Layman’s summary

Salt marshes, which are ecosystems located on the boundary between the bare sea flats and upland, provide important services to humans. The ecosystems form complex systems where all kind of processes interact. An example of this is the interaction between vegetation growth and sedimentation which is called the bio-geomorphic feedback. As sedimentation occurs, plants can start growing which in turn allows for more sedimentation. Human induced changes to the environment can lead to changes in these interactions leading to the decline of many salt marshes around the world. One example is the salt marsh located in the Oosterschelde. Due to the construction of an sea barrier, tidal action was removed from this area. As tides are a main contributor to salt marsh growth by providing sediment this led to a lower sediment availability. Due to erosion of the sediment by waves and the lack of new sediment supply this area is declining in size. In this study a model that simulates salt marsh development was adjusted to include this process by adding wave energy to the model. Putting a barrier in front of a developing salt marsh that declined in size due to wave erosion showed that the placement of barriers is a valid method for marsh protection against wave erosion. When the size of the placed barrier is changed this lead to a non linear relationship between marsh development and barrier size. This shows that only partial cover of the salt marsh by barriers is enough to protect the marsh against erosion. By allowing more wave energy onto the marsh by not fully covering the marsh could increase the variability in available niches and thus the amount of plant species. When nature conservation is considered this could thus provide important considerations for policy makers. Grazing of the landscape led to a decrease in the amount of side creeks that were formed during marsh development. The reason for this could be that the shorter plants can trap less sediment as a result of the grazing. This change then leads to a lower bio-geomorphic feedback leading to lower diversity in habitat and thus number of species.

Adding wave energy to a model simulating salt marshes to study and visualize marsh protection against sediment erosion by placement of barriers.

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Abstract

Salt marshes are important ecosystems, providing important services to society. Many are however declining in size due to the impact of human activities in estuaries. One example of such an impact is a change in the balance between sedimentation and erosion in the Oosterschelde due to the presence of a storm surge barrier, which has led to ongoing erosion of the salt marshes in the Oosterschelde basin. In this study a model that simulates salt marsh development was adapted to investigate whether and how wave barriers could counter the erosion of salt marshes. For this, the model was expanded with a wave model. Wave energy was found to interact with every aspect of marsh development ranging from sedimentation to vegetation growth. An increasing cover of the marsh by wave barriers had a non-linear effect in reducing wave impact leading to increased marsh development. This highlights that a partial cover of the marsh by barriers provided sufficient wave protection, and increase heterogeneity of the landscape and of biomass, which could optimize niche variability and hence biodiversity. Grazing of marsh vegetation resulted in lower creek complexity. It is hypothesized that this is because vegetation traps less sediment leading to increased topographic smoothing, reducing habitat heterogeneity. The size of barriers could be of importance considering marsh restoration as a large coverage of the marsh by barriers resulted in lower biodiversity and flow rate. This study highlights the potential of wave barriers to prevent marsh erosion as well as manage habitat complexity, facilitating a diverse marsh community.

Introduction

Salt marshes, located on the interface between tidal flats and the upland, form complex systems (1) and commonly develop in areas where sediment can settle, such as estuaries, barrier islands or near deltas (2). These ecosystems can provide important ecosystem services for the local population (3). Among these services are economical benefits such as recreation (4), waste treatment (5), protection against flooding and storms (6), preventing sediment erosion (7) and providing biodiversity (8).

The formation of salt marshes happens through a process called bio-geomorphic feedback and is the result of interacting biological and geological processes (9). Growth of vegetation on the salt marsh causes a decline in hydrodynamic energy (10), resulting in the gradual build up of sediment (11,12) which in turn allows for more vegetation growth in a positive feedback loop (13). The meandering and branching of the creek system in a salt marsh is mainly influenced by the cohesiveness of the sediment which is influenced by vegetation (14). In this way vegetation growth decreases the average distance from a point in the marsh to a creek, creating more efficient creek networks (15). Salt marsh dynamics mainly occur in two cycling phases. The first phase is characterized by lateral expansion of the salt marsh into the tidal flats (16). Self organization of the ecosystem arises from the bio-geomorphic feedback that happens in this phase (17). Due to this feedback a discontinuity can happen between the height of the salt marsh and the height of the tidal flat. This leaves the edge of the salt marsh vulnerable for wave energy causing plants to die off and form a cliff (17,18). Ultimately this can lead to a lateral erosion phase that is characterized by cliff erosion at the edges (16). A relationship between the tidal flat and its salt marsh exist where the erosion of sediment from the salt marsh increases sedimentation on the tidal flat. This allows pioneer vegetation to settle on the tidal flat in front of the eroding cliffs, removing wave energy and ultimately stopping the eroding phase (19,20). Despite their importance, salt marshes have been exploited by human populations since the middle ages. These changes often lead to alterations in species composition and ecosystem functioning or even disappearance of salt marshes for example when they are converted to farmland (21). These changes to the salt marsh, or the landscape in which they are located, could be a driver of its erosion (22,23). Sea level rise is another cause of salt marsh erosion. In order for a salt marsh to persist it must increase in elevation equal to at least the same rate as sea level rise (24). Salt marshes that have a low sediment supply are already experiencing difficulties under current sea level rise caused by the emission of greenhouse gases (25). Erosion of salt marshes due to sea level rise, occurs via lateral erosion of the salt marsh edges caused by wave energy (26). An increasing sea level will cause a higher water depth on the tidal flat in front of a salt marsh. This will result in higher wave energy compared to a situation were the sea level is lower (27). During past sea level rises an upward migration of salt marshes as plants could colonize higher ground prohibited salt marsh decline. Many shorelines have been altered by human development making upward movement of salt marshes impossible (28). Future sea level rise could potentially increase the number of salt marshes that are impacted by lateral erosion. In turn this could result in a steep decline of area covered by salt marshes (29). Such uncertainty about the effects of human influence is typical for complex systems such as salt marshes. One area where such human alterations have been happening since the middle ages is the Wadden Sea, located in the North Sea. This area houses 20 percent of the European coastal salt marshes and has important properties regarding biodiversity and coastal protection (30). The Wadden Sea lost about half of its primordial size due to land reclamation projects and only 10 percent of the primordial marsh size is left (31). Construction of dikes along the coast prevents natural salt marsh development (32) and natural development of new salt marsh is limited to a few sheltered areas that are mainly located behind barrier islands (33). To stabilize shrinking salt marshes or to promote marsh development at places where natural development does not occur, groynes have been placed to locally lower the influence of wave energy and trap sediment (32,34,35). Generally these groynes are made out of brushwood or stone at places where high wave energy would damage the brushwood groynes (36,37). However, salt marshes that have been created artificially by placing groynes tend to have an evenly distributed drainage pattern and show a lower biodiversity compared to naturally formed salt marshes (38). Development of new marsh areas could be a solution to protect dikes against future sea level rise. Building groynes alongshore could, besides providing protection against future sea level rise, give opportunities for nature conservation. For these applications it could be beneficial to understand the effect of placing a groyne has on the relationships between sedimentation, vegetation growth and biodiversity during marsh development. One such system where salt marshes naturally occur is the Oosterschelde. Salt marshes in this area are subject to decline due to altered sedimentation levels due to the development of an storm surge barrier. Placement of barriers in front of the marsh are considered as an countermeasure. Understanding how this area would develop after placement of structures is important when besides dike protection, nature restoration is a goal in this process. For stakeholder and policy makers it could be helpful to have an general idea of how such an environment could look like to help convince the general public of the importance of restoring marshes.

