Modeling Elevation Equilibrium and Human Adaptation in Southwest Bangladesh

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INTRODUCTION

The low-lying tidal reaches of the Ganges-Brahmaputra delta relies on a system of polders (embanked landscapes) to prevent against tidal inundation and storm surge. These polders have increased the total habitable and arable land allowing the region to sustain a population of ~20 million people. An unintended consequence of poldering has been the reduction of water and sediment exchange between the polders and the tidal network, which has resulted in significant elevation offsets of 1-1.5 m relative to that of the natural landscape. Tidal River Management (TRM) and other engineering practices have been proposed in order to alleviate the offset. Previous work suggests if implemented properly with sufficient suspended sediment concentrations (SSC), TRM can be effective on timescales of 5-20 years. However, communities must also agree on how and when to implement TRM. Here, we expand previous numerical simulations of sediment accumulation through field-based constraints of grain size, compaction, and sea level rise. We then model human decision-making for implementation of TRM practices.

Our sediment model employs a basic mass balance of sediment accumulation as a function of tidal height, SSC, settling velocity, and dry bulk density. Tidal height is determined from pressure sensors and superimposed sea level rise rate, as defined by the representative concentration pathways of the IPCC. SSC varies within a tidal cycle (0-3 g/L) and seasonally (0.15-0.77 g/L). Multiple grain sizes (14-27 µm) are used as proxies for settling velocity by Stokes' Law. Dry bulk density (900-1500 kg/m3) is determined from sediment samples at depths of 50-100 cm. The human dimension is introduced through an agent-based model for community decision-making regarding TRM.

