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

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Abstract

The Ganges-Brahmaputra-Meghna (GBM) delta plain within Bangladesh is one of the most vulnerable to relative sea level rise (RSLR) in the world especially under current anthropogenically modified (i.e., embanked) conditions. Tidal river management (TRM) as practiced in coastal regions of Bangladesh may provide an opportunity to combat RSLR by raising the land level through controlled sedimentation inside beels (depression within embanked polders) with re-opening of polders. To date, TRM has been applied to tide-dominated coastal regions, but the potential applicability of TRM for the beels within the polders of river-dominated and mixed flow (MF) regimes remains to be assessed. We apply a calibrated 2D numerical hydromorphodynamic model to quantify sediment deposition in a beel flooded through breaching of the polder dike under conditions of river-dominated, tide-dominated and MF regimes for different seasons and applying different regulation schemes for the flow into the beel. Simulation results show considerable seasonality in sediment deposition with largest deposition during the monsoon season. The potential of controlled flooding is highest in the tide-dominated region, where sediment accumulation can be up to 28 times higher than in the river-dominated region. Regulating flow into a beel increases trapping efficiency, but results in slightly lower total deposition than without regulation. We conclude that re-establishing flooding of the beel within the polder without regulating the flow into the beel through breaching of the polder dike is a promising strategy for the mixed and tide-dominated flow regions in the delta as the sediment accumulation can raise the land surface at a higher rate than RSLR and effective SLR (ESLR). In the more upstream river-dominated section of the delta, accumulation rates would be much lower, but the pressure of sea level rise on these areas is lower as well. Owing to the abundant availability of sediment, application of controlled flooding like TRM therefore provides an opportunity to counteract the impact of RSLR and ESLR by means of land raising, particularly along the tidal river reaches in the GBM delta.

KEYWORDS
flow regimes, re-opened polder, sea level rise, seasonality, sediment deposition, tidal river management

1 | INTRODUCTION

The 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 metres above mean sea level (AMSL) and 78% of the area below 5 metres AMSL (CCC, 2016). By utilizing earthen embankments, about 139 polders were constructed in the late 1960s and 1970s to protect the lower delta plain from flooding (van Staveren et al., 2017). Also, along the river reaches in the more inland part of the delta, the floodplain has been protected from monsoon flooding by embankments. Although these are not part of the Bangladesh tidal polder system, these protected river floodplains can be considered as a form of polders as well (sensu Schoubroeck & Kool, 2010). The construction of the tidal floodplain polders initially increased food productivity, but the embankments have largely prevented any sediment flow into the floodplain as well as the resulting natural aggradation of the delta plain.

The sediment flow through the GBM delta is large: in total about 750–1 billion tons of sediment per year is transported to the sea via the mainstream Ganges and Brahmaputra rivers (Islam et al., 1999). However, the supply of fresh-water flow from upstream areas has decreased over the past decades, especially during the dry season, due to upstream reservoir construction (Higgins et al., 2018). Together with the embankment of the tidal flood plains (van Staveren et al., 2017), this has resulted in massive within-channel sediment deposition at the rivers of SW Bangladesh (Alam, 1996). This has caused silting-up of the river channels and has decreased their water conveyance capacity during monsoon, resulting in higher flood water levels threatening the polders (Alam, 1996; Wilson et al., 2017). Also, drainage of the low-lying polders during the rainy season has become increasingly problematic, causing substantial seasonal water logging inside the polders (Awal, 2014).

In the century to come, climate change and sea level rise (SLR) will exacerbate the situation by increasing the risk of flooding and water logging. Over the period 1993–2012, the sea level at the GBM delta has risen by about 3.1–3.4 mm per year (Becker et al., 2020). Sea level projections for the year 2050 indicate a rise by 0.16–0.33 m under the RCP2.6 scenario and 0.22–0.40 m for the RCP 8.5 scenario with respect to the mean of 1986–2005 (Kopp et al., 2017). Goodwin et al. (2018) analysed 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 with respect to the mean of 1986–2005. According to Kulp and Strauss (2019), 10% of the current population of coastal areas, including Bangladesh, is threatened by chronic coastal flooding or permanent inundation due to SLR by the year 2100.

Land subsidence will further increase the vulnerability of this low-lying delta to SLR (Brown et al., 2018). A review of Brown and Nicholls (2015) reports subsidence rates in the GBM delta to range from 1.1 to 43.8 mm/year, with considerable spatial and temporal variation. While the study includes a myriad of shallow and deep, short- and long-term records, it is indicative of ongoing subsidence in the GBM delta, showing an average subsidence rate of 2.9 mm/year with a standard variation of 3.4 mm/year. Other studies on subsidence of GBM delta, such as Grall et al. (2018) indicated a range in subsidence rate from <0.2 to 5 mm/year. Krien et al. (2019) estimated the rate of subsidence to be 2–3 mm/year but mentioned that these numbers are highly uncertain and may have considerable spatial variation. In general, the subsidence rates increase seaward, where Holocene sediments become thicker and finer-grained (Grall et al., 2018; Wilson & Goodbred Jr, 2015). Adding the present-day median of the subsidence rate of 2.9 mm/year to the aforementioned scenario projections of sea level rise results till 2050 in Relative SLR (RSLR) projections ranging from 7.6 mm/year for the AMP4.5 scenario to 9.8 mm/year for RCP8.5. Additionally, the effect of local factors over the past 30 years on the SLR such as fresh-water flow from inland and tidal amplitude in the estuary for the coastal region of Bangladesh were explored by Pethick and Orford (2013) who indicated that the tides amplify inland due to poldering, while subsidence increases seaward due to thicker, finer grained packages. They suggested Effective SLR (ESLR) has been 12–16 mm/year, with 14.1 mm/year in the Pasur estuary over the past 30 years considering land subsidence, eustatic sea level change, fresh-water flow and tidal amplification.

Due to progressive siltation combined with interior subsidence (Auerbach et al., 2015), the river water levels have become higher than the land inside the polders. Problems of prolonged water logging and drainage congestion due to land subsidence and the silting up of the river channel beds in SW Bangladesh (Awal, 2014; Wilson et al., 2017) led in 1997 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 low-lying basins within the delta plain that historically were natural water-logged wetlands (Brammer, 1990). Today they are the lowest parts of the polders, where surface runoff accumulates through the internal drainage channels (Chakraborty, 2009).

Re-allowing tidal dynamics inside the beel during a 4-years period resulted in scouring and removal of sediment from the adjacent river bed, and the renewed sediment deposition inside the beel raised its land surface by 1 m (Adnan, 2006; Gain et al., 2017; van Staveren et al., 2017). As this intervention was primarily applied to restore the drainage capacity and navigability of the tidal river, it was termed as tidal river management (TRM). Since then, TRM has been applied to 12 beels in SW Bangladesh (Gain et al., 2017), where tides are a dominant driver of the dynamics of water and sediment. Previous TRM applications of controlled flooding and re-allowing sediment-rich water from a tide-dominated river into a polder lasted for 4–6 years. The resulting sediment deposition raised land surface of the beels inside the polders substantially by 0.2–1 m, but with large spatial variation in deposited amounts within a beel (Gain et al., 2017). Al Masud et al. (2018) reported higher food productivity and household income from livestock at former TRM sites compared with elsewhere in the region. Since TRM results in a rise of the polder land surface, it may provide an opportunity to elevate and maintain land above future sea level in other sinking deltas around the world as well, when there is sufficient fluvial or estuarine sediment available (Brown et al., 2018).

Allowing water in the lowlands through depoldering has been applied in several locations around the world. The 'Room for the River' project of the Netherlands used depoldering for flood prevention by allowing water inside previously embanked areas (van Staveren et al., 2014, van der Deijl et al., 2018, Verschelling, 2018). Controlled flooding of wetlands is used in Scheldt Estuary of Belgium as protection against river flood and storm surges (Climate ADAPT, 2014). To reduce the peak discharge in the river and to bring sediments and nutrients to the flood plain, controlled flooding is used in the Mekong delta as well (van Staveren et al., 2018). McInnes (2016) indicated that the loss of wetlands in Mississippi watershed which provide protection against storm surge will increase vulnerability to flooding of settlements and infrastructure in the future.

