Modeling the dynamics of salt marsh formation

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Abstract

The valuable ecosystem services of salt marshes are spurring marsh restoration projects around the world. However, it is difficult to forecast the final vegetated area based on physical drivers. Herein, we use a 3D fully coupled vegetation-hydrodynamic-morphological modeling system (COAWST), to simulate the final vegetation cover and the timescale to reach it from various forcing conditions. We found that marsh formation can be divided in three distinctive phases: a preparation phase characterized by sediment accumulation in the absence of vegetation, an encroachment phase in which the vegetated area grows, and an adjustment phase in which the vegetated area remains relatively constant while marsh accretes vertically to compensate for sea level rise. Sediment concentration, settling velocity, Sea Level Rise and tidal range each comparably affect equilibrium coverage and timescale in different ways. Our simulations show that The Unvegetated-Vegetated Ratio (UVVR) also relates to sediment budget in marsh formation under most conditions.

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Key words: Marsh restoration, COAWST, Vegetation dynamics, phases of restoration, expectance of restoration

Abstract

The valuable ecosystem services of salt marshes are spurring marsh restoration projects around the world. However, it is difficult to forecast the final vegetated area based on physical drivers. Herein, we use a 3D fully coupled vegetation-hydrodynamic-morphological modeling system (COAWST), to simulate the final vegetation cover and the timescale to reach it from various forcing conditions. We found that marsh formation can be divided in three distinctive phases: a preparation phase characterized by sediment accumulation in the absence of vegetation, an encroachment phase in which the vegetated area grows, and an adjustment phase in which the vegetated area remains relatively constant while marsh accretes vertically to compensate for sea level rise. Sediment concentration, settling velocity, Sea Level Rise and tidal range each comparably affect equilibrium coverage and timescale in different ways. Our simulations show that The Unvegetated-Vegetated Ratio (UVVR) also relates to sediment budget in marsh formation under most conditions.

Plain language summary

Salt marshes are valuable and unique landforms located at the interface between land and ocean. Given their important roles in ecosystem and global climate, projects for marsh restoration and expansion sprung up. However, it is difficult to predict the final extension of the vegetated area in a restored marsh and what drivers control vegetation cover. In this study, a state of the art numerical model was used to simulate marsh formation in a typical configuration used in land reclamation projects. The final vegetation cover and the timescale to reach it are derived from simulations with various sediment conditions, tides and Sea Level Rise. We found that marsh formation can be divided in three distinctive phases: a preparation phase characterized by sediment accumulation in the absence of vegetation, an encroachment phase in which the vegetated area grows, and an adjustment phase in which the vegetated area remains relatively constant while marsh platforms rise vertically to compensate for sea level rise. High sediment

concentration and greater grain size generally help marsh expansion and reduce the time needed to reach equilibrium, while high rates of sea level rise hinder marsh formation. Larger tides result in a higher coverage.

Introduction

Salt marshes are valuable and unique landforms located at the interface between land and ocean. Salt marshes are still common along many shorelines, despite a 25%~50% decline of their historic coverage in recent decades (Crooks et al. 2011, Duarte et al.2008). The most recent estimate of global marsh area exceeds 5 million Ha (Mcowen, 2017). Serving as a natural defense, salt marshes play an important role in reducing the damage of storms to coastal communities (e.g. Temmerman et al., 2013; ; Zhao and Chen, 2013; Moller et al., 2014). In the United States, shoreline protection by marshes against storms are valued up to \$5 million per km^2 (Costanza et al., 2008) and coastal wetlands were valued \$625 million in defending direct flood damages during Hurricane Sandy (Narayan et al. 2017). Other valuable ecosystem services provided by salt marshes include nutrient removal, carbon storage, and habitat for flora and fauna (Zedler et al., 2005). Therefore, salt marshes not only protect coastal communities but also sustain economies and healthy ecosystems. Recognizing the above services, multiple public and private agencies are attempting to create and sustain marshes (Barbier et al 2008; Bayraktarov et al 2016; Seddon et al 2020;). Restoration practices include shoreline protection, sediment trapping, and thin layer sediment placement techniques among others (Wigand et al, 2017; VanZomeren et al, 2018). These techniques are implemented in existing marsh systems to prevent marsh degradation or promote marsh expansion. Other projects aim at creating new marsh land using engineered structures (Li & Zhu, 2015; Staver