THE GANGES-BRAHMAPUTRA DELTA

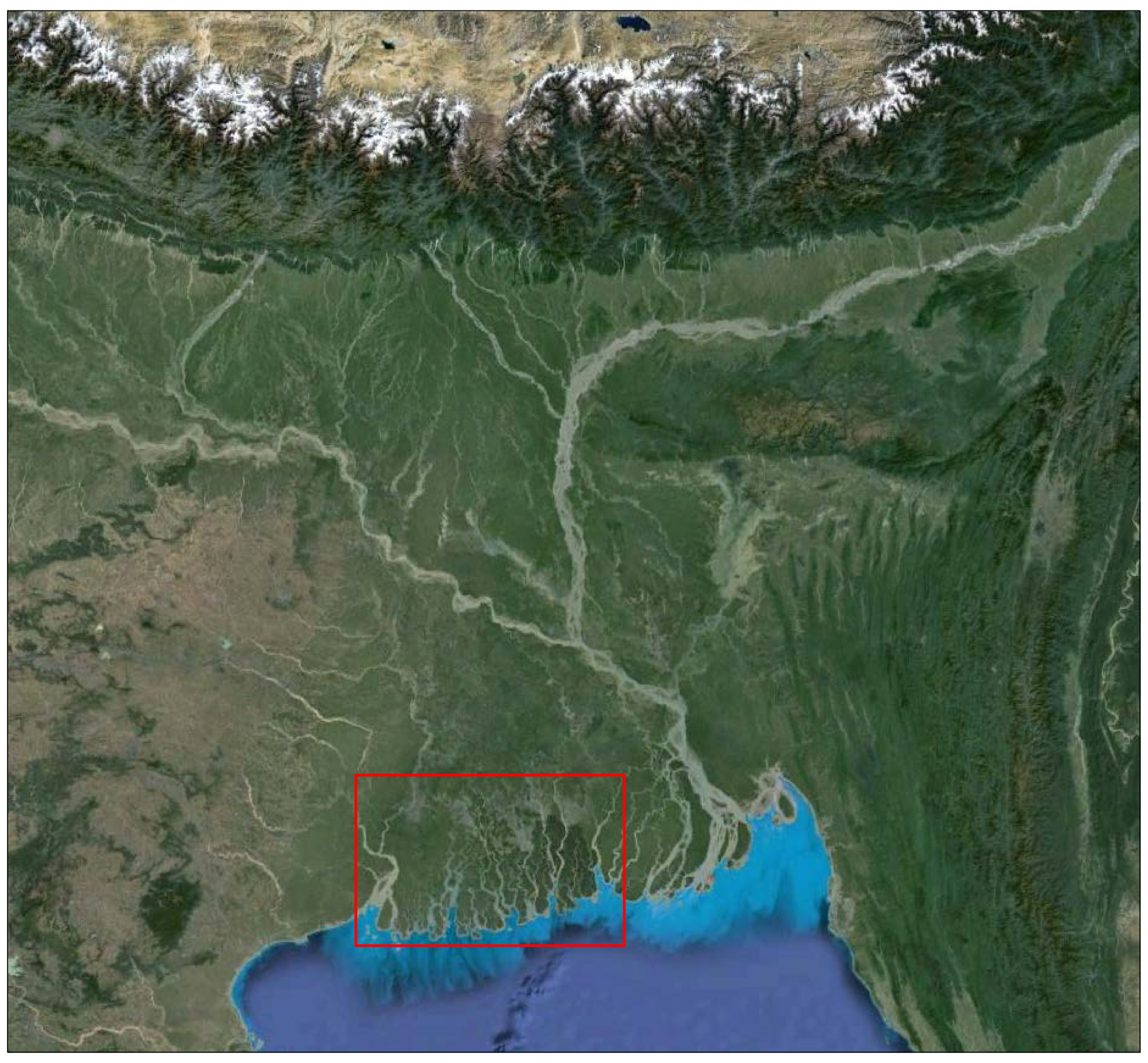


Fig 1 | Google Earth image of the Ganges-Delta. The poldered region is shown in red. The combined Ganges-Brahmaputra system conveys ~1.1 billion tons of sediment per year. The poldered region is disconnected from the fluvial network. However, nearly 200 million tons of sediment per year are reworked in the tidal network.

SEA LEVEL RISE OVER THE NEXT CENTURY

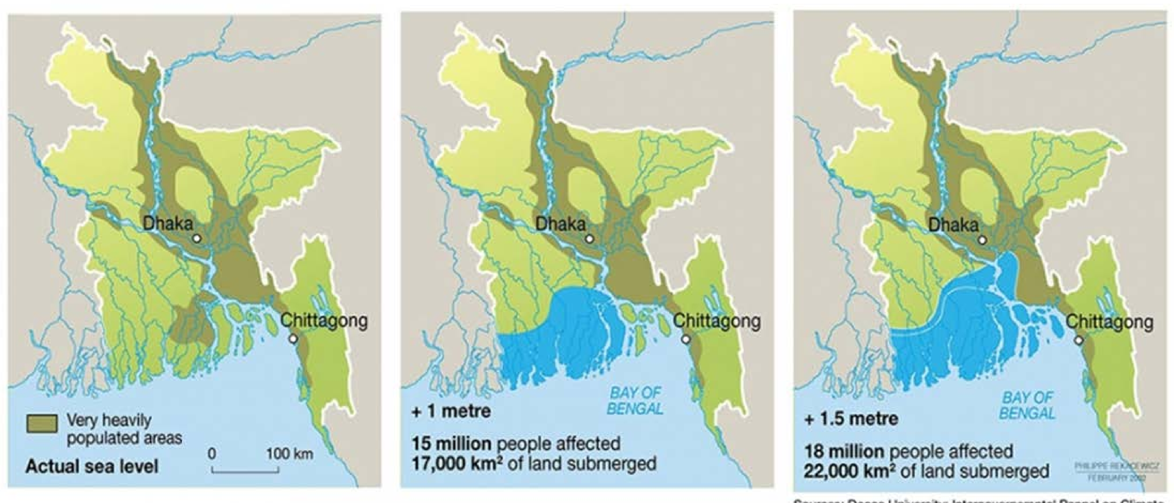
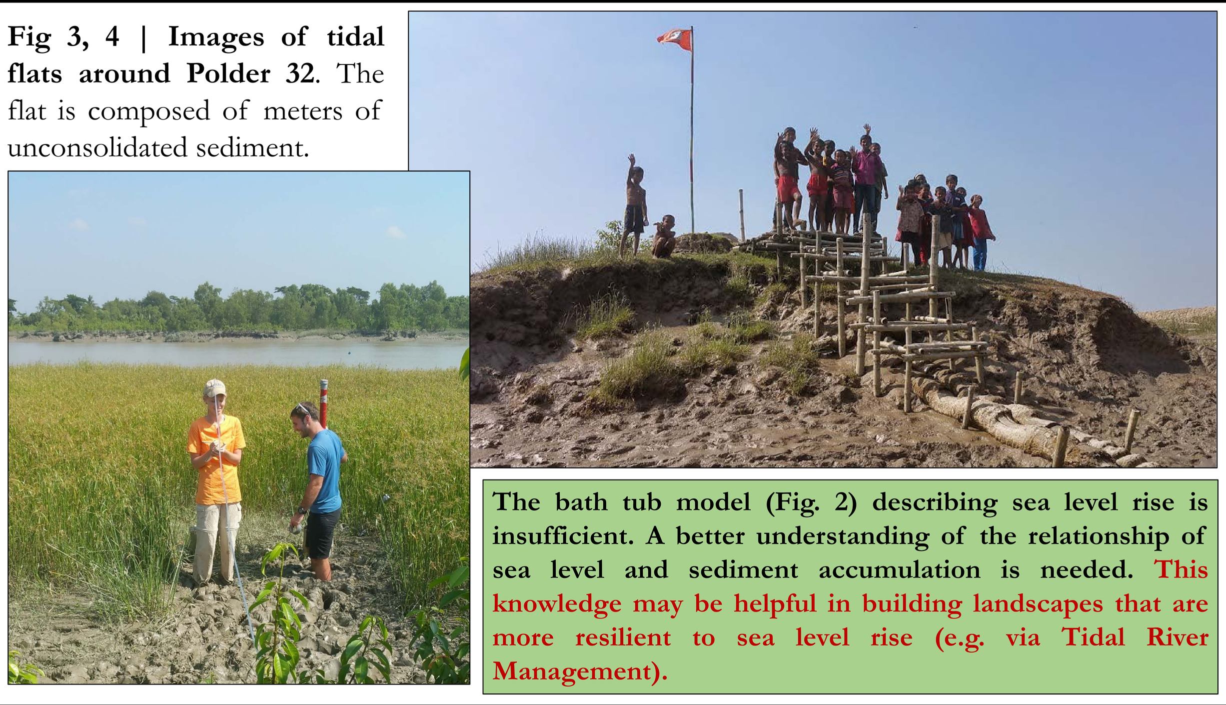