In a modeling study by Van de Vijsel et al. (2021) (39) it was shown that complex creek networks can be formed by simple bio-geomorphic feedback mechanisms. Furthermore a salt marsh that exhibits higher creek complexity see aggregate more sediment, have higher levels of water drainage and allow for more vegetation growth. These systems are therefore less prone to sea level rise. How this fits in a complex system such as a salt marsh that includes wave energy with on the one hand marsh erosion due to wave energy and on the other hand bio-geomorphic feedback resulting in marsh growth could give insights for marsh reconstruction using groynes. This study focuses on the non-linear effects that wave energy has on the vegetation development on salt marshes protected by a barrier. A model that simulates salt marsh development has been adapted to simulate the effects of wave energy. In this study the model proposed by Van de Vijsel et al. (2021) (39) that simulates the development of a salt marsh was adapted to include the effect of wave energy on sediment and plant growth. Marsh reconstruction was simulated by placing groynes in the model and bio-geomorphological processes during salt marsh development were studied using simulated vegetation coverage, sedimentation and creek flow. When barriers that absorb wave energy were added to simulate the potential they have to restore damaged marshes or stimulate marsh development typical signs of complex systems were found such as tipping points. Sediment availability to the system is of crucial importance when it comes to marsh development leading to a tipping point in marsh development sedimentation is too low. When restoring salt marsh areas it could be of importance to keep sedimentation in mind and possible adapt the planned barriers to allow for more sediment input. Restoration of ecosystems such as salt marshes can lead to opposition from stakeholders. To illustrate how a potential restored salt marsh could look like and possibly help alleviate opposition, renders of the landscape were made using the model output and blender.

Method

The model that is used in this study to simulate salt marsh development is based on a model simulating the growth of diatoms on a tidal flat (40). The model was then later adapted to simulate vegetation growth (39). In this study a wave energy model is used that interacts with the sediment supply and the vegetation growth of the model.

A pipeline was used to generate a landscape, run a mathematical model that simulates the development of a salt marsh and then use the output of the model to make a visualization using blender. The initial landscape is entirely flat and is bordered on one side by a dike and on the opposite sides by a tidal flat. Vegetation is allowed to grow in between these areas.

Model equations

Water flow in the model is described by depth averaged shallow water equations (41). In these equations u is the shore ward component and v the alongshore component. The equation describes the change of local water level h over time. The water flow resulting from eb is assumed to be continuous and total over a tidal cycle meaning that all water that is brought in by flood h_{in} also flows out during eb. Tides are assumed to be constant over time and thus h_{in} is modeled as a constant creating a evenly distributed constant influx of water over time on the marsh.

[1] $$\frac{\delta h}{\delta t}=-\frac{\delta(u,h)}{\delta x}-\frac{\delta(v,h)}{\delta y}+h_{\text{in}}$$

A thin layer of water is applied to regions that due to the sediment buildup reach above the water level and would therefore not be suitable for the shallow water equations. A drying wetting function was used for this.

[2] $$h=max(h,H_c)$$

The flow equations in shore ward u and alongshore v directions are dependent on a gravitational constant g and the sediment height S . Flow declines under influence of the bed shear stress $(\tau_{bx},\tau_{by},\tau_b)$, respectively shore ward, alongshore and combined, and water density ρ . Turbulent mixing is modeled using $\nabla=(\frac{\delta}{\delta x},\frac{\delta}{\delta y})$.

[3] $$\frac{\delta u}{\delta t}=-g\frac{\delta(h+S)}{\delta x}-u\frac{\delta u}{\delta x}-v\frac{\delta u}{\delta y}-\frac{\tau_{\text{bx}}}{\rho h}+\nabla(D_U\nabla u)$$

[4] $$\frac{\delta v}{\delta t}=-g\frac{\delta(h+S)}{\delta y}-u\frac{\delta v}{\delta x}-v\frac{\delta v}{\delta y}-\frac{\tau_{\text{bx}}}{\rho h}+\nabla(D_U\nabla v)$$

The bed shear stress is dependent on the Chézy coefficient C_z which is a variable that is dependent on the bed shear stress. This equation is used to generate a friction that is caused by the sediment bed. Where $\sqrt{u^2+v^2}$ is used to calculate the combined flow.

(5) $$\frac{(\tau_{bx},\tau_{by},\tau_b)}{\rho}=\frac{g}{{C_Z}^2}\sqrt{u^2+v^2}(u,v,\sqrt{u^2+v^2})$$

The Chézy coefficient is given by the following equation which is given by Baptist (42). The Chézy equation to calculate drag in the water column consist of two parts. The first part calculates a drag caused by the bed and vegetation growth where C_b is the Chézy roughness of the bed, C_d is the Chézy friction coefficient with maximal vegetation growth and B_l the shoot length. The second part is driven by the water column above the vegetation and increases logarithmic as the water level increases. Here k_c is the Von Karman constant and the h water height.

$$[6] \quad C_Z = \sqrt{\frac{1}{C_b^{-2} + \frac{C_d B B_l}{2g}}} + \frac{\sqrt{g}}{k_c} \ln\left(\frac{h}{B_l}\right)$$

The sedimentation equation is dependent on the sediment input, erosion of sediment and sediment transport. A higher effective water level h_e increases sediment input as a layer of water standing on the marsh would increase sediment input. At maximum rate the sediment input approaches a constant S_{in}. The erosion of sediment is dependent on a constant erosion parameter E_S which reflects how well the sediments erodes. The vegetation density combined with a constant stabilization ability of the vegetation ρ_E determine how well sediment is captured. Erosion increases as the bed shear stress or sediment height increases.

$$[7] \quad \frac{\delta S}{\delta t} = S_{\mathrm{in}} \frac{h_e}{Q_s + h_e} - E_s\left(1 - \rho_E \frac{B}{k}\right) S \frac{\tau_b}{\rho} + \nabla\left(D_S \nabla S\right)$$