The current TRM practice continuously requires tidal pumping of water inside a beel within a polder for several consecutive years. This hampers the use of the land for livelihood and economic activities during TRM operation. Such prolonged flooding without proper compensation, together with the observed uneven sediment deposition within the beels has put local stakeholders' acceptance of TRM under pressure (Gain et al., 2017).

To have faster and more uniform sediment deposition, different ways of flooding the beel through breaching polder dikes using 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 et al., 2013; Islam et al., 2020; Shampa & Paramanik, 2012; Talchabhadel et al., 2018). Those previous data and modelling studies have analysed the sediment deposition in beels along the tide-dominated rivers in SW Bangladesh by using different number of inlets in the polder. Using mathematical models of sediment deposition, it was found that compartmentalization and use of canals inside the polders lead to spatially uniform sediment accumulation (Amir et al., 2013). Previous model simulations showed promising results for the beels along the 40-km long Teka-Hari-Teligang river reach, about 100 km inland of the Pasur-Shibsa estuary (Figure 1). While flooding of beels with TRM has been incorporated and modelled within the tide-dominated region of the GBM delta, it has not been investigated for beels located in polders at river sections with river-dominated and mixed flow (MF) regimes. To evaluate the potential of TRM-like strategies of flooding of beels through dike breaches with the aim 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 critical controls of deposition, including river flow, tidal range and associated suspended sediment concentrations (SSC) in the feeding river branches should be investigated as well for these different flow regimes.

Here we explore the applicability of TRM-like controlled flooding of beels located in polders, along a gradient from the river-dominated to the tide-dominated flow (TDF) regime across the GBM delta. Using a calibrated 2D hydrodynamic flow model of Pakhimara Beel in SW-Bangladesh, where TRM is currently practiced (Islam et al., 2020), we simulated sediment deposition under different scenarios of: (a) flow regime of the feeding river (i.e., river-dominated, tidal-dominated, mixed); (b) seasons; and (c) regulation schemes of inundation of the beel (i.e., unregulated, or regulated using simultaneous or successive gates). From our results we determine how these boundary conditions affect total deposition and trapping efficiency, and tentatively evaluate the applicability of controlled flooding like TRM in low-lying polder areas across the SW Ganges delta of Bangladesh. With appropriate tidal characteristics and adequate sediment load in the rivers, TRM can potentially be applied to the low elevation areas inside the polders of Bangladesh to raise the land elevation through sediment deposition to counter the effect of RSLR.

2 | METHODS

2.1 | Study area

The study covers the southwestern part of the GBM delta of Bangladesh, bounded by Ganges River and Padma River in the north, Meghna River in the east, the Bay of Bengal in the south and the border between Bangladesh and India in the west (Figure 1). The population of the study area is about 38.52 million (BBS, 2012). The Gorai River in the western part, the Arial Khan River and the distributaries of the Meghna 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 Bangladesh (1985) and Wilson et al. (2017).

The average monthly rainfall (Ahasan et al., 2010; Figure 3) in Bangladesh and the average monthly discharge of the Gorai River branch (IWM, 2017; Figure 3) show a clear monsoon seasonality, with highest rainfall in July and highest river discharge in August. Following Lázár et al. (2015), the seasons for the area can be divided into (a) dry

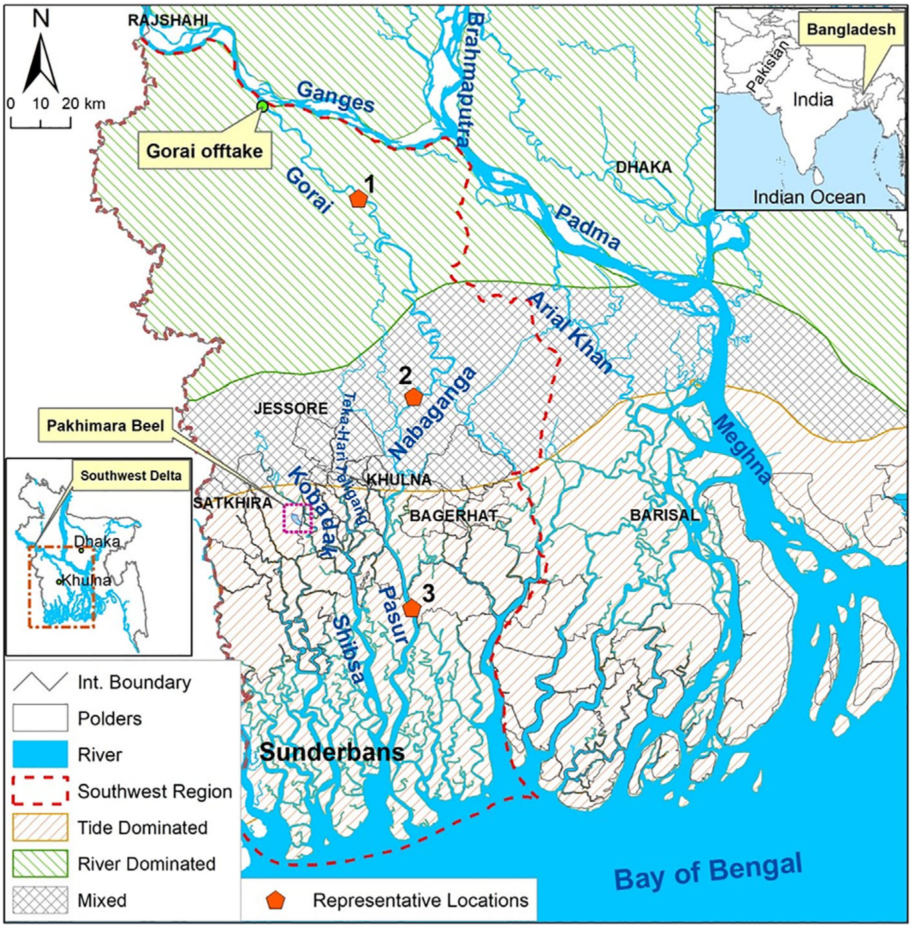


FIGURE 1 Regions of different flow regimes along the Gorai-Nabaganga-Pasur rivers and outline of the southwest region, Bangladesh, where the application of tidal river management is investigated in this study

season (November to February), (b) pre-monsoon (March to May) and (c) monsoon (June to October).

The primary rivers of Bangladesh, the Ganges, Brahmaputra and Meghna, reach the sea via the Meghna Estuary. Barua (1990) and Haque et al. (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 re-enters the estuaries in the west is much higher than the sediment load directly transferred seaward via the Gorai River from the Ganges. The lower delta plain is considered to trap 10% (about 100 million tons) of the annual Ganges-Brahmaputra sediment load released to the Gulf of Bengal (Rogers et al., 2013).

During the monsoon season, the river branches in the SW delta receive large volumes of flood water from the Ganges which causes flooding. However, the monsoon flooding is more extensive in the areas between the Gorai River and the Meghna River due to high flows of the Padma and the Meghna Rivers. The tidal flood plain and tidal flats in the coastal part of the delta experience enhanced flooding as well during the monsoon, but are predominantly subjected to regular flooding due to semi-diurnal high tides, even in the dry season.

Islam (2016) divided the SW delta in three sub deltas; the seaward coastal mangrove area as tidally active delta, the inland area comprising of greater Kushtia district and northern part of Jessore district as moribund delta and areas in between as mature delta. We divided the study area into three regions characterized by different flow regimes of the rivers that border the floodplain and polders: river-dominated (RDF), mixed river-tidal (MF) and tide-dominated (TDF) (Figure 1). The river-dominated flow (RDF) region extends to the south upto the 'tide-affected areas' delineated by FAO Bangladesh (1985) and Wilson et al. (2017). The region where these tide-affected areas overlap the southern part of the river floodplain delineated by Brammer (1990) is defined as mixed river-tidal flow region. The rest of the area in the south is defined as TDF region. The tidal floodplain polders constructed during 1960s and 1970s are identified by numbers by the Bangladesh Water Development Board (BWDB). Most of these polders lie within the region of TDF regime, and a few within the region of MF regime (Figure 1).