Fig 2 | Sea level rise scenarios (Present; +1 meter; +1.5 meters). Approximately 160 million people living on the delta plain could be adversely affected.

WHAT ABOUT THE SEDIMENT?

Fig 3, 4 | Images of tidal flats around Polder 32. The flat is composed of meters of unconsolidated sediment.



The bath tub model (Fig. 2) describing sea level rise is insufficient. A better understanding of the relationship of sea level and sediment accumulation is needed. This knowledge may be helpful in building landscapes that are more resilient to sea level rise (e.g. via Tidal River Management).

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POLDERED LANDSCAPES

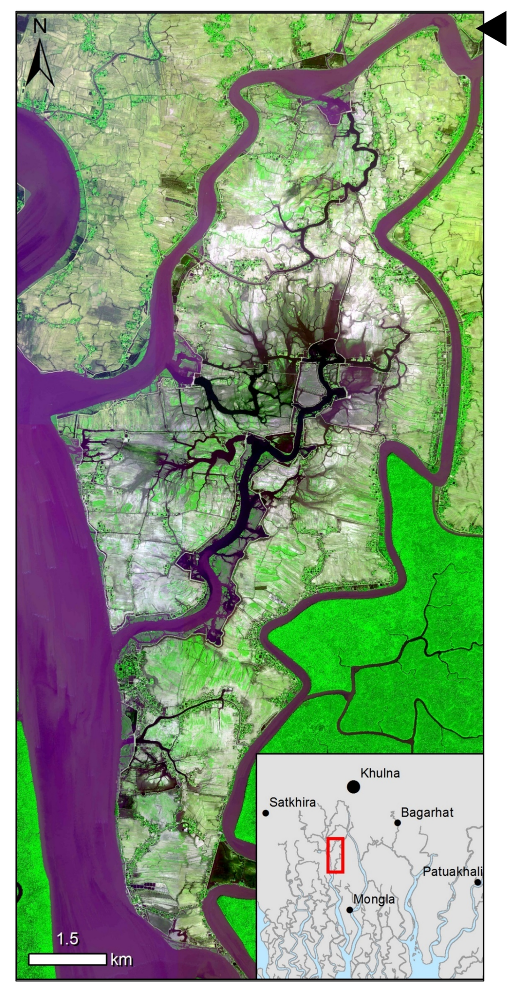


Fig 5 | Geoeye image of Polder 32. Bright green is the Sundarbans National Forest. Elevation offsets between the polder and the Sundarbans are ~1 m.

