Spatial and seasonal variability of sediment accumulation potential through controlled flooding of polders in the Ganges-Brahmaputra-Meghna delta of southwest Bangladesh

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Abstract

The densely populated coastal areas of the Ganges-Brahmaputra-Meghna (GBM) delta within Bangladesh are in danger of losing up to one fourth of their habitable land by 2100 due to relative sea level rise (RSLR). Tidal River Management (TRM) presents an opportunity to combat RSLR by raising the land level through controlled sedimentation in re-opened polder sections. To date, TRM has been applied to tide-dominated coastal regions, but the potential applicability of TRM for river-dominated flow and mixed flow regimes is yet to be assessed. We apply a calibrated 2D numerical hydromorphodynamic model to quantify sediment deposition in a re-opened polder section ('beel') under conditions of river-dominated, tide-dominated and mixed flow regimes for different seasons and flow regulations. Simulation results show seasonality in sediment deposition with monsoon season having the highest. The potential for TRM is largest along the reaches of the tide-dominated region where sediment deposition is highest in all three seasons (Pre-monsoon, Monsoon and Dry season), and almost 28 times higher than river-dominated region during monsoon. Regulating flow into a polder increases trapping efficiency, but slightly lower total deposition than without regulation. Our results show that re-establishing polder flooding without regulating the flow into the polder is a promising strategy for the mixed and tide-dominated flow regions in the delta as the sediment deposition can elevate the land more than the yearly rate of RSLR. Application of controlled flooding like TRM therefore provides opportunity to match the rate of RSLR throughout the GBM delta. TRM can potentially be applied to the sinking deltas around the world to counter RSLR.

Introduction

The low elevation coastal zone of the Ganges-Brahmaputra-Meghna (GBM) delta of southwestern (SW) Bangladesh is flat with an estimated 21% of the area having an elevation less than 1 meters above mean sea level (AMSL) and 78% of the area below 5 meters AMSL (CCC, 2016). By rising earthen embankments to protect the tidal lowlands from flooding during high tide, about 139 polders were constructed in the late 1960s and 1970s (van Staveren, Warner, & Khan, 2017). The polders increased food productivity initially, but hampered the sediment flow in the floodplains and natural aggradation of the delta plain. This sediment flow in the GBM delta is large: in total about 1 billion tons of sediments per year is transported to the sea (Islam, Begum, Yamaguchi, & Ogawa, 1999). With decreasing supply of fresh water flow from upstream during dry season, the rivers of SW Bangladesh have lost capacity to carry the sediment load, while sediment deposition on the delta plain dramatically reduced. This resulted in massive within-channel sediment deposition, causing silting-up of the river channels, decreasing their water conveyance capacity during monsoon and leading to higher flood water levels. Also, drainage of the low-lying polders during the rainy season has become increasingly problematic. Sea level rise (SLR) is one of the consequences of climate change that will exacerbate the situation by increasing the risk of flooding and water logging. This will directly affect millions of people living in polders (van Staveren *et al.* , 2017).

The Ganges-Brahmaputra-Meghna (GBM) delta is now in danger of loosing up to one fourth of its habitable land by 2100 due to sea level rise (Ericson, Vörösmarty, Dingman, Ward, & Meybeck, 2006). The coastal zone of Bangladesh has over 47,150 km^2 area and population of 38.52 million in the year 2011 (CCC, 2016). From tide gauges and altimetry observations, Intergovernmental Panel on Climate Change (IPCC) indicated that the global mean sea level (GMSL) has risen by 3.6 mm/year over the period of 2005 to 2015 (Oppenheimer *et al.* , 2019). GMSL is predicted to rise between 0.24 m under RCP 2.6 (0.17–0.32 m, likely range) and 0.32 m under RCP 8.5 (0.23–0.40 m, likely range) by 2050 (Oppenheimer *et al.* , 2019) with medium confidence (Oppenheimer*et al.* , 2019). "likely" denotes the likelihood of an outcome or result is 66-100% (Oppenheimer *et al.* , 2019). Sea level rise is not globally uniform and varies regionally as well (Oppenheimer *et al.* , 2019) which adds to the uncertainty of the projection at regional scale. Goodwin, Haigh, Brown, Nicholls, and Matter (2018) analyzed the effect of Adjusting Mitigation Pathway (AMP) on global warming and SLR in the future. AMPs are considered scenarios to restrict future warming to policy-driven targets, in which future emissions reductions are not fully determined now but respond to future surface warming each decade in a self-adjusting manner (Goodwin *et al.* , 2018). Goodwin*et al.* (2018) projected the sea level rise to be 0.21 m by 2050 for AMP4.5 scenario. AMP4.5 scenario considers global carbon emission to have 4.5°C warming above preindustrial by 2300. Sediment starvation and subsidence will increase the vulnerability of low-lying deltas to SLR (Brown *et al.* , 2018). Brown and Nicholls (2015) summarized 205 subsidence data on GBM delta from previous studies. Reported subsidence rates range from -1.1 mm/year to 43.8 mm/year, with considerable spatial and temporal variation. Brown and Nicholls (2015) calculated the median of the rate of subsidence as 2.9 mm/year with standard variation of 3.4 mm/year. The study is indicative of ongoing subsidence in the GBM delta. However, detailed study needs to be carried out as rate of yearly subsidence presented till now has large uncertainty with wide range.

Due to progressive siltation, the river channel beds of SW Bangladesh have become eventually higher than the land inside the polder resulting in prolonged water logging and drainage congestion (Awal, 2014). In 1997, this led to re-opening of the dike of one of the polders in SW Bangladesh to re-allow tidal water inside a beel (Adnan, 2006). Beels are the lowest parts of the delta plain polders, where surface runoff accumulates through the internal drainage channels (Chakraborty, 2009). Re-allowing tidal dynamics inside the beel resulted in removal of sediment from the adjacent river, and the land surface inside the beel raised substantially with the sediment deposited through the re-opening of the dike (Adnan, 2006; van Staveren *et al.,* 2017). As this intervention was primarily applied to retain the drainage capacity and navigability of tidal river, it was termed as tidal river management (TRM). Since then, TRM has been applied to 12 beels in SW Bangladesh (Gain, Benson, Rahman, Datta, & Rouillard, 2017) where tide plays a dominant role. Current practice of continuously allowing water inside a polder for several years restricts the use of the land for economic activities during TRM operation. Such prolonged flooding without proper compensation (Gain *et al.* , 2017), and observed uneven sediment deposition within the beels has questioned the acceptability of TRM by stakeholders.

The potential of seasonal flooding the land with controlled sedimentation through re-opening a polder such as TRM to raise the land will make the land available for part of the year for agriculture and for alternative livelihood such as fish farming, floating agriculture when flooded. Seasonal operation of TRM will not only raise the land but also bring nutrient rich sediments, act as natural pest control (van Staveren, van Tatenhove, & Warner*,* 2018) and avail the land for economic activities during the remaining seasons. The acceptability of TRM by stakeholders may thus be raised by providing opportunities for economic activities for earning livelihood round the year even when TRM is operated. Brown *et al.* (2018) stated that the mitigation measures to climate change and controlled sedimentation to maintain relative delta height is vital for survival over multi-centennial timescales. For sinking deltas around the world with sufficient sediment delivered by the rivers, this provides an opportunity to elevate land above predicted sea level rise by applying controlled flooding like TRM.The effect of re-opening of polders such as TRM has been studied by both historical data analysis (de Die, 2013; Gain *et al.* , 2017; van Staveren *et al.,* 2017) and mathematical model simulations (Amir, Khan, Khan, Rasul, & Akram, 2013; Shampa & Pramanik, 2012; Talchabhadel, Nakagawa, & Kawaike, 2018). Previous studies explored the effects of increasing number of inlets on sediment deposition inside the beel, compartmentalization, use of canals inside the polders within the Tekka-Hari-Kobadak-Shibsa River reach (SW Bangladesh), which is tide-dominated. Although the primary objective of TRM was to increase the tidal prism, it resulted at the same time in land elevation increase for all studied cases.