Vegetation causes an increase in sediment cohesiveness by growing a root network. This leads to a lower slope driven erosion rate for sediment which was modeled to be inversely related to sediment diffusion rate D_S. Higher stem density will decrease the abiotic sediment diffusivity D_0.

$$[8] \quad D_S = D_0\left(1 - \rho_D \frac{B}{k}\right)$$

The vegetation stem density B grows using a logistic function and growth rate r. As vegetation grows better on higher sediment levels a higher effective water level will decrease the growth rate. The death rate of the vegetation is coupled to the bed shear stress where E_B is a constant that represents the death rate per unit shear stress. D_B represents the diffusion of the vegetation. Dispersal via seeds is not included in the model.

$$[9] \quad \frac{\delta B}{\delta t} = r B\left(1 - \frac{B}{k}\right)\left(\frac{Q_q}{Q_q + h_e}\right) - E_B B \frac{\tau_b}{\rho} + \nabla\left(D_B \nabla B\right)$$

The effect of decreasing wave attenuation with sediment height is higher on a marsh compared to bare sediment (43). Wave energy is modeled using a constant input of wave energy that is limited by the sediment height and the vegetation stem density. Without sediment and vegetation the wave energy input approaches its maximum value E_{in}. Wave energy is absorbed linearly by sediment with constant ε_{se}, vegetation ε_{be} and barriers O that can be placed in front of a salt marsh with a constant strength ε_{oe}. Waves are absorbed by wind in x and y direction respectively under angle ω_x and ω_y. Wave energy diffuses proportional to the amount of wave energy present.

[10] $$\frac{\delta E}{\delta t}=E_{\text{in}}\frac{E_s}{E_s+S}\frac{E_b}{E_b+B}-\varepsilon_{se}SE-\varepsilon_{be}BE-\varepsilon_{oe}OE-\omega_x\frac{\delta E}{\delta x}-\omega_y\frac{\delta E}{\delta y}+\omega_{dm}\nabla^2 E$$

An wave energy term was added to both the sediment and vegetation equation which linearly decreases the sediment height and vegetation stem density as the wave energy increases ε_{es} , ε_{be} .

[11] $$\frac{\delta S}{\delta t}=S_{\text{in}}\frac{h_e}{Q_s+h_e}-E_s(1-\rho_E\frac{B}{k})S\frac{\tau_b}{\rho}+\nabla(D_S\nabla S)-\varepsilon_{es}ES$$

[12] $$\frac{\delta B}{\delta t}=r\,B(1-\frac{B}{k})(\frac{Q_q}{Q_q+h_e})-E_B B\frac{\tau_b}{\rho}\nabla(D_B\nabla B)-\varepsilon_{eb}EB$$

Initial and boundary conditions

A simulation landscape was made consisting of a gridsize of 2048 by 2048 cells. The landscape is made entirely flat by setting the sediment height to 0. The initial vegetation distribution is randomly chosen from a uniform distribution with an establishment probability of 0.05%. The initial wave energy is set to 0 and the initial water level is set to H_0 . The landscape is at one side adjacent to a dike and open at the other sides. At the open boundaries sediment is set to zero as erosion and sedimentation are in equilibrium, while vegetation, wave energy and water level are represented by Neumann boundary conditions meaning that the values will not change. Additionally groynes were placed in the marsh to absorb wave energy. These groynes were modeled in a similar way as dikes, meaning that they do not allow flow, sediment or vegetation through but wave energy is absorbed.

Each simulation is run for 40.000 tidal periods representing ~55 years of marsh development. During the simulation all equations are solved numerically using initial parameter setting for the equations (supplements table 1 and (39) supplements table 3.1, 3.2) for each grid cell. However the diffusion term for the sedimentation equation [11] was discretized in a different manner (39). Otherwise the equations were discretized using forward Euler discretization. First the wetting drying function [2] is applied, making sure that the entire landscape is eligible to be used in the flow equations [3, 4] which are then updated to calculate new values for u and v . The boundary conditions for u and v are applied and then the values for u and v are updated. After the flow is updated new values for sediment s [11], vegetation b [12] and wave energy e [10] are calculated, the boundary conditions applied and then these values are updated.

Initialization and set up of the landscape are done using python. While simulating is done utilizing a GPU for computations using the python package PyOpenCL (44) (version 2021.2.13). GPU computing provide high efficency and performance benefits compared to CPU computing. Therefore the model was written in c++ and compiled via PyOpenCL. Parameters are passed by PyOpenCL at the beginning of the simulation as well as the initial landscape. At set intervals of 400 tidal periods the landscape is retreived from the GPU and stored in the memory.

Analysis

Basic statistics were used to evaluate the model outcome such as the sum of sediment height, vegetation, water flow and wave energy. Since the model has no real notion of species a proxy was used to determine the biodiversity. Different species have different properties such as stem density a high standard deviation in the vegetation stem density could be used as a simple proxy for biodiversity. To evaluate the complexity of the creek systems average creek distance was used. This represents the average nearest distance to a creek from a random point in the landscape. To calculate the average creek distance the creeks were distilled from the sediment height model results using the extract_streams tool from the WhiteboxTools (45) (version 2.1.2) package for python. Using the QGIS raster proximity tool (46) (version 3.10.4) the average nearest creek distance was calculated. To asses the relationship between sediment input and biodiversity that was found the following function was fitted: $y=\frac{Asym}{1+e^{(xmid-x)*scal}}+B$ using the stat package for R (version 3.6.2). The R^2 value was calculated to assess the goodness of fit.

Benchmarking

To test the behavior of the model it was run for 40.000 time steps (~55 years) in a situation without wave energy and with wave energy (fig. S1a, S1b). Without wave energy vegetation will grow on the landscape except near the boundaries were sediment elevation is put to zero as a boundary condition. In this condition creek complexity (fig. S1a, S1b) average creek distance is low and biomass is high, 5.59 and ~1.253.855 g respectively (fig. S1e, S1f). Vegetation growth drives self organization and the formation of creek complexity. Adding wave energy to the model causes cliff erosion to occur. Vegetation will grow but as soon as wave energy builds up the marsh edges will move back until an equilibrium is reached (fig. S1b).

Positioning a barrier along the salt marsh will protect the marsh from eroding (fig. S1c). Sedimentation, vegetation growth and water flow were higher after placing the barrier. Visually the creek system was less complex after adding wave energy to the model (fig. S1c). The average creek distance lowered from 5.59 m to 7.54 m after adding wave energy and a barrier to protect the marsh.

