was discussed in section 7.4, no realistic climate change was assessed during this study, hence, singular and idealised climate change effects on the ecosystem were tested with the model. The effect of the relative sea level rise was mimicked by applying an instantaneous water level increase on the model. The water temperature was increased; however, a high-end average was applied in this study, merely to assess the possible adverse effects of temperature increase. Lastly, a storm simulation has been created by adapting the time series of wind data and implementing extra storms. By imposing these modified conditions (i.e. water level increase, temperature increase, and adapted wind time series) based on the assumptions made, the implications for sediment resuspension and -transport, and eelgrass development and eelgrass presence were examined. Since the abovementioned conditions due to climate change effects were assumed, the natural and realistic alterations of these conditions were considered outside the scope of this research. Therefore, because no actual or realistic climate change was assessed, an answer to the question of how the environmental conditions will change by climate change forcings (research question 4) could not be given.

# 8.1 Conclusions

The objectives of this research were to create a better understanding of shallow coastal (eco)system behaviour (i.e. the interaction of feedbacks) and to improve the ability to predict the system response to possible adverse environmental conditions of a changing environment due to climate change. In this chapter, the answers and conclusions to the research sub-questions (as defined in section 1.5) are presented and the general research question is answered.

## 1. Can climate change lead to a different ecological (bare) state, as seagrass dies?

Shallow seagrass ecosystems are vulnerable and prone to adverse external factors that influence the environmental conditions. These external factors can push the system from a vegetated to a bare state, with little chance of return. Possible threats to the system and to the seagrass development, in particular, are hindered light penetration due to increased turbidity or a larger water depth, and changes in water temperature. Climate change effects, such as sea level rise, water temperature increase, and increase in storminess, can affect and increase these threats to the seagrass ecosystem.

The model results of the studied climate change forcings, i.e. relative sea level rise, water temperature increase, and increased storminess, showed neither an indication nor a clearly defined threshold of the system shifting to the alternate and undesired bare state. However, as the eelgrass at the deepest locations is the closest to its light-/depth-limit, it is also more susceptible to changes in the environment. Increased decay could be observed compared to the results of the baseline case with dense eelgrass cover, in which eelgrass decay at deeper locations was already present at the end of the year-round simulation. In addition, it was found from the performed literature study that the sea level rise is able to push another eelgrass ecosystem from an initial stable dense meadow state towards a bistable state where eelgrass resilience is affected (Carr et al., 2012a). Furthermore, the same study states that eelgrass may be pushed into the bare sediment state by frequent disturbances, related to storm- and/or high-temperature events. It is therefore plausible that, for different, more adverse environmental conditions and for other geographic locations, climate change is able to cause ecosystem shifting to a bare state.

# 2. How do different climate change forcings (sea level rise, water temperature increase, and increased storminess) affect seagrass presence?

The climate change effects of sea level rise, water temperature increase, and increased storminess affect the light climate that is required for photosynthesis or the temperature climate for the eelgrass to grow. The higher the water temperature, the more light is needed for the eelgrass to compensate for the larger respiration rates, i.e. to produce the same amount of biomass.

Sea level rise increases the light attenuation directly due to a larger water depth but decreases turbidity at the same time, as wave orbital velocities become smaller. By analysing the model results of the SLR simulations, it was found that the overall effect of sea level rise is a negative balance of eelgrass growth over the year for a water depth larger than 2 m. In other words, this indicates that the direct increase of light attenuation by the increase in water depth is far more dominant than the indirect decrease of light attenuation by the reduced sediment resuspension due to waves.

Water temperature increase, e.g. as a result of global warming, causes the eelgrass growth- and decay rates to accelerate, leading to a faster decline in case of disturbances. This was also shown in the model results of the temperature simulation, as the growth and decay rates were increased substantially, especially for water depths smaller than 2 m.

Increased storminess causes the hydrodynamic forcings to be more dynamic and as a result, the sediment transport and related turbidity are enhanced and the light attenuation is therefore increased. The light climate is affected, as the scatter of light due to the increased suspended sediment concentration attenuates the light to a larger extent. In the model results of the storm simulation, i.e. with increased storm frequency during the year and thereby affecting the eelgrass development in different stages, the effect of a storm of the same magnitude was found to be dependent on the timing of the storm and the related eelgrass growth stage. This storm effect was found the largest when the eelgrass is in the early stage of development, i.e. during the growth season. The simulated May storm showed that it was possible that eelgrass presence was affected during the whole year.

## 3. What are the environmental conditions of the study site?

The environmental conditions of the study site were examined by using the available literature, mainly in the form of the Fehmarnbelt EIA reports, and the two datasets that were provided, the fieldwork data and the provided model input and output of the model used by DHI. The study site can be characterised as a sheltered, shallow microtidal coastal system that accommodates eelgrass and that has been intact for many years. It is a good example of a thriving eelgrass ecosystem in a temperate climate, is a low-nutrient environment and anthropogenic influences (e.g. shipping and nutrient loading) are very

limited, as the Rødsand lagoon is part of a Natura 2000-site. Moreover, the eelgrass populations are perennial; this means that the plants remain present during winter.

The geographic location is defined as a sheltered location, as two spits in the east and in the west, and a submerged sandbank in between the two spits, are in place. These features have been there for over 30 years, marking the area as a stable coastal environment. The lagoon is very shallow and a depth gradient in the bathymetry is present, as the water depth ranges from 8 m in the east to approximately the mean sea level in the west. The eelgrass is growing mainly in the shallow part of the lagoon, whereas the seabed is bare in the deeper parts. This is due to the light climate in these deeper waters; eelgrass development is hindered by insufficient available light at the bottom.

The hydrodynamic conditions in the Rødsand lagoon are primarily dependent on the meteorological conditions, as the wind is the main forcing of both the flow and waves. The flow- and wave conditions are in general relatively calm, except for wind directing from northeast to west-southwest together with increased wind velocities. In those conditions, flow is induced in the direction of the wind, waves are generated and the wave height depends on the fetch, and wind set-up (i.e. a tilted water level) is created, which in turn causes return flow in the horizontal and the vertical direction. As the sediment is entrained most easily at the bare seabed in the deeper parts of the lagoon, the sediment is transported towards the eelgrass beds in case of easterly winds. It was found that for wind velocities larger than 8 m s<sup>-1</sup> the suspended sediment concentration in the water column is increased substantially.

### 4. How do the environmental conditions change by climate change forcings?

Singular and idealised climate change effects on the ecosystem were tested with the model, hence, realistic climate change was not assessed during this study. By imposing modified conditions (i.e. water level increase, temperature increase, and adapted wind time series) based on the assumptions made, the implications for sediment resuspension and transport and eelgrass development and -presence were examined. Since the abovementioned conditions due to climate change effects were assumed, the assessment of natural and realistic alterations of the remaining environmental conditions was considered outside the scope of this research.

## 5. Which parameters are essential in defining the processes in the system and indicate the changes?

Eelgrass parameters for assessing plant development, like aboveground biomass, were found to be the most accurate and reliable in terms of indicating changes in the system and the system sensitivity to the environmental conditions. The plants respond to all the forces implied by the hydrodynamics and sediment dynamics due to the interaction of feedbacks. Also, short-term disturbances (i.e. storm events) are reflected in the eelgrass development, whereas other indicators such as the averaged SSC or the averaged hydrodynamic conditions remain the same.

The main research question was formulated as follows:

To which extent can the climate change effects of sea level rise, temperature increase, and increased storminess lead to a die-off of eelgrass in a shallow coastal system such as the Rødsand lagoon, by feedbacks of vegetation on hydrodynamics and sediment dynamics?

The results of the coupled model and the provided data of DHI showed the same behaviour in terms of eelgrass development, hydrodynamic conditions, and sediment transport at most locations, except in the deepest depth zone (4-6 m). This indicates that the general performance of the coupled model is adequate. The environmental conditions in the coupled model are apparently more benign than in the model of DHI, i.e. more beneficial for the eelgrass growth, as the eelgrass biomass was far higher at the shallow depths than that the data of DHI showed. Two reasons can be given for these more beneficial conditions: 1) the sediment import from the offshore boundary and spreading into the domain is underestimated, resulting in more beneficial light conditions at the bottom and 2) the model only takes into account the forcings and, therefore, the hydrodynamic processes in the direction of the transect, whereas processes (related to hydrodynamics and sediment transport) acting perpendicular to the transect are omitted.

When the environmental conditions were forced to be adverse, the eelgrass at the deepest locations of the transect (which are closest to their light-/depth-limit) showed an increased decay compared to the reference case (Baseline case 1), in which eelgrass decay at deeper locations was already present at the end of the year-round simulation. At the shallowest locations, i.e. in depth zones 0.5-1 m and 1-2 m, the observed eelgrass net yearly growth was less for all climate change effects compared to Baseline case 1.

The results of this study showed that large-scale die-off of eelgrass in a shallow microtidal coastal system (such as the Rødsand lagoon) due to the studied forcings is unlikely to happen, even under the assessed climate change effects. However, it is known from the literature that climate change effects such as sea level rise, water temperature increase, and increased storminess are

able to push an eelgrass ecosystem into the bare seabed state. For different, more adverse environmental conditions and other geographic locations, it could be possible that climate change is able to cause ecosystem shifting.

# 8.2 Recommendations

The recommendations, which either follow from the discussion or the conclusions of this study are presented in this section. Suggestions for further research are given, regarding new measurement campaigns at this study site and modelling of the interaction of feedbacks. Furthermore, possibly new research applications are recommended and the corresponding required extensions and possible improvements of the model are indicated.

### **Further research**

Hydralab+ is initiating a new measurement campaign at the study site, which is scheduled for the summer of 2018. To increase the benefits of this measurement campaign, keeping in mind the objective of studying the interaction of feedbacks and assessing the impact of climate change effects, it is advised to collect data at multiple locations in the lagoon, i.e. in different depth zones, and over a longer time. This improves the knowledge of the eelgrass development and the changes in the environmental conditions (waves, wind-induced flow) in the lagoon, both in space and time. The previous fieldwork was conducted at the end of August 2017, when the conditions were relatively calm and the eelgrass biomass was the largest. The data was collected locally, in the direct vicinity of the DHI platform NS04, also mentioned in this study as location 2; therefore, spatial field data was unavailable. Nevertheless, when only a short period of time is available for the measurement campaign (e.g. limited by costs), it is advised to conduct the measurements in dynamic environmental conditions and during different eelgrass development stages (e.g. autumn or winter).

During the model development, some software difficulties needed to be resolved. For example, it was found that the newest version of SWAN, which is responsible for the wave calculations in the Delft3D-WAVE module, and, therefore, the newest version of Delft3D were needed for the computation of wave dissipation by vegetation. Furthermore, the coupled model uses MATLAB to perform the coupling between Delft3D and the growth model, as there is no (standard) online coupling for hydrodynamic and morphodynamic modelling with vegetation development possible in the Delft3D suite. For submerged vegetation modelling in the Delft3D-suite, one can make use of the ecological D-Water Quality (DelWAQ) module for aquatic macrophytes; however, coupling with Delft3D-FLOW and Delft3D-WAVE is offline. Moreover, the macrophyte module of DelWAQ is extensive and detailed: plant development is based not only on light and temperature, but also on nutrient availability and –composition of the plant, other substances in the water column (detritus), grazing and harvesting, and other primary producers (algae, diatoms, etc.).

Deltares is working on the development of the Delft3D Flexible Mesh suite, which will be the successor of the current Delft3D suite. Implementing online coupling of hydro- and morphodynamic modelling with vegetation development would therefore be best in Delft3D Flexible Mesh, as this software suite is promising and will be the default program used for exactly these hydraulic design purposes in the near future. Lastly, the plant development in the growth model developed in this study is custom-made for eelgrass and can be easily implemented in the modelling sequence; however, additional validation studies are required. As eelgrass development is calculated per day in the growth model, this is the best timescale for the exchange of information in the online coupling with the hydrodynamic and morphodynamic module.

These software improvements would also benefit the future developments of modelling hydraulic infrastructure designs in the field of Building with Nature, i.e. using the natural system and ecosystem services in sustainable and adaptable designs. Building with Nature is a growing concept that will be applied more often in the future, therefore modelling vegetation and its feedbacks on the hydro- and morphodynamics will become a daily practice.

### **New applications**

The focus of this study was not on restoration purposes, but use has been made of extreme situations in the form of the present or very sparse vegetation. In future research, the possibilities for eelgrass restoration could be explored with the developed model. This can be examined by computing multiple simulations with other initial eelgrass covers, e.g. expressed as a percentage of the original cover (5%-10%-20%-50%) and to assess if, and for which percentage, the threshold between the two alternative stable states (plant decay and resulting in a bare seabed, or plant survival and growing back the stable eelgrass cover) will present itself. The added value of this model in case of eelgrass restoration research is that realistic cases can be modelled with different scenarios. There are locations in the world without eelgrass vegetation but where stable eelgrass growth is possible, and it could be interesting to assess the development of a stable eelgrass population at these locations to create a new ecosystem.

Also, artificial interventions, which might help improve restoration efforts by providing suitable hydrodynamic- and light conditions, can be assessed by using the developed coupled model. In that case, the characteristics of these artificial eelgrass

plants (drag coefficients, plant density, plant parameters, etc.) need to be implemented in the model. The locations for pilot studies on eelgrass restoration can be analysed and favourable locations can be selected beforehand with help of the developed numerical model. Logically, the local environmental conditions of the pilot study location need to be implemented, and extension of the growth model may be required, e.g. in terms of seed dispersion and direct implementation of bed shear stresses.

#### Model extensions and improvements

The model used in this study comprises an idealised representation of reality, as multiple processes were omitted, i.e. not taken into account or not implemented in the model. A few examples of these excluded processes are: flexibility, reconfiguration or swaying motions of plants due to hydrodynamic forcings, the direct effect of bed shear stress on eelgrass presence (e.g. as tolerance limit), potential plant adaptation to their environment, direct physical impact by waves, tidal influences, enhanced eelgrass deterioration by external factors (nutrient loading, competition, grazing, uprooting, diseases, etc.), eelgrass reproduction other than vegetative growth, and last but not least the bed morphology. In other (shallow) coastal ecosystems these above-mentioned processes could play a substantial role, and omitting these processes can have a large impact. Hence, it is advised to explore whether these processes need to be taken into account at the specific study site, and if so, to conduct further research on how to implement these processes in the model formulations. Moreover, the local environmental conditions of the new pilot study location need to be studied and implemented accordingly.

