1. Introduction

Sea level rise threatens the densely populated and ecologically significant low-lying, coastal region of Bengal. Mitigating the effects of sea level rise (SLR) in this region will be especially difficult considering current widespread land management practices and the ongoing geopolitical tension between India and Bangladesh.

Coastal Bengal is situated within the delta formed by the confluence of the Ganges and Brahmaputra rivers and straddles the border between West Bengal, India to the east and Bangladesh to the west. The region is home to ~30 million people (Center For International Earth Science Information Network-CIESIN-Columbia University, 2018) and the ecologically critical Sundarbans mangrove forest. Since the 1960s, the region has seen a vast transformation through the reduction in natural mangrove habitat and the widspread construction of earthen embankments. These embankments surround large swaths of clearcut land, known as polders, that accomodate the swelling population of the region.

While, preventing regular inundation by spring high tides, the creation of these embankments have had the unintended consequence of starving the interior of the polders of fresh sediment. Without this sediment, polder interiors have compacted resulting in signficant elevation offset (1.0 m to 1.5 m) relative to the natural mangrove forest (Auerbach et al., 2015). Polder elevations often sit precariously below local mean high water (MHW) levels leading to persistent waterlogging. Furthermore, many of these embankments are in disrepair and susceptible to breaching especially by storm surge as was the case with Cyclone Sidr (2007), Cyclone Aila (2009), and recently with Cyclone Amphan (2020).

Tidal river management (TRM) has been proposed as a possible augmentation of current land management practices to alleviate some of the issues caused by poldering. Under TRM, embankments are seasonally breached to allow tidal water inundation and sediment aggradation. Many low-lying areas may recover to an acceptable elevation within 5 to 10 years, though, some may take longer. There are a host of local socioeconomic, political, and governance consideration that may influence the success of TRM. Here, we neglect those considerations and focus on the general feasibility of TRM in regards to SLR and the sediment supply of the GB system. Future studies will focus on the social dynamics surround TRM.

Coastal Bengal is often seen as one of the most at-risk regions for SLR due to climate change. Infographics often depict large swaths of the Bengal coastline flooded under different SLR scenarios. However, this overly simplifies the threats to the region and neglects the significant sediment contribution of the GB system in mainintaining the natural elevation.

Estimates for increases in Relative Mean Sea Level (RMSL) in the GB delta range from 2.8 mm yr^{-1} to 8.8 mm yr^{-1}. However, RMSL neglects the widening of the tidal range in the polder region. On average, local high water levels in the polder region are increasing at a rate of 15.9 mm yr^{-1} (Pethick and Orford, 2013). While SLR is of paramount importance, tidal range amplification is the more imminent threat to the region. This is especially important considering the Bangladeshi government's recent reinvestment in poldering with a $400 million loan from the World Bank for the Coastal Embankment Improvement Project - Phase I (CEIP-I).

As for the natural mangrove system, it is unclear how changing water levels will affect elevation. Some studies have shown that the region is incredibly resilient to increasing water levels due, in large part, to the abudant sediment supply of the GB system. This sediment is delivered to the platform periodically during spring high tide which helps maintain an equilibirum elevation approximately equivalent to mean higher high water (MHHW). But, this large volume of sediment delivered to coastal Bengal is not guaranteed.

Water has long been the focus of the geopolitical disputes between India and Bangladesh. However, the reduction in waterflow across the border portends a significant decrease in sediment flux. Estimates suggest sediment flux may be reduced by 39 % to 75 % for the Ganges and 9 % to 25 % for the Brahmaputra resulting in a change in aggradation from 3.6 mm yr^{-1} to 2.5 mm yr^{-1} (Higgins et al., 2018).

The combination of increasing water levels and decreasing sediment supply may further intensify an already dire situation. Here, we use a zero-dimensional mass balance model of sediment aggradation to understand the impact that increasing water levels and decreasing sediment flux will have on the regions equilibrium elevation and consequently its resilience to climate change. We consider both the resilience of the natural mangrove system and the ability of the polder system to recover to a more resilient elevation through TRM.

2. Methods

2.1. Model design

We modeled the vertical accretion of a tidal platform ($d\eta/dt$) using a zero-dimensional mass balance approach initially described by Krone (1987) and validated by subsequent studies (Allen, 1990; French, 1993; Temmerman et al., 2003, 2004). The rate of vertical accretion is described as

$$\frac{d\eta(t)}{dt} = \frac{dS_m(t)}{dt} + \frac{dS_o(t)}{dt} + \frac{dP(t)}{dt} + \frac{dM(t)}{dt}, \tag{1}$$

where $dS_m(t)/dt$ is the rate of mineral sedimentation, $dS_o(t)/dt$ is the rate of organic matter sedimentation, $dP(t)/dt$ is the rate of shallow compaction after dewatering of the deposited sediment, and $dM(t)/dt$ is the rate of tectonic subsidence. We considered $dS_o(t)/dt$, $dP(t)/dt$, $dM(t)/dt$ to be constants and used characteristic yearly rates for each; while, $dS_m(t)/dt$ varies within a tidal cycle (Hale et al., 2019b) and requires additional treatment.