et al, 2020). The common configuration of these projects are sea walls or dikes shaping a rectangular area with an inlet to the ocean or estuary (Figure 1). This geometry mimics natural inlet systems, which creates asymmetric tidal velocities leading to net sediment transport into the bays (Pingree and Griffiths, 1979; Brown and Davies, 2010). The net sediment transport across an inlet depends on the morphology and marsh vegetation in the back barrier basin (Elias, 2012; Mariotti & Canestrelli, 2017). In this paper, we study the drivers responsible for marsh formation in an artificial, rectangular domain.

Assessing the likelihood of marsh survival in response to climate change has been the focus of research for several decades (e.g., McKee and Patrick 1988, Morris and Haskin 1990, Fagherazzi et al. 2012). Sediment supply has been identified as key factor to determine marsh survival (Mariotti & Fagherazzi 2010) as well as success in marsh restoration (Ganju 2019). Under different Sea Level Rise scenarios (abbreviate as SLR hereafter), reaching marsh equilibrium requires different sediment supply (Fagherazzi et al 2013). The ratio between unvegetated to vegetated area (UVVR) in a marsh system has been proposed as a simple metric to assess sediment budgets and resilience against SLR (Ganju et al 2017). Using this metric together with satellite images, vulnerable marsh locations can be easily determined. Although this method predicts marsh degradation relatively well, UVVR has never been used as a guiding metric where marshes are forming or expanding. The present work serves the purpose of closing this data gap. We will simulate marsh formation under a wide range of scenarios and unravel the link between vegetated marsh surfaces and sediment fluxes.

The driving forces of marsh formation vary from site to site. The only way to untangle the problem is to conduct systematic long-term studies isolating each variable. Computer models have the advantage of comparability and flexibility in studying marsh dynamics. Multiple models have been developed and applied to study salt marsh landscapes. Many efforts have been made to couple marsh vegetation and sedimentation processes (Temmerman, 2005) as well as marsh morphology and marsh biology (Mudd et al., 2004; Morris, 2006; Kirwan and Murray, 2007; D'Alpaos et al., 2007a; Mariotti and Fagherazzi, 2010). Mariotti and Canestrelli (2017) studied an idealized tidal basin with a model that includes vegetation, morphodynamics and 3D-hydrodynamics. Other models that simulated mangroves or marshes have focused on the channel network (Marciano et al. 2005; Van Maanen et al., 2015). Alizad et al (2016) developed a model for salt marshes in tidal estuaries and applied it to northeast Florida. The model resolves the hydrodynamics at high resolution, and couples it to the dynamics of vegetation. Here we present a coupled vegetation-hydrodynamic-morphological model and we apply it to an idealized system to explore marsh establishment. The Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System (Warner et al, 2010) is utilized, with a newly developed vegetation module. We were able to simulate marsh encroachment in an idealized basin and monitor sediment fluxes and feedbacks with vegetation through controlled experiments. More importantly, this is the first modeling study aimed at predicting the final equilibrium marsh coverage in response to various forcing conditions. Our results are important for marsh restoration and land reclamation as we provide the final vegetation configuration and the timescale to reach it for a range of forcing variables.

Methods

First, we introduce the numerical model with a description of the newly developed method to simulate marsh formation. Then, we detail the model domain set-up and modules used for the simulations. Finally, we present the modifications that we implemented on the hydrodynamic and vegetation components of the model.

2.1 Model Description

COAWST v3.7 includes separate modules for hydrodynamics (ROMS), sediment transport and terrain evolution (CSTMS), vegetation, atmosphere (WRF), sea ice and waves (SWAN or WW3). Sediment transport (Warner et al., 2008) and vegetation (Beudin et al. 2017) modules were coded within ROMS and are coupled with the SWAN wave model through the Model Coupling Toolkit. For the application presented in this work, we modified the sediment transport and the marsh growth routines (Kalra et al., in review) for a more dynamic marsh simulation. The long-term formation of the marsh is modeled by accelerating the process of deposition and erosion with a morphological factor (Roevlink et al 2006; Warner et al 2008). The deposition or erosion caused by the hydrodynamics are multiplied by the morphological factor and then added to or subtracted from the bed. However, this multiplication only happens at the interface of water and bed sediment, therefore, the sediment concentration in the water column is not affected by it. We initialize the model with sufficient bed sediment (10 meters of sediment layer) to allow for erosion as we are using a large morphological factor (200).