This study could be further developed into a full assessment of the combined effects of climate change on the coastal system in the long term (e.g. decades). This new assessment could provide an insight into the total and complex development of the coastal system related to climate change. The changes in morphology and all applicable realistic effects of climate change on the coastal system need to be subsequently taken into account. It has been proven that the developed coupled model of this study provides reliable results for year-round simulations and singular effects of climate change. Therefore, the model can be expanded for multiple years and for combinations of climate change effects acting on the coastal system without losing its reliability. Long-term time series of meteorological (and hydrodynamic) forcings, model implementation of changes in bathymetry (sediment transport), and computational time are needed to perform these tests. However, if one would like to reduce the computational time, one should consider input reduction to represent natural variability with a minimum number of conditions. The study on input reduction would then also be a part of further research.

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# Appendix A. Background information

# A.1 Additional information about eelgrass (*Zostera marina*)

# A.1.1 General characteristics of seagrasses

According to Larkum et al. (2006), there are characteristics of seagrasses that no other plant species than seagrasses possess. These can be listed as follows: a) seagrasses live only in estuarine or marine environments; b) they pollinate underwater with specialised pollen; c) they produce seeds under water; these seeds can be dispersed by both biotic and abiotic agents; d) they have specialised leaves with a reduced cuticle (protective cover of the epidermis) and their epidermis lacks stomata and acts as the main photosynthetic tissue; e) seagrasses have a rhizome system (which is important in anchoring) and their roots can live in an anoxic environment, which makes the plants dependent on oxygen transport from the leaves and the rhizome; f) seagrasses are able to compete successfully with other marine organisms.

# A.1.2 Taxonomy and origin

Seagrasses are marine angiosperms (flowering aquatic plants), living in the subtidal or intertidal zone and about 12 genera and 60 species are known (FNA, 2008; Green & Short, 2003; Larkum et al., 2006; Les et al., 1997; Short et al., 2010). The species that is key in this thesis is *Zostera marina* L., in English also called common seagrass or eelgrass. This species is part of a larger family of seagrasses, the Zosteraceae. Like most seagrass families, the Zosteraceae family is part of the subclass Alismatidae, a group of aquatic and wetland plant species. The Alismatidae are then again part of the Angiospermae.

So far, the exact origin of seagrasses is still unclear (Den Hartog & Kuo, 2006; Les et al., 1997). However, there is evidence (found in few fossils) that suggests colonisation of marine habitats by angiosperms, which were adapted to terrestrial conditions (Olsen et al., 2016) and that *Z. marina* originates from the Pacific Ocean between 8 and 20 million years ago (Olsen et al., 2004).

# A.1.3 Distribution

Seagrass grows on every continent in the world, except in Antarctica (Den Hartog & Kuo, 2006; Green & Short, 2003; Moore & Short, 2006). *Z. marina* is the most common seagrass species, living in temperate climate regions. The depth at which *Z. marina* typically grows is from 0 to -12m MSL (mean sea level) (Green & Short, 2003; Short et al., 2010), in both the intertidal and subtidal zone. Its presence has been recorded on both sides of the northern Atlantic Ocean as well as on both sides of the northern Pacific Ocean (Larkum, Orth, et al., 2006) in the shallow coastal zones. It even grows up north to the Arctic Circle and south to the Mediterranean Sea (Bach, 1993; Moore & Short, 2006; Short et al., 2010). The global distribution of *Z. marina* is shown in Figure 1.



Figure 1 Distribution of Zostera marina (Short et al., 2010)

# A.1.4 Internal processes

#### Oxygen production and transport

Seagrasses are, like most plants, able to produce oxygen by photosynthesis when there is light. In case there is no light, e.g. during the night, the internal oxygen pressures decline. Then the seagrass is also able to take up oxygen from its surroundings by passive diffusion. Both water and sediment can supply oxygen to the plant: oxygen from the water then diffuses into the leaves and the roots are able to absorb oxygen from the substrate. However, since the root zone is usually anoxic, the latter process is uncommon (Borum et al., 2006).

The oxygen in the plant can also be transported to parts in need of oxygen, due to a gradient in oxygen levels. The rhizomes and roots are often oxygen-demanding; therefore the oxygen is transported from the leaves, where most of the production takes place, to these parts of the plant (Borum et al., 2006).

#### Nutrients

Nutrients are of vital importance to all living organisms, as they are building blocks for organic matter. The major elements in living organic matter are carbon (C), nitrogen (N), and phosphorus (P), but additionally, a large number of other elements, especially metals, occur as micronutrients. The stoichiometric composition of seagrass organic matter (i.e. the ratio of the different elements) is variable within certain bounds, depending on the organism's capacity to take up required nutrients during growth.

Romero et al. (2006) define the major nutrient resources for seagrass as carbon dioxide (CO<sub>2</sub>), nitrogen (present in the form of nitrate, NO<sub>3</sub>, and ammonium,  $NH_4^+$ ), and phosphorus (present in the form of phosphate,  $PO_4^{3^-}$ ). If any of these nutrients occur in low concentrations, growth will be limited. Usually, one assumes the validity of Liebig's law of the minimum (Bach, 1993; Romero et al., 2006): growth is controlled by the most limiting element(s), even when other resources are abundantly available.

Seagrass is well-adapted to growth under relatively low nutrient conditions. When nutrient concentrations rise due to eutrophication, this increases the (physiological) potential growth rate of seagrass, but in practice, usually other species (phytoplankton, algae) will be competitively superior under these conditions, and seagrass will eventually disappear due to competition.

Overall, seagrass affects the carbon and nutrient levels, both locally (in the direct surroundings of the plant) and on a larger scale (e.g. the coastal zones) by storage in the plant tissue (Mateo et al., 2006; Romero et al., 2006). Furthermore, the oxygen levels in both the water column (Larkum et al., 2006) and the substrate (Borum et al., 2006) are influenced by the seagrass to a large extent (release of excessive oxygen produced by photosynthesis).

### **Epiphytes**

Epiphytes (Greek: epi = on, phyt = plant) are organisms that grow on other plants and can be of different origin (e.g. bacteria, fungi, algae) (Borowitzka et al., 2006). The presence and amount of epiphytes on seagrass leaves is coupled to the abundance of nutrients: when nutrient levels are high, epiphytic growth is favoured (Borum, 1985; Romero et al., 2006)

Flow affects the presence of epiphytes and vice versa. In calm conditions (i.e. low flow velocities), epiphytic species of larger size and with correspondingly larger drag may increase in abundance, but when the flow velocity increases, these larger epiphytes are easily removed by the flow (Koch et al., 2006) and smaller epiphytic species with smaller drag may be favoured.

Furthermore, epiphytes can cause a decrease in light availability for photosynthesis by shading the seagrass and interference in diffusive processes, such as oxygen and nutrient absorption by the seagrass leaves (Romero et al., 2006). Especially, when the majority of the epiphytic growth concerns algae, which also use oxygen and nutrients from the surrounding water, a competitive interference between the seagrass and the epiphytes can develop (Romero et al., 2006).

# A.2 Climate change and its effects on the coastal system

Climate change effects for the Rødsand study site were examined. The rates of impact of sea level rise, temperature increase, and increased storminess were based on the most recent downscaling assessment of climate change for the Baltic Sea, the Second BALTEX Assessment of Climate Change for the Baltic Sea basin (The BACC II Author team, 2015), and the reported influence of climate change on the study site in the Fehmarnbelt Environmental Impact Assessment (EIA) reports (FEHY, 2009, 2013b, 2013d; FEMA, 2013).

## **BACC II Assessment**

The BACC II Assessment is based on the global scenarios provided by the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate change (IPCC, 2007). The global climate change scenarios that the IPCC uses in AR4 are emission scenarios described in the Special Report on Emissions Scenarios (SRES). The SRES scenarios exist of four families (A1, A2, B1, and B2), each of them analysing different development trajectories of climate change driving forces such as demographic, economic, and technological developments and the resulting greenhouse gasses. Unfortunately, the SRES scenarios do not include supplementary climate change policies that have been initiated.

The global scenarios have changed in the fifth assessment of the IPCC, AR5 (IPCC, 2014). They are no longer based on emission scenarios (SRES), but are the so-called Representative Concentration Pathways (RCP's), based on radiative forcing projections and include assumptions of future population behaviour (land use, climate policy, lifestyle, population density, etc.). Furthermore, changes in climate policy can be implemented in these scenarios, unlike in the SRES scenarios. The range of the RPC scenarios is larger than the SRES scenarios; however, some scenarios are equivalent.

As the BACC II Assessment only considers the (older) SRES scenarios, these outcomes are also used in this thesis. It is possible that the results of this thesis slightly underestimate the impact of climate change effects, due to use of the "outdated" SRES scenarios. To reflect on this presumption, the calculations can be performed in future research with the RCP scenarios, which include new insights into climate change.

## Salinity

Due to the geographic location of Denmark, with the landmass extending into the sea, the many fjords, sills, and islands, the exchange flow between the Baltic Sea and the North Sea is largely blocked. The salinity in the Baltic Sea is, in general, very low compared to the salinity of the North Sea, as the inflow of freshwater is the main source for this basin. Especially in the western part of the Baltic Sea, there is a large salinity gradient in both horizontal and vertical directions. This could affect the eelgrass, for example in its resilience. However, since the occurrence of eelgrass has been recorded in the western Baltic Sea and the Rødsand lagoon for a very long time, it is assumed that these differences in salinity are not of major importance in this research and therefore excluded. The same holds for a possible change in salinity due to climate change, which is also omitted.

According to the BACC II Assessment, the climate change scenario simulations indicate that salinity may decrease in the region of the Danish Straits. However, these changes in salinity result from changes in rainfall run-off and as the models for run-off are severely biased, the increase or decrease of salinity is inconclusive. The Fehmarnbelt EIA reports conclude that the effect on changes in salinity is unknown, due to the combination of increased precipitation, evaporation and temperature. However, they also mention that the higher water level due to SLR will increase the salinity.

## Sea level rise (SLR)

Sea levels are rising globally due to the melting of polar ice sheets and thermal expansion of the sea water (The BACC II Author team, 2015). Nevertheless, there is a large complexity in the spatial patterns of sea level rise (SLR). Additionally, Scandinavia experiences glacial isostatic adjustments (vertical land movement), resulting in an uncertain degree of (relative) SLR in the Baltic Sea. Furthermore, it should be noted that the overall projections of SLR over the 21<sup>st</sup> century contain substantial uncertainty, and scientists disagree on the level of confidence of different modelling approaches.

BACC II assessed a mid-range sea level rise scenario using model projections. Based on the SRES A1B scenario, the mid-range SLR scenario predicts a global SLR of + 0.7 m ( $\pm$  0.3 m) at the end of the 21<sup>st</sup> century. It should be noted that, with the new RCP projections of the Fifth Assessment Report of IPCC (2014), the global sea level is likely to increase with 0.26 to 0.82 m for the years 2090-2099 compared to the baseline of 1990-1999. BACC II made a regionalised projection for the Baltic Sea, revealing a relative SLR for the mid-range scenario of 0.5-0.6 m in the Rødsand lagoon (Figure 1.4A). A heuristic high-end scenario, computed from high estimates of the projected SLR in the Baltic Sea, reveals that for 2090-2099 the regionalised projected sea level rise is expected to be +1.10 m, which is an additional 0.5 m of SLR (Figure 1.4B).

#### Temperature

The increase in water temperature for this specific study site (Rødsand lagoon) has been derived from the BACC II Assessment. The seasonal average sea surface temperature was computed by scenario simulations using SRES A1B and A2 for the years 2090-2099 with respect to the baseline years 1990-1999. A projected change in seasonal average sea surface temperature in the southern part of the Baltic Sea is expected (Figure 2): in winter (December-January-February) the projected temperature increase is 2.4°C, in spring (March-April-May) the increase is 2.6°C, in summer (June-July-August) 1.8°C, and in autumn (September-October-November) 2.0°C.

According to the Fehmarnbelt reports (FEHY, 2009, 2013b, 2013d; FEMA, 2013), the air temperature will increase up to 4 °C and the increase would be the strongest in May and June in the southern Baltic Sea area. Another effect of temperature increase is a decreasing probability for sea ice in this region: both the ice-covered area and the duration in days when sea ice occurs are expected to decrease (FEHY, 2013d; FEMA, 2013).



Figure 2 Projected change in seasonal ((a) DJF, (b) MAM, (c) JJA, (d) SON) and annual (e) average sea surface temperatures in the Baltic Sea (The BACC II Author team, 2015). The location of the study site is indicated with a black rectangle

## A.3 Sediment dynamics and the effects on vegetation

In this section, the basics of sediment transport found in the literature are presented and the effect of sediment dynamics on vegetation is discussed.

### Sediment transport formulations

The sediment transport formulations used in Delft3D-FLOW version 4 are the TRANSPOR2004 formulations (van Rijn et al., 2004) and are based on the principles of Van Rijn (1993). In these references, bedload transport and suspended sediment transport are described separately. This section presents the most important and relevant formulations, focussed on the Delft3D-model used in this thesis. Both waves and currents are involved; therefore, both the wave- and current-related parts are described here.

Dijkstra (2012) used these equations as well and described the effects of vegetation on these equations. This information is also incorporated and mentioned here.

#### Suspended sediment transport

The total suspended sediment transport  $S_s$  [kg m<sup>-1</sup> s<sup>-1</sup>] is found by the multiplication of the sediment concentration and the flow velocity and integration over the vertical (z-direction):

$$S_s = \rho_s \int_{z_a}^{h} c(z)u(z) dz$$
(A.1)

 $z_a$  is a reference height above the bed [m], *h* is the water level [m], *c* is the sediment concentration per fraction [kg m<sup>-3</sup>],  $\rho_s$  is the density of sediment [kg m<sup>-3</sup>], and *u* is the flow velocity [m s<sup>-1</sup>]. The flow velocity profile and the effect of vegetation on flow have been described in section 1.3.3. The sediment concentration profile *c(z)* is calculated by using the advection-diffusion equation (mass balance) for each sediment fraction:

$$\frac{\partial c}{\partial t} + \frac{\partial uc}{\partial x} + \frac{\partial vc}{\partial y} + \frac{\partial (w - w_s)c}{\partial z} - \frac{\partial}{\partial x} \left( \varepsilon_{s,x} \frac{\partial c}{\partial x} \right) - \frac{\partial}{\partial y} \left( \varepsilon_{s,y} \frac{\partial c}{\partial y} \right) - \frac{\partial}{\partial z} \left( \varepsilon_{s,z} \frac{\partial c}{\partial z} \right) = 0$$
(A.2)

where *u* and *v* are the flow velocity components  $[m s^{-1}]$  in the horizontal direction and *w* in the vertical direction,  $w_s$  is the settling velocity and  $\varepsilon_{s,x}$ ,  $\varepsilon_{s,y}$  and  $\varepsilon_{s,z}$  are the sediment diffusion coefficients in the three directions for each fraction  $[m^2 s^{-1}]$ . The eddy diffusivities are a combination of molecular viscosity, horizontal subgrid mixing calculated by the model, and three-dimensional turbulence calculated by the k- $\varepsilon$  turbulence model. This k- $\varepsilon$  turbulence model is adapted for the flow through vegetation (see Appendix C.3); therefore, the eddy diffusivities are influenced by vegetation. The flow velocity components are also affected by the presence of vegetation by the change of the velocity profile (see section 1.3.3)

The exchange of sediment with the bed is determined by the bed boundary condition:

$$-w_{s}c - \varepsilon_{z}\frac{\partial c}{\partial z} = D - E \tag{A.3}$$

where *D* is the sediment deposition rate and *E* is the sediment erosion rate of each sediment fraction. The formulations for the fluxes are significantly different for cohesive and non-cohesive sediment.