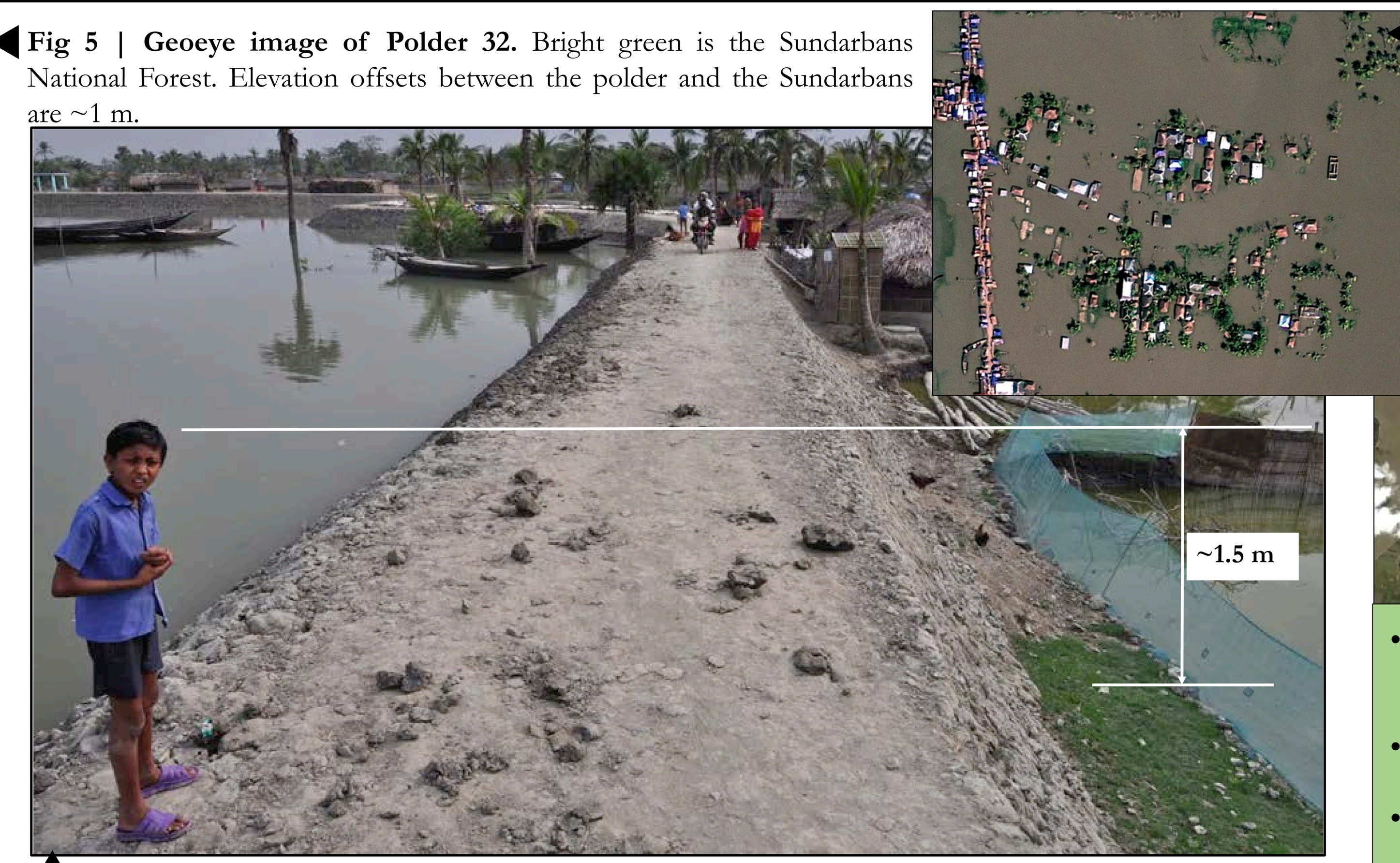


Fig 6 | Picture from an embankment on the southeast side of Polder 32. The picture was taken during a spring high tide. The offset between the interior of the polder and the high tide is ~1.5 m.

Fig 7, 8 | Flooding from Cyclone Aila (2009). The embankment surrounding Polder 32 failed in multiple locations resulting in tidal inundation for ~18 h/day.

- **Poldering has had the unintended consequence of starving the interior land of fresh sediment.**
- **The interiors have compacted and are now below high tide. (Fig. 6)**
- **Storm surge can overtop the embankments and lead to sustained tidal inundation. (Fig. 7,8)**
- **How can we remediate this offset?**

