Highlights

DRAFT: Sediment model

Christopher M. Tasich,Jonathan M. Gilligan,Steven L. Goodbred

- Research highlights item 1
- Research highlights item 2
- Research highlights item 3

DRAFT: Sediment model

Christopher M. Tasich*, Jonathan M. Gilligan** and Steven L. Goodbred Jr

Department of Earth & Environmental Sciences, Vanderbilt University, Nashville TN 37235, USA

ARTICLE INFO

Keywords:
TRM
polders
sea level rise

ABSTRACT

The low-lying, coastal region of the Ganges-Brahmaputra (GB) delta has relied on poldering (the creation of embanked islands) to mitigate the effects of tidal inundation and storm surge since the 1960s. The result has been an increase in total habitable and arable land allowing for the sustenance of 20 million people within the tidal deltaplain. However, poldering produced the unintended consequence of starving the interior landscapes of sediment resulting in a significant elevation offset (1-1.5 m) from that of the natural system. Engineering efforts, such as tidal river management (TRM), propose a controlled inundation effort to allow sediment exchange with the tidal network. Some local TRM efforts have succeeded, while other have not. However, there have been few quantitative analyses aimed at understanding the relationship between tidal inundation and sediment accumulation. Furthermore, sea level rise (SLR) and decreases in suspended sediment concentrations (SSC) due to damming of rivers may also affect sediment accumulations in the future. We use a combination of field based observations and modeling to simulate the long-term evolution of both the poldered and the natural system in the GB delta.

Our model employs a mass balance with sediment accumulation controlled by tidal height above the platform, SSC, settling velocity, and dry bulk density. Tidal height is determine using pressure sensor data with projected SLR superimposed. SSC varies within both one tidal cycle (0-3 g/L) and seasonally (0.15-0.77 g/L). Grain size (14-27 μm) is used as a proxy for determining settling velocity. Dry bulk density (900-1500 kg/m3) is determined from sediment samples at depths of 50-100 cm. We use a Monte Carlo simulation to project sediment accumulation probabilities over the next century. Furthermore, we simulate perturbations to the system such as decreases in SSC due to recent damming of the Ganges in India. Baseline results suggest the P32 system could recover to that of the natural system in only 7 years. However, aggressive SLR projections or decreases in SSC result in mean high water out-pacing sediment accumulation for both P32 and the natural mangrove forest.

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 widespread 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

*Corresponding author
**Principal corresponding author
chris.tasich@vanderbilt.edu (C.M. Tasich); jonathan.gilligan@vanderbilt.edu (J.M. Gilligan); steven.goodbred@vanderbilt.edu (S.L. Goodbred)
ORCID(s): 0000-0001-7511-2910 (C.M. Tasich); 0000-0001-7511-2910 (S.L. Goodbred)
https://twitter.com/ctasich (C.M. Tasich)
https://www.linkedin.com/profile/view?id=christasich (C.M. Tasich)

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 many subsequent studies (Allen, 1990; French, 1993; Temmerman et al., 2003, 2004). The rate of vertical accretion is described as

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

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 compaction of the deposited sediment, and $dM(t)/dt$ is the rate of regional tectonic subsidence. For the purpose of this study, we neglected organic matter sedimentation and tectonic subsidence. We also effectively internalize the compaction term by using dry bulk density within the mineral sedimentation term. Thus, we set terms $dS_o(t)/dt$, $dP(t)/dt$, and $dM(t)/dt$ to zero.

In order to solve $dS_m(t)/dt$, we began by assuming

$$h(t) = \zeta(t) - \eta(t), \qquad (2)$$

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

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

Independetly, we assume the rate of mineral sedimentation to be

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

where w_s is the nominal settling velocity of 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). Additionally, Stoke's law assumes unhindered settling and likely overestimates actual settling rates and, therefore, mineral sedimentation rates. However, the model only considers a median grain size which likely underestimates mineral sedimentation rates. Furthermore, model calibration should correct for these errors. Thus, our modeled w_s should be considered a high, but not unreasonable approximation. In order to solve for $C(t)$ in Eq. 4, we first defined a mass balance of sediment within the water column as

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

which can be expanded and rerranged as

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

Furthermore, we only allowed deposition to occur on the rising limb of a tide which is consistent with previus studies (Krone, 1987; Allen, 1990; French, 1993; Temmerman et al., 2003, 2004). We introduced a mathematical switch to turn off the flux of sediment from the boundary term during the falling limb of the tide. We implement this as a Heaviside function defined as

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

Eq. 6 then becomes

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

From here, we can solve Eq. 8 and then Eq. 4 when $h(t) > 0$.