For cohesive sediment, the fluxes D and E are calculated with the Partheniades-Krone formulations:

$$E = MS(\tau_{cw}, \tau_{cr,e})$$

$$D = w_s c_b S(\tau_{cw}, \tau_{cr,d})$$
(A.4)

Here, *M* is the erosion parameter [kg m<sup>-2</sup> s<sup>-1</sup>],  $\tau_{cw}$  is the bed shear stress exerted by current and waves [N m<sup>-2</sup>],  $\tau_{cr,e}$  and  $\tau_{cr,d}$  are the critical bed shear stresses for erosion and deposition and  $c_b$  is the average sediment concentration in the model layer closest to the bed [kg m<sup>-3</sup>]. *S* is a step function, defined by:

$$S(\tau_{cw}, \tau_{cr,e}) = \begin{cases} \left(\frac{\tau_{cw}}{\tau_{cr,e}} - 1\right) & \text{for } \tau_{cw} > \tau_{cr,e} \\ 0 & \text{for } \tau_{cw} \leq \tau_{cr,e} \end{cases}$$

$$S(\tau_{cw}, \tau_{cr,d}) = \begin{cases} \left(1 - \frac{\tau_{cw}}{\tau_{cr,d}}\right) & \text{for } \tau_{cw} < \tau_{cr,d} \\ 0 & \text{for } \tau_{cw} \geq \tau_{cr,d} \end{cases}$$
(A.5)

Presence of vegetation influences the fluxes of deposition and erosion by means of the actual bed shear stress  $\tau_{cw}$ , as this parameter is proportional to the flow velocities close to the bed squared ( $\tau_{cw} \propto u_*^2$ ).

For non-cohesive sediment, the settling velocity  $w_s$  of a sediment fraction is computed following the method of Van Rijn (1993) using the diameter of the suspended sediment  $d_s$ :

$$w_{s} = \begin{cases} \frac{\Delta g d_{s}^{-2}}{18\nu} & \text{for } 65 \ \mu \text{m} < d_{s} \le 100 \ \mu \text{m} \\ \frac{10\nu}{d_{s}} \left[ \left( 1 + \frac{0.01\Delta g d_{s}^{-3}}{\nu^{2}} \right)^{0.5} - 1 \right] & \text{for } 100 \ \mu \text{m} < d_{s} \le 1000 \ \mu \text{m} \\ 1.1 \left( \Delta g d_{s} \right)^{0.5} & \text{for } 1000 \ \mu \text{m} < d_{s} \end{cases}$$
(A.6)

where  $\Delta = \frac{\rho_s - \rho_w}{\rho_w}$  is the relative density of the sediment [-] and v is the kinematic viscosity of water ([m<sup>2</sup>s<sup>-1</sup>], = 1 · 10<sup>-6</sup>).

Also, for non-cohesive sediments, the vertical sediment mixing coefficient  $\varepsilon_s$  is related to the vertical fluid mixing coefficient  $\varepsilon_f$  which is calculated by the k- $\varepsilon$  turbulence model:

$$\varepsilon_{s} = \beta \varepsilon_{f}$$

$$\beta = 1 + 2 \left( \frac{W_{s}}{U_{*,cw}} \right)^{2}$$
(A.7)

 $\beta$  [-] is the van Rijn coefficient, limited by Van Rijn (1993) to  $1 \le \beta \le 1.5$  due to the limited knowledge of the physical processes involved.  $u_{*,cw}$  is the friction velocity at the bed due to waves and currents [m s<sup>-1</sup>].

#### **Bed load transport**

The bed load transport of sediment  $S_b$  [kg m<sup>-1</sup>s<sup>-1</sup>] as a result of waves and currents is given by van Rijn (1993) as:

$$S_{b} = 0.006 \rho_{s} w_{s} d_{50} M^{0.5} M_{e}^{0.7}$$
(A.8)

where  $d_{50}$  is the median sediment diameter [m], M is the sediment mobility number [-], and  $M_e$  is the excess sediment mobility number [-] defined as:

$$M = \frac{v_{eff}^{2}}{\Delta g d_{50}}$$

$$M_{e} = \frac{(v_{eff} - v_{cr})}{\Delta g d_{50}}$$
(A.9)

where  $v_{cr}$  is the critical depth-averaged velocity for the initiation of motion based on the Shields curve [m s<sup>-1</sup>] and  $v_{eff}$  is the effective velocity due to wave and currents [m s<sup>-1</sup>]:

$$v_{eff} = \sqrt{v_R^2 + u_{orb}^2}$$
 (A.10)

 $v_r$  is the magnitude of an equivalent depth-averaged velocity computed from the velocity in the bottom computational layer, assuming a logarithmic velocity profile [m s<sup>-1</sup>].  $u_{orb}$  is the amplitude of the near-bed peak orbital velocity in direction of wave propagation [m s<sup>-1</sup>]:

$$u_{orb} = \frac{\omega a}{\sinh(kh)} = \frac{\pi H}{T \sinh(kh)}$$
(A.11)

where *a* is the wave amplitude (= H/2) [m],  $\omega$  is the angular frequency =  $\frac{2\pi}{T}$  [rad s<sup>-1</sup>], and *H* and *T* are the wave height [m] and wave period [s], respectively.

The influence of vegetation on the bed load transport is only indirectly taken into account (Dijkstra, 2012). Vegetation causes a reduction of flow velocity close to the bottom, resulting in a lower  $v_r$  and a corresponding lower  $v_{eff}$ . This results in an overall lower sediment mobility.

# Appendix B. Data

This appendix elaborates on the data collections that were made available; in particular, the data from the fieldwork and the model data output of DHI. The analysis of the fieldwork data and the suitability of the data for the setup of the numerical model are discussed.

# B.1 Overview required and obtained data

In Table 1 to Table 3, the obtained data that has been used for modelling and their sources are presented. Orange means that this data is not available or not of the needed quality and red data means that this parameter is not known at all.

| Table 1 Seagrass data   |                 |   |  |  |
|---|-----------------|---|--|--|
| Parameter   | Source          | Why required?   |  |  |
| Modulus of elasticity, specific density,  | UL              | Position in the water column; effect on hydrodynamics |  |  |
| Plant length, width, spatial density  | UL              | Effect on hydrodynamics                               |  |  |
| Spatial cover (patchiness)  | UL/UHull        | Effect on hydrodynamics                               |  |  |
| Epiphyte cover  | UL              | Actual PAR reaching blades                            |  |  |
| (Combined) tolerance limits for bed shear stress, temperature, light limitation | UL + literature | Response modelling                                    |  |  |
| Timescales of deterioration/recovery  | UL + literature | Response modelling                                    |  |  |
| History of eelgrass occurrence + -health<br>in Rødsand                          | None            | General understanding of driving processes            |  |  |
| Seasonal eelgrass dynamics  | Model data DHI  | Growth modelling                                      |  |  |
| Light attenuation over the water column (background value)                      | FZK, DHI        | Growth modelling                                      |  |  |

| Table 2 Hydrodynamic data   |                                   |   |  |  |
|---|-----------------------------------|---|--|--|
| Parameter   | Source                            | Why required?                                       |  |  |
| Flow velocity in water column (in/outside patch)  | Model data DHI                    | Typical conditions + calibration                    |  |  |
| Near-bed flow velocity (and turbulence)   | None                              | Bed shear stress                                    |  |  |
| Water depth   | Model data DHI,<br>EMODnet (2016) | Typical conditions                                  |  |  |
| Bathymetry  | EMODnet (2016)                    | Typical conditions                                  |  |  |
| Wave height, wave period  | Model data DHI                    | Wave model calibration, determines bed shear stress |  |  |
| Wind speed, water level, temperature,<br>storm frequency (time series with<br>seasonal variation) | Model data DHI                    | Boundary conditions, forcing                        |  |  |

| Table 3 Sediment data                             |                               |   |  |  |
|---|-------------------------------|---|--|--|
| Parameter   | Source                        | Why required?   |  |  |
| Grain size, bed composition                       | Literature<br>(calibrated)    | Sediment transport modelling  |  |  |
| Suspended sediment concentration (SSC) timeseries | Literature, Model<br>data DHI | Sediment transport and turbidity modelling;<br>calibration erosion/sedimentation parameters |  |  |
| Fall velocity                                     | None (calibrated)             | Sediment transport and turbidity modelling  |  |  |
| Bed shear stress                                  | DHI (calculated)              | Sediment transport and turbidity modelling  |  |  |
| Erosion parameter                                 | None (calibrated)             | Sediment transport and turbidity modelling  |  |  |

# B.2 Data Fieldwork August 2017

During the fieldwork in the last week of August 2017, multiple participants from the Hydralab+ project were involved in the data collection. The participants were from University of Hull, University of Loughborough, Forschungszentrum Küste Hannover, and DHI. The data was collected by different measurement equipment, which will be described in this section. Also, the collected data will be presented.

# B.2.1 Frame

The first piece of equipment that has been used for short-term local data collection is a frame, which has been deployed at several locations in the vicinity of the platform for 30 minutes. The parameters that have been measured during these short time series are light attenuation (PAR Odyssey), flow velocity at a fixed height above the bed (ADV), wave heights and water depth (ADV pressure sensor), and eelgrass cover (underwater camera)





Figure 3 Photo of the frame on site

Figure 4 Illustrative overview of the frame as deployed (FZK, M. Thom)

#### Light attenuation

Five photosynthetic active radiation sensors (PAR-sensors) or light sensors of Odyssey have been mounted on the frame at different heights above the bed. These heights above the bed were kept constant during all the measurements. A sixth PAR-sensor was located on the survey boat, as a reference of the radiation at the water surface. The PAR-sensors measured the radiation intensity every 10 minutes, which consequently means that for every location, three measurements of radiation over the water column were performed.

### Flow velocity in/outside eelgrass patch

An ADV (Acoustic Doppler Velocimeter, Nortek) was mounted on the frame and recorded the flow velocity at a fixed level (0.20 m) above the bed with a frequency of 32 Hz during the 30-minute deployment at every site. It is important to mention that it measured the flow velocity inside or outside the eelgrass patches, depending on the eelgrass cover per site.

### Wave height and water depth (pressure)

The ADV records, besides the flow velocity, the pressure at the location of the ADV at the same rate as the velocity (32Hz). This means that the pressure that the water column imposes on top of the ADV is recorded, including waves (in case they are present). The pressure sensor was located 0.70 m above the bed. The recorded pressure needs to be related to the atmospheric pressure to determine the absolute water depth. By averaging the pressure data over a longer time, the mean water depth and the corresponding wave height can be resolved.

### **Eelgrass cover**

An underwater camera on the frame was used to detect whether eelgrass was present at the frame location, to have an indication of the density of the patch and to view the state of the eelgrass (healthy and green, epiphytes present). The underwater camera footage taken during the fieldwork in August 2017 is shown in Figure 5.



# Figure 5 Eelgrass cover at sites A to K

## B.2.2 ARC-Boat

Short time series over transects have been sailed multiple times in the vicinity of the platform. The data has been collected with an ADCP (Acoustic Doppler Sontek M9) mounted to an "ARC-Boat": a remote-controlled boat developed by HR Wallingford. RTK GPS (a special form of DGPS) was used to provide spatial reference within the dataset. Parameters that have been measured are bed depth, flow velocities over the water column, and bathymetry.



Figure 6 ARC-Boat (R. Houseago)

Figure 7 Sailed transects during fieldwork (29 Augusts 2017)

## B.2.3 Eelgrass experiments (morphology and biomechanics)

Eelgrass samples were collected from the Rødsand lagoon between the DHI buoy and platform. They were stored in a plastic container filled with seawater, also retrieved from the site, at ambient temperature. The samples were used in morphological and biomechanical experiments within 48 hours after collection.

### Description of the experimental procedure

From the collected samples, 15 plants including roots and rhizomes and undamaged leaves were selected. The number of leaves (both photosynthetically active and decaying) was recorded for each plant and all blades were separated from the shoot. Mass, length and both the minimum and maximum width and thickness of the shoots and blades were measured (morphological tests). From each blade obtained from a plant, samples were used in biomechanical tests for characterising the flexural rigidity (Peirce, 1930). Each sample was tested with a cantilever apparatus (Figure 8) to obtain an estimate of its bending properties. During the test, the sample was slowly moved forward until the end of the specimen touched the inclined plate. The horizontal projection of the sample is then the cantilever length. The test was repeated using the end of either side of the specimen (four times), as this reduces the influence of local properties of the specimen on the test.