Previous TRM applications of controlled flooding by re-allowing sediment-rich water from a tide- dominated river into a polder indicated that the resulting sediment deposition can raise the polder land surface substantially but unevenly (Gain *et al.* , 2017). Yet, controlled temporary flooding has not been investigated for polders along river sections with a river-dominated and mixed flow regime. To evaluate the potential of TRM-like strategies of controlled flooding of polders to raise the land throughout the delta, their efficiency needs to be explored first for a wider range of flow regimes across the GBM delta. The effect of seasonality of river flow, tidal ranges and associated suspended sediment concentrations (SSC) in the feeding river branches should be investigated as well for these different flow regime, since SSC and tidal range are major controls of sediment deposition (Islam, Middelkoop, Schot, Dekker, & Griffioen, 2019), and show a strong seasonal variability (IWM, 2010; 2017).

We investigate the applicability of TRM-like controlled flooding of polders along a gradient from river-dominated to tide-dominated flow regime across the GBM delta by investigating the resulting sediment deposition for different flow regimes of the feeding rivers, for different seasons, and regulation of polder inundation. For this purpose, we developed scenarios that comprise these different boundary conditions. Using a calibrated model 2D hydrodynamic flow model for Beel Pakhimara, which is an ongoing TRM located in SW-Bangladesh (Islam*et al.* 2019), we simulated sediment deposition for these scenarios to determine how these boundary conditions affect total deposition and trapping efficiency.

This is an exploratory study at the delta scale to investigate the applicability of controlled flooding like TRM across different regions characterized by river-dominated and mixed flow regimes in the southwest of Bangladesh. The input variables utilized for selected locations for each flow regime are considered to be representative of the respective regions.

Methods

Study area

The study covers the 41,900 km^2 southwest part of GBM delta of Bangladesh, bounded by Ganges River and Padma River in the north, Meghna River in the east, Bay of Bengal in the south and the international border between Bangladesh and India in the west (Figure 1). The population of the study area is about 38.52 million according to the recent census conducted by Bangladesh Bureau of Statistics (BBS) (BBS, 2012). Polders are located in the southern part of the study area. The Gorai River in the western part and the Arial Khan River in the eastern part are the primary sources of fresh water flow. The river flow in southwest Bangladesh is affected by tides entering from the south.. The areas experiencing reversal of water flow direction (horizontal tide) due to tide during dry season were designated as tide affected areas by FAO (1985) and Wilson *et al.* (2017).

During monsoon the rivers receive large volumes of flood water from the Ganges and the Padma Rivers, which causes wide-spread flooding in the delta. The tidal flats located in the southern part of the study area experience flooding as well, but primarily due to high tide. The extent of river floodplain and tidal floodplain for the coastal areas of Bangladesh were depicted by Brammer (1990). Brammer (1990) defined as tidal floodplain those areas that consist of numerous tidal rivers and creeks, being subject to flooding during high tide even in dry season, and as river floodplain those areas that become flooded seasonally due to high water level in the rivers specially during monsoon. The tide-affected area defined by FAO (1985) and Wilson *et al.* (2017) overlaps the southern part of the river floodplain delineated by Brammer (1990) (Figure 1).

We divided the study area in three regions with their own flow regimes: river-dominated flow, tide-dominated flow and mixed flow. The tidal floodplain is identified as the region of tide-dominated flow regime, the area with river floodplain but affected by tide is defined as region of mixed flow regime and remaining as region of river-dominated flow regime (Figure 1). Within each region we selected a representative location for our analyses: 1- river-dominated flow regime, 2 - mixed flow regime, and 3 - tide-dominated flow regime (Figure 1). Average elevation of the region of river-dominated flow, mixed flow and tide-dominated flow regimes, calculated using the elevation data collected from Shuttle Radar Topography Mission (SRTM) are about 10 m, 2.2 m and 1.7 m AMSL, respectively. Most of the polders lie within the region of tide-dominated flow regime, few in the region of mixed flow regime and none within the region of river-dominated flow regime (Figure 1).

The average monthly rainfall for the years 1901 to 2015 (Arefin & Mallik, 2017; Figure 3) and the average monthly discharge of Gorai River branch (IWM, 2017; Figure 3) indicate that rainfall is highest in June and discharge is highest in August. Seasons for the study area were defined by combining these rainfall and discharge data with the suggestions made by Lázár *et al.* (2015) into dry season (November to February), pre-monsoon (March to May) and monsoon (June to October).

The Gorai-Nabaganga-Pasur River reach of SW Bangladesh was selected for this study (Figure 1). The Gorai River is a distributary of the Ganges River, has its bifurcation from Ganges River at about 50 km downstream of the Bangladesh-India border, and reaches the sea about 300 km further downstream as Pasur River and other branches (Figure 1). The Gorai has very little fresh water flow in the dry season, but discharges large amounts of water during the monsoon (Moly, Rahman, & Saadat, 2015) (Figure 3). The water level over the entire Gorai River is influenced bsy the tides (Figure 2) during the dry and pre-monsoon seasons. During monsoon the high river discharge nullifies the effect of tides (Figure 2). The upper Gorai River represents the region of river-dominated flow regime during monsoon. Therefore, we used the hydro-morphodynamic conditions at Location 1 ("Gorai Railway Bridge" measurement station of Bangladesh Water Development Board (BWDB) on the Gorai River reach) (Figure 1) as input for the modeling under the river-dominated flow regime.

The Pasur River is the most downstream section of the Gorai-Nabaganga-Pasur River system and meets the sea in south. The Pasur lies in the region of tide-dominated flow regime (Figure 1). The hydro-morphodynamic conditions at Location 3 ("Mongla" measurement station of BWDB on the Pasur River reach) were used as input for the modeling under the tide-dominated flow regime (Figure 1). The flow of the Pasur River is dominated by tides around the year (Figure 2); still, the mean water level of the Pasur rises during the monsoon, then still experiencing an average tidal range of about 2 m (Figure 2 and Figure 4). Salinity varies seasonally between about 20 ds/m (deci-siemens per meter) during the pre-monsoon season and about 5 ds/m in monsoon (Ghosh, Kumar, & Roy, 2016).

The Nabaganga River is the section of the Gorai-Nabaganga-Pasur River reach which is about 150 km north from the sea shore, and lies within the region of mixed flow regime (Figure 1). The hydro-morphodynamic conditions at Location 2 ("Gazirhat" measurement station of BWDB on Nabaganga River) were used as input for the modeling under the mixed flow regime (Figure 1). The mixed flow region is affected by tide during all seasons, although during monsoon tidal ranges are damped due to the flood water coming from upstream (Figure 2). Average tidal range at location 2 varies from 0.3 m during monsoon to 1.45 m in the pre-monsoon period (Figure 4).

Data collection and analysis

For all three regions of different flow regimes, time series of river discharge, water level, and suspended sediment concentration (SSC) at representative locations were collected (Figure 1). Available data were collected from governmental agencies such as Bangladesh Water Development Board (BWDB), Water Resources Planning Organization (WARPO) and non-governmental research institutes such as Institute of Water Modelling (IWM), Center for Environmental and Geographic Information Services (CEGIS), as well as reports and papers. Hourly water level data were available for all representative locations., but continuous measurements of discharge and SSC were available only for short periods of time, or at irregular time intervals. The average monthly discharge of the Gorai River at the bifurcation from the Ganges River and average monthly rainfall are presented in Figure 3. The annual hydrographs for the different flow regimes at the selected locations are shown in Figure 2. From these data, mean tidal range and average SSC during three seasons for three flow regimes were calculated.

Setup of hydro-morphodynamic model

To understand the effects of different flow regimes, seasonality and regulation of flow into a re-opened polder section on sedimentation inside a beel with TRM, we used a two-dimensional numerical hydro-morphodynamic model that was developed and calibrated for Beel Pakhimara, which is an active TRM in southwest Bangladesh (Islam *et al.* 2019). Model simulations were carried out using Mike 21FM (developed by DHI) in which hydrodynamic processes and sediment transport are simulated simultaneously (DHI, 2012a). As the grain size of the sediment is fine (less than 63 µm) for the study area (Datta & Subramanian, 1997; IWM, 2010), the MT (mud transport) module of Mike 21FM was used for calculating cohesive sediment transport.