FIELD OBSERVATIONS

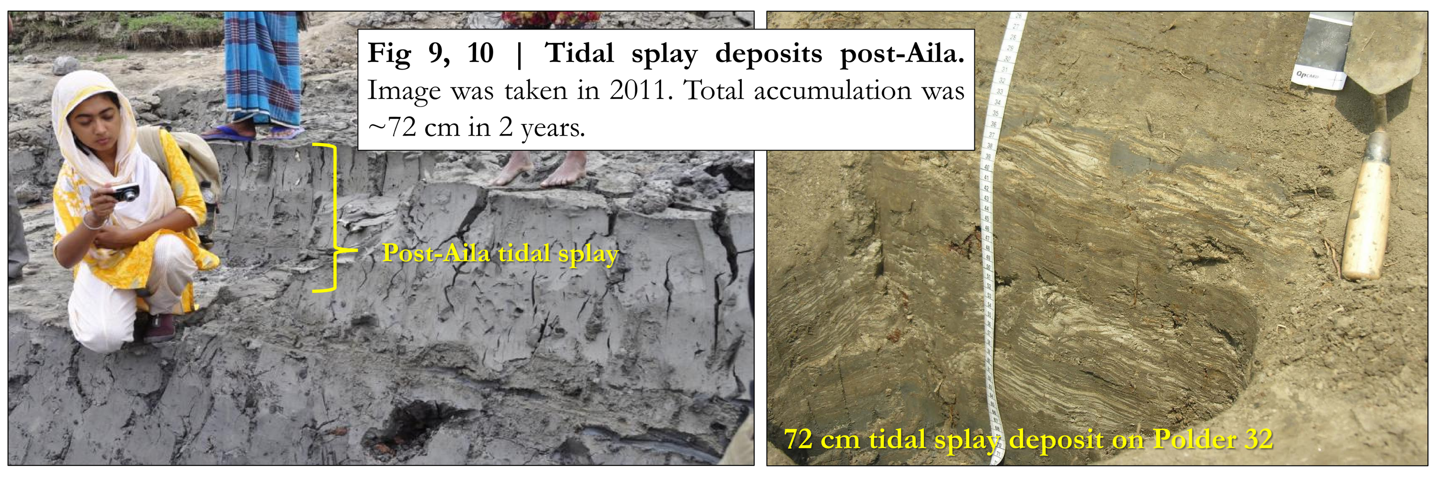


Fig 9, 10 | Tidal splay deposits post-Aila. Image was taken in 2011. Total accumulation was ~72 cm in 2 years.

Fig 11 | Tidal height data from Polder 32. The tidal heights were inferred from CTD pressure sensor data. The natural elevation (green) is in equilibrium with mean high water (MHW). Polder elevations (pink) are ~1.2 m below MHW.

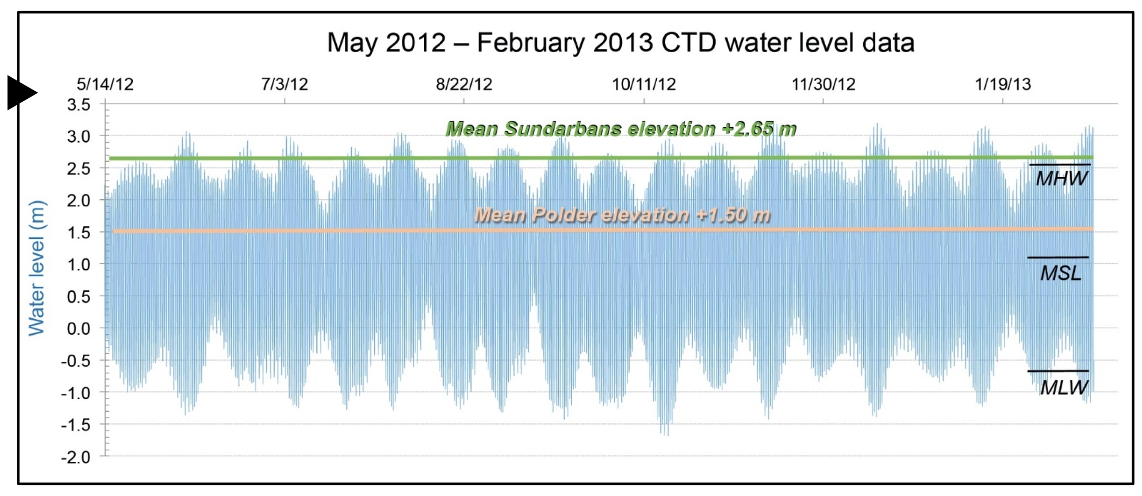
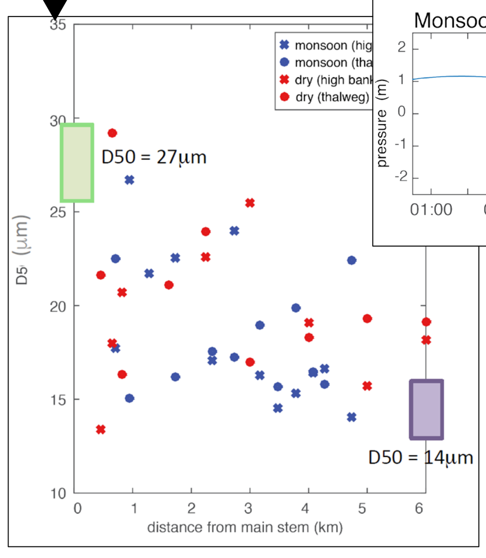


Fig 12 | D50 grain sizes around Polder 32. Measurements were taken during both the monsoon and dry season. Particle diameter increases towards the main stem of the tidal network. D50 for main stem is in green and in purple for the interior of the Sundarbans.