Figure 8 Schematic representation of Peirce's cantilever apparatus

### **Results of the fieldwork experiments**

Table 4 shows the results of the number of blades per shoot. Table 5 and Table 6 both show the morphology and biomechanics of the shoot and healthy blades, respectively. Finally, Table 7 shows the morphology and biomechanics of decaying leaves; however, they are less important for this thesis.

| Table 4 Blades per shoot                                   |      |        |             |  |
|--|------|--------|-------------|--|
| Parameter  | Mean | Median | Sample size |  |
| Number of<br>photosynthetically active<br>blades per shoot | 3.5  | 4      | 15 plants   |  |
| Number of decaying<br>(brown/yellow) blades per<br>shoot   | 2    | 2      | 15 plants   |  |

# . .

## Table 5 Shoot morphology (measured from transition rhizome-shoot to shoot-blades)

| Parameter                      | Mean   | Standard<br>deviation | Coefficient of<br>variation [%] | Sample size |
|--------------------------------|--------|-----------------------|---------------------------------|-------------|
| Length [mm]                    | 199.08 | 44.54                 | 22.37                           | 25          |
| Minimum width [mm]             | 3.02   | 0.54                  | 17.88                           | 25          |
| Maximum width [mm]             | 4.09   | 0.80                  | 19.56                           | 25          |
| Minimum thickness [mm]         | 1.34   | 0.64                  | 47.76                           | 25          |
| Maximum thickness [mm]         | 1.78   | 0.62                  | 34.83                           | 25          |
| Density [kg dm <sup>-3</sup> ] | 1.05   | 0.24                  | 22.86                           | 25          |

Table 6 Blade morphology and biomechanics (only blades still attached to the plant, mostly green)

| Parameter                              | Mean     | Standard deviation | Coefficient of<br>variation [%] | Sample size |
|--|----------|--------------------|---------------------------------|-------------|
| Length [mm]                            | 497.17   | 238.23             | 47.92                           | 51          |
| Minimum width [mm]                     | 3.94     | 0.68               | 17.26                           | 51          |
| Maximum width [mm]                     | 4.16     | 0.68               | 16.35                           | 51          |
| Minimum thickness [mm]                 | 0.24     | 0.07               | 29.17                           | 51          |
| Maximum thickness [mm]                 | 0.47     | 0.12               | 25.53                           | 51          |
| Density [kg dm⁻³]                      | 0.89     | 0.15               | 16.85                           | 51          |
| Flexural rigidity [Pa m <sup>4</sup> ] | 2.34E-06 | 2.00E-06           | 85.47                           | 75          |
| Young's Bending modulus<br>[MPa]       | 253.82   | 130.01             | 51.22                           | 75          |

|--|

|  |          | _                  |                                 | _           |
|--|----------|--------------------|---------------------------------|-------------|
| Parameter                              | Mean     | Standard deviation | Coefficient of<br>variation [%] | Sample size |
| Width [mm]                             | 4.41     | 0.51               | 11.56                           | 25          |
| Thickness [mm]                         | 0.33     | 0.07               | 21.21                           | 25          |
| Density [kg dm <sup>-3</sup> ]         | 1.30     | 0.31               | 23.85                           | 25          |
| Flexural rigidity [Pa m <sup>4</sup> ] | 3.13E-06 | 2.56E-06           | 81.79                           | 21          |
| Young's Bending modulus<br>[MPa]       | 407.88   | 211.48             | 51.85                           | 21          |

The coefficient of variation is a relative measure for the distribution around the mean of the variable (Jonkman et al. 2016). It is the ratio of the standard deviation to the mean, here expressed as a percentage:

$$CV = \frac{\sigma}{|\mu|}$$

The lower the coefficient of variation is, the more accurate the results will be.

The flexural rigidity is estimated from the cantilever length *L* as

$$E_b I = \frac{mgL^3}{8l} \left( \frac{\cos(\theta/2)}{\tan \theta} \right)$$

and when the leaf cross section is considered elliptical, Young's bending modulus  $E_b$  is calculated as

$$E_{b} = \frac{8}{\pi} \frac{mg}{lw} \frac{L^{3}}{t^{3}} \left( \frac{\cos(\theta/2)}{\tan\theta} \right)$$

where  $\theta$  is the inclination of the cantilever apparatus (Figure 8), m and I are the mass and the length of the specimen, and w and *t* are the average width and thickness of the specimen.

# B.2.4 Platform

A measuring station has been collecting data for over a longer time period (months) on a platform in the Rødsand lagoon. This was installed in a known seagrass area in the western part of the Rødsand lagoon, at location NS04 (Figure 4.1). According to DHI, the data set includes time series of meteorological conditions, currents, wave heights, turbidity, salinity, temperature, sediment concentration, grain size, and light attenuation as well as the state of the vegetation (Table 8).





Figure 9 Platform (DHI)

Figure 10 Illustrative overview of experimental setup platform (DHI)

| Table 8 Overview o | f instruments insta | lled on the mo | nitoring platform |
|--------------------|---------------------|----------------|-------------------|
|                    |                     |                |                   |

| Instrument               | Height above bed [m] | Parameters  |
|--------------------------|----------------------|---|
| ADV uplooking            | 0                    | Velocity components ( <i>u</i> , <i>v</i> , <i>w</i> ), turbulent kinetic |
|                          |                      | energy  |
| ADV downlooking          | 2.5                  | Velocity components ( <i>u</i> , <i>v</i> , <i>w</i> ), turbulent kinetic |
|                          |                      | energy, distance to the bed   |
| Aquadopp uplooking       | 0                    | Current speed and –direction, waves                                       |
| Aquadopp downlooking     | 2.5                  | Current speed and direction near the bed, data for                        |
|                          |                      | bed shear stress  |
| WetLabs WQM 2x           | 0.5 and 1.5          | Turbidity, salinity, temperature, fluorescence,                           |
|                          |                      | oxygen  |
| LICOR light sensor 2x    | 0.5 and 1.5          | Light intensity   |
| DHI sense high-frequency | 0                    | Wave information  |
| pressure sensor          |                      |   |
| LISST 100-X              | -                    | Sediment grain size distribution (2.5 -500 μm)                            |
|                          |                      | Not continuous measurements   |
| Underwater camera        | -                    | Daily images of eelgrass  |
| Meteorology station      | -                    | Simple meteorological information   |

# B.3 Data Results Fieldwork August 2017

# B.3.1 Frame

# Light attenuation

The radiation intensity over the water column has been scaled to a percentage of the surface radiation measured at the same instance. Figure 11 shows the percentage of light that remains in the water column for each site.



## Flow velocity in-/outside eelgrass patch

The flow velocity inside or outside the eelgrass patch, depending on the eelgrass cover per site, has been measured but not further examined since the flow conditions were extremely calm.

### Wave height and water depth (pressure)

The data of the pressure sensor has been examined for one site only (site A). It was found that the water level was almost constant over time. Due to the calm conditions, no wave climate could be derived from this data, as the wave amplitudes were too small and were recorded within the noise ratio.

#### **Eelgrass cover**

The state and cover of the eelgrass were examined at each site by the use of an underwater camera. Table 9 shows the eelgrass cover derived from the footage for all sites except for site C, where no footage was recorded.

| Eelgrass cover  | Site             |
|-----------------|------------------|
| Dense cover     | B, D, G, H, J, K |
| Dense cover, at | I                |
| meadow edge     |                  |
| Medium cover    | А                |
| Bare sediment   | E, F             |
| (unknown)       | С                |

#### Table 9 Overview of eelgrass cover at sites A to K

### B.3.2 ARC-Boat

#### Flow velocity over the water column

The flow velocity over the water column measured by the ADCP has been visualised in Figure 12. The magnitude of the velocity for every bin has been plotted. Since the ADCP was set to determine the vertical bin width automatically, not every measurement point in the transect counts the same bins over the vertical. The horizontal bin width is determined by the sailing speed of the ARC-Boat. The bottom tracking profile has been plotted in the same figure to show the level of the seabed.



Figure 12 ADCP Flow velocity profile over depth for one transect from the platform to the buoy (heading 320 degrees). The sites of the frame deployment are indicated: in red (Sites F and J) means within a 5-metre range, in green (Sites A and B) within a 10-metre range.

Flow velocity profiles over the water column were examined. These profiles were averaged over multiple pings to see whether the sites with substantial eelgrass cover (A, B, F) showed a different flow velocity profile over the vertical than sites without eelgrass (F).

As can be seen from the transect (Figure 12), the flow velocity does not differ much instantaneously (over the vertical, in ydirection), but over spatially and during the measurement (in x-direction), the flow velocity first shows an increase and decrease over the complete water column. This is illustrated by the changing colours as going from left to right in the transect.

The main conclusion is that velocity profiles over the water depth around sites F, J, B, and A, even averaged over multiple pings, showed no significant difference between the sites with eelgrass and the sites without eelgrass.

## **B.3.3** Eelgrass experiments

The complete results of the morphology and biomechanical experiments are presented in Appendix B.2.2. Each plant has on average 3.5 healthy leaves and 2 decaying leaves. The length of the shoot is on average  $19.9 \pm 4.5$  cm, and has a width of 3.5 mm and thickness of 1.5 mm. The length of the blades is on average  $49.7 \pm 23.8$  cm and has an approximate width of 4 mm and thickness of 0.3 mm.

## B.3.4 Platform

**Remark:** It should be noted that only the ADV data has been made available. Unfortunately, due to the very calm conditions, the recorded velocity was extremely low. The pressure showed the same noise in water level as the ADV from the frame (see section B.2.1), no conclusive outcomes on wave data could be derived either.

# **B.4 Conclusions Data Fieldwork**

The data obtained from the fieldwork in August 2017 shows no significant effect of eelgrass feedback on the coastal system under these conditions. The conditions during this measurement campaign in the summer were absolutely calm and can be considered as nearly instantaneous. Moreover, the spatial scale that has been examined during this measurement campaign is in fact, relatively small and characterised as the 'patch scale'. However, to reflect on the behaviour of the complete coastal system, also spatial specific data is needed for both calm and dynamic conditions.

These data only provided insight into the local ecosystem behaviour for calm conditions, instead of the desired variability in space and in environmental conditions, i.e. including dynamic conditions. It is now known that for (extremely) calm conditions, no feedback of the eelgrass on the system behaviour can be observed.

# Appendix C. Physical model

# C.1 Bathymetry and layer refinement optimisation

In this appendix, all figures that belong to section 5.2 Physical model, but were not shown before, are included.



Figure 13 visualises the modelled transect with the hydrodynamic ( $\sigma$ -)grid layering, the locations that are defined at different depths and therefore in different depth zones (the contours indicated by dashed black lines) in the transect. Depth zone 0.5-1 m starts approximately at location 4 and stretches until 3,500 m, depth zone 1-2 m ranges between 3,500 m and 6,000 m and from 9,500 m to 11,500 m (due to the elevated bathymetry) and includes locations 2, 3, and 9. Depth zone 2-4 m also comprises of two stretches, i.e. from 6,000 m to 9,500 m and from 11,500 m to 16,000 m, including locations 6 and 12. The last depth zone stretches until the end of the modelled transect and contains locations 14, 15 and 16.

At different locations, the vertical layering has been optimised by comparing velocity profiles over the water column (see figures below). The layering has been adapted to still show the same vertical resolution and accuracy as for a very detailed layering (e.g. 100 layers of 1%). In red, the original used profile before the adaptation of the layering, in black the very detailed layering and in blue the finally used adapted layering. The optimised and used layer refinement is given in Table 5.2 (see section 5.2).



# C.2 Optimisation of the sediment parameters

The optimisation of sediment parameters was performed for the physical model containing the online coupling Delft3D-FLOW-WAVE without vegetation (no vegetation included in Delft3D) and only for the first week of the year. Table 10 contains the performed simulations and the parameters that have been varied during the procedure, Figure 14 to Figure 17 show the results of the simulations for location 9, however locations 4 and 15 were also looked into. These three locations were chosen based on their depth: shallow (location 4), intermediate (location 9), and deep (location 15), respectively.

| Testnr       | Tau_cr | M [kg m <sup>-2</sup> | IniSedThick | IniSedThick | Remarks  |
|--------------|--------|-----------------------|-------------|-------------|--|
|              |        | 5 J                   |             | sand [m]    | Quising anthing of the continuent server stars   |
| presentINEW2 | 0.04   | 16-2                  | 0.05        | 5           |  |
| 1            | 0.02   | 1e-5                  | 0.5         | 0.5         | lest1-9 with test parameters tau_cr and M, IniSedThick constant (=0.5 meter for both mud and sand).  |
| 2            | 0.03   | 1e-5                  | 0.5         | 0.5         |  |
| 3            | 0.04   | 1e-5                  | 0.5         | 0.5         |  |
| 4            | 0.02   | 2e-5                  | 0.5         | 0.5         |  |
| 5            | 0.03   | 2e-5                  | 0.5         | 0.5         |  |
| 6            | 0.04   | 2e-5                  | 0.5         | 0.5         |  |
| 7            | 0.02   | 3e-5                  | 0.5         | 0.5         |  |
| 8            | 0.03   | 3e-5                  | 0.5         | 0.5         |  |
| 9            | 0.04   | 3e-5                  | 0.5         | 0.5         | <b>Conclusion test 1-9:</b> Sediment concentration in the water column far too high, therefore IniSedThick mud set to original 0.05 m          |
| 10           | 0.02   | 1e-5                  | 0.05        | 0.5         | Test 10-13 are dummy tests what causes the increased SSC   |
| 11           | 0.03   | 1e-5                  | 0.05        | 0.5         | rest 10-15 are durinity tests, what causes the increased ose   |
| 12           | 0.04   | 1.5e-5                | 0.05        | 0.5         |  |
| 13           | 0.04   | 1e-5                  | 0.05        | 0.5         | Same as present1NEW2, but then with lower IniSedThick sand → gives still very high SSC, therefore IniSedThick sand set to 5 m (original value) |
| 14           | 0.02   | 1e-5                  | 0.05        | 5           | Test1-9 with test parameters tau_cr and M, IniSedThick constant (=0.05m for mud and 5 m for sand)  |
| 15           | 0.03   | 1e-5                  | 0.05        | 5           |  |
| 16           | 0.02   | 1.5e-5                | 0.05        | 5           |  |
| 17           | 0.03   | 1.5e-5                | 0.05        | 5           |  |
| 18           | 0.04   | 1.5e-5                | 0.05        | 5           |  |
| 19           | 0.02   | 2e-5                  | 0.05        | 5           |  |
| 20           | 0.03   | 2e-5                  | 0.05        | 5           |  |
| 21           | 0.04   | 2e-5                  | 0.05        | 5           |  |
| 22           | 0.04   | 1e-5                  | 0.025       | 2.5         | Extra tests to see the influence of IniSedThick mud/sand ratio   |
| 23           | 0.04   | 1e-5                  | 0.025       | 5           |  |
| 24           | 0.02   | 2e-5                  | 0.025       | 5           | Higher erosion with less sediment available (compare with test 19)   |
| 25           | 0.04   | 1e-5                  | 0.06        | 5           | (higher IniSed I hick mud)   |
| 26           | 0.04   | 1e-5                  | 0.075       | 5           | (nigher IniSed I nick mud)   |
| 27           | 0.04   | TG-2                  | 0.1         | 5           |  |
| 28           | 0.03   | 2e-5                  | 0.05        | 5           | Extra tests 28-35 based on test 19 and 20 with higher fall velocity (Stokes) = 8e-4 m s-1  |
| 29           | 0.02   | 2e-5                  | 0.05        | 5           | Based on test 19 with higher fall velocity (Stokes)  |
| 30           | 0.03   | 2e-5                  | 0.1         | 5           | Most representative SSC for all three locations, these sediment parameter settings are used in subsequent simulations                          |
| 31           | 0.02   | 2e-5                  | 0.1         | 5           |  |
| 32           | 0.03   | 5e-5                  | 0.05        | 5           |  |
| 33           | 0.02   | 5e-5                  | 0.05        | 5           |  |
| 34           | 0.03   | 5e-5                  | 0.1         | 5           |  |
| 35           | 0.02   | 5e-5                  | 0.1         | 5           |  |

Table 10 Settings of the different sediment parameters for all optimisation simulations

The settings of Run 30 (light blue line in Figure 17) were used subsequently as they showed the largest resemblance to the converted NTU data provided by DHI. These settings are also given in Table 5.3.