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, having its bifurcation from the Ganges River at about 50 km downstream of the Bangladesh-India border, and reaches the sea about 300 km further downstream via the 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 as much as $\sim$3000 m^3/s during the monsoon (Moly et al., 2015; Figure 3). The estimated yearly wash load of Gorai River is about 30 million tons (Mirza, 2006) most of which is transported during the monsoon season (Figure 3). The water level over the entire Gorai River is influenced by the tides during the dry and pre-monsoon seasons (Figure 2). This is due to disconnection of Gorai River from Ganges during these seasons, resulting from siltation of the river channel (Hale et al., 2019; Winterwerp & Giardino, 2012). During the monsoon period, the high river discharge reduces the effect of tides considerably for the upper reaches of the Gorai River (Figure 2(a)). The upper Gorai River represents the region of RDF regime during monsoon.

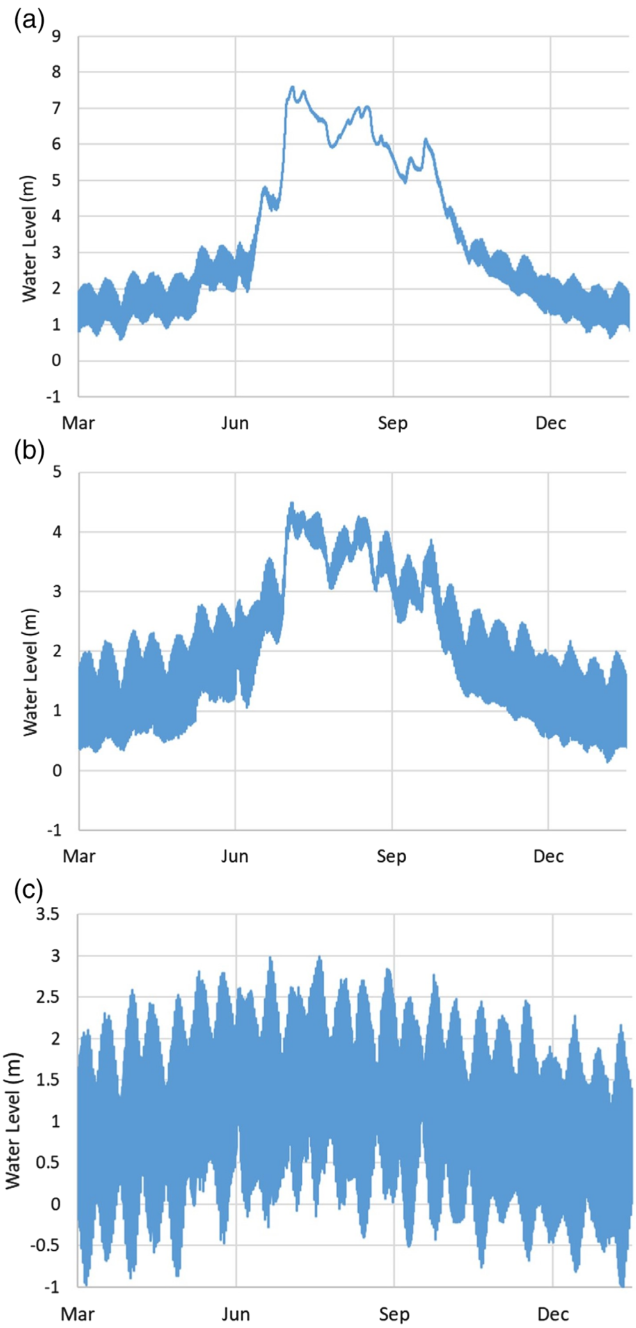


FIGURE 2 Hydrograph for (a) river-dominated flow (RDF) regime, (b) mixed flow (MF) regime and (c) tide-dominated flow (TDF) regime on the Gorai-Nabaganga-Pasur river (locations 1, 2 and 3 in Figure 1). Water levels are relative to PWD datum. PWD is the datum for the Public Works Department of Bangladesh with the zero datum at 0.46 m below MSL

The Nabaganga River reach is located about 150 km north from the Bay of Bengal, within the region of MF regime (Figure 1). Here the flow is affected by tides during all seasons, although tidal ranges are damped during monsoon due to the flood water coming from upstream (Figure 2(b)). Average tidal ranges vary from 0.3 m during the monsoon season to 1.45 m in the dry and pre-monsoon periods (Figure 2(b)). The Pasur River is the most downstream section of the Gorai-Nabaganga-Pasur River system and meets the Bay of Bengal in the south and represents TDF regime. The flow of the Pasur River is dominated by tides year round (Figure 2(c)): during the monsoon, the mean water level of the Pasur rises by 0.5–1.0 m but still experiences a semi-diurnal average tidal variation of about 2 m (Figure 2(c)). Salinity varies seasonally between about 20 dS/m (deci-Siemens per metre) during the pre-monsoon season and about 0–5 dS/m during the monsoon (Ayers et al., 2017; Ghosh et al., 2016).

2.2 | Data collection and analysis

For our modelling exercises, we selected three sites along the Gorai-Nabaganga-Pasur gradient according to the different flow regimes (Figure 1). Location 1 is in the region of RDF, and to represent its hydro-morphodynamic conditions we used the measured data from the 'Gorai Railway Bridge' station (SW99) of BWDB on the Gorai River as input for the modelling (Figure 2(a)). Location 2 is in the region of MF, and hydro-morphodynamic conditions were obtained from the 'Gazirhat' station of BWDB on the Nabaganga River (Figure 2(b)). Location 3 is within the region of tidal flow; here the hydro-morphodynamic conditions were obtained from the 'Mongla' station of BWDB on the Pasur River reach (Figure 2(c)). Average floodplain elevation at location 1 is about 5.6 m AMSL, at Location 2 it is 1.2 m AMSL and at location 3 it is about 1 m AMSL (Coastal DEM from Kulp & Strauss, 2018).

Time series of river discharge, water level and SSC at representative locations were collected from BWDB and Institute of Water

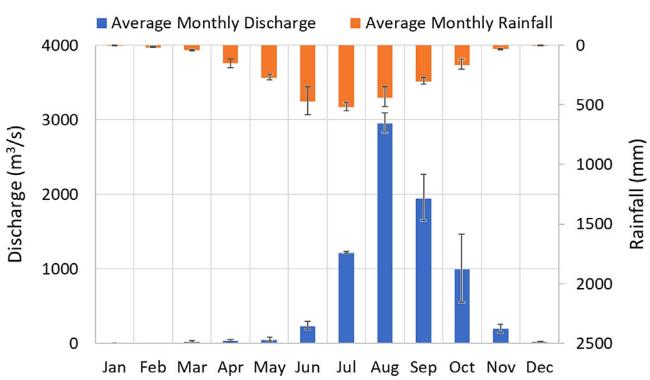


FIGURE 3 Average monthly discharge of the Gorai River at the bifurcation from the Ganges River and average monthly rainfall of Bangladesh from 2010 to 2017 with standard deviation

Modelling (IWM). The method of data collection of those two institutes was different. BWDB measured SSC by dividing the entire cross section of the river into several segments, and collected in each segment samples using a Binklay silt sampler at 20% and 80% of the channel depth. The samples were kept in a container for about 100 s immediately after the collection and within this time the amount of sediment deposited was considered as coarse fraction and rest of the sediment was considered as fine fraction which was determined in the laboratory later. A weighted average method was used to calculate the average SSC values from the sample measurements (Rahman et al., 2018). IWM measured SSC by collecting water samples with a pump bottle sampler. The river cross section was divided into several segments and water samples were collected on an hourly basis from each segment at 20, 60 and 80% depth. The samples were analysed in the laboratory of IWM (IWM, 2017).