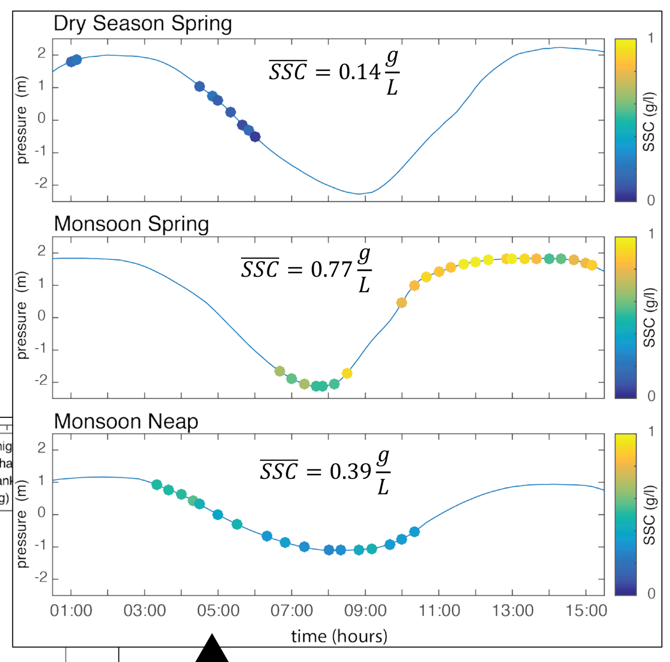
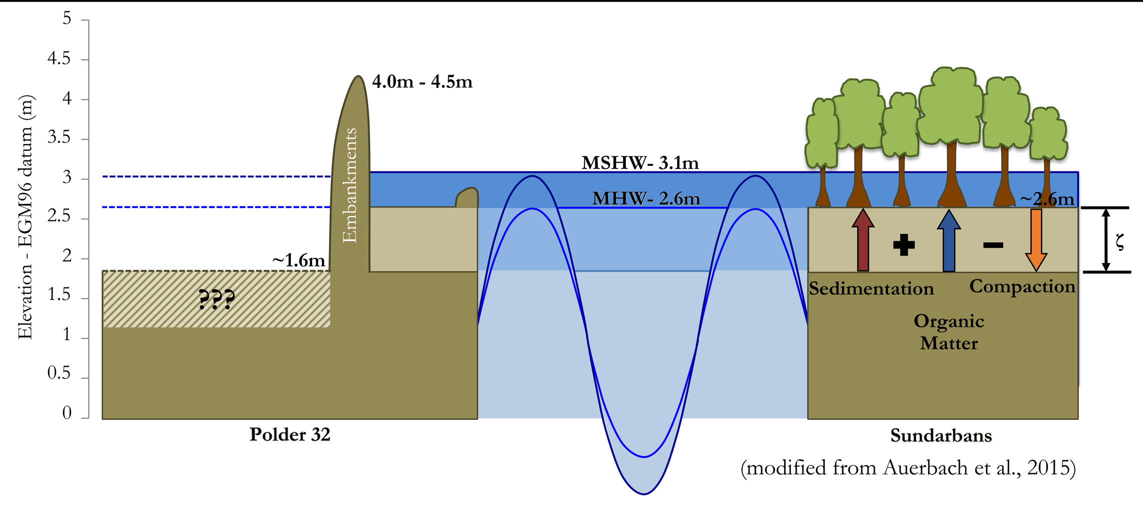


Fig 13 | Suspended sediment concentrations around Polder 32. SSC is highest during spring tides. Mean SSC is significantly lower in the dry season as compared to the monsoon season.

SEDIMENT AGGRADATION MODEL



NUMERICAL MODEL

$$\frac{d\zeta}{dt} = \frac{dS}{dt} + \frac{dO}{dt} - \frac{dP}{dt} \quad (1)$$

$$\frac{dS}{dt} = \int \frac{w_s C(t)}{\rho} dt \quad (2)$$

$$\frac{d[h(t) - \zeta]C(t)}{dt} = -w_s C(t) + C(0)\frac{dh}{dt} \quad (3)$$

PARAMETERS

Settling Velocity (w_s)

Dry Bulk Density (ρ)

Suspended Sediment Concertation (SSC)

Tidal Height (h)

Fig 14 | Conceptual model of Polder 32 and the adjacent Sundarbans. The Sundarbans are assumed to be at equilibrium with the tides. Sediment accumulation is defined by Eq. 1 where $\frac{dS}{dt}$ is sedimentation rate, $\frac{dO}{dt}$ is deposition of organic matter, and $\frac{dP}{dt}$ is compaction rate. Sedimentation rates are much greater than organic deposition and compaction rates. Therefore, we can simplify to Eq. 2 and solve the integral using a finite-difference approximation (Eq. 3).