Figure 14 Results of the optimisation runs 1-9



Figure 15 Results of the optimisation runs 10-13



Figure 16 Results of the optimisation runs 14-27



Figure 17 Results of the optimisation runs 28-35 (with 19 and 20 for comparison)

# C.3 Implementing vegetation in Delft3D-FLOW

## C.3.1 Roughness method

Lesser et al. (2004) found that, when the depth is changing severely across the domain, it is important to specify a roughness height which is independent of the water depth. The applied roughness formula is therefore the White-Colebrook formulation (equation (C.1)), which includes the Nikuradse roughness height  $k_s$ , resembling the roughness of the bed. The corresponding Chézy friction coefficient *C* is calculated respectively:

$$C = 18\log\left(\frac{12h}{k_s}\right) \tag{C.1}$$

The roughness height  $k_s$  amounts several grain diameters for a very smooth bed and can be several centimetres for calculations with vegetation included.

However, modelling the submerged vegetation as a modified bed roughness would give incorrect results. Essentially, the vegetation is then represented as large bed structures (Baptist et al., 2007). In this way, the vertical flow velocity profile cannot be represented correctly: lower flow velocities above the vegetation and higher flow velocities near the bed are assumed, inducing higher bed shear stresses. This would negatively affect the sediment transport, causing more erosion at the vegetated areas than at bare areas. In reality, the flow velocity through the vegetation is lower than above the vegetation, leading to lower bed shear stresses and therefore less erosion compared to bare areas (see subsection 1.3.3).

#### C.3.2 Modified turbulence method

Until now, it has been proven that implementing vegetation as modified bed roughness is not consistent with reality. Another way of implementing the vegetation into the model is by adapting the k- $\varepsilon$  turbulence model. In case of a well-mixed basin and when vertical circulations are important, the k- $\varepsilon$  turbulence model is used. Two non-linearly coupled partial differential equations are used to compute the transport of turbulent kinetic energy (k) and energy dissipation ( $\varepsilon$ ).

In Delft3D, the theory about effects of vegetation on momentum and turbulence equations developed by Uittenbogaard (2000) is implemented in the '(Rigid) 3D vegetation model' and has been extensively tested. The theoretical background is given below, largely based on the formulations and explanations in the Delft3D-FLOW manual (Deltares, 2017).

#### **Theoretical background**

Cylindrical stems with length  $h_{veg}$  with diameter *b* and drag coefficient  $C_D$  represent the plants. The drag coefficient  $C_D$  should have a value of approximately 1, as the plants are represented as cylinders. The spatial density of the plants is included by using the number of stems per m<sup>2</sup> N.

The influence of the vegetation on vertical mixing is incorporated as an extra source term T in the kinetic turbulent energy (k) equation and an extra source term  $T\tau^{-1}$  in the equation for turbulent kinetic energy dissipation ( $\varepsilon$ ):

$$\frac{\partial k}{\partial t} = \frac{1}{1 - A_p} \frac{\partial}{\partial z} \left\{ \left( 1 - A_p \right) \left( \nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial z} \right\} + T + P_k - B_k - \varepsilon$$
(C.2)

$$\frac{\partial \varepsilon}{\partial t} = \frac{1}{1 - A_p} \frac{\partial}{\partial z} \left\{ \left( 1 - A_p \right) \left( \nu + \frac{\nu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial z} \right\} + \frac{T}{\tau} + P_\varepsilon - B_\varepsilon - \varepsilon_\varepsilon$$
(C.3)

where  $A_p$  is the horizontal cross sectional plant area, P and B are the production and buoyancy terms and T is the amount of work spend on the fluid:

$$T(z) = F(z)u(z) \tag{C.4}$$

Here, *F* is the friction force of the cylindrical stems on the flow:

$$F(z) = \frac{1}{2} \rho_0 C_D b N |u(z)| u(z)$$
(C.5)

The number of stems per area N and the stem diameter b are therefore the basic input parameters and the horizontal cross sectional plant area  $A_p$  is given by:

$$A_p = \frac{\pi}{4}b^2N \tag{C.6}$$

Furthermore,  $\tau$  is here the minimum of the dissipation timescale of free turbulence  $\tau_{free}$  and the dissipation timescale of eddies between the plants  $\tau_{veq}$ :

$$\tau = \min\left(\tau_{free}, \tau_{veg}\right)$$

$$\tau_{free} = \frac{1}{c_{2\varepsilon}} \frac{k}{\varepsilon}, \quad \tau_{veg} = \frac{1}{c_{2\varepsilon}\sqrt{c_{\mu}}} \sqrt[3]{\frac{L^2}{T}}$$
(C.7)

where L(z) is the eddy size [m] limited by the smallest distance between the stems:  $L(z) = C_l \sqrt{\frac{1-A_p}{N}}$ . According to

Uittenbogaard (2000), the value for the coefficient  $C_l$  of 0.8 is found applicable for vegetation.

### **Practical implementation**

To implement the vegetation in the Delft3D-FLOW module, the structure of the plants needed to be specified. This is done in a \*.inp-file, which is needed to be generated manually offline (Deltares, 2017). In this \*.inp-file, the value for the coefficient  $C_l$  (= 0.8) is specified together with the number of time steps between updates of the plant development and the vertical structure of the plants. For plants of different heights, a new type of plant is described by four columns containing the height of the plant, the stem diameter, the number of stems and the drag coefficient ( $C_D$  =1). As also the spatial density of the plants will vary, the horizontal distribution per m<sup>2</sup> per plant type is specified by means of a \*.dep-file, containing the number of stems per grid cell of each plant type.

# C.3.3 Dynveg calculations

To reflect on the model implementation of vegetation as rigid cylinders and the impact on the results of omitting plant flexibility, the dynamic interaction between flexible vegetation and the flow has been simulated using Dynveg (Dijkstra, 2012). This is a numerical model that was developed by Dijkstra & Uittenbogaard (2010) and consists of an existing 1DV k- $\epsilon$  turbulence model simulating flow combined with a model that simulates the bending of plants based on the force balance, accounting for both plant position and buoyancy. The model output is a vertical profile of hydrodynamic parameters (e.g. flow velocity and eddy viscosity), plant position (deflected height  $k_{veg}$ ), equivalent drag coefficient  $C_{Deq}$ , the force acting on the plant, and the bed shear stress. Please see the research of Dijkstra (2012) for detailed information.

Based on the plant characteristics assumed for this study (Table 11) and the flow velocities resulting from Baseline case 1 (with vegetation, Table 12), Dynveg simulations were performed for the four depth zones using the values for locations 4 (0.5-1 m), location 9 (1-2 m), location 6 (2-4 m) and location 15 (4-6 m). The results of these Dynveg simulations are also given in Table 12.

| Parameter               | Location 4 | Unit                 |
|-------------------------|------------|----------------------|
| Stem/leaf diameter      | 0.004      | [m]                  |
| Stem thickness          | 0.0015     | [m]                  |
| Leaf thickness          | 0.00035    | [m]                  |
| Flexural rigidity       | 2.34E-06   | [Pa m <sup>4</sup> ] |
| Young's bending modulus | 253.82     | [MPa]                |
| Specific leaf density   | 890        | [kgm <sup>-3</sup> ] |

Table 11 Plant parameters derived from the fieldwork of August 2017

| Fable 12 Input parameters fro | om the coupled model, | the calculated buoyancy | and Cauchy number and                 | results of the Dynveg calculations |
|-------------------------------|-----------------------|-------------------------|---------------------------------------|------------------------------------|
| ······                        |                       |                         | · · · · · · · · · · · · · · · · · · · |                                    |

| Parameter                               | Location 4 | Location 9 | Location 6 | Location 15 | Unit                |
|---|------------|------------|------------|-------------|---------------------|
| Depth zone                              | 0.5-1 m    | 1-2 m      | 2-4 m      | 4-6 m       | [-]                 |
| Water depth                             | 0.57       | 1.77       | 3.33       | 5.91        | [m]                 |
| Mean flow velocity in                   | 0.0154     | 0.0159     | 0.0163     | 0.0223      | [ms <sup>-1</sup> ] |
| layer just above plants                 |            |            |            |             |                     |
| Modelled vegetation                     | 0.9        | 0.85       | 0.77       | 0.22        | [m]                 |
| height (summer value)                   |            |            |            |             |                     |
| Number of plants                        | 150        | 190        | 110        | 6           | [m <sup>-2</sup> ]  |
|   |            |            |            |             |                     |
| Buoyancy B                              | 48         | 40         | 30         | 0.7         | [-]                 |
| Cauchy number Ca                        | 190        | 171        | 133        | 5.8         | [-]                 |
| Equivalent drag                         | 1.4        | 1.88       | 1.89       | 1.98        | [-]                 |
| coefficient C <sub>Deg</sub>            |            |            |            |             |                     |
| Deflected plant height k <sub>veg</sub> | 0.57       | 0.78       | 0.72       | 0.21        | [m]                 |

A few remarks must be made to Table 12. First of all, the buoyancy parameter and Cauchy number were calculated using equations (1.10) and (1.11), see subsection 1.3.5. The results of the Dynveg simulations show that the plant length for location 4 is larger than the water depth. This is possible in reality, meaning that the plant stands upright in the water column and the top of the plant is deflected at the water surface. The values used for the flow velocity and the plant parameters are the averaged values, i.e. flow velocities averaged over the year and plant parameters averaged over the examined specimen during the fieldwork of August 2017. The results of the Dynveg simulations showed that  $C_{Deq}$  has an approximate value of 2 for all locations. The calculated deflected plant height  $k_{veg}$  (in low flow conditions) is almost the same as the modelled upright vegetation height, as was expected.

# C.4 Coupling interval Delft3D-FLOW-WAVE

Figure 18 shows the small differences in wave height that are resolved at different coupling intervals between the Delft3D-FLOW and WAVE module. The differences are so small that the largest-tested coupling interval of 180 minutes has been chosen for the continuation of the model setup.



Figure 18 Computed wave height with coupling interval of A) 60 minutes B) 120 minutes and C) 180 minutes

# Appendix D. Growth model

In this appendix, the eelgrass growth model equations as used in this study for the state variables are presented. The formulations and explanations are largely based on the research of Carr et al. (2012a, 2012b) and their predecessors (Bach (1993), Verhagen & Nienhuis (1983) and Zharova et al. (2001)), but they also include the applied adaptations to fit the purpose and suitability for this research: to assess the (inter)annual morphology and condition of eelgrass meadows under environmental stressors. All coefficients, parameter values, and limitation functions that have been used, can be found in Tables 1 and 2 in this appendix.

## D.1 Model equations

The aboveground biomass per m<sup>2</sup> B is the product of the total number of shoots per m<sup>2</sup> N and the biomass per shoot P:  $B = N \cdot P$ . New shoot recruitment and biomass production are direct functions of daily available irradiance (related to the suspended sediment concentration in the water column) and average water temperature. Respiration is scaled only as a function of the daily average water temperature. A fraction of the aboveground production is transferred to a combined rhizome biomass R. The growth model uses belowground (or rhizome) biomass as energy storage for vegetative growth, i.e. to form a new shoot, thereby supporting shoot recruitment. Mortality of an individual shoot in turn affects both the associated aboveground biomass and some small fraction of the belowground biomass through uprooting. Not included in the growth model are the energy translocation to the rhizomes prior to leaf and shoot senescence and biomass allocation into flowering and seed components for sexual reproduction.

The change in the total number of shoots per m<sup>2</sup> is the product of the total number of shoots and the difference between shoot recruitment and loss. Shoot recruitment is a function of the maximum recruitment rate  $max_{Ngrow}$  and is limited by the irradiance ( $F_i$ ), photosynthetic productivity as a function of temperature ( $F_{phot}$ ), a maximum shoot density function ( $N_{lim}$ ), and a maximum aboveground to belowground biomass ratio ( $R_{lim}$ ). For simplicity, shoot mortality ( $N_{loss}$ ) is assumed to be independent of light and temperature and is therefore a constant fraction of N.

$$\frac{dN}{dt} = N(t) \cdot \left( \max_{N_{grow}} F_I(I) F_{phot}(T) N_{\lim} R_{\lim} - N_{loss} \right)$$
(D.1)

Similar to the change in the number of shoots, photosynthetic growth of the aboveground shoot biomass is a function of the maximum photosynthetic growth rate ( $\max_{phot}$ ) and is constrained by the irradiance ( $F_1$ ), the temperature-related photosynthetic productivity ( $F_{phot}$ ), a leaf age function ( $F_{age}$ ), and the maximum shoot biomass limitation function ( $P_{lim}$ ). Respiration, causing loss of biomass, is represented as a function of the maximum respiration rate  $\max_{resp}$  and temperature  $F_T$ .

$$\frac{dP}{dt} = P(t) \cdot \left(\max_{phot} F_I(I)F_{phot}(T)F_{age}P_{lim} - \max_{resp} F_T(T)\right)$$
(D.2)

The belowground biomass associated with the rhizome structure of eelgrass, R, is modelled as bulk quantity: not for every shoot individually but for the total of eelgrass plants per m<sup>2</sup>. Rhizome growth is due to the translocation of aboveground production. Loss of rhizome biomass is due to respiration, translocation of rhizome biomass to form a new shoot, and due to uprooting when a shoot is lost.

$$\frac{dR}{dt} = k_{transfer} N \frac{dP^+}{dt} - \gamma F_T(T) R - \frac{dN^+}{dt} P_{new} + k_{uproot} \frac{dN^-}{dt}$$
(D.3)

As explained, the vegetation height  $h_{veg}$  is a function of the biomass per shoot *P*, the specific density of the plant  $\rho_{veg}$ , and the number of leaves. The width and thickness of the leaves are held constant.