Visualization

The model exports sediment height and vegetation data which is used to make visualisations in blender (47) of how an possible marsh produced by the model could look like with the goal to give a general public an impression of how a restored marsh could look like. Sediment heights are extrapolated to generate clear height differences in the landscape. Vegetation cover from the model and sediment height dictate plant placement in the renders. The marsh is divided in three vegetation zones: pioneer (Salicornia europaea, Suaeda maritima), low (Atriplex portulacoid, Juncus maritima) and high (Limonium vulgare, Artemisia maritima) marsh. Depending on the sediment height these zones are allocated. The dikes are covered in grass on top and have stones at the bottom. Plants are placed using Blenders particle system. In this way the amount of plants that could be placed is much higher since each plant is surrounded by an amount of children that are rotated randomly. Bottom textures depend on the location of the marsh i.e. marsh textures are placed on the marsh and sea textures are placed at the sea. Objects such as different birds and trees were placed manually to complement the generated landscape.

Results

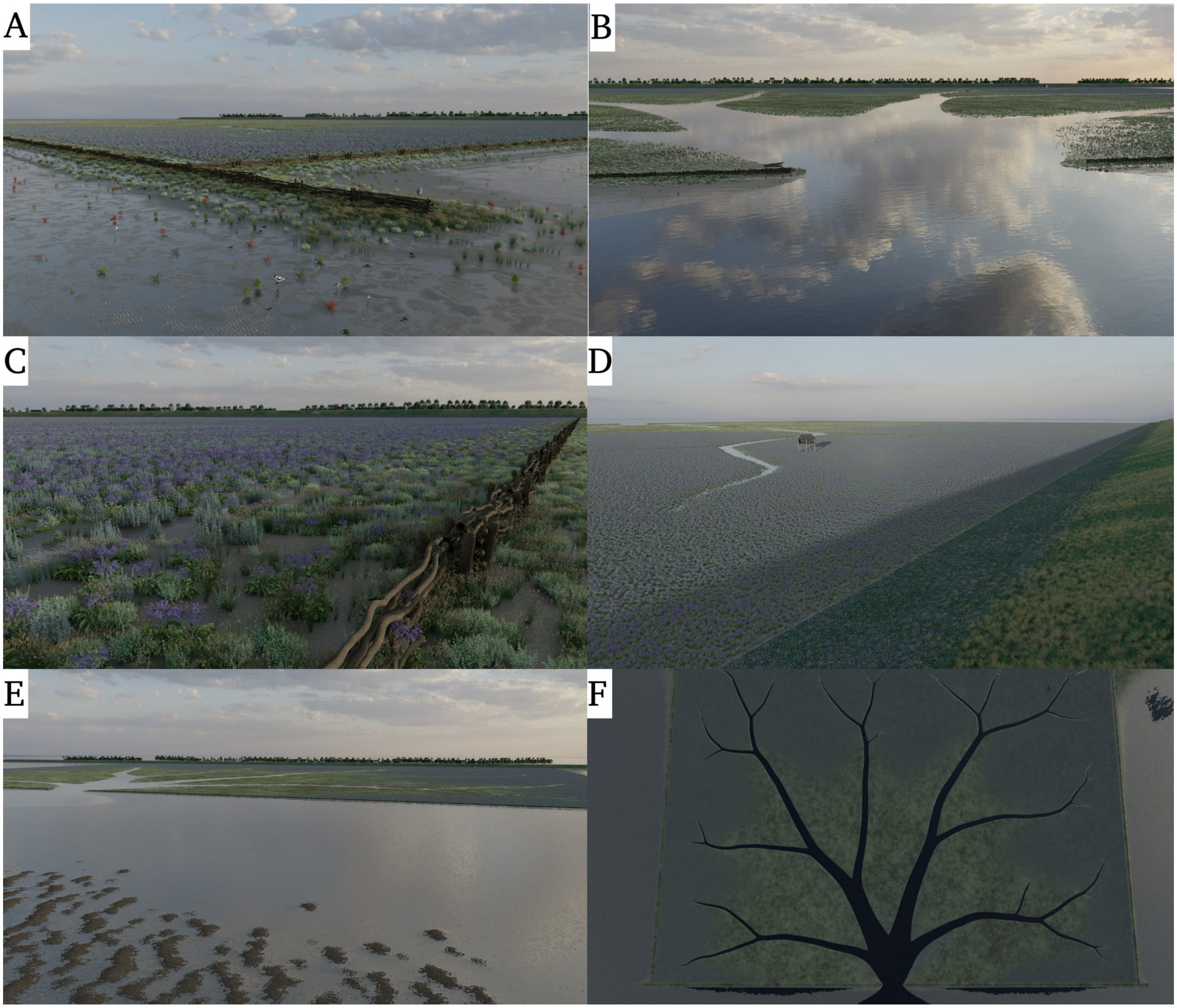

Figure 1) Renders made using the model output and blender. (a-d) detail images of the resulting landscape focusing on specific parts of the marsh. (e, f) aerial overview of the marsh.

To visualize how a restored salt marsh using barriers could look like, the output of one of the model simulations was used to create renders using blender (fig. 1). Renders were made from several angles to give a good overview of the modeled area. To make the landscape look more natural objects were added afterwards such as trees and buildings.