Other data, including channel geometry, land use and rainfall were obtained from governmental agencies such as BDWD and Water Resources Planning Organization (WARPO), and from non-governmental research institutes such as IWM, Center for Environmental and Geographic Information Services (CEGIS), as well as reports and papers (Table 1). Water level data were available for all representative locations, but continuous measurements of discharge and SSC were available for short periods of time only, 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.

Sediment rating curves were used to generate input SSC for the model when measured SSC data were unavailable. The rating curves have been determined by IWM using the measured data. The equation for the rating curve for the Gorai River is $Q_s = 0.0394^*(Q_w)^{1.265}$, where Q_s is the sediment discharge (in kg/s) and Q_w is river discharge (in m^3/s). Q_s was converted to SSC through division by Q_w. This was used at location 1 within the river dominated flow region (IWM, 2017). The rating curve determined by IWM for the Pasur River is: $SSC = 422.72e^{1.89^*V}$ for flood tide and $SSC = 137.05e^{2.13^*V}$ for ebb tide, with SSC = suspended sediment concentration (mg/L) and V = mean river flow velocity (in m/s). These were used at Location 3 within tide dominated flow region (IWM, 2015). For the MF region at Location 2, rating curves were generated from the collected data of IWM and BWDB. For this location, $SSC = 0.0637^*(Q_w)^{1.078}$ was used for the monsoon season. For the rest of the year when the flow is heavily influenced by tides at Location 2, we used a separate rating curve for the flood tide: $SSC = 124.11^*(Q_w)^{0.13}$ and one for ebb tide: $SSC = 54.11^*(Q_w)^{0.21}$. The data collected from IWM and BWDB indicate that the vertical profiles of SSC do not show major variations within the water column (Figure 4), which is similar to the finding of Garzanti et al. (2011) and Barua (1990) for the Ganges River and the southwestern estuary.

TABLE 1 Overview of collected data

Type of data	Monitoring period	Method of data collection	References
Land surface elevation	2000, 2010 and 2018	Shuttle Radar Topography Mission (SRTM), Lidar and artificial neural network	Kulp and Strauss (2018)
Land use	2011	Field survey	Ministry of Land, Bangladesh
Hydrometric: Water level	Kobadak (September 2015–October 2016; January–April 2017); Gorai (1980–2017); Nabaganga (1980–2017); Pasur (1980–2017)	Staff gauge and pressure cell	IWM (2017) and BWDB
Hydrometric: Discharge	Kobadak (August–September 2016; February–April 2016; March–April 2017); Gorai (1980–2016); Nabaganga (1983–2006)	ADCP	IWM (2017) and BWDB
Suspended sediment concentration	Kobadak (November–December 2015; February–April 2016; August–September 2016; March–April 2017; all from 06.00 to 18.00 h daily at 1 hourly intervals); Gorai (sporadically between 1989 and 1998 and 2010 and 2018); Nabaganga (sporadically between 2012 and 2016); Pasur (sporadically between 2012 and 2016)	Pump bottle sampler	IWM (2017) and BWDB
Canal and river alignment and cross sections	2016 and 2017	Echo-sounder and satellite image	IWM (2017) and Google earth
Alignment of the dike surrounding Pakhimara Beel and its design cross-section	2017	Field survey	IWM (2017)
TRM operation rules	2017	Consultation of documents and experts	IWM (2017)
Satellite imagery	2016, 2013 and 2009	Image analysis	Google Earth

2.3 | Setup of hydromorphodynamic model

The effects on the sedimentation of different flow regimes, seasonality and regulation of flows into a re-opened beel were analysed using a two-dimensional (2D) numerical hydromorphodynamic model. This model was developed and calibrated for Pakhimara Beel (700 ha), which is an active TRM project in southwest Bangladesh (Islam et al., 2020). Model simulations were carried out using Mike 21FM (developed by DHI) in which hydrodynamic processes and sediment transport are simulated simultaneously (Hydraulics, 2012a). As the grain size of the sediment is fine (less than 63 μm) in the study area (Datta & Subramanian, 1997; IWM, 2010), the MT (mud transport) module of Mike 21FM was used for calculating cohesive sediment transport.

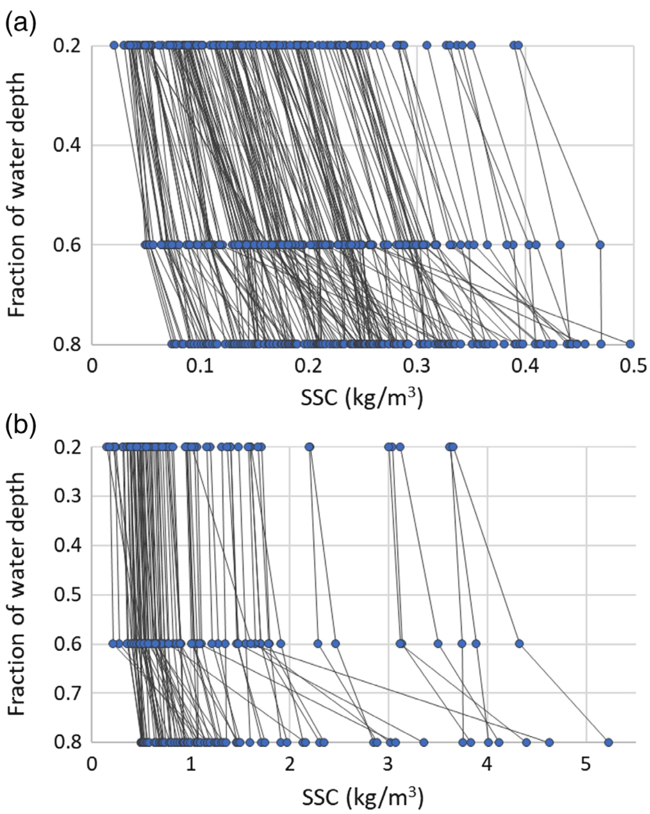


FIGURE 4 The vertical distribution of SSC within the water column of rivers in Southwest Bangladesh for SSC lower than 500 kg/m^3 (a) and for SSC higher than 500 kg/m^3 (b). These data were measured by IWM and BWDB. BWDB, Bangladesh Water Development Board; IWM, Institute of Water Modelling; SSC, suspended sediment concentrations

Mike 21FM calculates the hydrodynamic (HD) processes based on the solution of the three-dimensional incompressible Reynolds averaged Navier–Stokes equation (Hydraulics, 2012a). The model uses an approximate Riemann solver to calculate the convective fluxes at the interface of the cell of the 2D mesh (Hydraulics, 2012a). The MT module uses the advection-dispersion equation (ADE) and the concept of Krone (1962) for sediment deposition. The ADE is solved using the third-order finite difference scheme, known as the ULTIMATE scheme, which is based on the QUICKEST scheme (Hydraulics, 2012b). For morphological simulation, the bathymetry is updated for each time step according to net sedimentation (Hydraulics, 2012b).

To represent the bathymetry of Pakhimara Beel, a mesh with flexible cell size was used where the 2D cells have shapes from triangle to octagon. A finer mesh was opted to represent the inlet canal (cell area of about 170 m^2) and a coarser mesh (cell area up to 5000 m^2) was used for the floodplain to reduce the computational intensity (Islam et al., 2020).