To solve for $dS_m(t)/dt$, we began by conceptualizing a tidal platform periodically inundated by sinusoidal tides. We first defined depth to be

$$h(t) = \zeta(t) - \eta(t), \tag{2}$$

where $\zeta(t)$ is the water-surface elevation and $\eta(t)$ is the sediment-surface elevation which also implies that

$$\frac{dh(t)}{dt} = \frac{d\zeta(t)}{dt} - \frac{d\eta(t)}{dt}. \tag{3}$$

Independently, we assume while $h(t) > 0$, the rate of mineral sedimentation is

$$\frac{dS_m(t)}{dt} = \frac{w_s C(t)}{\rho_b}, \tag{4}$$

where w_s is the nominal settling velocity of a sediment grain, $C(t)$ is the depth-averaged suspended sediment concentration (SSC) in the water column, and ρ_b is the bulk density of the sediment. We assumed no resuspension of mineral sediment which is practical and consistent with previous studies (Krone, 1987; Allen, 1990; French, 1993; Temmerman et al., 2003, 2004).

In order to solve for $C(t)$ in eq. (4), we first defined a mass balance of sediment within the water column as

$$\frac{d}{dt}[h(t)C(t)] = -w_s C(t) + C_b \frac{dh(t)}{dt}, \tag{5}$$

which can be expanded and rerranged as

$$\frac{dC(t)}{dt} = -\frac{w_s C(t)}{h(t)} - \frac{1}{h(t)}[C(t) - C_b]\frac{dh(t)}{dt}. \tag{6}$$

We assumed advection of new sediment to only occur during flood tide by constraining mass flux from the boundary term when $dh/dt > 0$. We formalized this mathematically using a Heaviside function which serves as a binary switch and is given as

$$S = \frac{dh}{dt}, \quad H(S) = \begin{cases} 0 & \text{if } S < 0 \\ 1 & \text{if } S \geq 0. \end{cases} \tag{7}$$

Eq. (6) then becomes

$$\frac{dC(t)}{dt} = -\frac{w_s C(t)}{h(t)} - \frac{H(S)}{h(t)}[C(t) - C_b]\frac{dh(t)}{dt}. \tag{8}$$

Eqs. (8), (4) and (1) were then solved in that order to obtain the change in elevation during one time step.

We integrated this series of equations for each inundation cycle using an explicit Runge-Kutta method of order 5(4) (Dormand and Prunce, 1980) implemented in Python using SciPy (Virtanen et al., 2020). We used an adaptive step size which provided computational efficiency by decreasing step size as needed - i.e. beginning and end of an inundation cycle. To avoid numerical errors due to very small depths in eq. (8), we only allowed the model to integrate while water depths were >1 mm. Outside of the integration (i.e. while the platform was dry), we continued to apply linear rates for ${dS_o(t)}/{dt}$, ${dP(t)}/{dt}$, ${dM(t)}/{dt}$.

We indentified indundation cycles by filtering the tidal curve for water-surface elevations that were above the corresponding sediment-surface elevation. The time of first element of the filtered data was used to initialize the integration. The adaptive step size method required a continuous function for water-surface elevations so we converted the tidal data to an interpolated univariate spline during the integration. The integration continued until the water-surface elevation fell below the sediment-surface elevation. We repeated this process for all subsequent inundation cycles through the prescribed length of each simulation to obtain a final elevation.

2.2. Field observations and model parameters

Tidal data

The tidal curve was derived from observations at Sutarkhali station. Water-surface elevations were collected every 10 minutes from January 1, 2019 to December 31, 2019 using an Onset U20L-01 HOBO water level data logger. The data were processed and upsampled to 1 s temporal resolution using the oce package in R (3.6.3) (Kelley and Richards, 2020). The tidal curve was then shifted to place mean water at ~1.6 m below the Sundarban sediment-surface. This results in ~50 cm to 60 cm of inundation during most spring high tides and is consistent with survey data (Auerbach et al., 2015; Hale et al., 2019b; Bomer et al., 2020b). We repeated this tidal curve for each subsequent year of the simulation with a superimposed sea level rise rate of 5 mm yr^{-1}.

Organic matter, shallow compaction, and subsidence

Bomer et al. (2020a) found organic matter only accounts for ~0.9 % ± 0.1 % of the ~2.42 cm yr^{-1} ± 0.26 cm yr^{-1} yearly bulk sedimentation. Using this, we set ${dS_o(t)}/{dt}$ to 0.2 mm yr^{-1}.

Shallow compaction is difficult to constrain for the region and likely varies significantly due to natural variability in stratigraphy and anthropogenic activity (e.g. subsurface fluid extraction and accelerated oxidation of below-ground biomass due to drying of the sediment). Auerbach et al. (2015) suggested shallow compaction rates of 0.4 cm yr^{-1} for natural compaction and 0.8 cm yr^{-1} for accelerated compaction (combined natural and anthropogenic compaction). We adopted their values of ${dP(t)}/{dt}$.

Estimates of subsidence vary for the region and are hard to disentangle from compaction. Many studies (Pethick and Orford, 2013; Goodbred and Kuehl, 2000; Stanley and Hait, 2000) combine compaction and subsidence. Auerbach et al. (2015) considered both compaction and subsidence separately by using values in the literature (Pethick and Orford, 2013; Goodbred and Kuehl, 2000; Stanley and Hait, 2000) estimated subsidence to be 0.3 cm yr^{-1}. We set ${dM(t)}/{dt}$ to this value.

Settling velocity, suspend sediment concentration, and bulk density

We used Stoke's law to determine w_s. Stoke's law assumes unhindered settling which likely overestimates actual settling rates and, therefore, mineral sedimentation rates. However, we only considered settling for a singular, median grain size which likely underestimated mineral sedimentation rates from coarser grains. Model calibration further corrected for these errors. Thus, the w_s given by Stoke's law should be considered an imprecise, but reasonable approximation.

For C_b, we use observed values of SSC from Hale et al. (2019a) that are characteristic of the tidal channels in the region.

For ρ, we used values derived from conversations with Steven Goodbred and Carol Wilson.

Software and/or data availability

Acknowledgements

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