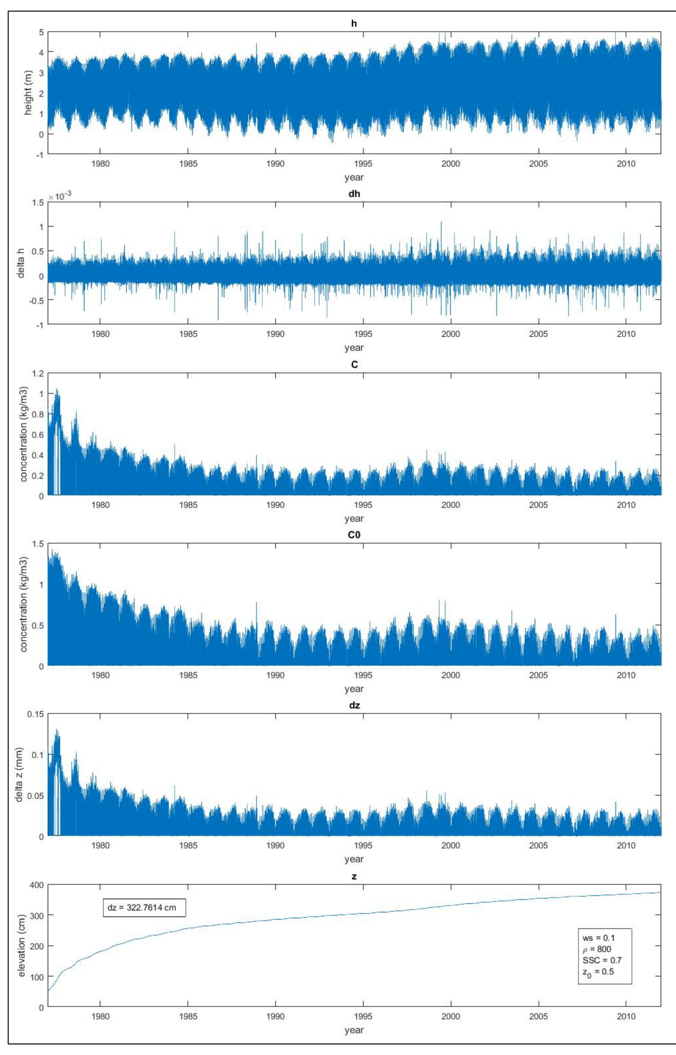


Fig 15 | Model results from historic tide gauge data (1977-2011). The model time step is equal to the tide gauge resolution (1 h). Model results show an asymptotic relationship with MHW.

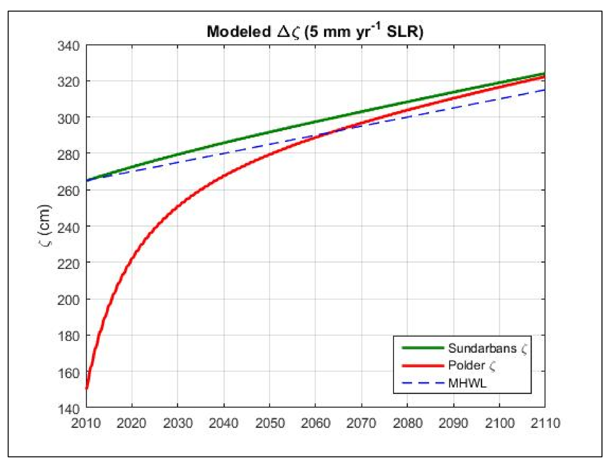
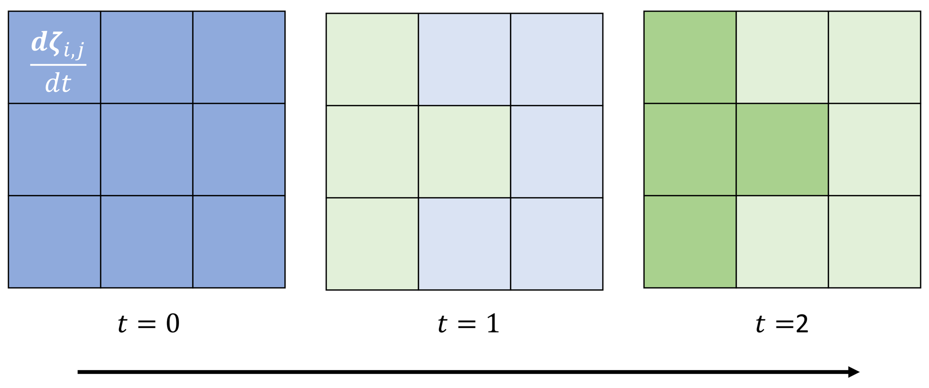


Fig 16 | Model projections using historic data and superimposing 5 mm of sea level rise per year. Using realistic parameters, Polder elevations eventually equilibrate to that of the natural level.