The model was calibrated for Pakhimara Beel by considering the field data of water level, discharge and SSC (Islam et al., 2020). The size of 80% of the beels as identified by Adnan et al. (2020) for the southwest region of Bangladesh is equal or smaller than Pakhimara Beel. Manning's coefficient, shear stress and settling velocity were the primary parameters for calibrating the hydrodynamic and morphodynamic model. Sensitivity analysis of the model was carried out with varying Manning's coefficient from 0.1 to 0.01 s/m$^{1/3}$, shear stress from 0.01 to 0.1 N/m^2 and settling velocity from 0.0001 to 0.001 m/s. To calibrate these model parameters, the coefficient of determination (R^2) and the normalized root mean square error (NRMSE) obtained for different parameter combinations were calculated by comparing the modelled results with the observed data for

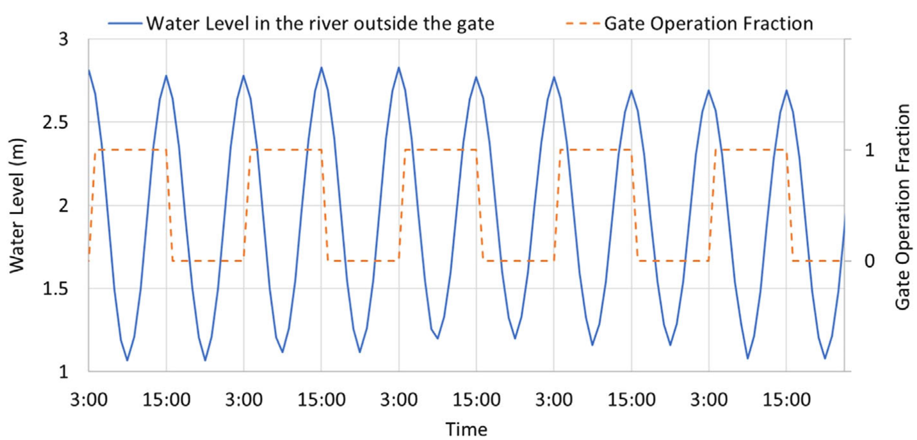


FIGURE 5 The cyclicity of water level in the river outside the gate and operation of the gates (1 = open, 0 = closed) for the scenario with both gates operating simultaneously

the different input variables. For Manning's coefficient of 0.032 s/$m^{1/3}$, shear stress of 0.08 N/m^2 and settling velocity of 0.0005 m/s, the highest obtained R^2 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., 2020). The calculated goodness of fit for the developed model indicates that the calibrated model resulted in good agreement between the observed and simulated data.

2.4 | Scenario development

The calibrated model for Pakhimara Beel (700 ha; average land elevation of 0.57 mPWD; Islam et al., 2020) was used to simulate new scenarios developed here for (a) different regions, (b) the three different seasons and (c) regulated and unregulated flow. To accomplish this, we simulated sedimentation in the beel as if it were situated at locations 1, 2 and 3, by adjusting the land elevation, hydrodynamic and SSC accordingly. The original bathymetry of Pakhimara Beel was adjusted using the relative differences in land level between the locations derived from the Coastal DEM generated by Kulp and Strauss (2018). We only used the relative differences between the areas, to avoid a potential systematic bias in the absolute elevation estimates of the coastal DEM. We then supplied the model for Pakhimara Beel with water levels and SSC that were adapted according to the scenarios of different flow regimes and seasonality (Figure 2, Figures 7 and 8). As data was not continuously available for 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. The water level at the start of the model simulation for river dominated flow, MF and tide dominated flow regions during the dry season were 2, 1.7 and 1.3 m respectively, for the pre-monsoon season 2.1, 1.8 and 1.5 m and for the monsoon season 7.2, 4.1 and 2.1 m. Although we are aware that we do not capture within-season variations at longer-time scale, we use this approach to explore the main seasonal differences in sediment accumulation. As the sediment concentration does not vary considerably along the water column (Figure 4), no adjustment of SSC for differences in inlet height was applied.

In all scenarios we considered a situation with two 40-m wide inlets positioned at opposite sides of a simulated beel with similar dimensions of Pakhimara Beel. The same time series data of water level, discharge and SSC were applied for both inlets. In addition to unregulated flow into the beel, we also considered scenarios with flow regulation using gates at these two inlets. For the flow regulation, we assumed that the inlet gates were opened during the peak of the high tide and closed 12 h later during the peak of next high tide (Figures 5 and 6). Two gate operation schemes were simulated: (a) a 'simultaneous' gate operation with the gates at both inlets open and closed simultaneously (Figure 5); (b) a 'successive' gate operation where first one gate is opened to admit inflow and then closed to retain the water, and 12 h later the other gate is opened to release the water (Figure 6). Allowing inflow through one inlet and release through the other was done to represent throughflow across the beel. As gates are operated manually in Bangladesh, it was assumed in the simulations that the opening and closing of the gate requires 1 h. The developed scenarios by combining flow regimes, seasonality and flow regulations are summarized in Table 2.

An additional scenario for the tide dominated flow regime was developed for the monsoon season with a length of 154 days by placing the set of data for 14 days repeatedly. This scenario was applied to the tide dominated flow region for unregulated flow. The scenario is termed as TM_{add}. This was considered to assess the effect of cumulative land elevation gain during a full season on total sediment accumulation.

2.5 | Analysis of the simulated scenarios

The total mass of sediment accumulation over the season was calculated for all the developed scenarios from the simulations of the three adjusted hydromorphodynamic models. Sediment accumulation for different seasons was calculated using the total mass of sediment deposition over the representative 14 days of simulation to account for spring-neap variation of tides and scaled for the total number of

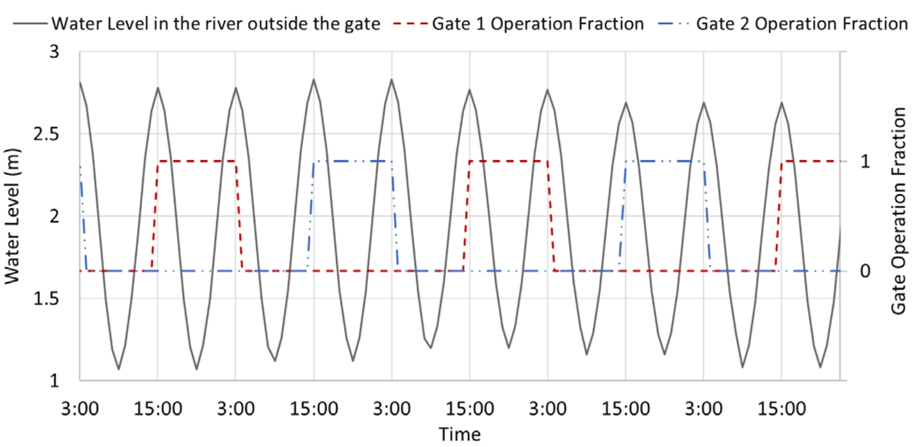


FIGURE 6 The cyclicity of water level in the river outside the gate and operation of the gates (1 = open, 0 = closed) for the scenario with 'successive' gate operation