In order to capture the effects of vegetation on flow, variables such as plant density, stem height, stem diameter, and stem thickness need to be determined. Recent field data indicates that all these variables can be related to the seasonal peak biomass (Morris & Haskins, 1990; D'Alpaos et al, 2007a). The biomass of halophyte vegetation, especially low marsh species like *Spartina alterniflora*, greatly depends on elevation within the tidal range. Low marsh areas are more inundated, triggering waterlogging, while higher elevations are characterized by high salinity that inhibits vegetation growth. Therefore, an optimum elevation for marsh growth is required, and marsh biomass could be described as a parabolic curve based on elevation (Morris et al, 2002). Here, we chose to model *S. alterniflora* for its wide distribution in tidal marshes in the USA. Biomass is calculated as:

$$B = B_{\max}\,(D - D_{\min})\,(D - D_{\max}) \qquad D_{\min} < D < D_{\max} \tag{1}$$

$$D_{\max} = -0.73\ x\ 2D_{\min} + 0.092 + D_{\min} \qquad D_{\min} = h + z_{\mathrm{MHW}} \tag{2}$$

where B is the depth dependent biomass and $B_{\max}$ is the maximum biomass specified in Table 1 (supplement). $D_{\min}$ and $D_{\max}$ are the minimum and maximum depths for *S. alterniflora* survival. The actual water depth in the model consists of average water depth referenced to regional mean sea level (h) and varying tidal water level (z). $D_{\min}$ is the water depth when the tide is at local mean high tide (z_{MHW}), while $D_{\max}$ is a function of $D_{\min}$ according to equation

2.

2.2 Design of Numerical Experiments

We designed an idealized case that mimics a natural inlet basin in a barrier island system or an engineering structure built for land reclamation that naturally imports sediment (Fig. 1A~D). We then adopt realistic values of sea level rise, tidal range, sediment concentration, and grain size (Table 2 in supplement). Since we focus on the colonization and evolution of inter-tidal marshes in sheltered areas, we do not consider waves for simplicity.

The domain consists of square grid cells (200 m x 200 m in the horizontal) with 10 vertical layers. The open boundary is 8 km wide and 15 m deep, while the inlet is 1.2 km wide (Figure 1E). The inlet area is 145 km^2 with a uniform water depth of 2 m and with an additional random elevation of $\pm$ 0.05 m. Density and porosity of the bed sediment were fixed across experiments while grain size changes with settling velocity in different simulations (Table 2 in supplement).

We also specify an area about 1 km wide near the open boundary where sediment deposition is not allowed (Figure 1E). This area imitates the breaking zone where wave and flow are strong enough to maintain sediment in suspension without deposition. Specifically, all settling fluxes of sediment through vertical layers were set to zero so that grid elements in contact with this area inherit the sediment concentration at the boundary. By doing this, we allow the hydrodynamics to develop according to our geometric configuration while keeping constant sediment conditions at the boundary. Deposition was then linearly increased to model-calculated values between the end of this area and the inlet. This configuration allows us to constrain the sediment input and net budget to the system.

2.3 Simulations

The vegetation routine was modified to represent the natural development of a tidal marsh and optimize model performance. In Table 1 (supplement)we report a list of parameters used in the simulations. A location is converted to marsh only when it is dry and of suitable elevation. Then following the parabolic distribution (equation 1), the biomass is updated based on elevation in each time step. A spin-up run was conducted for each tidal range case (Table 2 in supplement, Fig. 1F). The goal of the spin-up run is to reach an equilibrium depth at the inlet so the filling of the basin occurs as a result of sediment import form the ocean. To simulate sea level rise (SLR), we keep the mean water level unchanged and uniformly decrease the bottom elevation of the entire domain.