The hydrodynamic (HD) processes of Mike 21FM are calculated based on the solution of three-dimensional incompressible Reynolds averaged Navier-Stokes equations (DHI, 2012a). The model uses an approximate Riemann solver to calculate the convective fluxes at the interface of the cell of the 2D mesh (DHI, 2012a). The MT module uses the advection-dispersion equation (ADE). The ADE is solved using the third-order finite difference scheme, known as the ULTIMATE scheme, which is based on the QUICKEST scheme (DHI, 2012b). For morphological simulation, the bathymetry is updated for each time step according to net sedimentation (DHI, 2012b).

To represent the bathymetry of Beel Pakhimara, a mesh with flexible cell size was used where the 2D cells had shapes from triangle to octagon. Finer mesh was opted to represent the inlet canal (cell area of about 170 m2) and coarser mesh (cell area up to 5000 m2) was used for the flood plain to reduce the calculation intensity (Islam *et al.*, 2019). For our analysis we supplied the model for Beel Pakhimara with water levels and SSC, that were adapted in accordance to the scenarios of different flow regime and seasonality (**Figure 2, 4 and 5**). These input variables were provided for Locations 1, 2 and 3 with respect to their flow regime (**Figure 1**).

The model was calibrated for Beel Pakhimara by comparing the observed water level, discharge and SSC with simulated ones (Islam *et al.*, 2019). Manning's coefficient, shear stress and settling velocity were the primary parameters for calibrating hydrodynamic and morphodynamic model. Sensitivity analysis of the model was carried out with varying Manning's coefficient from 0.1 s/m1/3 to 0.01 s/m1/3, shear stress from 0.01 N/m2 to 0.1 N/m2 and settling velocity from 0.0001 m/s to 0.001 m/s. To understand the uncertainty of the model, coefficient of determination (R2) and the normalized root mean square error (NRMSE) were calculated by comparing the modelled results with the observed data for the different input variables. For spatial average value of Manning's coefficient of 0.032 s/m1/3, shear stress of 0.08 N/m2 and settling velocity of 0.0005 m/s, the R2 for water level, discharge and sediment concentration were 0.87, 0.88 and 0.84, respectively. The NRMSE (%) for water level, discharge and sediment concentration were 9.7, 16.6 and 18.3, respectively (Islam *et al.*, 2019). The calculated goodness of fit for the developed model indicates that the calibrated model resulted in good agreement between the observed and simulated data.

Scenario development

The calibrated model for Beel Pakhimara was used to simulate the developed scenarios for different regions. Time variant water level and SSC representing different flow regimes were used as input variables to investigate the sediment dynamics of different regions. To compensate for the difference in land level between the river-dominated and the tide-dominated region, the water levels used for location 1 representing river-dominated region were vertically shifted accordingly. The mean difference between the water level at location 1 and location 3 (**Figure 1**) during dry season was calculated as 1.03 m. The water level of location 1 was lowered by 1.03 m to compensate for the land level difference between river-dominated and tide-dominated region. Sediment rating curves presented in IWM (2017) were used to generate input variables for the model when measured SSC data were unavailable. As data was not available continuously in all three locations, model simulations were carried out for 14 days consecutive to capture the effect of spring and neap tide for each season and to have consistent scenarios for all three locations. It was assumed that the simulated periods are representative of the seasons.

The scenarios were defined by varying flow regimes, seasonality and flow regulation schemes into the beel within the polder. In addition to unregulated flow into the beel, gate operation rules for the regulated flow scenarios were adopted from Islam *et al.* (2019): one or both gates remained open for 12 hours to allow the flow of sediment-rich water to enter the beel and were closed for the following 12 hours. By doing so, no flow inside the beel occurs for 12 hours allowing the sediment to settle from the stagnant water. Two different rules of gate operation were considered: simultaneous and successive (Islam *et al.*, 2019). For simultaneous gate operation, both gates are opened and closed at the same time for both inlets (Islam *et al.*, 2019). For the successive gate operation of two inlets, their gates are alternatingly open and closed (Islam *et al.*, 2019). In that case the flow enters through one inlet, and leaves the beel through the other. This gate operation aims to ensure throughflow across the beel instead filling and draining through the same gate. The gates in Bangladesh are manually operated, and operation is time consuming. Therefore, it was assumed that the opening and closing of the gate will require 1 hour. The developed scenarios by combining flow regimes, seasonality and flow regulations are presented in **Table 1.**

Table 1: Scenario matrix considering the flow regulation, seasonality and flow regime

Flow Regime		**Flow Regulations**	**Flow Regulations**	**Flow Regulations**
		Open	**Simultaneous gates**	**Successive gates**
River dominated	**Seasons**	Pre-monsoon	Pre-monsoon	Pre-monsoon
		Monsoon	Monsoon	Monsoon
		Dry	Dry	Dry
Mixed Flow	**Seasons**	Pre-monsoon	Pre-monsoon	Pre-monsoon
		Monsoon	Monsoon	Monsoon
		Dry	Dry	Dry
Tide dominated	**Seasons**	Pre-monsoon	Pre-monsoon	Pre-monsoon
		Monsoon	Monsoon	Monsoon
		Dry	Dry	Dry

Analysis of the simulated scenarios

The total mass of sediment deposition over the season for all the developed scenarios was calculated from the simulations of the various hydro-morphodynamic models. Sediment deposition for different seasons was estimated using the total mass of sediment deposition over the representative 14 days of simulation and scaled for the total number of days in a season.

The trapping efficiency was calculated for all the scenarios to understand the effect of seasonality of SSC and different flow regime on the quantity of sediment delivered inside the beel and sediment retained. It was defined as the fraction of the incoming suspended sediment that is retained or deposited over the entire simulation period (Verschelling, van der Deijl, van der Perk, Sloff, & Middelkoop, 2017). Total incoming sediment load and sediment load retained were calculated using the water discharge and SSC at the inlets extracted from the model simulation. The difference between the incoming and outgoing sediment load at the inlets over the entire simulation period was considered as sediment load retained.

Results

Figure 4 shows the mean water level and tidal range along the gradient from river-dominated to tide-dominated flow regime across the GBM delta for the three main hydrological seasons. Mean water level gradually decreases from the reaches with river-dominated flow to tide-dominated flow (Figure 4). The mean water level is lowest during dry season and highest during monsoon for reaches of all three flow regimes (Figure 4). The water level gradient from river-dominated flow regime to tide-dominated flow regime is steepest during monsoon and mildest during pre-monsoon season (Figure 4). The reaches with river-dominated flow regime have the largest seasonal variation of mean water level being about 5 m between dry season and monsoon. In contrast, seasonal variation in mean water level is smallest in the reaches under tide-dominated flow, being about 1 m between dry season and monsoon. Mean tidal range also varies seasonally, being largest during pre-monsoon and smallest during monsoon seasons for all reaches across the GBM delta (Figure 4). Tidal range varies seasonally for all flow regimes with lowest during monsoon and highest during pre-monsoon season. The highest variation of about 90 cm occurs in reaches under the mixed flow regime, and lowest is about 20 cm in the reaches under the tide-dominated flow regime

Considering the seasonality, the average SSC is highest during monsoon in the reaches of river-dominated and mixed flow regime, whereas the average SSC is highest during pre-monsoon in the tide -dominated regime sections (Figure 5). Along the gradient from river-dominated to tide-dominated regime, tidal range and average SSC change gradually along the transect (Figure 4 and Figure 5). The reaches of mixed flow experience the highest average SSC during the monsoon season (Figure 5).

The results of the different model scenarios are compared for the total sediment accumulation over the seasons and for the trapping efficiency. The results demonstrate that estimated total sediment deposition over the season inside the beel of the re-opened polder varies per season for all flow regimes (Figure 6). At all locations, total sediment accumulation over the seasons is highest during the monsoon season (Figure 6). For the tide-dominated regime, seasonal variation in sediment accumulation is smaller than for the river-dominated and mixed flow regimes. The sediment deposition during monsoon is almost 50% higher than during the dry season for the tide-dominated flow regime, whereas it is ten times higher for the river-dominated regime, and almost 40 times higher for the mixed flow regime (Figure 6).