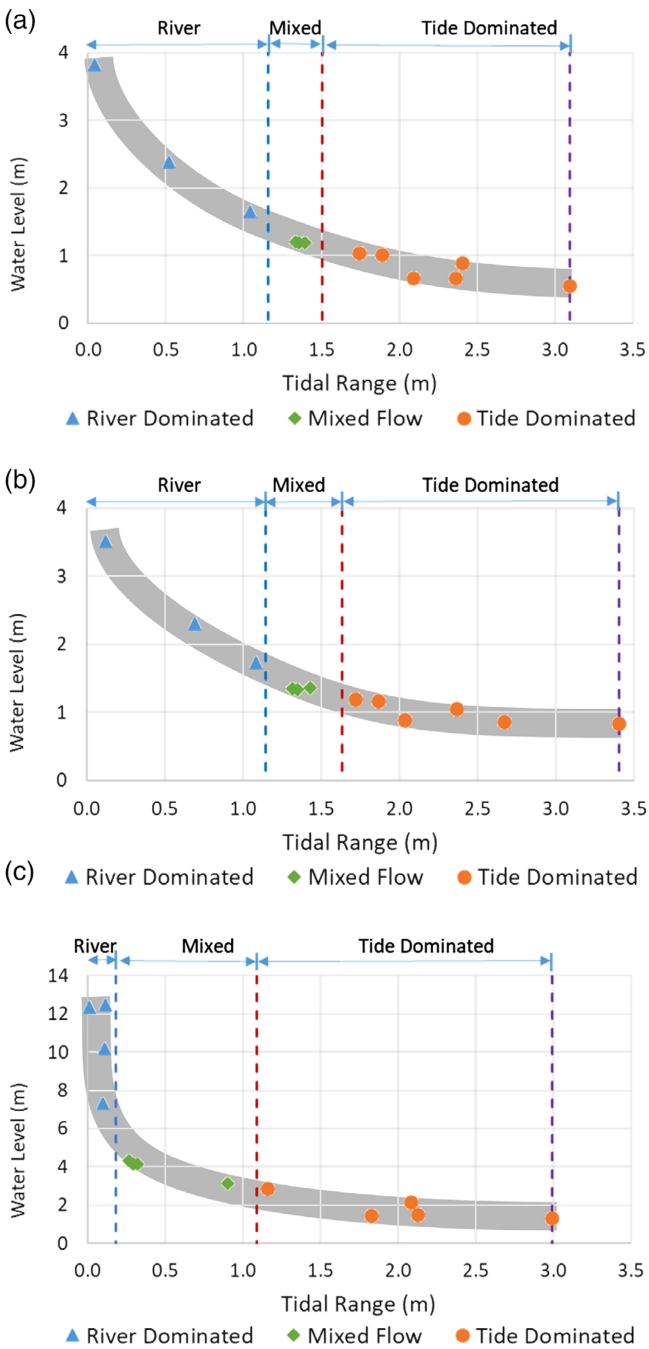


FIGURE 7 Mean tidal ranges and water levels for different flow regimes during (a) dry season, (b) pre-monsoon and (c) monsoon. The blue triangles represent river dominated flow, the green rectangles represent mixed flow and the orange circles represent tide dominated flow; the grey area represents the variation of tidal ranges. Water levels are relative to PWD datum. PWD is the datum for the Public Works Department of Bangladesh with the zero datum at 0.46 m below MSL

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 is defined as the fraction of the incoming suspended sediment, that is, retained or deposited over the entire simulation period (Verschelling et al., 2017). Total incoming and outgoing sediment loads 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.

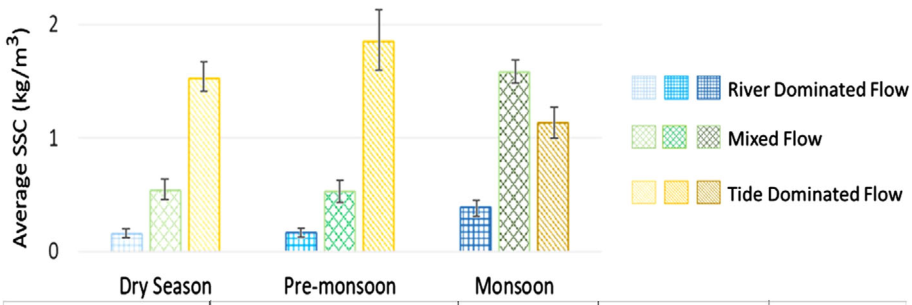
3 | RESULTS

Figure 7 shows the mean water level and tidal range along the gradient from RDF to TDF regime of the Gorai-Nabaganga-Pasur River reach within the GBM delta for the three main hydrological seasons. Mean water level gradually decreases from the reaches with RDF to TDF. The mean water level is lowest during dry season and highest during monsoon for reaches of all three flow regimes. The water level gradient between Location 1 (RDF) and Location 3 (TDF) is steepest during the monsoon and more gradual during the pre-monsoon season. Seasonal variation in water levels at Location 1 is largest with ~5 m between dry season and monsoon. At the tidal dominated Location 3 there is only ~1 m difference in average water level between the dry season and the monsoon season. The mean tidal range also varies seasonally, being largest during pre-monsoon and smallest during monsoon seasons at all three locations. The difference in the mean tidal range between monsoon and pre-monsoon season is largest (i.e., 90 cm) at Location 2 with the MF regime, and only 20 cm at Location 3.

SSC shows considerable seasonality as well: the average SSC is highest during monsoon in the reaches of RDF and MF regimes, whereas the average SSC is highest during the pre-monsoon for the TDF regime (Figure 8). During all seasons, the SSC is larger than 1 kg/m^3 in the river stretches within the region of TDF regime. Along the gradient from RDF to TDF regime, the tidal range and average SSC change gradually along the transect (Figures 7 and 8).

Due to the lack of available continuous data series, simulated periods of sedimentation with our models were restricted to 14 days. Sediment deposition over 14 days of simulation was upscaled to estimate the sediment accumulation for the seasons. Spatial or temporal upscaling to estimate sediment deposition has also been applied by Vionnet et al. (2018), Constantinescu et al. (2016), Simon et al. (2013) and Smith et al. (2011). Even though the scaling introduces some uncertainty, it demonstrates which flow region has higher potential for controlled flooding like TRM to raise the land. The comparison between the sediment accumulation upscaled from 14 days simulation time and that calculated for an entire monsoon season, scenario TM_{add}, indicates relatively small overestimation with upscaling by about 9%. Therefore, the effect on total sediment deposition by incremental land elevation inside the beel with sedimentation over one monsoon season, is minimal.

The model results for the different scenarios demonstrate that the total sediment deposition during each season inside the reopened beel varies per season for all flow regimes (Figure 9). At all locations, total sediment accumulation over the seasons is highest



		Dry Season	Pre-monsoon	Monsoon
River Dominated	Average SSC (kg/m^3)	0.15	0.16	0.39
	Standard deviation	0.04	0.04	0.07
Mixed flow	Average SSC (kg/m^3)	0.54	0.53	1.58
	Standard deviation	0.09	0.1	0.1
Tide Dominated	Average SSC (kg/m^3)	1.52	1.85	1.13
	Standard deviation	0.13	0.26	0.13

FIGURE 8 Seasonal variation of suspended sediment concentrations with standard deviation for the three flow regimes

TABLE 2 Scenario matrix considering the flow regulation, seasonality and flow regime

		Flow regulations		
Flow regime		**Open**	**Simultaneous gates**	**Successive gates**
River dominated (RDF)	Seasons	Pre-monsoon	Pre-monsoon	Pre-monsoon
		Monsoon	Monsoon	Monsoon
		Dry	Dry	Dry
Mixed Flow (MF)	Seasons	Pre-monsoon	Pre-monsoon	Pre-monsoon
		Monsoon	Monsoon	Monsoon
		Dry	Dry	Dry
Tide dominated (TDF)	Seasons	Pre-monsoon	Pre-monsoon	Pre-monsoon
		Monsoon	Monsoon	Monsoon
		Dry	Dry	Dry

during the monsoon season. For the TDF regime (Location 3), seasonal variation in sediment accumulation is smaller than for the RDF and MF regime. The sediment accumulation during the monsoon is almost 50% higher than during the dry season for the TDF regime and for the MF regime almost 40 times higher during the monsoon season than during the dry season (Figure 9). During the dry and pre-monsoon seasons the water levels in the rivers with RDF regime are lower than the average land elevation of the region. Therefore, the sediment deposition is zero during the dry and pre-monsoon seasons for the RFD regime as the beel does not become flooded then. During the monsoon season, the volume of water inside the beel gradually increases in the river for MF regime (Figures 2(b) and 10). Similar effects are seen for the RDF regime (Figures 2(a) and 10). The effect of tides is much stronger for the TDF regime even during the monsoon season (Figures 2(c) and 10).

Along the gradient from RDF to TDF regime, the total sediment accumulation within the beel increases substantially for all three seasons. For example, during the monsoon season, total sediment accumulation with unregulated flow is 5200 ± 950 tons for the RDF regime, 100,300 ± 18,360 tons for the MF regime and 129,800 ± 23,750 tons for the TDF regime. Sediment accumulation for the scenario TM_{add} was 116,374 tons, which is about 9% less than the scaled total of 129,800 tons. The total sediment accumulation for the TDF regime is highest among the flow regimes for all seasons, and almost 28 times higher than accumulation for the RDF regime during the monsoon season (Figure 9).

Regulation of flow into the beel affects sediment deposition within the beel. Model simulations show for the RDF regime that the sediment deposition is similar for regulated and unregulated flow during the monsoon period with successive gate operation resulting in about 2% less sediment deposition when compared to unregulated flow. For the TDF and MF regimes, unregulated flow into the re-opened polder results in higher sediment deposition inside the beel (Figure 9b,c). During the monsoon, unregulated flow into the beel for the MF regime results in 16% more deposition than regulated flow with successive gates and 5% more than the simultaneous gates. In case of the TDF regime, unregulated flow results in 31% more deposition inside the beel than regulated flow with successive gate operation and 12% more than when opening and closing the gates simultaneously.