2.2. Model inputs

We obtained model inputs from field measurements. We observed tidal height, grain size, suspended sediment concentration (SSC), and dry bulk density around Polder 32 over multiple field seasons from 2011 to 2016 (Auerbach et al., 2015; Hale et al., 2019a,b).

For h, we extracted one year of contiguous tidal data from from a pressure sensor deployed within the tidal channel near Polder 32. We used the oce package in R (3.6.3) to create an idealized tidal curve from our data (Kelley and Richards, 2020). The tidal curve was then shifted down so that mean higher high water would be 0.3 m above the Sundarban platform and 1.8 m above the polder surface (ζ). We replicated this tidal curve for each subsequent year for the length of the model run. Field observations confirm these benchmark elevation (Auerbach et al., 2015; Hale et al., 2019b; Bomer et al., 2020). In order to simulate sea level rise, the subsequent year tidal curves were increased at a linear rate of $2\,\mathrm{mm\,yr^{-1}}$ which is consistent with field observations.

For C_{in}, we use observed values of SSC from Hale et al. (Hale et al., 2019a) that are characteristic of the tidal channels in the region. Similar to Temmerman et al. (Temmerman et al., 2003, 2004), we scaled the observed tidal channel SSC by a factor as the flood waters are expected to have a lower SSC than the tidal channel due to lower flow velocities. For our preliminary study, we use a k-factor of 0.7. In future model iterations, we will better explore this relationship and determine an appropriate k-factor.

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

3. Results

4. Discussion

5. Conclusions

Software and/or data availability section

Acknowledgements

References

Allen, J.R.L., 1990. Salt-marsh growth and stratification: A numerical model with special reference to the Severn Estuary, southwest Britain. Marine Geology 95, 77–96. doi:10/dpcnnc.

Auerbach, L.W., Goodbred Jr., S., Mondal, D.R., Wilson, C.A., Ahmed, K.R., Roy, K., Steckler, M.S., Small, C., Gilligan, J.M., Ackerly, B.A., 2015. Flood risk of natural and embanked landscapes on the Ganges–Brahmaputra tidal delta plain. Nature Climate Change 5, 153–157. doi:10/gc3fxh.

Bomer, E.J., Wilson, C.A., Hale, R.P., Hossain, A.N.M., Rahman, F.M.A., 2020. Surface elevation and sedimentation dynamics in the Ganges-Brahmaputra tidal delta plain, Bangladesh: Evidence for mangrove adaptation to human-induced tidal amplification. CATENA 187, 104312. doi:10/ggszhr.

Center For International Earth Science Information Network-CIESIN-Columbia University, 2018. Population Estimation Service, Version 3 (PES-v3). doi:10.7927/H4DR2SK5.

French, J.R., 1993. Numerical simulation of vertical marsh growth and adjustment to accelerated sea-level rise, North Norfolk, U.K. Earth Surface Processes and Landforms 18, 63–81. doi:10/drw2f8.

Hale, R., Bain, R., Goodbred Jr., S., Best, J., 2019a. Observations and scaling of tidal mass transport across the lower Ganges–Brahmaputra delta plain: Implications for delta management and sustainability. Earth Surface Dynamics 7, 231–245. doi:10/gf2cdq.

Hale, R.P., Wilson, C.A., Bomer, E.J., 2019b. Seasonal Variability of Forces Controlling Sedimentation in the Sundarbans National Forest, Bangladesh. Frontiers in Earth Science 7, 211. doi:10/ggjhb2.

Higgins, S.A., Overeem, I., Rogers, K.G., Kalina, E.A., 2018. River linking in India: Downstream impacts on water discharge and suspended sediment transport to deltas. Elem Sci Anth 6, 20. doi:10/gc5tf8.

Kelley, D., Richards, C., 2020. Oce: Analysis of Oceanographic Data.

Krone, R., 1987. A Method for Simulating Marsh Elevations, in: Coastal Sediments, American Society of Civil Engineers, New Orleans, Louisiana. pp. 316–323.

Pethick, J., Orford, J.D., 2013. Rapid rise in effective sea-level in southwest Bangladesh: Its causes and contemporary rates. Global and Planetary Change 111, 237–245. doi:10/s8h.

Temmerman, S., Govers, G., Meire, P., Wartel, S., 2003. Modelling long-term tidal marsh growth under changing tidal conditions and suspended sediment concentrations, Scheldt estuary, Belgium. Marine Geology 193, 151–169. doi:10/dqg2zs.

Temmerman, S., Govers, G., Wartel, S., Meire, P., 2004. Modelling estuarine variations in tidal marsh sedimentation: Response to changing sea level and suspended sediment concentrations. Marine Geology 212, 1–19. doi:10/dsjcj6.