Along the gradient from river-dominated to tide-dominated flow regime, the calculated total sediment deposition for all three seasons increases substantially. During monsoon, total sediment deposition with unregulated flow is about 4,600 tons at the location of river-dominated flow, about 100,200 tons at the location of mixed flow and about 129,800 tons at the location of tide-dominated flow regime. The total sediment deposition at the location of tide-dominated regime is highest among the flow regimes for all seasons, and almost 28 times higher than at the location of the river-dominated flow regime during monsoon season (Figure 6).

Regulation of flow into the re-opened polder affects sediment deposition within the polder. Model simulations show for the location of river-dominated flow regime that using successive gate operation results in about 18% more sediment deposition during the monsoon period. Conversely, for the location of the tide-dominated and mixed flow regimes unregulated flow into the re-opened polder results in higher sediment deposition (Figure 6). During monsoon, unregulated flow into the re-opened polder results in about 19% more deposition than regulated flow with successive gates at the location of the mixed flow regime, and about 45% more for tide-dominated flow regime.

Trapping efficiencies calculated from the modelling display seasonal variability (Figure 7). Generally, trapping efficiencies at the locations of mixed flow and tidal flow regime are highest during the pre-monsoon and lowest during the dry season. At the locations of mixed flow and tide-dominated flow regime, trapping efficiency is high during monsoon season as well. However, at the location of river-dominated flow trapping efficiency is generally highest during monsoon and lowest during the pre-monsoon season. Trapping efficiency generally increases gradually along the gradient from river-dominated to tide-dominated flow regime during pre-monsoon when the mean tidal range is highest for all flow regimes and increases in a downstream direction (Figure 4). Maximum trapping efficiencies for unregulated flow are low: about 6% at the location of river-dominated, 10% at the location of mixed flow and 13% at the location of tide-dominated flow regime. Regulation of flow increases the trapping efficiency for all the regions and seasons (Figure 7). For the river-dominated flow regime regulation of flow into the re-opened polder during monsoon increases trapping efficiency by about 5 times when compared to unregulated flow. For tide-dominated and mixed flow regimes this increase is about 4 times. This demonstrates that the temporary trapping of the flood water within a beel by gate regulation indeed leads to a larger proportion of the sediment to settle.

Discussion

The model simulations demonstrate how sediment deposition in re-opened polders along the gradient from river-dominated to tidal flow regimes in the GBM delta is controlled by these regimes, SSC and gate regulation. This supports to identify the regions where such water management practice is effective with regards to increasing land elevation by sediment deposition to combat RSLR.

Water level, tidal range and SSC vary seasonally and along the gradient from river-dominated to tide-dominated flow region (Figure 4 and Figure 5). During monsoon heavy rainfall causes excess overland flow, flood and land erosion in upstream areas. This results in high discharge, increased river water level (Figure 2) and higher SSC in the rivers (Figure 5), all contributing to a larger sediment load in the rivers available for sediment deposition by flooding of the polders.

During the dry season, all river reaches within the GBM delta are influenced by the tide, specially the rivers lacking river flow from upstream, such as the Gorai (Figure 4). Consequently, sediment deposition by re-opening the polders during the dry season depends on the sediment delivered from the sea by the tides. The primary rivers of Bangladesh, Ganges, Brahmaputra and Meghna, reach the sea via the Meghna Estuary. Haque, Sumaiya, & Rahman (2016) indicated that part of sediment discharged through the Meghna estuary into the eastern Gulf of Bengal re-enters the estuaries in the west, such as through the estuary of the Pasur River. The amount of sediment that that re-enters the estuaries in the west is much higher than the sediment load directly transferred via the Gorai river from the Ganges towards the western estuaries (Milliman & Haq, 1996; Rogers, Goodbred Jr, & Mondal, 2013). Consequently, the SSC in the feeding rivers is in all seasons much lower in the river-dominated flow region than in the tide-dominated and mixed flow regions (Figure 5). With higher SSC and daily inflow- and outflow of water due to the tides a much larger sediment load is transferred into the beels at the locations of mixed flow and tide-dominated flow regime than for the river-dominated flow regime (Figure 4). Accordingly, sediment deposition inside the beel is larger for the mixed flow and tide-dominated flow regions (Figure 4-6). Still, during monsoon, with higher water discharge from upstream, less sediment is pushed inland from the sea (Figure 2 and Figure 5), resulting into slightly lower SSC than during pre-monsoon and dry seasons in the tide-dominated flow region (Figure 5, location 3). Moreover, the cumulative effect of high sediment loads in the upstream rivers and tide driven sediments brought towards inland results in highest SSC during monsoon in the mixed flow region, even higher than for the tide-dominated flow region (Figure 5).

Total deposition depends on a combination of factors. The total sediment deposition inside the beel during a season depends on the length of that season. The longest season - monsoon – is characterized by the highest river water discharge (Sarker, 2006; Shaha & Cho, 2016) and relatively higher SSC (Figure 5) which result in highest sediment deposition for all flow regions (Figure 6). Due to highest mean tidal range (Figure 4) in the reaches of the tide-dominated flow region during monsoon, sediment deposition is the largest, (Figure 6) even though average SSC is slightly lower (Figure 5) in the feeding river when compared to the mixed flow region. At the location of river-dominated flow sediment enters the beel and leaves slowly with receding peak discharge in the river during monsoon. Here, the beel is not daily re-supplied with fresh sediments, since there is very small tidal variation during monsoon (which is unable to drive a daily, tidal sequence of water inflow and outflow within the polder (Figure 4). This combined with lower SSC results in lowest sediment deposition for the location of river-dominated flow regime compared to other flow regimes during monsoon season (Figure 6). It can be inferred that tide-driven daily supply of fresh sediment towards the beel within the polder is essential for higher sediment deposition. The combined effect of lowest average SSC (Figure 5) and water discharge (Shaha & Cho, 2016) during dry season in the feeder rivers translates to lowest sediment deposition for all three locations representing different flow regimes.

The trapping efficiency is highest during pre-monsoon for the locations of tide-dominated flow and mixed flow regime (Figure 7) as the larger tidal range results in a larger daily delivery of sediment inside the beel (Figure 4). Because of the absence of tidal dynamics and gradual recession of flood water in the river (Figure 2) during monsoon, the volume of water retained inside the beel is mostly undisturbed at the location of the river-dominated regime increasing the residence time and rate of sediment deposition (Figure 6). This results in highest trapping efficiency for the location of river-dominated flow regime (Figure 7), although total deposition is lower due to lower SSC of the incoming water.

Flow regulation results in a higher trapping efficiency, because the residence time of water and sediment inside the beel increases. However, in spite of the higher trapping efficiency, total sediment deposition is less. This is because with unregulated inlets, suspended sediment is daily resupplied inside the beel with tides. Sediment can enter the beel only half of the time with flow regulations because the inlets are closed and opened in 12 hours cyclic order (see section 2.4). The double time of beel opening without regulation is results in higher sediment deposition. Remarkably, the same regulation scheme has the opposite effect for the river-dominated flow regime. The tidal range for the river-dominated flow regime is very small during monsoon; hence there is no tidal dynamics and cyclicity of sediment delivered into the beel. Instead, sediment enters the beel with high water level in the river and leaves it slowly with the recession of flood water. The sediments carried by the rivers of SW Bangladesh is very fine (less than 63 µm) having low settling velocity (about 0.05 cm/s) (Barua, Kuehl, Miller, & Moore, 1994). Due to sthis low settling velocity, a large portion of sediments entering the beel stays in suspension and recedes with tide as even the highest trapping efficiency achieved with flow regulation is about 30%.

More sediment can be delivered with simultaneous gate operation than with the successive gate, because two inlets open at the same time instead of one. This obviously results in larger sediment deposition for tide-dominated flow regime and mixed flow regime. However, the effect is opposite during monsoon at the location of river-dominated flow regime. With both gates open at the same time for simultaneous gate operation, the average velocity of receding flow inside the beel is higher than the successive gate with which one gate is open at an instance. Due to higher receding velocity, more sediment returns to the feeding river which before it can settle in the polder, as the tidal range is lowest during monsoon at the location of river-dominated regime, resulting in lower sediment deposition.