Calculated trapping efficiencies display seasonal differences as well (Figure 11). Generally, trapping efficiencies for the MF and TDF regimes are highest during the pre-monsoon and monsoon, and lowest during the dry season. In contrast, the trapping efficiency for the

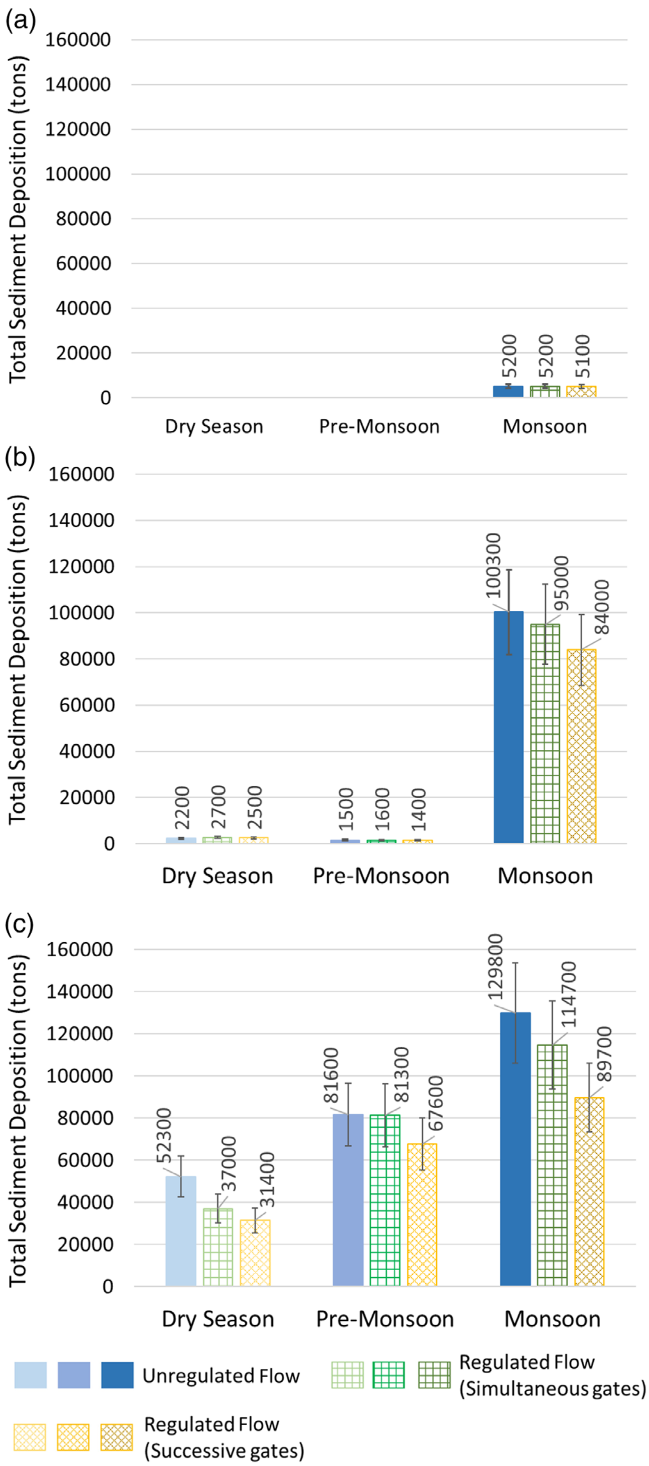


FIGURE 9 Seasonal sediment deposition for (a) river-dominated flow (RDF) regime, (b) mixed flow (MF) regime and (c) tide-dominated flow (TDF) regime under different flow regulations. As the average land elevation is higher than the river water level, there is no sediment deposition in the beel within the region of RDF regime during the dry and pre-monsoon seasons

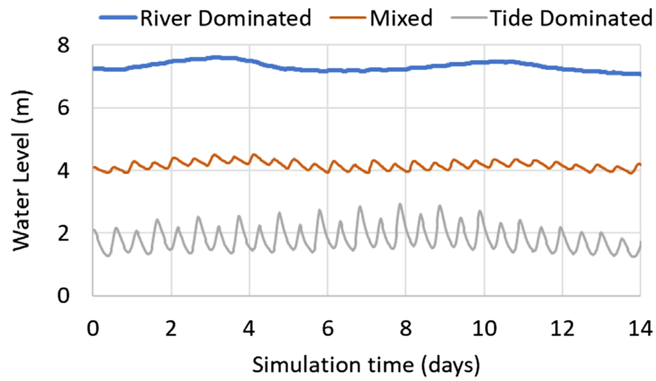


FIGURE 10 Comparison of water level inside the beel during monsoon for different flow regions. Water levels are relative to PWD datum. PWD is the datum for the Public Works Department of Bangladesh with the zero datum at 0.46 m below MSL

RDF regime is highest during the monsoon season only and lowest during the pre-monsoon and dry seasons as no accumulation is measured. Trapping efficiency generally increases along the gradient from RDF to TDF regime during pre-monsoon when the mean tidal range is highest for all flow regimes and increases in a downstream direction (Figure 7). Unregulated flow during monsoon season results in the smallest trapping efficiency: about 6% for the RDF regime, 10% for the MF regime and 13% for the TDF regime. Regulation of flow substantially increases the trapping efficiency for all the regions and seasons (Figure 11). For the RDF regime regulation of flow into the re-opened polder during monsoon increases trapping efficiency for the beel by about five times when compared to unregulated flow. For TDF and MF regimes this increase is about four 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.

4 | DISCUSSION

4.1 | Controls of deposition

The model simulations quantify to what extent sediment deposition in beels located in the southwest part of GBM delta after re-opening the polder dike depend on (a) water flow regimes, (b) SSC in the feeding channel, (c) the amount of sediment actually entering the beel and (d) the efficiency of the beel in trapping this sediment. The first two determine together the amount of sediment potentially available for deposition. The latter two are determined by the beel area, gate size and regulation of the incoming flow. Here we discuss the spatial and temporal variations in these controls and the potential differences in sedimentation in beels across the delta.

Water level, tidal range and SSC vary seasonally and along the gradient from river-dominated (RDF) to TDF region (Figures 7 and 8). During the dry and the pre-monsoon seasons, river flow in all river reaches within the southwest part of GBM delta is influenced by the tide, especially in those rivers that are lacking substantial river flow from upstream, such as the Gorai river (Figure 7). Also, sediment in the river reaches with TDF and MF regimes is delivered during these

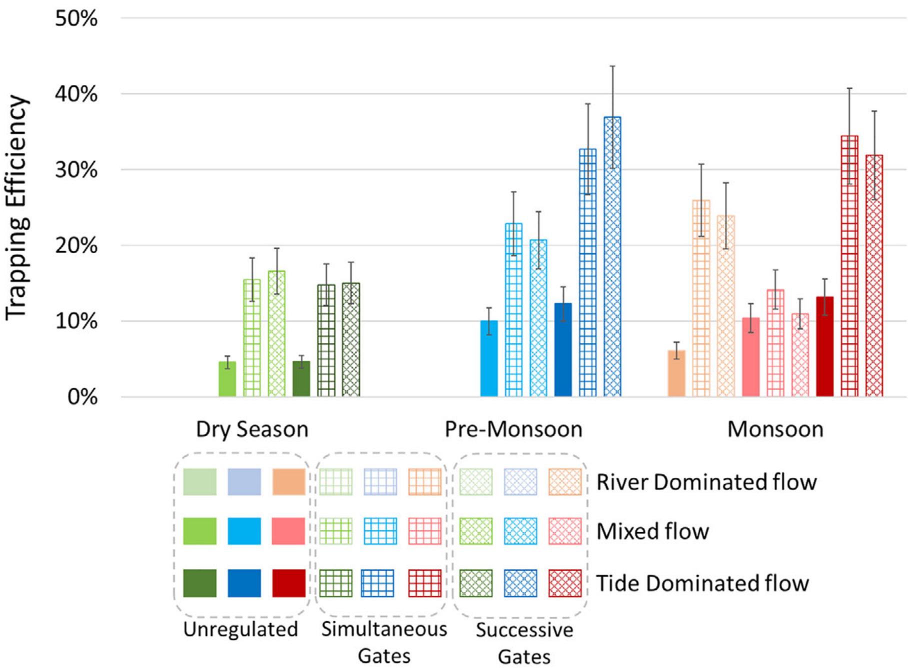


FIGURE 11 Calculated trapping efficiency for all the scenarios. The colour gradient from lighter to darker represents the gradient of flow from river-dominated (RDF) to tide-dominated (TDF)