Optimal UVVR and Timescale analysis

Vegetation coverage is calculated with the Unvegetated-Vegetated Ratio (UVVR) first proposed by Ganju et al (2017). In order to determine the equilibrium UVVR and the time it takes to reach it, we regress the UVVR-time series with equation 3.

$$UVVR = E(1 + \mathrm{A}e^{-bt}) \quad (3)$$

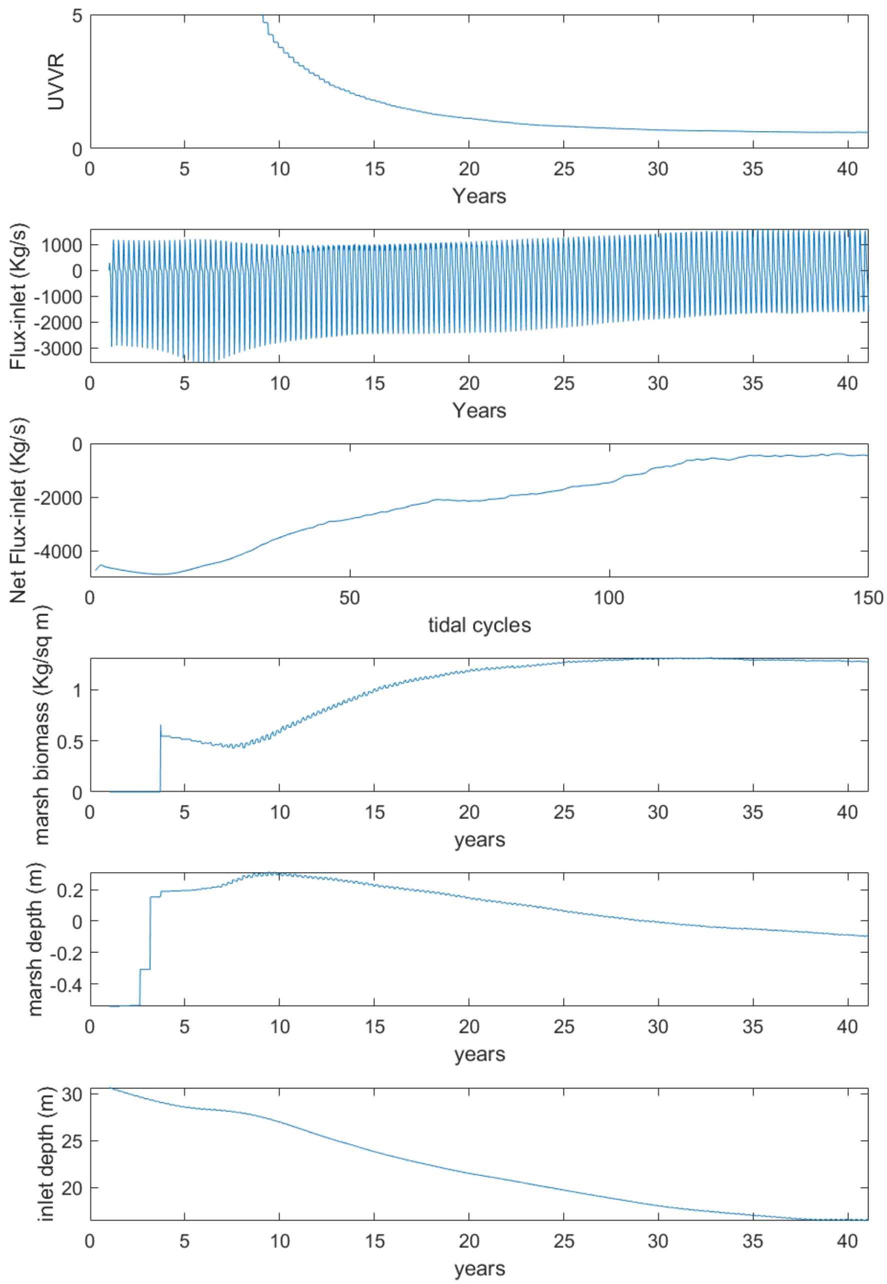
E represents the asymptotic value that UVVR will eventually reach. The percentage of total area covered by marshes is therefore $\frac{1}{1+E}$. A and b control the velocity at which the equilibrium is reached. In the simulations, it is impossible to exactly determine when the system reaches equilibrium without a certain approximation (Fig. S3). Thus, instead of calculating the time of optimal UVVR, we calculate the time it takes to reach 95% of the vegetated area. That is, solving for t in equation 3 when UVVR reflects 95% of $\frac{1}{1+E}$. This solution is hereafter called t_{95}. This method works for most cases except those with very high SLR (exceeding 25mm/year). In this scenario it is highly possible that flooding becomes too severe before a stable UVVR is reached. Since there is not a stable UVVR, these simulations are not included in the analyses.