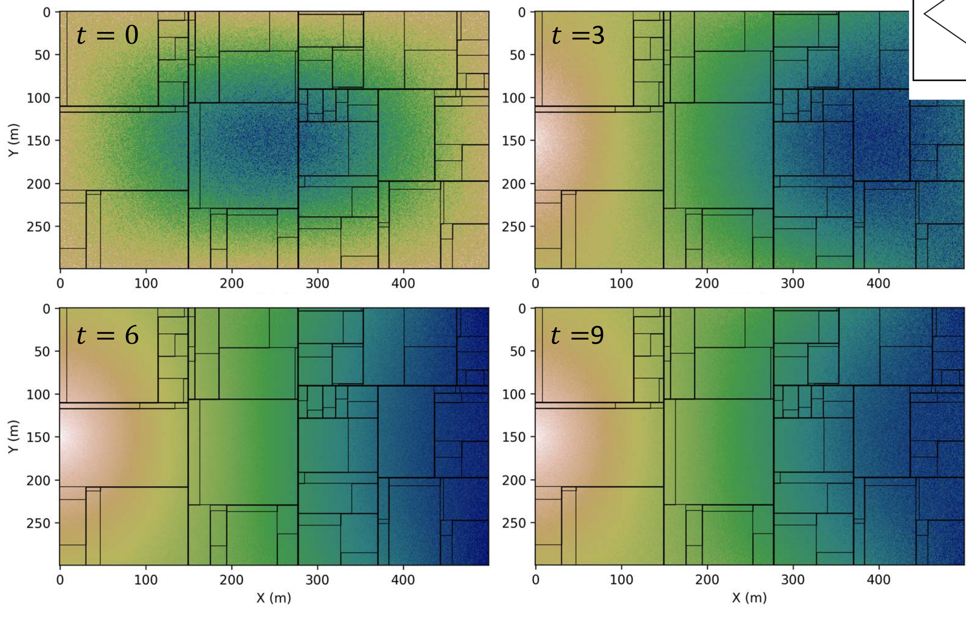
TIDAL RIVER MANAGEMENT MODEL



$$SSC_{i,j} = SSC_{breach} \cdot Distance^{-2.3} \quad (4)$$

Fig 17 | Conceptual model of tidal river management. Each pixel represents a patch of land. The numerical model of sediment aggradation is run for each patch. Here, we use all the same parameters for the sediment aggradation model for each patch with the exception of SSC. SSC scales as a function of distance to the sediment source (i.e. a breach in the embankment) (Eq. 4) (Allison et al., 1998).

Fig 18 | Hypothetical polder subdivided into landowner plots with active tidal river management. The polder at $t = 0$ is prior to TRM. The landscape relief is "saucer-like" with the highest elevations (~0.5 m) nearest the embankment and the lowest elevations (~0.0 m) in the middle. A breach is then placed in the middle of the leftmost embankment and elevation changes based on the sediment aggradation model for each pixel. The **blacklines** represent landowner plots.



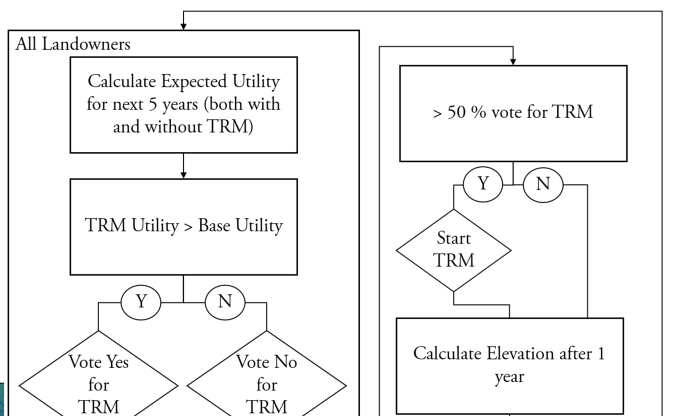


Fig 19 | Conceptualized agent-based model of tidal river management with voting. Each landowner in Fig. 18 aggregates all of their pixels and calculates expected utility with and without TRM. The agents then vote for or against TRM based on this expected utility. Future work will include different mechanisms of agent interaction (e.g. bargaining amongst landowners).