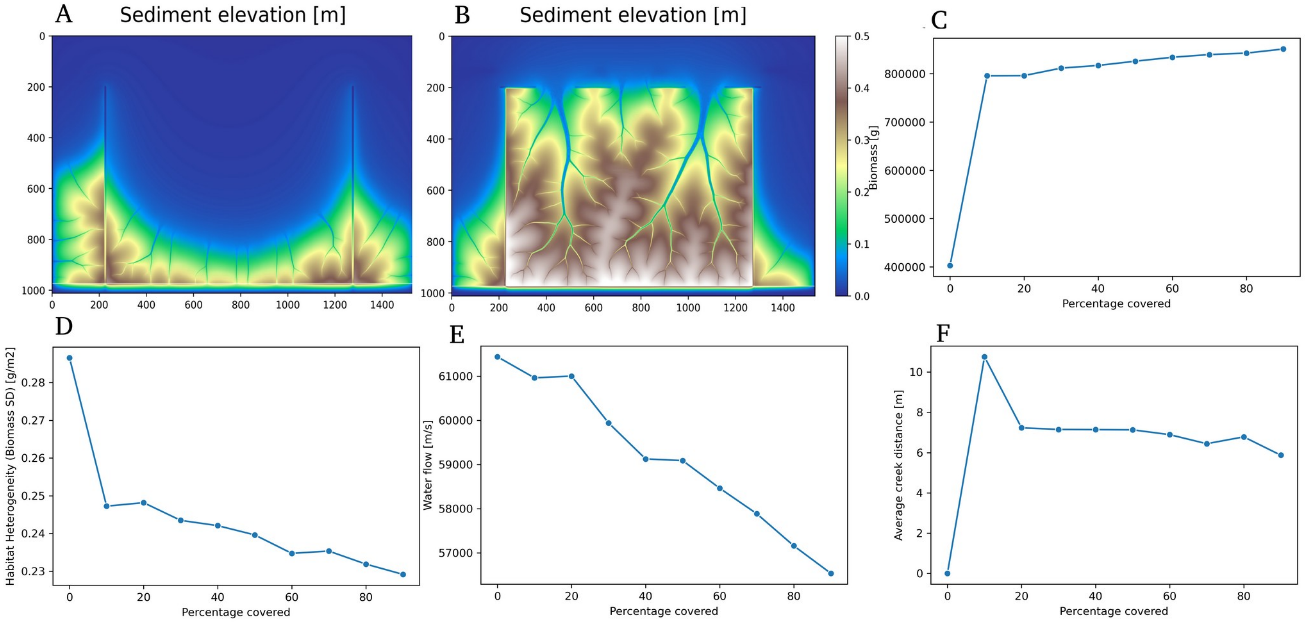

Figure 2) Increasing the coverage of a marsh by a barrier. (a,b) resulting sediment elevation for respectively a coverage of 0, 50%. (c) total biomass, (d) standard deviation of the biomass, (e) total water flow and (f) average creek density for a range of barrier coverage (0-90%).

A small change in the environment of a salt marsh can completely change the ecosystem from a bare tidal flat towards an salt marsh consisting of complex creek networks. Figure 1a, 1e show the transition from tidal flat towards salt marsh that could develop due to barriers that were put in place. Such tipping points are a typical feature of complex systems such as salt marshes. To test how well a barrier can protect a developing salt marsh against wave energy, differently sized barriers were placed in front of a marsh (fig. 2a, b). Only a small percentage (10-20%) of the edge of a salt marsh has to be covered by a barrier to push the system over the tipping point and put it in a state of high vegetation growth (200%) (fig. 2c). As barrier coverage increases the biomass variability decreases from ~0.29 to 0.23 gm^{-2} (fig. 2d). When considering nature conservation it would be most favorable to be close to the tipping point as the standard deviation which could be an proxy for biodiversity decreases from there. Figure 1f gives an example how this could look like in a salt marsh. Pioneer ecosystem species can grow at spots were climax vegetation can not grow close to the openings in the barrier. The water flow decreases from ~ 61.000 to 56.000 m/s (fig. 2e) indicating a lower creek efficiency. However the average creek distance is relative stable (fig. 2f) indicating that the number of creeks does not decrease but the increased barriers lower the outflow water capacity.

The amount of sedimentation on a salt marsh follows plays an important role in determining if a salt marsh can develop and follows a logistic pattern. As the supply of sediment increases the salt marsh can develop while low sediment input limits plant growth resulting in wave energy to build up inside the barrier resulting in no marsh development (fig. 3a). As sediment stays low, lake formations starts within the barriers which decline in size as sediment input increases (fig. 3b, 3c). Figure 1b shows how this would look like for an situation with relatively high sediment input and thus small lake formation. Low sediment input leading to high wave energy results in a high biomass standard deviation which decreases from ~0.32 to ~0.24 gm^{-2} (fig. 3e, 1f) as the sediment input increases. This can be of importance when considering nature conservation as the standard deviation of plant biomass could be explained as an proxy for biodiversity. A non-linear least squares function was fitted to the biodiversity data to assess the relationship resulting in a R^2 of 0.99. Water flow increases from ~37.000 to ~50.000 m/s as creeks develop to more efficient structures (fig. 3f) as sedimentation increases.

A smaller area within the barriers can make an area suitable for marsh development when sediment input is restricted (fig. 4a, b). Doing this lowers the logistic threshold so that the marsh can develop. Putting an extra barrier in the middle helps decreasing the build up of wave energy resulting in an wave energy decrease of ~3.000.000 J (fig. 4c) and a biomass increase of ~500.000 g (fig. 4d). When designing barriers to promote marsh development the amount of sedimentation within the barriers should be taken into account. As sediment interacts with wave energy the area within the barriers could be made smaller or barriers could be used that allow for more sedimentation.

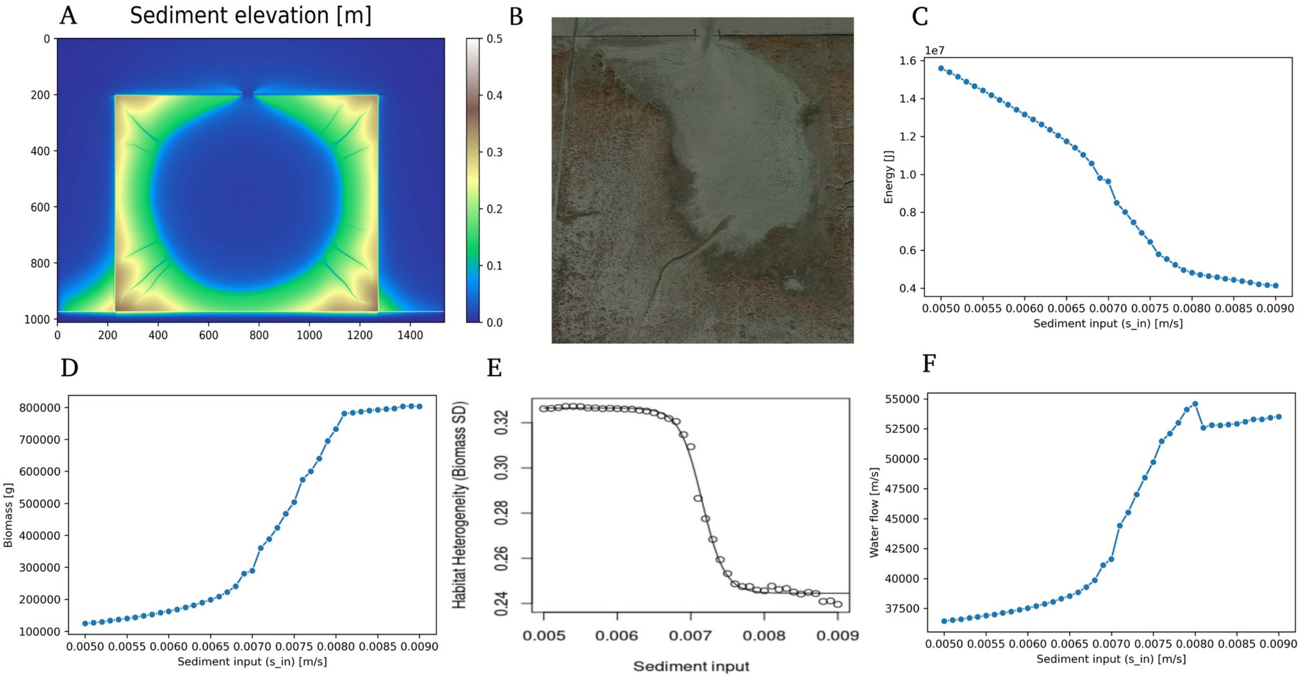

Figure 3) Increasing sediment input s_{in} *over a range (0.005-0.009). (a) sediment elevation resulting from the simulation given* $s_{\text{in}}=0.005$ *. (b) Example of developing salt marsh in the Wadden Sea (* $53^o 20' 55{,}96\, N$ $5^o 44' 53{,}51\, E$ *) with lake formation in the middle. (c) total wave energy, (d) total biomass, (e) fitted non-linear least squares function on the standard deviation of biomass (* $R^2=0.99$ *) and (f) total water flow for each simulation.*