Results

First, we examine the evolution of a specific simulation which serves as a standard case (Std). Then, results from each set of experiments where one of the four independent variables (SLR rates, sediment input, settling velocity or tidal range) is varied were presented.

3.1 Standard Case

The Std case adopts SLR, sedimentary conditions, and tidal range (Table 1 in supplement) from observations near the artificial land-gaining structure at the Yangtze River mouth (AI Wei et al, 2018). By analyzing the time series of marsh biomass and UVVR, we find that UVVR stabilizes much earlier than marsh biomass (Fig. S4). In the Std case (Table 2 in supplement), UVVR variations decrease to less than its variance after 25 years, while marsh biomass variations are minimal after 40 years. Therefore, marsh extension reaches equilibrium faster than the entire system (Figure S4).


UVVR
Years
Flux-inlet (Kg/s)
Years
Net Flux-inlet (Kg/s)
tidal cycles
marsh biomass (Kg/sq m)
years
marsh depth (m)
years
inlet depth (m)
years

At the beginning of the simulation, there is a period of rapid import of sand for around 35 tidal cycles which is equivalent to about 9 years (area shaded in blue in Figure 2). The net import of sediment through the inlet was on average 4516 kg/s. Most sediment enters the bay while a small fraction fills the inlet as shown in Figure 2F as well as in Figure S2A&B. The inlet is slowly silting when the bay bed accretes and vegetation starts to encroach the area at the end of this phase (Fig. S2B). The slow filling of the inlet (0.73 m/year of average inlet bathymetric change) is due to a reduction in tidal prism, which decreases the flow at the inlet triggering deposition. The sediment imported in this period fills the bay and brings the bottom elevation close to the threshold for vegetation growth. The average water depth of the marsh area is 0.29 m at the end of this phase while the average maximum depth for marsh survival is 0.396 m. The UVVR value is very high during the first 10 years, which means that there is little or no land in the suitable elevation range for vegetation encroachment. As we can see in Figure S2-B, at the end of this period the bottom of the bay is characterized by different depositional areas with channels dissecting them and bringing sediment. The bottom slope in the deep-water area close to the inlet remains similar to the starting bathymetry, while the flat areas near the boundaries are silting up. We name this period “Preparation Phase” as it serves the purpose of preparing suitable areas for marsh colonization.

The next phase, called herein “Encroachment Phase” as shaded in green in Figure 2, lasts about 20 years and it is characterized by vegetation encroachment. Percent of vegetation coverage increases from 22% to 59%. Sediment import continues, but with a decreasing rate (2193 Kg/s on average). Through time, the flux of sediment favors both an expansion of the salt marshes as well as promotes accretion in the area already colonized by vegetation (Fig. 2A&E). In this period, the unvegetated area near the inlet becomes shallower. As the rate of sediment import drops, the speed of marsh expansion decreases (from 1008 m^2/day to 183.6 m^2/day). Figure S2-C shows the end bathymetry of this period, where the entire bay is filled with the exception of the large channels near the inlet.