In the "Special Report on the Ocean and Cryosphere in a Changing Climate", IPCC indicates that the global mean sea level (GMSL) has risen by 3.6 mm/year over the period of 2005 to 2015 (Oppenheimer *et al.* , 2019). GMSL is predicted to rise between 0.24 m under RCP 2.6 (0.17–0.32 m, likely range) and 0.32 m under RCP 8.5 (0.23–0.40 m, likely range) by 2050 (Oppenheimer *et al.* , 2019) with medium confidence (Oppenheimer *et al.* , 2019). Goodwin *et al.*(2018) projected the sea level rise to be 0.21 m by 2050 for AMP4.5 scenario. The study on subsidence of GBM delta by Brown and Nicholls (2015) compiled of 205 literatures indicates that the rate of subsidence ranges from -1.1 mm/year to 43.8 mm/year which varies spatially and temporally with the median as 2.9 mm/year and standard variation of 3.4 mm/year. When a linear trend for the rate of SLR per year and the median of the subsidence rate per year are considered, the rate of relative SLR (RSLR) ranges from 7.6 mm/year for AMP4.5 and 10 mm/year for RCP8.5. We consider the density of the sediments in the floodplain as 1300 kg/m^3 suggested by Allison and Kepple (2001) and Rogers and Overeem (2017) for GBM delta to calculate the change in land elevation through sediment deposition. The sediment deposition during the monsoon season by unregulated flow into the beel within the polder for river-dominated flow, mixed flow and tide-dominated flow regions are estimated as about 0.5 mm, 11 mm and 14.3 mm, respectively.

Rogers and Overeem (2017) indicate that in the GBM delta the agredation rate by sedimentation can be more than the estimated average rate of local sea level rise. This is in agreement with our findings. Amir *et al.* (2013); de Die, (2013); Gain *et al.* , (2017); Shampa and Pramanik (2012); Talchabhadel *et al.* (2018); van

Staveren*et al.,* (2017) investigated the polders along the river reaches with tide-dominated flow and inferred that allowing sediments inside the polder with TRM raises the land level with sedimentation. However, they did not compare the rate of land level rise to the RSLR. Our estimation shows that controlled flooding for sediment accumulation has high potential for tide dominated and mixed flow region. As all the polders are within tide-dominated flow region and mixed flow region (Figure 1), controlled flooding by re-opening the polder during monsoon can potentially assist the polders to mainntain the height to overcome projected RSLR for the worst case scenario. However, the rate of SLR as well as the rate of subsidence considered have large uncertainly and wide range. As the average land elevation for river-dominated flow regime is about 10 m AMSL, it can safely be asumed that it will not be flooded due to relative SLR even in monsoon with the average of highest water level along the river reaches of about 7 m. However, with SLR the region of tide-dominated and mixed flow regimes will presumably shift upstream making TRM effective for larger areas in the future.

Conclusion

We explored the potential of re-opening of polders to re-establish sediment deposition and land raise in the SW Ganges-Brahmaputra-Megna (GBM) delta. For this purpose we carried out scenario analyses representing the seasonal variability river discharge, suspended sediment concentration (SSC) and tidal range in river branches across the delta, and applying different flow regulation operations for the polder. Our scenario analyses demonstrate that:

- Flow regimes are primary controls of sediment deposition inside a polder of TRM operation. Along the gradient from river-dominated (north) to tide-dominated (south) flow regime, the total sediment deposition increases considerably. Sediment accumulation within polders along the reaches with a tide-dominated flow regime can be 28 times higher than in polders along the reaches of river-dominated flow regime. Therefore, the potential for TRM is much higher along the reaches of tide-dominated flow regions. With SLR the region with tide-dominated flow regime will presumably shift inland making TRM effective for larger areas in the future.
- Seasonality of sediment deposition is evident in all flow regions. Highest sediment deposition by re-opening the polder occurs during monsoon season for all reaches of the GBM delta. Highest river discharge and relatively higher SSC during monsoon season provides highest sediment load in the rivers for raising the polder land surface. In the tide-dominated region the seasonal variation of sediment deposition is remarkably small, due to the strong tidal effect in all seasons.
- Tidal range, SSC and discharge in the river govern the sediment dynamics and sediment deposition inside the polder. Increase in river discharge, SSC and tidal range result in larger sediment deposition inside the polder. Sediment deposition is highest during monsoon owing to with highest river discharge and relatively higher SSC in the feeder rivers, and lowest during dry season when river discharge and SSC in the feeder river is lowest. The highest tidal range along with only slightly lower SSC during monsoon translates to highest sediment deposition in the polders in the reaches with tide-dominated regime.
- Regulation of flow into the re-opened polder considerably affects total sediment deposition in the polder. Unregulated flow results in highest sediment deposition during monsoon for the regions with tide-dominated flow and mixed flow regimes which experience tidal effect even in monsoon. Thus, it is potentially an effective means to increase sediment deposition.
- All polders of GBM delta are situated within the mixed flow region and tide-dominated flow region. The total sediment deposition results in an increment of land elevation for mixed flow region and tide-dominated flow region that is more than the highest rate of projected relative sea level rise. Although the uncertainty of projected SLR for 2050 is relatively low (Oppenheimer *et al.* , 2019), subsidence included in RSLR have large uncertainty and wide range (Brown & Nicholls, 2015) with large spatial and temporal variation. It can be safely assumed that RSLR will not induce flooding for river-dominated flow region because the average land elevation is about 10 m AMSL with average of

highest water level along the river reaches of about 7 m AMSL.

The effect of projected SLR and subsidence can thus be countered with the application of indigenous practice like TRM to re-open the dike to allow sediments inside polders through controlled flooding, even for the low elevation coastal zone of Bangladesh. This study illustrates that with enough sediment availability, sinking deltas around the world can combat the projected RSLR by applying controlled flooding with re-opening the dike like TRM.

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Tables

Table 1: Scenario matrix considering the flow regulation, seasonality and flow regime

Figure Legends

Figure 1: Regions of different flow regimes of southwest Bangladesh

Figure 2: Hydrograph for (a) river-dominated flow regime, (b) mixed flow regime, (c) tide-dominated flow regime

Figure 3: Average monthly discharge of Gorai River at the bifurcation from Ganges River and average monthly rainfall of Bangladesh

Figure 4: Mean tidal ranges and water levels for different flow regimes during (a) Dry season, (b) Pre-monsoon and (c) Monsoon. The blue triangles represent river dominated flow, the green rectangles represent mixed flow and the orange circles represent tide dominated flow; the grey area represents the variation of tidal ranges

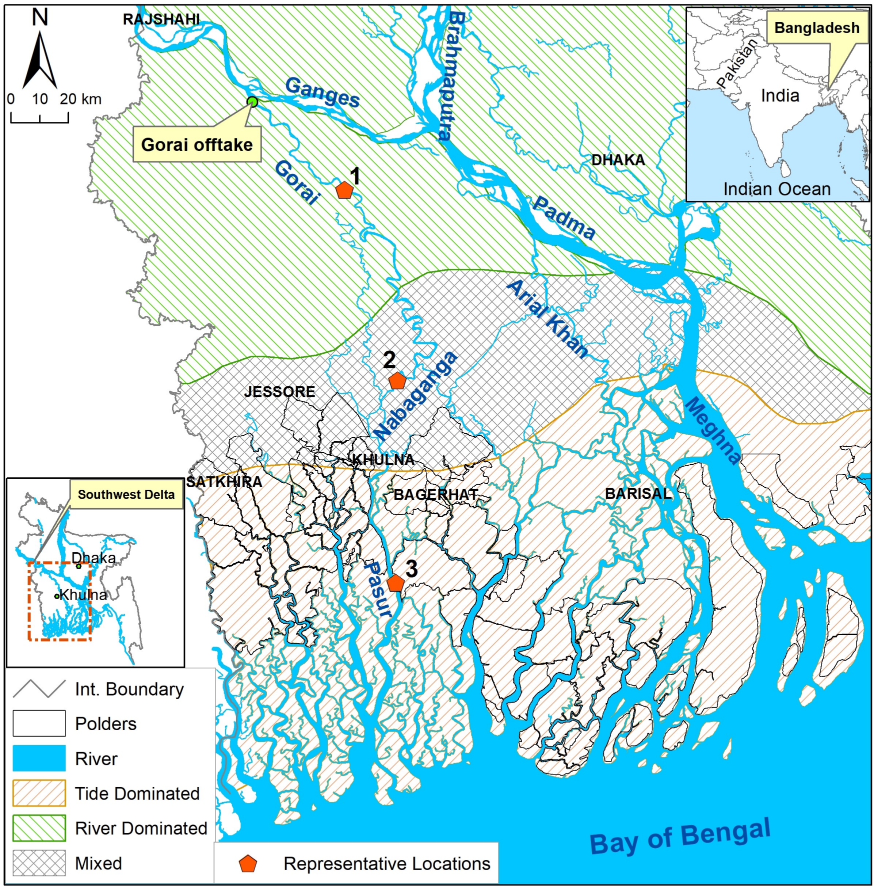
Figure 5: Seasonal variation of SSC for different flow regimes