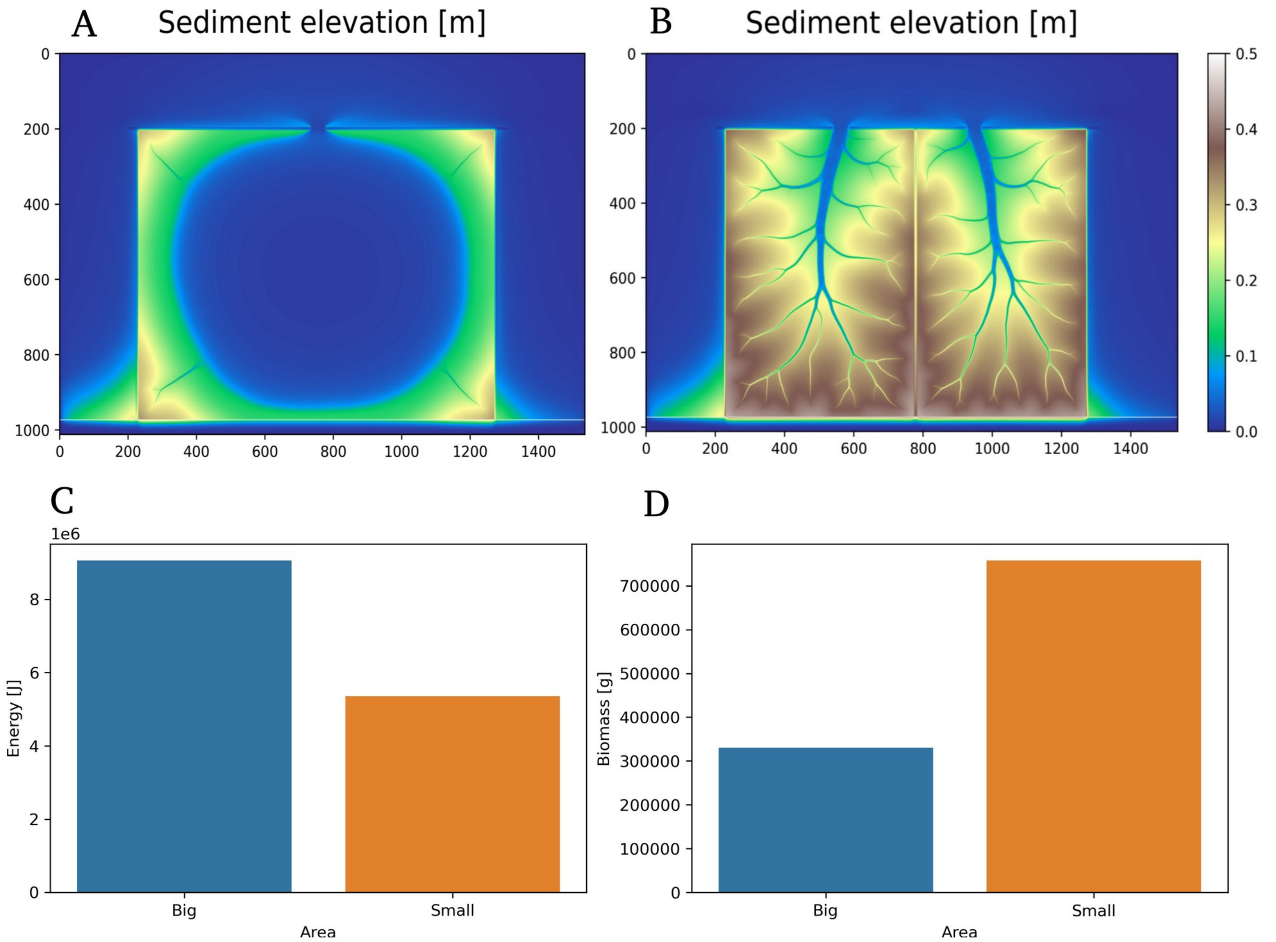

Figure 4) Simulation with low sediment input s_{in} *. (a) lake formation due to lack of sediment. (b) Smaller areas can help marsh formation. (c) total wave energy and (d) total biomass for both simulations with different area size.*

Grazing on a salt marsh allows more wave energy onto the marsh which lowers the complexity of its creek network. This was studied by lowering the ability of plants to dampen waves, E_b gradually [10]. Increasing this parameter lowers the biomass development (fig. 5d) of salt marshes significantly. Resulting marshes show less developed creeks systems (fig. 5a-c) and exhibit a smaller amount of side creeks. An example of the creek network of a salt marsh can be found in figure 1f. Grazing results in the disappearance of the smaller creeks. Wave exposure in marshes that are grazed upon is higher (~4.000.000 J) compared to marshes where plants can dampen waves more efficient (2.800.000 J) (fig. 5d). Biomass lowered due to the increased wave energy from ~920.000 to ~760.000 g (fig. 5e) and the average creek distance increased from ~6.0 to ~11.0 m (fig. 5f).