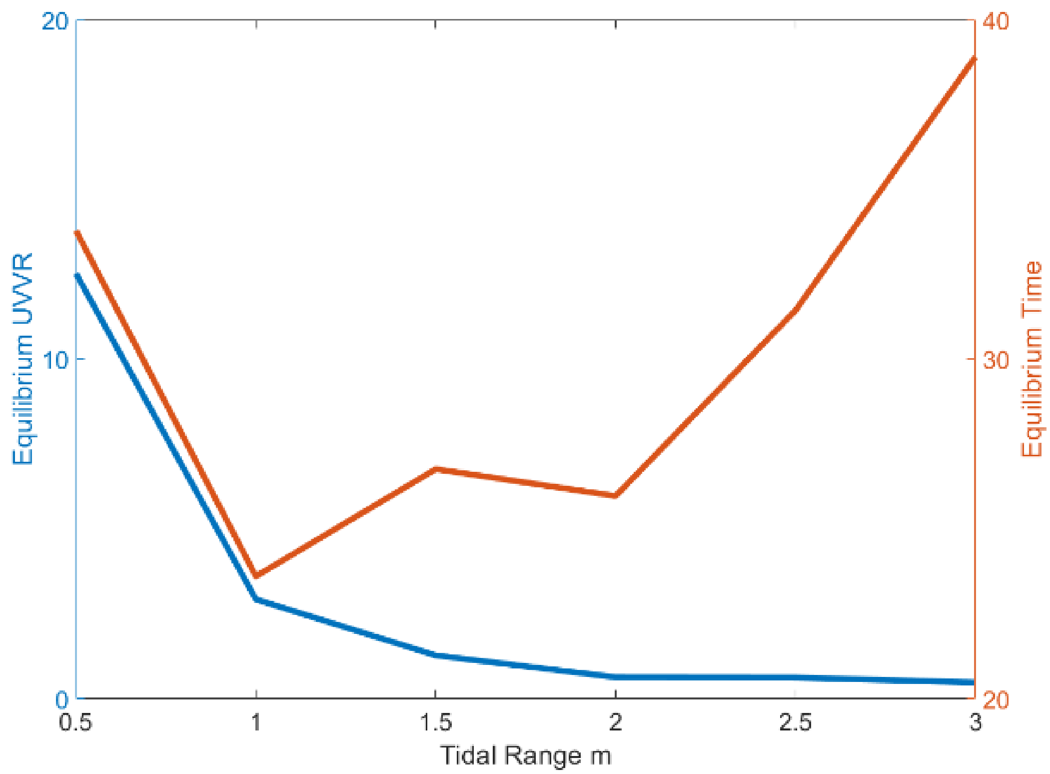
The system eventually reaches equilibrium in terms of planimetric marsh area, with dendritic channels dissecting the marsh and an area of deep water around the inlet. In the last phase, named Adjustment Phase (shaded green area in Figure 2), the marsh area remains relatively unchanged while the marsh elevation is increasing to keep pace with SLR. In this phase the marsh is accreting to compensate SLR. The marsh coverage represented by UVVR in fig.3a remains stable for the last 5~10 years while the platform elevation keeps pace with SLR (fig.3D&E).

3.2 Response to SLR, Tidal Range, and Sediment Characteristics

Equation 3 fits well to the data with $R^2 = 0.998$ for the Std case. Generally, a lower equilibrium UVVR is accompanied by a lower timescale to reach equilibrium. When conditions favor a large marsh area, usually vegetation can reach that coverage faster (Fig. 3A).

The equilibrium UVVR is very high for low input sediment concentration (0.005 kg/m^3) and decreases for higher concentrations. The decrease is more noticeable between 0.005 and 0.1 kg/m^3, suggesting that there might be a minimum sediment supply required to facilitate vegetation encroachment (Figure 3A). A larger settling velocity means more sediment can deposit in suitable locations for vegetation colonization during high tide. Therefore, with a high settling velocity, the equilibrium UVVR decreases and it is accompanied by a small equilibrium time (Figure 3B).

SLR hinders marsh expansion so equilibrium is reached with a smaller coverage and with a time delay. However, at low rates of SLR, the time needed to reach equilibrium remains constant, while at high rates it increases significantly. Despite t_{95} increases nonlinearly with SLR, the equilibrium UVVR grows linearly (Fig. 3C).