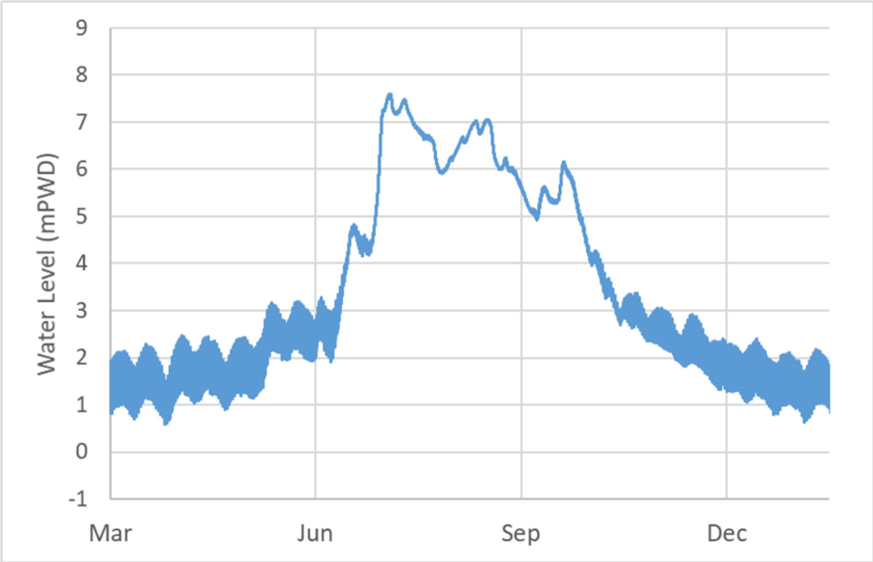
Figure 6: Seasonal sediment deposition for (a) river-dominated flow regime, (b) mixed flow regime and (c) tide-dominated flow regime under different flow regulations. (d) the legends of the figures (a), (b) and (c)

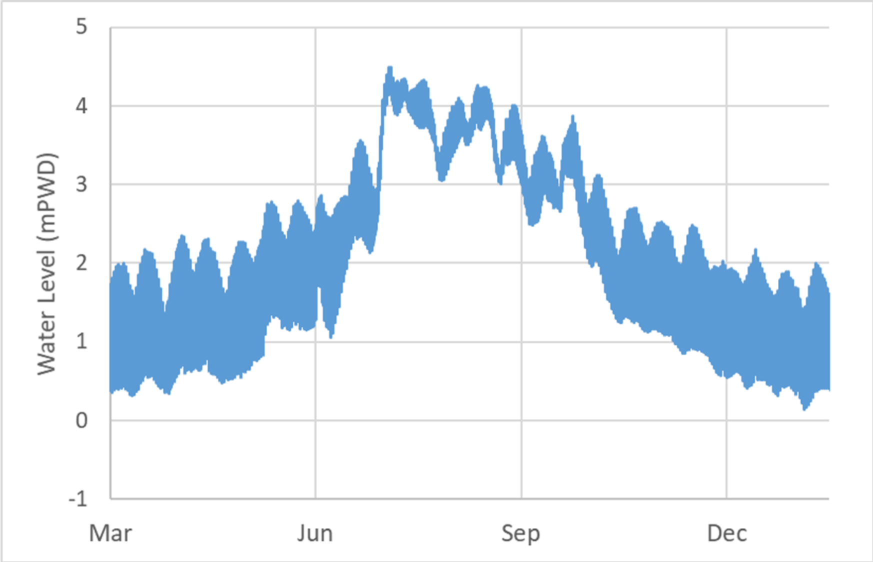
Figure 7: Estimated trapping efficiency for all the scenarios. The colour gradient from lighter to darker represents the gradient of flow from river-dominated to tide-dominated.

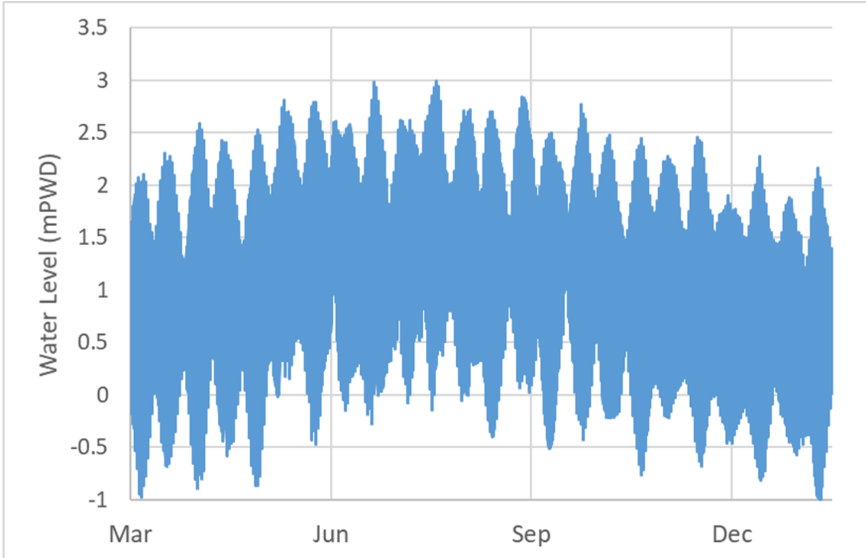
Data Sharing Statement

Data used in this research is provided by IWM. The authors do not have the right to share data.