$$\frac{dh_{veg}}{dt} = \frac{\frac{dP}{dt}}{\rho_{veg} \cdot \# leaves}$$
(D.4)

| Table 13 Limitation functions, their descriptions and values and sources used by Carr et al. (2012a, 2012b) |   |                             |  |  |  |  |  |
|---|---|-----------------------------|--|--|--|--|--|
| Limitation functions  | Description and values  | Source                      |  |  |  |  |  |
| $I = I_0 \exp(-K_d h)$  | Irradiance at depth in E m <sup>-2</sup> d <sup>-1</sup> (mol photons m <sup>-2</sup> d <sup>-1</sup> )<br>where <i>h</i> is the water depth and $K_d$ is the light | Lawson et al.(2007)         |  |  |  |  |  |
|   | attenuation coefficient   |                             |  |  |  |  |  |
| $I_k = I_{k20} \theta_k^{1-20}$   | Saturation irradiance as a function of temperature  | Zharova et al. (2001)       |  |  |  |  |  |
|   | where $I_{k20}$ is the saturation value at 20°C set to 25.5   |                             |  |  |  |  |  |
| <b>T</b> 20   | and $\theta_k$ is the shape value set to 1.04   |                             |  |  |  |  |  |
| $I_c = I_{c20} \theta_c^{1-20}$   | Compensation irradiance as a function of temperature  | Zharova et al. (2001)       |  |  |  |  |  |
|   | where $I_{c20}$ is the compensation value at 20°C set to 2.4  |                             |  |  |  |  |  |
|   | and $\theta_c$ is the shape value set to 1.17   |                             |  |  |  |  |  |
| $F_{I}(I) = 0 \text{ for } I \le I_{c}$<br>$F_{I}(I) = 1 \text{ for } I \ge I_{k}$                          | Light limitation function   | Zharova et al. (2001)       |  |  |  |  |  |
| $F_I(I) = \frac{I - I_c}{I_k - I_c} \text{ for } I_c \le I \le I_k$   |   |                             |  |  |  |  |  |
| $\left(\frac{T_{opt}-T}{T_{opt}}\right)^2$  | Temperature photosynthesis limitation function, used  | Zharova et al. (2001)       |  |  |  |  |  |
| $F_{phot}(T) = K_{0phot}^{(1opt)} \text{ for } T \le T_{opt}$   | for the replication of Carr's reference case study. $T_{opt}$ is  |                             |  |  |  |  |  |
| $\left(\frac{T-T_{opt}}{T}\right)^2$  | the optimum temperature for photosynthesis set to   |                             |  |  |  |  |  |
| $F_{phot}(T) = K_{mphot}^{(T_{max} - T_{opt})}$ for $T \ge T_{opt}$   | 21.5°C. $T_{max}$ is the maximum temperature for  |                             |  |  |  |  |  |
| inphot of   | photosynthesis set to 34°C. $K_{Ophot}$ and $K_{mphot}$ are shape   |                             |  |  |  |  |  |
| $T_{-}(T) = 2^{T} - 2^{0}$  | coefficients set to 0.01 and 0.00001 respectively.  | D. I. (1000)                |  |  |  |  |  |
| $F_{phot}(T) = \theta_1^{T-20}$   | lemperature photosynthesis limitation function, used  | Bach (1993)                 |  |  |  |  |  |
|   | In the Rødsand lagoon case study. $\Theta_1$ is the shape value set to 1.08.  |                             |  |  |  |  |  |
| $F_{age} = 1$ for $age \le min_{age}$   | Leaf age limitation function. min <sub>age</sub> is set to 70 days,   | Carr et al. (2012a, 2012b)  |  |  |  |  |  |
| $F_{age} = 0.01$ for $age \ge max_{age}$  | max <sub>age</sub> is set to 175 days. For the reference case, the  | including adaptation of     |  |  |  |  |  |
| $(age - min_{age})$   | mean leaf age is equal to 90 days, as recommended by  | limit function              |  |  |  |  |  |
| $F_{age} = 1 - 0.99 \frac{1}{(max - min)}$  | Carr et al. Therefore $F_{age}$ has a value of 0.8114. For the  |                             |  |  |  |  |  |
| for min $\leq aae \leq max$   | Rødsand study case, <i>F<sub>age</sub></i> will have a value of 1   |                             |  |  |  |  |  |
| $101 mm_{age} \le uge \le max_{age}$  | (therefore not used in the equations).  |                             |  |  |  |  |  |
| $F_T(T) = \theta_{loss}^{T-20}$   | Temperature respiration scaling function. $\theta_{loss}$ is the  | Zharova et al. (2001), Bach |  |  |  |  |  |
|   | shape value set to 1.05 for Carr's reference case study   | (1993)                      |  |  |  |  |  |
|   | and 1.07 for the Rødsand lagoon case study.   |                             |  |  |  |  |  |
| $N_{lim} = 1 - \left(\frac{N}{N_{cc}}\right)^2$   | Maximum shoot density $N_{cc}$ set to 1000 shoots m <sup>-2</sup> .<br>For $N < N_{cc}$ , otherwise set to 0.   | Carr et al. (2012a, 2012b)  |  |  |  |  |  |
| $(P)^2$   | Maximum biomass <i>P<sub>cc</sub></i> of a single shoot set by Carr et  | Carr et al. (2012a, 2012b)  |  |  |  |  |  |
| $P_{lim} = 1 - \left(\frac{1}{P_{cc}}\right)$   | al. to 0.5 gC. In Rødsand case validation P <sub>cc</sub> was set to  | including new limit         |  |  |  |  |  |
|   | 0.375 gC. Limitation function was unavailable,  | function                    |  |  |  |  |  |
|   | implemented in the same way as $N_{lim}$ . For $P < P_{cc}$ ,   |                             |  |  |  |  |  |
|   | otherwise set to 0.   |                             |  |  |  |  |  |
| $(BRratio)^2$   | Above to belowground biomass ratio limitation. This   | Carr et al. (2012a, 2012b)  |  |  |  |  |  |
| $R_{lim} = 1 - \left(\frac{R_{lim}}{R_{lim}}\right)$  | was used by Carr et al. as Heaviside step function, but   | including adaptation of     |  |  |  |  |  |
| with <i>BRratio</i> with 24.  | turned out to cause wiggles as the limit was reached.   | limit function              |  |  |  |  |  |
|   | Therefore this limit function was introduced,   |                             |  |  |  |  |  |
|   | implemented in the same way as $N_{lim}$ . Set to 0 if  |                             |  |  |  |  |  |
|   | BRratio>BRratio <sub>max</sub> , set to 1 if BRratio<0 (i.e. if R>B).   |                             |  |  |  |  |  |

#### Table 14 Model parameters, their descriptions and values and sources used by Carr et al.

| Model parameters             | Description and values  | Source                        |  |
|------------------------------|---|-------------------------------|--|
| <i>max<sub>resp</sub></i>    | Respiratory loss rate: 0.014 d <sup>-1</sup>                        | Bach (1993)                   |  |
| max <sub>phot</sub>          | Maximum specific growth rate: 0.095 d <sup>-1</sup>                 | Bach (1993)                   |  |
| max <sub>Ngrow</sub>         | Maximum shoot recruitment: 0.04 d <sup>-1</sup>                     | Calibrated by Carr            |  |
| N <sub>loss</sub>            | Shoot mortality rate: 0.0065 d <sup>-1</sup>                        | Carr et al. (2012a)           |  |
| <i>k</i> <sub>transfer</sub> | Transfer coefficient of above to belowground biomass: can vary      | Zharova et al.(2001), Carr et |  |
|                              | from 0.17 to 0.4, in both cases set to 0.3                          | al.(2012a), Bach (1993)       |  |
| γ                            | Belowground (rhizome) respiration rate: 0.009 d <sup>-1</sup>       | Zharova et al. (2001)         |  |
| P <sub>new</sub>             | Biomass of a new shoot and single leaf: 0.0024 gC                   | Zharova et al. (2001)         |  |
| <i>k</i> <sub>uproot</sub>   | Uprooting coefficient: set to 0.002                                 | Zharova et al. (2001)         |  |
| $\rho_{veg}$                 | Specific density of the vegetation: 0.125 gC m <sup>-1</sup>        | Carr et al (2012a), data DHI  |  |
| #leaves                      | Average number of leaves: 3 for Carr's case, 3-3.5 for Rødsand case | Carr et al (2012a), data DHI  |  |

# D.2 Optimisation Reference case: Carr et al. (2012a)

For the different SSC values for spring/summer (*SSCyear*) and autumn/winter (*SSCautumn*) in the replication of the Carr et al. case, multiple runs have been performed with the growth model, see Table 15. Logically, the average SSC in autumn/winter (applied from 1 September – 1 January) is larger than the average SSC during the rest of the year due to increased hydrodynamic forcings. The *SSCautumn* has also been applied during 1 January – 1 March, but during this time of year the light climate is already low and aboveground biomass is at its minimum, therefore higher attenuation of light is less important. Hence, subsequent runs have been performed with *SSCautumn* from 1 September – 1 January only.

| Run | No  | SSCyear | SSCautumn | Fage   | Ndiff   | Pdiff =  | Bdiff   | Rdiff   | Remarks                               |
|-----|-----|---------|-----------|--------|---------|----------|---------|---------|---------------------------------------|
|     |     |         |           |        |         | hvegdiff |         |         |                                       |
| 1   | 380 | 5       | 8         | 1      | -0.0885 | 0.0441   | -0.0404 | 0.1368  |                                       |
| 2   | 300 | 6       | 7         | 1      | -0.0131 | -0.1338  | -0.1486 | -0.0471 |                                       |
| 3   | 310 | 6       | 7         | 1      | -0.0278 | -0.0979  | -0.1285 | -0.0252 |                                       |
| 4   | 310 | 5       | 7         | 1      | 0.0840  | -0.0476  | 0.0404  | 0.1273  |                                       |
| 5   | 350 | 5       | 7         | 1      | 0.0177  | 0.0711   | 0.0876  | 0.1847  |                                       |
| 6   | 350 | 5       | 7         | 0.8114 | 0.0177  | -0.2768  | -0.2542 | -0.0745 |                                       |
| 7   | 350 | 6       | 7         | 0.8114 | -0.0893 | -0.4003  | -0.5254 | -0.3058 |                                       |
| 8   | 400 | 5       | 7         | 0.8114 | -0.0695 | -0.1298  | -0.2082 | -0.0129 |                                       |
| 9   | 413 | 5       | 7         | 0.8114 | -0.0928 | -0.0976  | -0.1995 | -0.0003 | N based on Carr                       |
|     |     |         |           |        |         |          |         |         |                                       |
| 11  | 370 | 5       | 8         | 1      | -0.0705 | 0.0187   | -0.0506 | 0.1247  |                                       |
| 12  | 360 | 5       | 8         | 1      | -0.0528 | -0.0083  | -0.0615 | 0.1189  |                                       |
| 13  | 350 | 5       | 8         | 1      | -0.0353 | -0.0367  | -0.0733 | 0.0982  |                                       |
| 14  | 340 | 5       | 8         | 1      | -0.0180 | -0.0669  | -0.0860 | 0.0835  |                                       |
|     |     |         |           |        |         |          |         |         |                                       |
| 20  | 413 | 5       | 5         | 0.8114 | 0.0178  | 0.1305   | 0.1459  | 0.1922  | N based on Carr                       |
| 21  | 450 | 5       | 5         | 0.8114 | -0.0461 | 0.1957   | 0.1586  | 0.2149  |                                       |
| 22  | 569 | 5       | 5         | 0.8114 | -0.2599 | 0.3452   | 0.1751  | 0.2563  | N based on stable N mentioned by Carr |
| 23  | 569 | 6       | 7         | 0.8114 | -0.4767 | 0.0438   | -0.4120 | -0.1329 | · · · ·                               |
| 24  | 569 | 5       | 8         | 0.8114 | -0.4529 | 0.0674   | -0.3550 | -0.0024 |                                       |
| 25  | 640 | 5       | 8         | 0.8114 | -0.5984 | 0.1505   | -0.3578 | 0.0122  | N based on initial conditions         |
|     |     |         |           |        |         |          |         |         | dense meadow mentioned                |
|     |     |         |           |        |         |          |         |         | by Carr                               |
| 26  | 640 | 6       | 7         | 0.8114 | -0.6141 | 0.1162   | -0.4266 | -0.1276 |                                       |
| 27  | 640 | 6       | 8         | 0.8114 | -0.6928 | 0.0014   | -0.6904 | -0.2397 |                                       |
| 28  | 640 | 6       | 6         | 0.8114 | -0.5357 | 0.2231   | -0.1931 | -0.0132 |                                       |
| 29  | 640 | 5       | 5         | 0.8114 | -0.3915 | 0.4063   | 0.1739  | 0.2660  |                                       |
| 30  | 640 | 6       | 8         | 0.8114 | -0.6986 | -0.0125  | -0.7198 | -0.2654 | SSCautumn applied only                |
|     |     |         |           |        |         |          |         |         | 1Jan-1March & 1Sept-1Jan.             |

 Table 15 Performed simulations for the optimisation of the reference case (Carr et al. 2012a). Shown in green are the simulations with

 different parameter settings that show the largest correspondence with the original data of Carr et al.

The optimal results for the change in state variables (-diff, given in percentages) and corresponding initial number of shoots N are shaded green in Table 15. To be clear: the number of shoots N of run 1 shows a total yearly decrease of 8.85%. The intention is to have a stable system, in which case the –diff values for all state variables would be close to zero (i.e. little to no net growth nor decay of plants). Also, the variable  $F_{age}$  has been varied: when  $F_{age}$  was taken into account, the leaf age was averaged and  $F_{age}$  was 0.8114.  $F_{age}$  has a large influence on the –diff values, as the only difference between runs 5 and 6 is  $F_{age}$ . The values of  $F_{age}$  are not very realistic: the values should vary over time and per plant component to fully simulate the age structure and limitation, or  $F_{age}$  should be excluded.