The effect of tidal range is complex. The equilibrium marsh coverage increases when tidal range increases, while the t_{95} indicates that there is an optimal interval of tidal ranges for vegetation encroachment (Figure 3D). A too small or large tidal range slows down marsh expansion. In microtidal environments the tidal prism is small, and this leads to limited fluxes of sediment toward the marsh. As mentioned in the previous section, we expect marsh evolution to go through three phases and a small tidal range will make the "Preparation phase" especially challenging as it requires a large amount of sediment flux to prepare the bay for vegetation. Thus, a high vegetation area could only be reached when the tidal range produces adequate sediment fluxes to go through the "Preparation phase" and perhaps "Encroachment phase" fast. On the other hand, a large tidal range not only brings more sediment; it also enlarges the shear stress variations within a tidal cycle leaving a shorter time suitable for deposition. This might lead to a delay in reaching equilibrium, since only a small portion of the sediment brought by the relatively larger tidal flux actually settles in the basin.

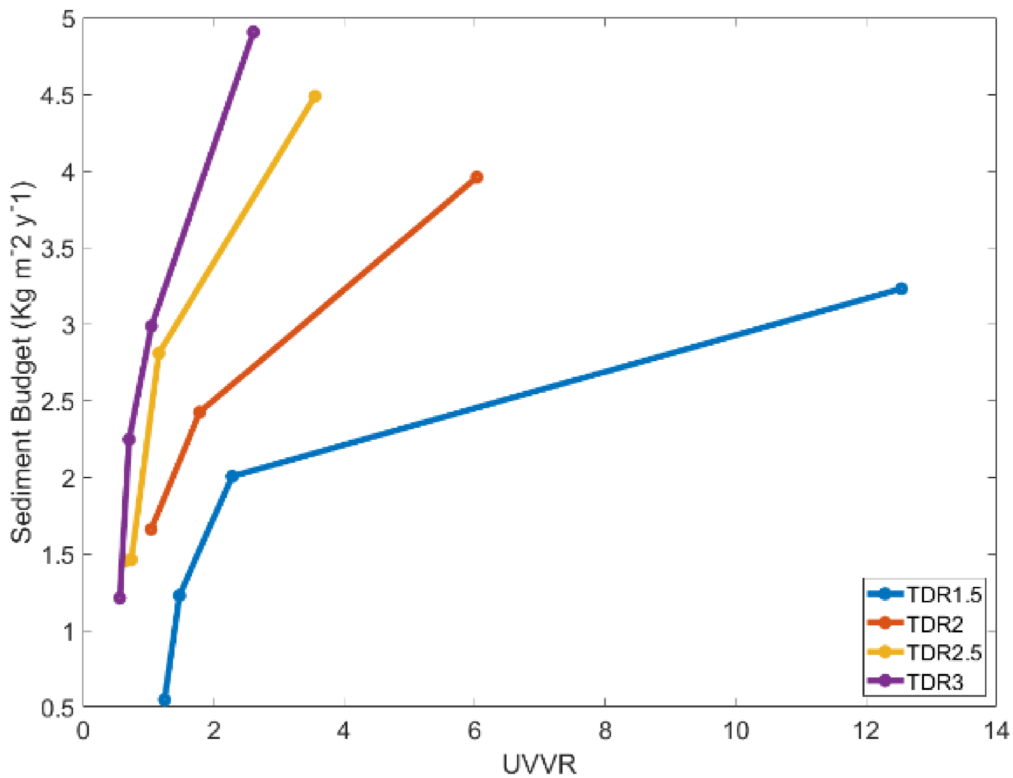
Discussion

Previous studies have shown dependence of marsh formation on various external factors such as sediment availability (DeLaune et al. 1990), land subsidence, or change of tidal water levels (Cole and Steven W 1994). Our results show that within the tested conditions, marsh restoration or land reclamation projects have optimal spatiotemporal coverage limits. With a 3D model, we found that short-term equilibrium is achieved by a rapid initial import of sand and marsh development. In all, we argue that this short-term equilibrium where marshes are able to maintain a constant extent should serve as a guide for coastal marsh restoration and land reclamation. Tidal asymmetries (Friedrichs and Aubrey, 1988) and settling lag effects (Postma, 1961; Bartholdy, 2000) likely play a role in accumulating sediment inside the basin from an initial disequilibrium condition until the marsh starts developing and traps more sediment.