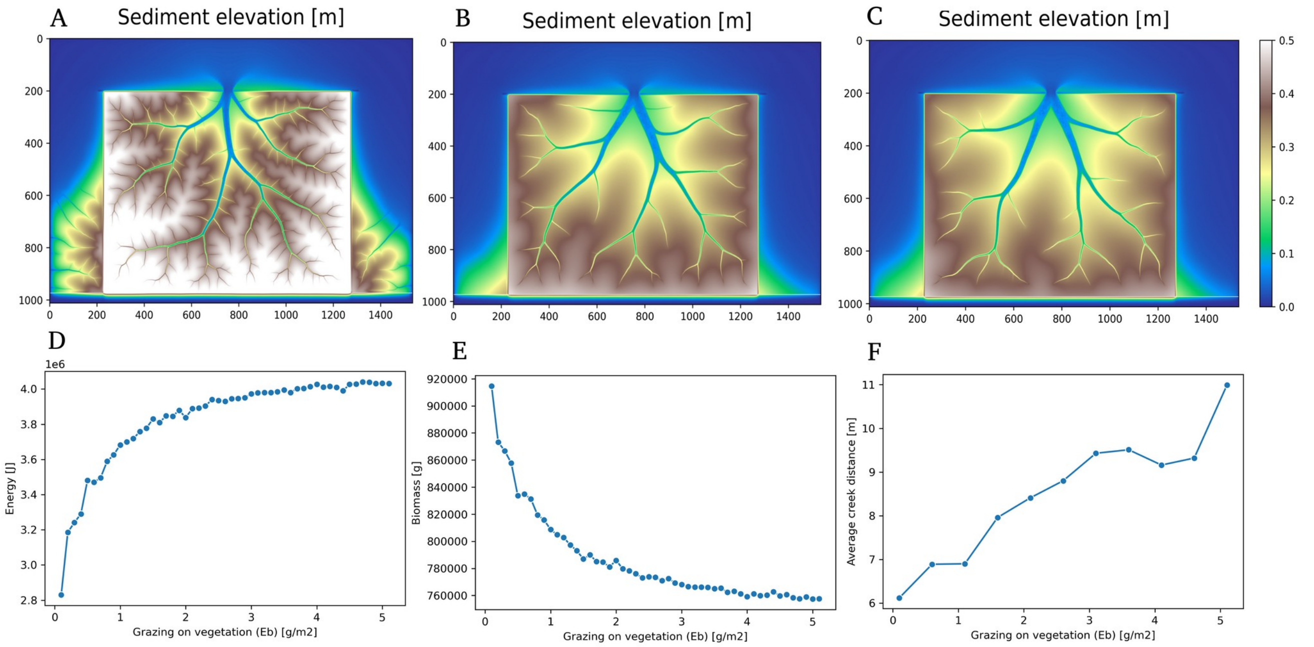

Figure 5) Increasing grazing on the vegetation E_b *. (a-c) Resulting sediment elevation due to increased grazing for respectively* $E_b=(0.1, 2.5, 5.0)$ *. (d) total wave energy, (e) total biomass and (f) average creek distance for a range of* E_b *(0.1-5.0).*

Discussion

In this study it is found that creating protected areas using barriers was an effective strategy to stimulate marsh development by reducing wave energy allowing for sedimentation and in this way starting the bio-morphological feedback. This traditional barrier shape has been found as one of the better shapes to trap sediment and stimulate marsh development (35). However this may not be the cases for all locations as it was found that placing stone walls in front of the marsh allowed for better sediment transport (32). Testing the effect different shapes of barriers have on wave energy absorption and thus on sedimentation and vegetation development could give valuable insights for restoration processes to policy makers.

One of the ways in which marshes decline by erosion is when sedimentation is too low for the marsh compared to the erosion caused by wave energy. This can happen when due to changing environments sediment input is lowered or due to sea level rise. When these changes to the environment are human induced, they can make ecosystems vulnerable for fast transformations and lead to tipping points (48). For salt marshes tipping points have been found where at a certain speed of sea level rise the marsh could not persist anymore (49,50). In this study such a tipping point for sedimentation was found in the form of a non-linear relation between sedimentation and marsh development. One explanation for the existance of these tipping points in salt marsh ecosystems is that vegetation is not able to colonize new area under certain environmental circumstances, such as low sedimentation, and in this the bio-geomorphic feedback loop can not start (51). Therefore when considering marsh restoration it could be useful to give a thought at local sediment balances to estimate the chance of success (52). Placing multiple barriers to divide the area in smaller spaces helped lower energy input increasing sedimentation (fig. 4a, b). These results suggest that placement of barriers could help at locations where sedimentation is low for example due to human induced changes to the environment such as flood protections (53). This could also include future sea level rise scenarios where suspended sediment concentrations have to be high enough for marsh growth to be able to keep up (54). Another way of increasing sediment input is by sediment nourishment (55). Placing barriers could however be a more desired solution against erosion since the sediment make up of dredged up sediment differs from that of suspended sediment in the sea (56). This dredged up sediment has a different cohesion which could lead to increased soil creep and leads to a less complex creek network consisting of fewer creeks and side creeks (39).

Salt marshes that have been restored tend to be less developed compared to their natural counter parts. Showing less extensive creek networks and a lower biodiversity (57). One explanation for this is when an area has been used as grazing grounds the sediment could have been become compacted resulting in a layer that does not erode, resulting in lower creek formation (58). In this study a situation with grazing was tested where grazing impacted the ability of plants to absorb wave energy declined by increased grazing. Resulting from this wave energy on the entire marsh increased (fig. 5d) resulting in a lower vegetation cover (fig. 5e). This has also been observed in grazed salt marshes in the Wadden Sea where grazing decreases the wave absorbing capabilities of salt marshes (32,59). The development of salt marsh creek networks highly depend on the occurrence of topographic depressions that occur early in development (60). As grazing increases plants will trap less sediment as less vegetation decreases the sediment cohesiveness (14). In this way this mechanism could allow for less topographic differences in the landscape which could explain the lower creek complexity that was found as grazing intensified (fig. 5f).

Water flow decreased as coverage by the barriers increased while average creek distance stayed the same in this model. This could mean that the creek network becomes less efficient as coverage increases due to limitations to the available space for creeks. A similar result has been found by (35) where the historical barrier shapes as implemented in this study caused lowest flow rates. A study to the effects of low flow rates on biodiversity and marsh stability could give helpful insights to the question if these type of barriers could be a good means of marsh restoration. When restoring salt marshes by building barriers the findings from this study could be kept in mind as biodiversity is often one of the main concerns in nature restoration (8). The model does not take into account explicit sedimentation (see assumptions and uncertainties). An update to the model to include sedimentation influx by the incoming tides could give better insight in how a barrier limits sediment input.

Effective communication of complex model results to policy makers and stakeholders is often difficult as they are often overloaded with information of short in time (61). A recent trend to overcome this difficulty is the integration of the visualization process in the modeling and data acquirement instead of during post processing as has been done historically (62). Recent research has shown that policy makers and stakeholders that are aware of efforts made to visualize results will indeed use them (63). In this study the visualization process done using Blender to visualize the model output was set up from the start. The renders of the landscape that were made could potentially be used to show policy makers and stakeholders how an restored salt marsh using barriers to block wave energy could look like. To even further help visualize a 3d render of the landscape could be made allowing participants to "walk" in the landscape using an VR set.

Assumptions and uncertainties

Parameters used in the model are estimated and not taken from measurements. Therefore the results of the simulations are more principle seeking compared to models that are made to simulate as accurate as possible.