#### The graphs of the above- and belowground biomass of the optimal simulations are shown in Figure 19A-E.

Figure 19 Graphs of the most optimal simulations for the reference case (Carr et al. 2012a) and the original figure. A) Run 3, B) Run 4, C) Run 5, D) Run 13, E) Run 20, F) Original figure from Carr et al (2012a)

Run 4 was found to be most representative, as the change of state variables at the end of the year compared to the beginning of the year was the smallest and therefore the most stable.
# D.3 Optimisation Research case: Rødsand lagoon

To calibrate the growth model for the Rødsand case, location 9 has been investigated. Table 16 contains the performed simulations and the parameters that have been varied during the procedure.

| Table 16 – Optimisation of the research case (Rødsand lagoon, location 9) Shown in green are the simulations with different parameter |
|---|
| settings that show the smallest –diff values (indicating stable growth during the year)   |

| Dura     | maxN  | #100000 | Khook | Dee    | NO  | Fage   |   | DNACE         | Maite   | Dalite  | Ddiff   | Ddiff        | Bornovika                         |
|----------|-------|---------|-------|--------|-----|--------|---|---------------|---------|---------|---------|--------------|-----------------------------------|
| KUN      |       | #leaves | NDACK | PCC    | 100 | гаде   |   | <b>KIVISE</b> | 1 2172  |         | 1 2260  | <b>KUIII</b> | Remarks                           |
| 1        | 0.028 | 3       | 0.28  | 0.375  | 100 | 1      |   | 10.0132       | -1.31/2 | -0.0085 | -1.3309 | -0.3012      |                                   |
| 2        | 0.028 | 3       | 0.28  | 0.375  | 110 | 1      |   | 8.7568        | -1.3204 | 0.0827  | -1.1286 | -0.2607      |                                   |
| 3        | 0.028 | 3       | 0.28  | 0.375  | 120 | 1      |   | 7.5327        | -1.3240 | 0.1587  | -0.9553 | -0.1745      |                                   |
| 4        | 0.028 | 3       | 0.28  | 0.375  | 130 | 1      |   | 6.3458        | -1.32/8 | 0.2229  | -0.8090 | -0.0998      |                                   |
| 5        | 0.028 | 3       | 0.28  | 0.375  | 150 | 1      |   | 4.1322        | -1.3365 | 0.3256  | -0.5758 | 0.0232       |                                   |
| 6        | 0.028 | 3       | 0.28  | 0.375  | 200 | 1      |   | 2.9703        | -1.3632 | 0.4919  | -0.2007 | 0.2321       | No convergence for run 1-6        |
| 7        | 0.035 | 3       | 0.28  | 0.375  | 100 | 1      |   | 5.6811        | -0.5878 | -0.0085 | -0.6013 | -0.1380      |                                   |
| 8        | 0.035 | 3       | 0.28  | 0.375  | 110 | 1      |   | 4.2253        | -0.5920 | 0.0827  | -0.4604 | -0.0500      |                                   |
| 9        | 0.035 | 3       | 0.28  | 0.375  | 120 | 1      |   | 3.0800        | -0.5967 | 0.1587  | -0.3434 | 0.0250       |                                   |
| 10       | 0.035 | 3       | 0.28  | 0.375  | 130 | 1      |   | 2.6189        | -0.6017 | 0.2229  | -0.2447 | 0.0897       |                                   |
| 11       | 0.035 | 3       | 0.28  | 0.375  | 150 | 1      |   | 4.1913        | -0.6129 | 0.3256  | -0.0878 | 0.1953       |                                   |
| 12       | 0.035 | 3       | 0.28  | 0.375  | 200 | 1      |   | 11.0935       | -0.6475 | 0.4919  | 0.1629  | 0.3723       | No convergence for run 7-12       |
| 13       | 0.04  | 3       | 0.28  | 0.375  | 100 | 1      |   | 3.3675        | -0.2167 | -0.0085 | -0.2270 | 0.0084       | Convergence: RMSE smallest,       |
|          |       |         |       |        |     |        |   |               |         |         |         |              | Ndiff -21%, Bdiff approx. same    |
|          | 0.04  | 2       | 0.20  | 0.075  | 110 |        |   | 2.6405        | 0.224.0 | 0.0027  | 0.4200  | 0.0070       | as data DHI. hvegmax 0.85 m       |
| 14       | 0.04  | 3       | 0.28  | 0.375  | 110 | 1      |   | 3.6485        | -0.2218 | 0.0827  | -0.1208 | 0.0870       |                                   |
| 15       | 0.04  | 3       | 0.28  | 0.375  | 120 | 1      |   | 4.8940        | -0.2274 | 0.1587  | -0.0327 | 0.1537       |                                   |
| 16       | 0.04  | 3       | 0.28  | 0.375  | 130 | 1      |   | 6.5357        | -0.2335 | 0.2229  | 0.0414  | 0.2110       |                                   |
| 17       | 0.04  | 3       | 0.28  | 0.375  | 150 | 1      |   | 10.1205       | -0.2470 | 0.3256  | 0.1590  | 0.3041       |                                   |
| 18       | 0.04  | 3       | 0.28  | 0.375  | 200 | 1      |   | 18.8569       | -0.2882 | 0.4919  | 0.3454  | 0.4584       |                                   |
| 19       | 0.028 | 3.5     | 0.28  | 0.4375 | 100 | 1      |   | 7.9102        | -1.3172 | 0.1348  | -1.0049 | -0.1941      |                                   |
| 20       | 0.028 | 3.5     | 0.28  | 0.4375 | 110 | 1      |   | 6.5061        | -1.3204 | 0.2129  | -0.8265 | -0.1041      |                                   |
| 21       | 0.028 | 3.5     | 0.28  | 0.4375 | 120 | 1      |   | 5.1629        | -1.3240 | 0.2779  | -0.6781 | -0.0272      |                                   |
| 22       | 0.028 | 3.5     | 0.28  | 0.4375 | 130 | 1      |   | 3.9126        | -1.3278 | 0.3329  | -0.5529 | 0.0393       |                                   |
| 23       | 0.028 | 3.5     | 0.28  | 0.4375 | 150 | 1      |   | 2.1618        | -1.3365 | 0.4207  | -0.3535 | 0.1483       |                                   |
| 24       | 0.028 | 3.5     | 0.28  | 0.4375 | 200 | 1      |   | 6.1916        | -1.3632 | 0.5629  | -0.0331 | 0.3320       | No convergence for run 19-24      |
| 25       | 0.035 | 3.5     | 0.28  | 0.4375 | 100 | 1      |   | 3.3763        | -0.5878 | 0.1348  | -0.3738 | 0.0096       |                                   |
| 26       | 0.035 | 3.5     | 0.28  | 0.4375 | 110 | 1      |   | 2.6419        | -0.5920 | 0.2129  | -0.2531 | 0.0876       |                                   |
| 27       | 0.035 | 3.5     | 0.28  | 0.4375 | 120 | 1      |   | 3.1937        | -0.5967 | 0.2779  | -0.1529 | 0.1539       |                                   |
| 28       | 0.035 | 3.5     | 0.28  | 0.4375 | 130 | 1      |   | 4.5394        | -0.6017 | 0.3329  | -0.0685 | 0.2109       |                                   |
| 29       | 0.035 | 3.5     | 0.28  | 0.4375 | 150 | 1      |   | 7.8222        | -0.6129 | 0.4207  | 0.0656  | 0.3036       |                                   |
| 30       | 0.035 | 3.5     | 0.28  | 0.4375 | 200 | 1      |   | 16.0445       | -0.6475 | 0.5629  | 0.2798  | 0.4578       | No convergence for run 25-30      |
| 31       | 0.04  | 3.5     | 0.28  | 0.4375 | 100 | 1      |   | 4.5317        | -0.2167 | 0.1348  | -0.0527 | 0.1414       | 5                                 |
| 32       | 0.04  | 3.5     | 0.28  | 0.4375 | 110 | 1      |   | 6.4256        | -0.2218 | 0.2129  | 0.0383  | 0.2106       |                                   |
| 33       | 0.04  | 3.5     | 0.28  | 0.4375 | 120 | 1      |   | 8.5431        | -0.2274 | 0.2779  | 0.1137  | 0.2692       |                                   |
| 34       | 0.04  | 3.5     | 0.28  | 0.4375 | 130 | 1      |   | 10,7165       | -0.2335 | 0.3329  | 0.1771  | 0.3194       |                                   |
| 35       | 0.04  | 3.5     | 0.28  | 0.4375 | 150 | 1      |   | 15 0304       | -0 2470 | 0.4207  | 0 2776  | 0.4006       |                                   |
| 36       | 0.04  | 3.5     | 0.28  | 0.4375 | 200 | 1      |   | 25.0399       | -0 2882 | 0.5629  | 0.4369  | 0 5343       | No convergence for run 31-36      |
| 50<br>C1 | 0.04  | 3.5     | 0.20  | 0.4373 | 100 | 1      |   | 15 5220       | 0.2002  | 0.3025  | 0.4505  | 0.3543       | No convergence for full 51 50     |
| 51       | 0.04  | 2       | 0.24  | 0.5    | 100 | 1      |   | 7 45 27       | 0.0492  | 0.2605  | 0.5100  | 0.3099       |                                   |
| 52       | 0.04  | 2       | 0.28  | 0.5    | 100 | 1      |   | 7.4527        | -0.2107 | 0.2422  | 0.0779  | 0.2450       |                                   |
| 53       | 0.04  | 3       | 0.28  | 0.5    | 90  | T      |   | 5.1207        | -0.2120 | 0.1587  | -0.0197 | 0.1687       | convergence: RMSE small, Ndff     |
|          |       |         |       |        |     |        |   |               |         |         |         |              | hvegmax 1.12 m. too large!        |
| S4       | 0.04  | 3       | 0.28  | 0.5    | 110 | 1      |   | 9.9607        | -0.2218 | 0.3104  | 0.1574  | 0.3049       |                                   |
| S5       | 0.04  | 3       | 0.28  | 0.5    | 120 | 1      |   | 12.4969       | -0.2274 | 0.3672  | 0.2233  | 0.3570       |                                   |
| S6       | 0.04  | 3       | 0.28  | 0.5    | 150 | 1      |   | 19,9003       | -0.2470 | 0.4919  | 0.3664  | 0.4735       |                                   |
| S7       | 0.04  | 3       | 0.24  | 0.5    | 100 | 0.8114 |   | 12,7043       | 0.0492  | 0.2128  | 0.2515  | 0.3169       | hvegmax large for all runs S1-S7  |
| SR       | 0.04  | 3       | 0.28  | 0.5    | 100 | 0.8114 | - | 4,5139        | -0.2167 | -0.1166 | -0.3585 | -0.0861      |                                   |
| 50       | 0.04  | 3       | 0.28  | 0.5    | 100 | 0.8144 | - | 5 3706        | -0 2167 | 0.1526  | -0.0310 | 0.1633       |                                   |
| \$10     | 0.04  | 2       | 0.20  | 0.5    | 100 | 1      | - | 7 0259        | 0.0492  | 0.0413  | 0.0885  | 0 1679       | Convergence: All -diff values are |
| 510      | 0.04  | 5       | 0.24  | 0.5    | 100 | T      |   | 1.0255        | 0.0452  | 0.0415  | 0.0005  | 0.1075       | slightly positive, hvegmax 0.88m  |
| S11      | 0.04  | 3       | 0.24  | 0.5    | 90  | 1      |   | 5.1663        | 0.0548  | -0.0651 | -0.0067 | 0.0872       | Convergence: RMSE smaller         |
|          |       |         |       |        |     |        |   |               |         |         |         |              | than run S10, -diff values go to  |
|          |       |         |       |        |     |        |   |               |         |         |         |              | 0, hvegmax 0.88 m                 |

Multiple simulations show convergence, which means that all –diff values are close to zero (stable growth, no growth or decay). The optimal simulations are indicated in green, of which run 13 shows the largest resemblance to the model data of DHI.

The best fitting value for  $maxN_{grow}$  is 0.04 (same as for Carr). An average number of leaves of 3 and background light attenuation  $K_{back}$  of 0.28 have been found to be the most representative for location 9. From the DHI model data, it is known that  $K_{back}$  is slightly different for all 20 locations in the lagoon, but can be assumed constant in the modelled transect to reduce complexity.

As explained in section 5.3, the model data of DHI predicts a decrease in aboveground biomass at all locations in the lagoon, at location 9 this decrease is 15%. Run 13, shown in Figure 20A, best represents this yearly decrease, and also the RMSE between the original DHI model data (in black) and the modelled aboveground biomass (in magenta) is the smallest. This best simulation also calculates a maximum  $h_{veg}$  that is in the same order of magnitude as the average measured plant length during the fieldwork (Figure 21), which was 0.70 metres. However, the graph shows a clear lag behind the original data, thereby underestimating the growth in spring and early summer, and underestimating decay from mid-August until mid-November. If a stable growth situation were to be modelled, i.e. the –diff values are approximately zero, Run S10 (Figure 20C) or S11 (Figure 20D) would give the best results. Runs 13 and S3 (Figure 20B) both suffer from large losses in shoot density over the year, as N shows a decrease at the end of the year of 21% (Figure 21). Clearly, all simulations underestimate growth in spring and early summer and likely both overestimate growth and underestimate decay from mid-August until the end of the year.



Figure 20 Graphs of the most optimal simulations for the research case (Rødsand lagoon, location 9). A) Run 13, B) Run S3, C) Run S10 and D) Run S11. In black is the model data of DHI shown during the year



# Appendix E. Results

In this appendix, the results of the year-round model simulations as described in section 5.5 and chapter 6 are shown in tables per depth zone and in graphs. Section E.1 contains tables with interpretations of the graphs that follow from the model simulations. The next section contains the graphs of the results of the STORM1 (with vegetation) and the STORM1-NoVeg simulations (see section 6.6) per location. Thereafter, the results of all the simulations with climate change effects (SLR1 and SLR2, TEMP1 and STORM1) are shown per state variable per location in the transect.

## E.1 Interpreted results

The model results of the simulated eelgrass development for all simulations have been analysed, the interpretation is given in the tables in this section. The eelgrass aboveground biomass development at the different transect locations was analysed according to the depth zone in which the locations can be divided, together with the initial aboveground biomass at the start of the year per location. (see Table 17).

| Tuble 17 Transect locations with their depth 20he and mitial aboveground biomass |           |            |                |   |  |  |  |  |  |  |  |
|--|-----------|------------|----------------|---|--|--|--|--|--|--|--|
| Location   | Depth [m] | Depth zone | Grid point [-] | Present biomass at the<br>start of the year |  |  |  |  |  |  |  |
| 16   | 5.3       | 4-6 m      | 1              | 0.6   |  |  |  |  |  |  |  |
| 15   | 5.91      | 4-6 m      | 13             | 0.7   |  |  |  |  |  |  |  |
| 14   | 5.27      | 4-6 m      | 22             | 3.33  |  |  |  |  |  |  |  |
| 12   | 4.1       | 2-4 m      | 47             | 6.24  |  |  |  |  |  |  |  |
| 9  | 1.77      | 1-2 m      | 60             | 18.23                                       |  |  |  |  |  |  |  |
| 6  | 3.33      | 2-4 m      | 78             | 13.88                                       |  |  |  |  |  |  |  |
| 4  | 0.57      | 0.5-1 m    | 125            | 12.67                                       |  |  |  |  |  |  |  |
| 3  | 1.32      | 1-2 m      | 110            | 11.94                                       |  |  |  |  |  |  |  |
| 2  | 1.62      | 1-2 m      | 104            | 22.1  |  |  |  |  |  |  |  |