Water Level (mPWD)
9
8
7
6
5
4
3
2
1
0
-1
Mar
Jun
Sep
Dec


Water Level (mPWD)
5
4
3
2
1
0
-1
Mar
Jun
Sep
Dec



Water Level (mPWD)
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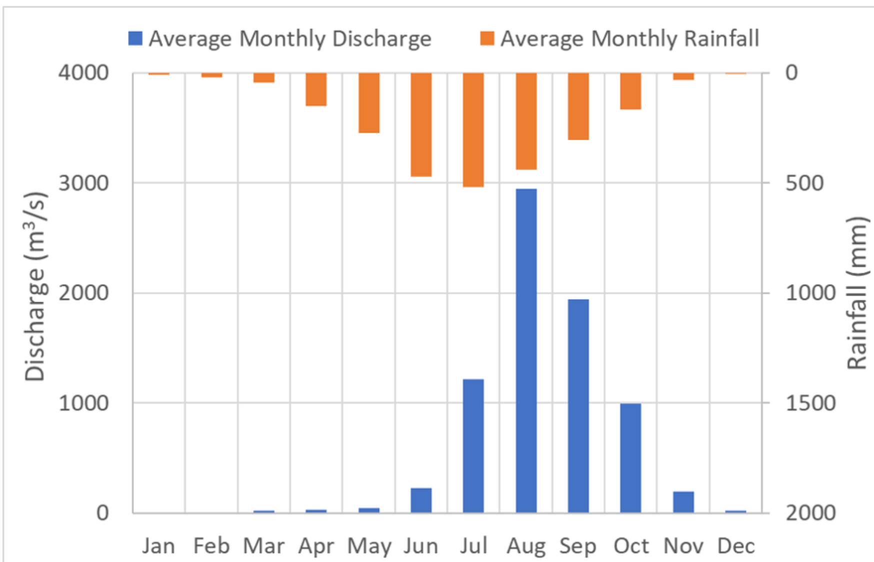
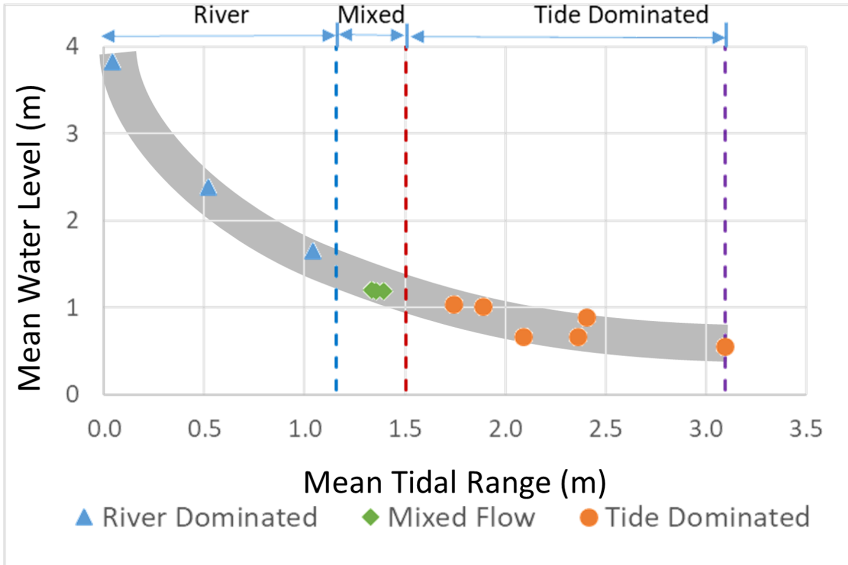
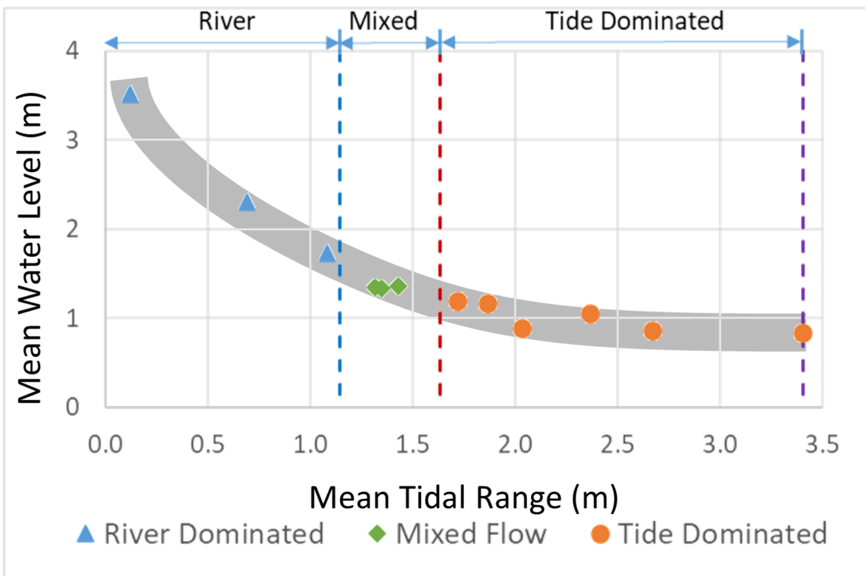
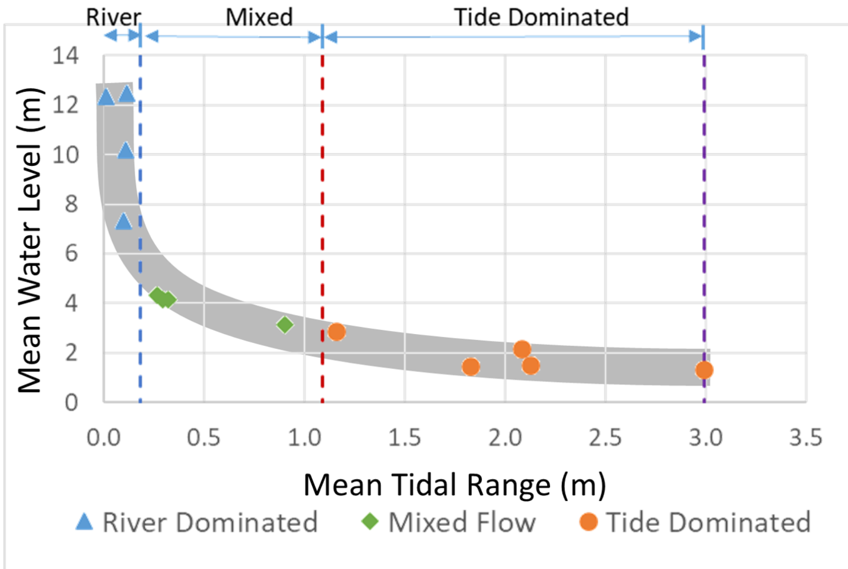
3
2.5
2
1.5
1
0.5
0
-0.5
-1
Mar
Jun
Sep
Dec

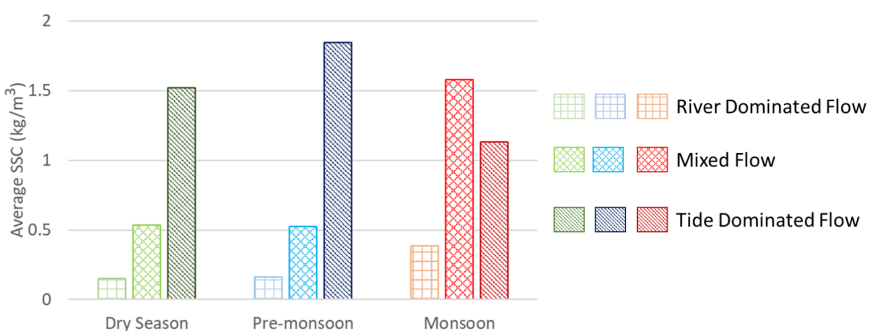


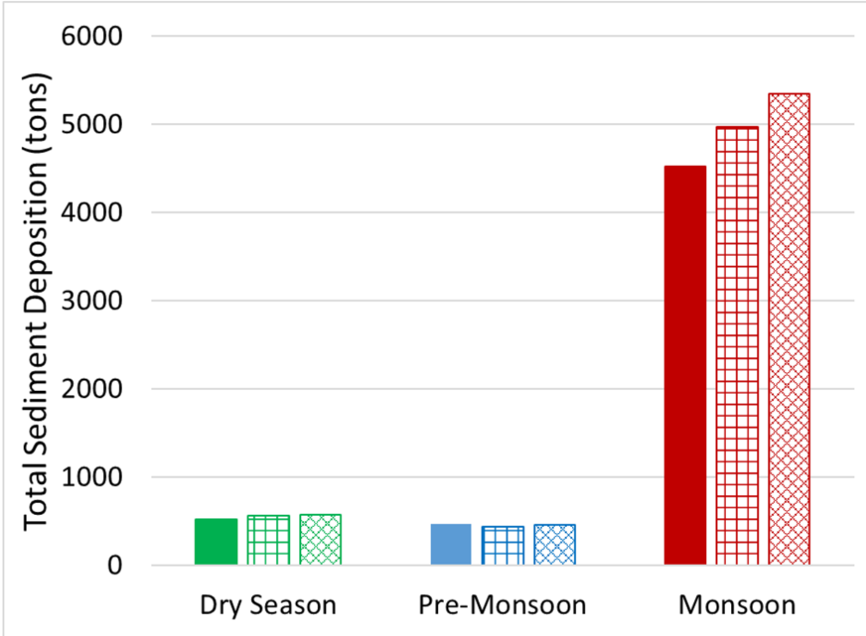
Average Monthly Discharge
Average Monthly Rainfall
Discharge (m³/s)
4000
3000
2000
1000
0
Rainfall (mm)
0
500
1000
1500
2000
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