The model contains a few assumption that were made so that it could be solved more efficiently. The model assumes constant eb discharge and does not take into account influx of water by flood. A similar assumption was made in earlier models (64). By doing this it is not necessary to model the tidal water flow and thus increasing the time it takes to numerically solve the equations. Another assumption is that sediment input is modeled as a homogeneous process rather than an local process. While this assumption makes sense in localized areas this assumption causes a little bit more problems when adding barriers. Since adding a barrier to one side of the marsh will cause a different sediment deposition and sediment composition consisting of more fine coarsed sediment (65).

While modeling this effect was accounted for by decreasing the sediment input s_{in}, however a more detailed sediment function that captures the effect that barriers have on the sediment input could give a more detailed insight into salt marsh development (35).

Colonization by vegetation is modeled by random processes, a random field is defined were under influence of a settlement chance vegetation patches develop which then diffuse over the marsh. Wave energy is assumed to be independent of vegetation colonization. Naturally seedlings are most prone to damage induced by waves leading to windows of opportunity were colonization of salt marshes by vegetation happens in waves (51). Adding a colonization effect of wave energy to the model could help further understand the effect wave energy has on early marsh formation and how this influences spatial pattern formation and also understand if barriers provide windows of opportunity for vegetation growth. In this way barriers could help protecting the coast against future sea level rise (66).

The standard deviation in stem density on the marsh was used as a proxy for biodiversity. The assumption that was made is that a difference in stem density is the result of increased stress which allows for more biodiversity by increasing number of available niches on the marsh. A possible improvement of this analysis could be to develop a biodiversity score consisting of the different variables that are important to niche formation such as sediment height, exposure to energy, exposure to water flow and local stem density.

Conclusion

Creek structures of salt marshes are highly variable and can range from parallel channels to complex branching formations. This variety in complexity can be explained by bio-geomorphic feedback loops where growing vegetation allows for more sedimentation and in turn stimulate more vegetation growth.

The addition of wave energy to a model that simulates this feedback loop causes cliff erosion at the edges of a salt marsh when the wave energy is too high or when sedimentation is too low. While building barriers in front of a salt marsh to deflect wave energy lowers the inflow of sediment to a salt marsh; they can help to restore a salt marsh or protect it against erosion. Placing an barrier in front of a salt marsh can lower the tipping point so that marsh development can happen. These tipping points are the result of non linear relationships in marsh development. In cases where the sedimentation is low, wave energy can build up between the barriers preventing marsh formation Here dividing the area into smaller sections can help reduce the wave energy buildup. When vegetation does not deflect the wave energy enough, for example when it is being grazed upon, the waves decrease the bio-geomorphic feedback resulting in less complex creek formation. This shows the importance waves have on the bio-geomorphic feedback that is responsible for the creek structure in salt marshes. Covering only a small part of the marsh by barriers provides enough coverage against waves to allow marsh formation while covering a large part could decrease biodiversity by lowering habitat heterogeneity which could be important considerations when restoring salt marshes systems such as the Oosterschelde is considered.

Supplements

Table S1) The added parameters to the model and their default values, units and interpretation.

Variable	Unit	Value	Interpretation
E_{in}	J	0.00395	The wave energy input per time step
E_s	m	0.5	Ability for sediment to absorb wave energy input
E_b	g/m^2	0.5	Ability for vegetation to absorb wave energy input
ε_{se}	m^{-1}	0.00212	Wave energy damping by sediment
ε_{be}	m^2/g	0.005	Wave energy damping by vegetation
ε_{oe}	-	0.5	Wave energy damping by barrier
ω_x	-	0.45	Incoming wind angle in x direction
ω_y	-	0.45	Incoming wind angle in y direction
ω_{dm}	J	0.2	Diffusion in x and y direction
ε_{es}	J^{-1}	0.006	Sediment erosion by wave energy
ε_{eb}	J^{-1}	0.005	Vegetation erosion by wave energy

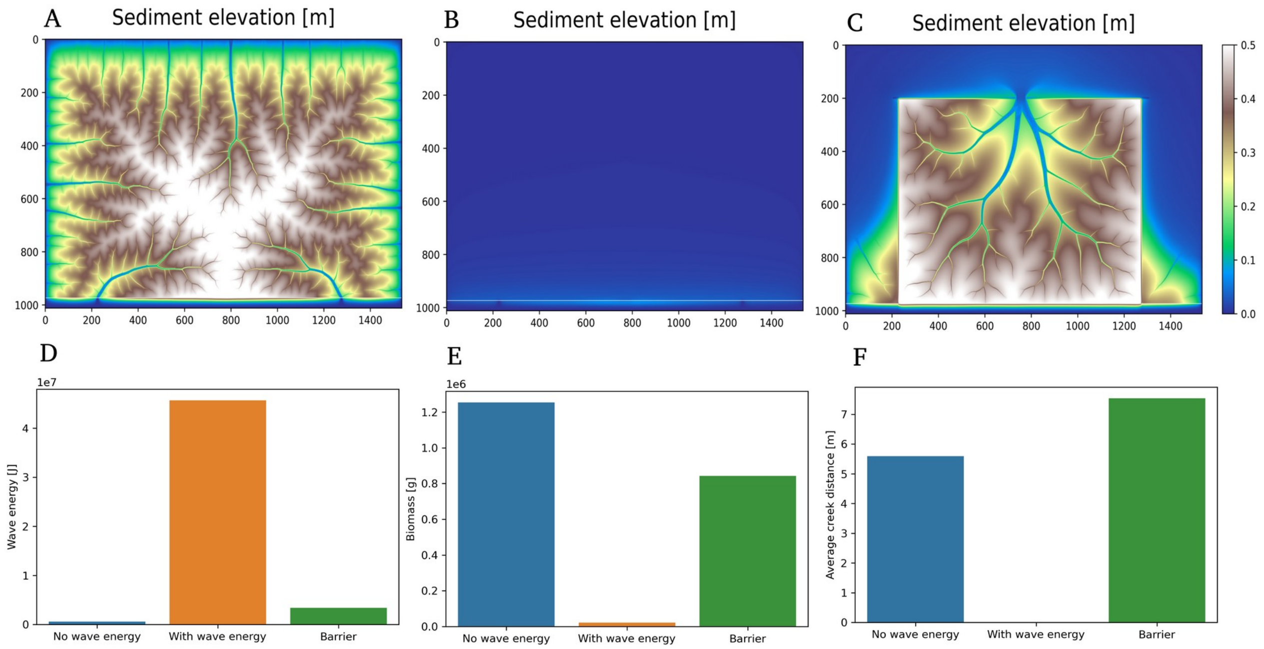

Figure S1) Comparison between sediment elevation resulting from the model without wave energy (a), with wave energy (b) and addition of an barrier (c). (d) total wave energy, (e) total biomass and (f) average creek distance for each simulation.

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