Marshes prefer to maintain smaller area when confronted with a higher SLR rates. Similar results were found by Mariotti and Canestrelli (2017) on marsh resilience to SLR. However, when it comes to equilibrium marsh area, our results should be explained differently. First, all SLR rates are constant in this study meaning the sediment needed to keep up with sea level does not change over time. A higher SLR will create more space to be filled in by the same amount of sediment if other conditions remain the same. So the only way to keep up with SLR and maintain a stable marsh area is to focus deposition on a limited area and use the given sediment to build up vertically.

Marsh systems respond to SLR through sediment fluxes (Ganju et al 2017). Degrading marshes showed evidence of co-evolving UVVR and sediment budget i.e. the more negative is the sediment budget, the higher is UVVR. However, whether this relation holds and how sediment budget and UVVR are related is unknown in forming marshes. The Forming marshes generally follows a pathway of decreasing sediment surplus from high initial values to a value around 0.05

kg m^{-2} year^{-1} (Fig. 4). If we consider these snap shots at different times as individual systems, they represent a wide range of forming marshes in terms of forcing conditions and vegetation coverage. Systems that evolved closer to equilibriums maintain a lower sediment budget because the system is in the "Adjustment phase". These systems generally keep up with SLR and the net sediment import goes to vertical accretion of the marshes. On the other end of the spectrum, systems that are just starting vegetation colonization import sediment at a significantly higher rate than older ones. Overall, the sediment budget scale well with UVVR in most cases. Combining our results with Ganju et al 2017, a higher UVVR leads to greater sediment flux with importing fluxes in



forming marshes and exporting in degrading marshes. A lower UVVR often accompanied by small sediment fluxes and reflects a near equilibrium state.

Most models of marsh evolution are vertically integrated and tend to exaggerate bottom friction. This problem could be significant as vegetation produces vertically variant momentum extraction as well as turbulence across the water column (Sheng et al 2012; Marjoribanks et al 2014). Models that couple morphology and biology either simulate a transect over a long period of time or use a simplification of the hydrodynamics to determine the two-dimensional structure of a salt marsh, typically focusing on the channel network. The study carried out by Mariotti and Canestrelli (2017) only investigated two variables: sediment input and SLR. The model by Alizad et al. (2016) did not consider sediment transport, assuming a prescribed deposition at each location. In reality vegetation and morphology are co-evolving, particularly during marsh formation. Despite all these efforts, the use of a fully coupled model focusing on vegetation and sediment budget is still warranted.

Conclusion

Marsh restoration projects have been carried out for decades with little comprehensive understanding of what controls the final vegetation coverage and the time needed to reach it. Our results close this gap by providing UVVR and equilibrium timescale under a variety of forcing conditions. SLR inhibits marsh expansion thus leading to lower vegetation coverage and longer equilibrium time. Restoration projects with more sediment supply and fine sediments are more likely to succeed in a short timeframe. The expectance of marsh coverage increases with tidal range but only moderate tides (1~2 meters) favor fast colonization. UVVR was proved to relate well with sediment budget in forming marshes. High UVVR coincides with rapid sediment import, while low UVVR indicates marshes approaching equilibrium that need limited amount of sediment to keep up with sea level. We also found that marsh development follows three phases: a Preparation Phase characterized by abiotic deposition, and Encroachment Phase in which vegetation colonizes the intertidal area, and an Adjustment Phase where the vegetated area is constant and accretion balances sea level rise. These results should help predict future restoration outcomes and provide important data for coastal defense or land reclamation. By using our results, it is possible to determine at what stage a marsh restoration is by looking at sediment fluxes and UVVR, what would be the final outcome of the restoration, and the equilibrium timescale.

Acknowledgement

Data points in Figure3 and Figure4 as well as an example of simulation output files for each of the four forcing conditions are available at https://zenodo.org/record/5207786 . Shared under Creative Commons Attribution 4.0 International, all files are open to public for download. The chart alone could support our main conclusions. Readers are welcome to download simulation files to further understand model performance. Funding is in part from USGS and from CSC (China Scholarship Counsil).

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