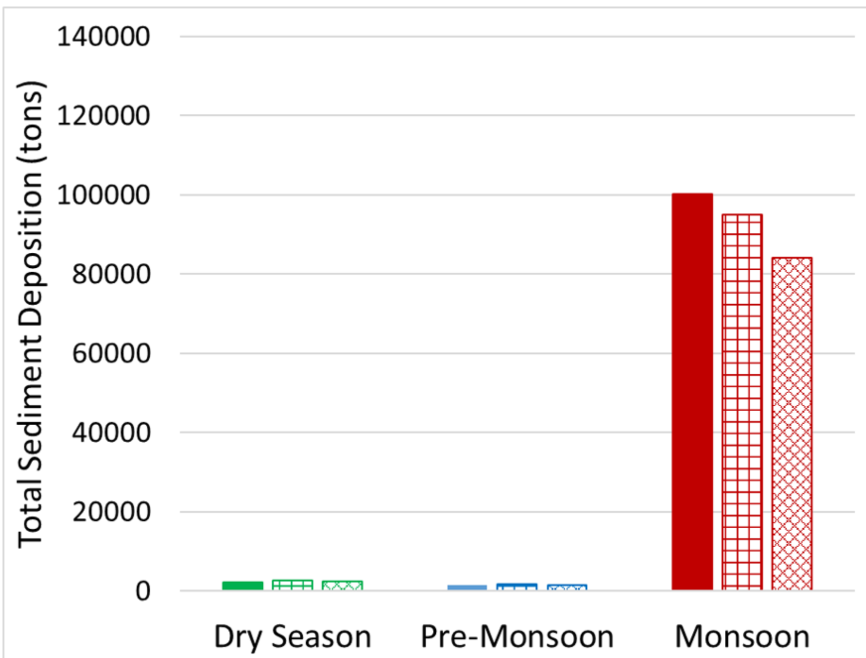

River
Mixed
Tide Dominated
Mean Water Level (m)
0
1
2
3
4
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Mean Tidal Range (m)
River Dominated
Mixed Flow
Tide Dominated

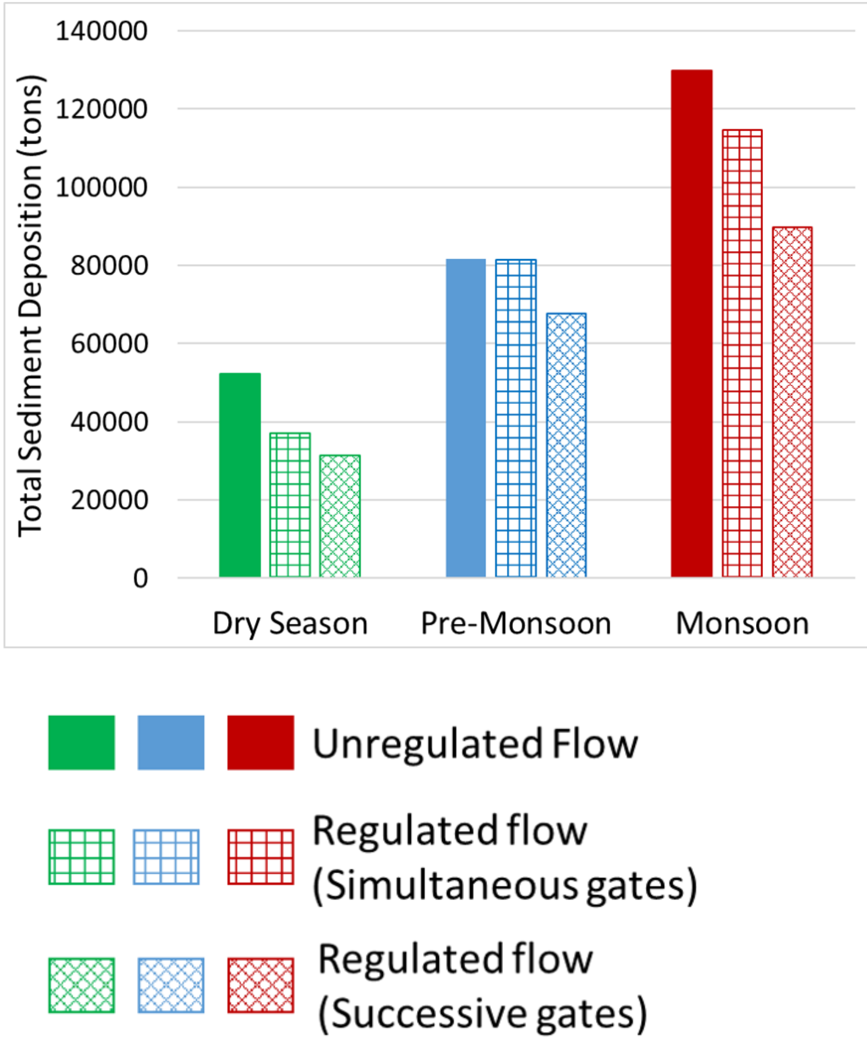

River
Mixed
Tide Dominated
Mean Water Level (m)
0
1
2
3
4
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Mean Tidal Range (m)
River Dominated
Mixed Flow
Tide Dominated


River
Mixed
Tide Dominated
Mean Water Level (m)
Mean Tidal Range (m)
River Dominated
Mixed Flow
Tide Dominated

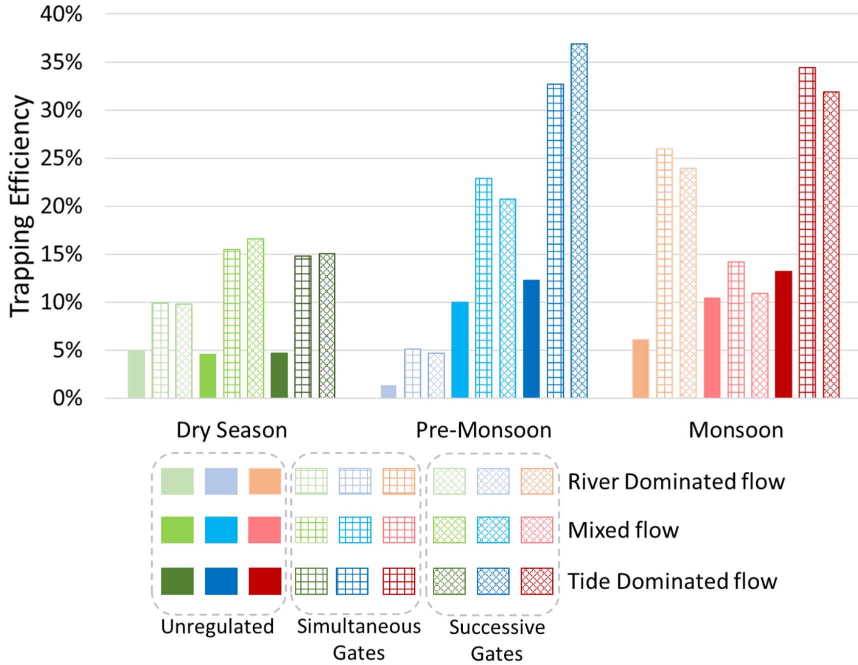

Average SSC (kg/m3)
Dry Season
Pre-monsoon
Monsoon
River Dominated Flow
Mixed Flow
Tide Dominated Flow


Total Sediment Deposition (tons)
6000
5000
4000
3000
2000
1000
0
Dry Season
Pre-Monsoon
Monsoon


Total Sediment Deposition (tons)
140000
120000
100000
80000
60000
40000
20000
0
Dry Season
Pre-Monsoon
Monsoon



Total Sediment Deposition (tons)
140000
120000
100000
80000
60000
40000
20000
0
Dry Season
Pre-Monsoon
Monsoon
Unregulated Flow
Regulated flow (Simultaneous gates)
Regulated flow (Successive gates)



40%
35%
30%
25%
20%
15%
10%
5%
0%
Trapping Efficiency
Dry Season
Pre-Monsoon
Monsoon
River Dominated flow
Mixed flow
Tide Dominated flow
Unregulated
Simultaneous Gates
Successive Gates