Table 17 Transect locations with their depth zone and initial aboveground biomass

| Depth zone 0.5-1 m (Location 4) |   |                                      |   |                              |                                   |  |   |  |  |  |
|---------------------------------|---|--------------------------------------|---|------------------------------|-----------------------------------|--|---|--|--|--|
| Scenario                        | Growth rate   | Decay rate                           | Top of the<br>curve                                 | Max<br>Biomass               | Time of max<br>biomass            | Net yearly<br>growth/decay<br>(biomass at end<br>of theyear) | Remarks   |  |  |  |
| Baseline<br>case 1              | used as<br>reference                                    | used as<br>reference                 | Rounded with<br>one maximum                         | 52.2                         | 9 September                       | Growth (24.77)   | Highest yearly net growth compared to<br>the scenarios. Growth from begin March-<br>mid-July and mid-July-mid-September.<br>Decrease in biomass from mid-September-<br>end December   |  |  |  |
| SLR1                            | slightly<br>slower than<br>BC1                          | slightly<br>slower than<br>BC1       | more flattened<br>than BC1, with<br>rounded shape   | 49.87                        | 2 September                       | Growth, but less<br>than BC1 (22.92)                         | Less distinct peaks than BC1. The<br>maximum biomass is on average the same<br>from begin August-mid-September  |  |  |  |
| SLR2                            | slower than<br>BC1, milder<br>curve                     | slower than<br>BC1                   | more rounded<br>than BC1                            | 46.9                         | 5,10 August<br>and 2<br>September | Growth, but less<br>than BC1 (20.84)                         | Less distinct peaks than BC1 and than<br>SLR1. The maximum biomass is on average<br>the same from mid-July-mid-September  |  |  |  |
| TEMP1                           | faster than<br>BC1, steeper<br>curve                    | faster than<br>BC1, steeper<br>curve | more flattened<br>than BC 1, with<br>horizontal top | 54.9<br>(higher<br>than BC1) | 25 August and<br>9 September      | Growth, but less<br>than BC1 (23.25)                         | Growth rate mid-March-begin June<br>steeper than from begin June-mid-July.<br>The maximum biomass is on average the<br>same for mid-July-mid-September (graph<br>almost horizontal)   |  |  |  |
| STORM1                          | same as<br>BC1, but<br>disturbed by<br>the May<br>storm | same as BC1                          | same as BC1   | same as<br>BC1               | same as BC1<br>(9 September)      | Growth, slightly<br>less than BC1<br>(24.59 vs 24.77)        | The storms only have temporary effects on<br>the biomass. The May storm has the most<br>impact (slight decrease in biomass over<br>the first 3 days of the storm). November<br>storm increases the decay rate slightly,<br>September storm also decreases biomass<br>slightly |  |  |  |

| Depth zone 1-2 m (Locations 2, 3 and 9) |  |   |  |  |                                 |   |   |  |  |  |  |
|---|--|---|--|--|---------------------------------|---|---|--|--|--|--|
| Scenario                                | Growth rate  | Decay rate  | Top of the<br>curve                                | Max<br>Biomass   | Time of max<br>biomass          | Net yearly<br>growth/decay<br>(biomass at end<br>of the year)   | Remarks   |  |  |  |  |
| Baseline<br>case 1                      | used as<br>reference   | used as<br>reference  | Distinct peaks,<br>only one<br>maximum<br>value    | Location<br>2: 79.9,<br>Location<br>3: 45.4,<br>Location<br>9: 61.4                        | 9-10<br>September               | At all locations:<br>Growth<br>Location 2: 34.3<br>Location 3: 19.9<br>Location 9: 25.5   | At all locations, the trends for all scenarios<br>are the same. In general, the peaks are<br>more distinctive for locations 2 and 9 than<br>for location 3                          |  |  |  |  |
| SLR1                                    | slightly<br>slower than<br>BC1   | slightly<br>faster than<br>BC1  | more flattened<br>than BC1, with<br>rounded shape  | Location<br>2: 72.8,<br>Location<br>3: 42.4,<br>Location<br>9: 55.7                        | 10 August (at<br>all locations) | At all locations:<br>Growth, but less<br>than BC1 (same<br>as TEMP1)<br>Location 2: 30.7<br>Location 3: 18.3<br>Location 9: 22.9                  |   |  |  |  |  |
| SLR2                                    | slower than<br>BC1, milder<br>curve  | same as BC1   | more flattened<br>than BC1, with<br>rounded shape  | Location<br>2: 65.2,<br>Location<br>3: 38.6,<br>Location<br>9: 50.0                        | 10 August (at<br>all locations) | At all locations:<br>Growth, but far<br>less than BC1<br>(lowest of all<br>scenarios)<br>Location 2: 26.8<br>Location 3: 16.3<br>Location 9: 20.1 |   |  |  |  |  |
| TEMP1                                   | At all<br>locations:<br>faster than<br>BC1, steeper<br>curve begin<br>April-begin<br>June, flatter<br>curve begin<br>June-mid-<br>July | At all<br>locations:<br>faster than<br>BC1, steeper<br>curve                  | more flattened<br>than BC1, with<br>horizontal top | Higher<br>than BC1.<br>Location<br>2: 84.6,<br>Location<br>3: 47.9,<br>Location<br>9: 65.8 | mid-July                        | At all locations:<br>Growth, but less<br>than BC1<br>Location 2: 30.9<br>Location 3: 18.1<br>Location 9: 22.7                                     |   |  |  |  |  |
| STORM1                                  | same as BC1,<br>but<br>disturbed by<br>the May<br>storm  | same as BC1,<br>but<br>temporary<br>increased by<br>the<br>September<br>storm | same as BC1  | same as<br>BC1   | same as BC1<br>(9 September)    | At all locations:<br>Growth, but<br>slightly less than<br>BC1<br>Location 2: 33.2<br>Location 3: 19.3<br>Location 9: 24.6                         | The impact of both the May storm and the<br>September storm seems to be largest for<br>this depth zone, this might be due to the<br>largest biomass present at shallow<br>locations |  |  |  |  |

| Depth zone 2-4 m (Locations 6 and 12) |                                |                                |  |   |   |   |   |  |  |  |  |
|---------------------------------------|--------------------------------|--------------------------------|--|---|---|---|---|--|--|--|--|
| Scenario                              | Growth<br>rate                 | Decay rate                     | Top of the curve   | Max<br>Biomass                              | Time of max<br>biomass                                  | Net yearly<br>growth/decay<br>(biomass at end<br>of the year)       | Remarks   |  |  |  |  |
| Baseline<br>case 1                    | used as<br>reference           | used as<br>reference           | More sharply<br>peaked for location<br>6 than for location<br>12                                     | Location<br>6: 32.0<br>Location<br>12: 10.8 | Location 6: 9<br>September<br>Location 12:<br>10 August | At both locations:<br>decay<br>Location 6: 12.5<br>Location 12: 3.9 | Location 6 shows a peak in biomass in mid-<br>July and stays then stable until mid-<br>September. Location 12 does not show a<br>peak in mid-July, but the biomass stays<br>stable from begin August-mid-September.<br>The net yearly decay is far larger for<br>location 12 (~37.5%) than for location 6<br>(~10%) |  |  |  |  |
| SLR1                                  | slower<br>than BC1             | slower than<br>BC1             | more flattened and<br>more rounded<br>than BC1 for both<br>locations, with less<br>distinctive peaks | Location<br>6: 24.9<br>Location<br>12: 7.0  | Both 10<br>August                                       | At both locations:<br>decay<br>Location 6: 9.2<br>Location 12: 2.4  | Same values of high biomass between<br>mid-July-begin September (flat top of<br>curve)  |  |  |  |  |
| SLR2                                  | slower<br>than BC1<br>and SLR1 | slower than<br>BC1 and<br>SLR1 | more flattened and<br>more rounded<br>than BC1 for both<br>locations, with less<br>distinctive peaks | Location<br>6: 20.0<br>Location<br>12: 5.2  | Location 6: 7<br>August<br>Location 12: 5<br>August     | At both locations:<br>decay<br>Location 6: 7.1<br>Location 12: 1.7  | Same values of high biomass between<br>mid-July-begin September (flat top of<br>curve)  |  |  |  |  |

| TEMP1  | Location   | Location 6: | Location 6: High  | Location | 16 July (both  | At both locations: | Growth and decay rates are different for |
|--------|------------|-------------|-------------------|----------|----------------|--------------------|--|
|        | 6: faster  | Faster than | peak at mid-July  | 6: 33.3, | locations)     | decay              | both locations                           |
|        | than BC1,  | BC1         |                   | Location |                | Location 6: 10.1   |  |
|        | steeper    | Location    |                   | 12: 10.0 |                | Location 12: 2.8   |  |
|        | curve      | 12: same as |                   |          |                |                    |  |
|        | Location   | BC1         |                   |          |                |                    |  |
|        | 12: slower |             |                   |          |                |                    |  |
|        | than BC1,  |             |                   |          |                |                    |  |
|        | milder     |             |                   |          |                |                    |  |
|        | curve      |             |                   |          |                |                    |  |
| STORM1 | same as    | same as     | same behaviour in | Location | Location 6: 9  | At both locations: | Both locations suffer from a decrease in |
|        | BC1, but   | BC1, but    | peaks as BC1      | 6: 31.22 | September      | decay              | growth during the May storm and an       |
|        | disturbed  | temporary   |                   | Location | Location 12: 1 | Location 6: 11.8   | increase in decay for the September      |
|        | by the     | increased   |                   | 12: 10.4 | September      | Location 12: 3.6   | storm. The influence of the November     |
|        | May storm  | by the      |                   |          |                |                    | storm is negligible                      |
|        |            | September   |                   |          |                |                    |  |
|        |            | storm       |                   |          |                |                    |  |

| Depth zone 4-6 m (Locations 14, 15 and 16) |  |   |  |   |   |   |  |  |  |  |
|--|--|---|--|---|---|---|--|--|--|--|
| Scenario                                   | "Growth"<br>rate   | Decay rate  | Top of the<br>curve  | Max<br>Biomass<br>=<br>Summer<br>peak             | Time of max<br>biomass =<br>summer peak | Net yearly<br>growth/decay<br>(biomass at end<br>of the year)               | Remarks  |  |  |  |
| Baseline<br>case 1                         | used as<br>reference   | used as<br>reference  | At all locations:<br>"Top" is a peak<br>in biomass but<br>otherwise<br>decay | Location<br>14: 2.4<br>Location<br>15,16:<br>0.2  | 15 July (all<br>locations)              | At all locations:<br>decay!<br>Location 14: 0.65<br>Location 15,16:<br>0.03 | At all locations and for all scenarios:<br>summer biomass is not exceeding the<br>initial (1January) biomass, therefore all<br>locations show net decay over the whole<br>year. There is some growth at location 14<br>from end-May-mid-July, but during the<br>rest of the year biomass is declining for all<br>locations. Max biomass in this depth zone<br>will be the summer "peak" in the graph |  |  |  |
| SLR1                                       | slower than<br>BC1   | slower than<br>BC1  | At all locations:<br>"Top" is a peak<br>in biomass but<br>otherwise<br>decay | Location<br>14: 1.3<br>Location<br>15,16:<br>0.13 | 15 July (all<br>locations)              | At all locations:<br>decay!<br>Location 14: 0.23<br>Location 15,16:<br>0.02 |  |  |  |  |
| SLR2                                       | slower than<br>BC1 and SLR1  | slower than<br>BC1 and<br>SLR1  | At all locations:<br>almost no peak<br>observed                              | no peak<br>observed                               | 15 July (all<br>locations)              | At all locations:<br>decay!<br>Location 14: 0.14<br>Location 15,16:<br>0.01 |  |  |  |  |
| TEMP1                                      | slower than<br>BC1 (but<br>faster than<br>SLR1 and<br>SLR2)  | slower than<br>BC1 (but<br>faster than<br>SLR1 and<br>SLR2)   | At all locations:<br>"Top" is a peak<br>in biomass but<br>otherwise<br>decay | Location<br>14: 1.8<br>Location<br>15,16:<br>0.14 | 15 July (all<br>locations)              | At all locations:<br>decay!<br>Location 14: 0.26<br>Location 15,16:<br>0.01 |  |  |  |  |
| STORM1                                     | same as BC1,<br>but disturbed<br>by the May<br>storm (at all<br>locations, but<br>at location 16<br>to negligible<br>extent) | Location 14:<br>same as<br>BC1, but<br>slightly<br>increased by<br>the<br>September<br>storm. Other<br>locations:<br>same as<br>BC1, no<br>influence of<br>September<br>or<br>November<br>storm | At all locations:<br>"Top" is a peak<br>in biomass but<br>otherwise<br>decay | Location<br>14: 2.2<br>Location<br>15,16:<br>0.2  | 15 July (all<br>locations)              | At all locations:<br>decay!<br>Location 14: 0.59<br>Location 15,16:<br>0.03 | The storm impact at these locations seems<br>far less than for locations of other depth<br>zones.  |  |  |  |

# E.2 Modelled behaviour of the shallow coastal (eco)system

The interaction of feedbacks and the difference in system behaviour for eelgrass presence versus eelgrass absence was assessed with the results of the simulations STORM1 and STORM1-NoVeg for the dynamic environmental conditions of the May storm

(16-20 May). The STORM1-NoVeg simulation had the same environmental conditions, but only sparse initial vegetation was implemented (like for Baseline case 2). During the May storm, which is a westerly storm, location 4 ran frequently dry due to the wind set-down and the shallow depth of the lagoon. The results of all parameters (flow profiles and waves, bed shear stresses, SSC, and light conditions) at the locations are shown in this section. The black lines are the results from the STORM-NoVeg simulation, i.e. here the eelgrass vegetation is absent, whereas the coloured lines indicate the results with eelgrass vegetation (of the STORM1 simulation).

#### Flow velocity profiles

The flow velocity profiles over the vertical are shown for 18 May 21.00hr, as the wind velocity is then the highest (see Figure 6.6) and the corresponding flow magnitudes are the largest. Location 4 has run dry at this exact moment in time; therefore no velocity profile is shown here.



#### Wave heights

The wave heights for all locations, as computed by the Delft3D-WAVE module of the coupled model, during the May storm are shown here. At the offshore boundary, time series of wave heights are forced on the model domain, these wave height boundary conditions are reflected in the wave heights at location 16. Furthermore, it can be noted that the wave heights increase with larger water depths.





#### **Bed shear stress**

The bed shear stress exerted by the flow and waves during the May storm as computed by the model is shown for every location. The maximum values of the bed shear stress are larger for the depth zone 1-2 m (i.e. location 2, 3, and 9).





#### Suspended sediment concentrations

Related to the bed shear stress is the suspended sediment concentration in the water column, as given in the figures below for the finest fraction ( $d_{10} = 10 \ \mu$ m) and for all locations. The SSC for location 16 is constant for both simulations, as the SSC was imposed here (on the offshore boundary). The set of figures is the depth-averaged SSC during the May storm for all locations. Moreover, the sediment concentration profile over the vertical was examined for all locations for the same dynamic flow conditions as the velocity profiles (i.e. 18 May 21.00hr); however, it was found that the suspended sediment of the  $d_{10}$  fraction was relatively uniformly distributed for all locations and did not show large differences between vegetation presence and vegetation absence.





#### Light climate

The available bottom light for the year 2005 computed in Baseline case 1 is given for all four depth zones. The surface irradiance over the year 2005 is plotted together with the yearly bottom irradiance for depth zone 4-6 m, but is of course valid for the whole lagoon, i.e. for all depth zones. Again, it is visible that the larger the water depth, the more the surface light is attenuated and the smaller the available light at the bottom.





# E.3 Climate change effects

In this section, the results of the simulated plant parameters (state variables *B*, *N*,  $h_{veg}$ , and *R*) of the climate change scenarios SLR1 and SLR2, TEMP1 and STORM1 are shown per location. Also, the results of Baseline case 1, on which the climate change effect simulations are based, are plotted in the same graphs for comparison.

## E.3.1 Location 2





E.3.2 Location 3





### E.3.3 Location 4





## E.3.4 Location 6











E.3.6 Location 12





## E.3.7 Location 14











E.3.9 Location 16