seasons from the sea (Bay of Bengal) by the tides (Barua, 1990; Haque et al., 2016). Consequently, sediment accumulation in the re-opened beels during the dry and pre-monsoon seasons depends on the sediment delivered from the Bay of Bengal. Lack of fresh water flow to deliver sediments during the dry and the pre-monsoon seasons in the rivers with the RDF regime, ~220 km inland from the Bay of Bengal, results in lower SSC (~0.15 kg/m^3) in the rivers compared to the rivers with the MF and the TDF regimes (~0.54 and 1.68 kg/m^3 respectively; Figure 8).

During monsoon, river discharge, water levels and SCC in the river reaches with RDF and MF regimes are considerably higher than during the other seasons (Figure 8). Hence, a larger sediment load is available in the rivers feeding the beel, and the beel inundates at larger depth (Figure 10). Allen et al. (1980) suggested that the tide influences the suspended sediment transport towards inland from the sea which decreases with damping of tide. The monsoon flood water coming down the Gorai River dampens the effect of tides in the lower reaches, and reduces the tide-driven inland transfer of sediment from the sea into the estuaries. As a result, the tidal range and SSC in the rivers with TDF regime are lowest, 2 m and 1.13 kg/m^3 respectively, during the monsoon period. However, the total sediment load is highest during the monsoon for all three flow regimes due to larger discharge and higher water level. As the rivers with the MF regime receive sediment from both the upstream and downstream directions during the monsoon season, the SSC in river reaches with MF regime are higher than in the rivers with TDF and RDF regimes by ~40 and ~300% respectively.

Given the water levels and SSC in the feeding rivers, the next control of actual deposition in a beel is the amount of water and sediment that can enter the beel during a tidal cycle. This actual deposition in the beel subsequently depends on a combination of factors. The total sediment accumulation inside the beel during any season depends on river water levels that drive flooding of the beels and SSC of the incoming water. Christiansen et al. (2000) concluded that sediment deposition inside a tidal wetland increases with larger tidal range and SSC. Here we observe with higher SSC, daily inflow and outflow of water due to the tides and larger tidal range, a much larger sediment load is transferred into the beels located in the MF and TDF regions than in the RDF region during all three seasons (Figure 9). Accordingly, sediment deposition inside the beel is larger in the MF and TDF regions for all three seasons (Figure 9). As the water levels in the rivers with RDF regime are lower than the average land elevation during the dry and the pre-monsoon seasons, water does not enter the beels within the RDF region during these seasons, resulting in no sediment deposition inside the beel (Figure 9). With considerably larger tidal range and SSC during pre-monsoon and dry seasons in the rivers with TDF regime than the MF regime (Figures 7 and 8), the sediment deposition within the beels is substantially higher here (Figure 9). Due to a considerably higher tidal range during the monsoon in the rivers with TDF regime than the MF regime, a higher volume of sediment is delivered into the beel for the TDF regime than MF regime, even though the SSC is slightly lower in TDF regime (Figures 7 and 8). This results in higher sediment deposition during monsoon inside the beels in the TDF region than in the MF region (Figure 9). Verschelling et al. (2017) indicated that the sedimentation inside a tidal wetland is influenced positively by the river stage. As water level, discharge and sediment load in the rivers are the highest during the monsoon season, the sediment accumulation is highest inside the beels for this season. The rivers with TDF regime have much larger tidal range during the monsoon season compared to the rivers with MF regime. Thus, larger sediment load is transferred into the beels. This results in higher sediment accumulation for the TDF regime even with slightly lower SSC than MF regime during the monsoon season (Figure 9).

Due to the lack of tidal range and lower SSC in the rivers with RDF regime, sediment accumulation during monsoon is substantially lower in the RDF region than in the MF and TDF regions (Figure 9). For the RDF regime, sediment enters the beel and leaves slowly with receding peak discharge in the river during the 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 pumping of water inflow and outflow within the beel (Figure 7). This combined with lower SSC results in lowest sediment accumulation for the RDF regime compared to other flow regimes during monsoon season (Figure 9). 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 8) and water discharge (Shaha & Cho, 2016) during the dry season in the feeder rivers translates to the lowest sediment accumulation for all three flow regimes. The highest sediment accumulation inside the beels in all flow regimes during monsoon is found (Figure 9) because the monsoon results in high discharge, raised water levels, and increased sediment loads over a period of 150 days.

The larger daily delivery of sediment inside the beel owing to the larger tidal range (Figure 7) results in a higher trapping efficiency. Consequently, the highest trapping efficiency occurs during the season with highest tidal range, pre-monsoon season (Figure 7), in the beels within the MF and TDF regions 3 (Figure 11). Because of the absence of tidal dynamics and gradual increase and recession of flood water in the rivers with a RDF regime (Figures 2 and 10) during monsoon, the volume of water retained inside the beel is mostly undisturbed increasing the residence time and rate of sediment deposition (Figure 9). This results in high trapping efficiency for the RDF regime (Figure 11), 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 SSC inside the beel increases. This is similar to the findings of Deijl et al. (2017) who studied two fresh water tidal wetlands in the Rhine-Meuse delta in the Netherlands and concluded that trapping efficiency inside a tidal wetland can be enhanced with longer residence time. However, total sediment deposition is less with flow regulation in spite of the higher trapping efficiency. This is because with unregulated inlets, suspended sediment is resupplied daily inside the beel with tides. With flow regulation, sediments can enter the beel only half of the time because the inlets are closed and opened in 12 h cyclic order (see Section 2.4). The double time of beel opening without regulation results in higher sediment deposition. Remarkably, the same regulation scheme has very little effect for the RDF regime. The tidal range for the RDF regime is very small during the monsoon season; 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. Due to high water levels which rise and fall gradually with flood water and the absence of tide during the monsoon season in the RDF region, the regulation of flow inside the beel with gate operation has hardly any effect on sediment deposition inside the beel.

More sediment can be delivered to a beel with simultaneous gate operation than with the successive gate operation because two inlets are open at the same time instead of one. This obviously results in larger sediment deposition for TDF and MF regimes. However, the effect is opposite during monsoon for the RDF regime. When compared to successive gate operation with only one gate open, with simultaneous operation of two gates, a larger volume of water and sediment enters and leaves the beel during a tidal cycle, without sufficient time for the sediment to settle during the turn of the tide. As a result, more sediment returns without having settled to the feeding river during each gate operation cycle under the simultaneous gate scenario.

4.2 | Aggradation rates and sea level rise

When the annual rate of SLR 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 (Goodwin et al., 2018) to 9.8 mm/year for RCP8.5 (Kopp et al., 2017). Pethick and Orford (2013) explored the effect of local factors on the SLR such as fresh-water flow from inland and tidal amplitude in the estuary and predicted the effective SLR (ESLR) to be 12 to 16 mm/year with 14.1 mm/year in the Pasur estuary. In order to calculate the change in land elevation due to sediment accumulation, we consider the density of the sediments in the floodplain after these become part of the soil profile to be 1300 kg/m^3 as suggested by Allison and Kepple (2001) and Rogers and Overeem (2017) for GBM delta. The sediment accumulation for year-round operation of TRM by unregulated flow into the beel within the polder for RDF, MF and TDF regions are then estimated as about 0.57, 11.4 and 29 mm/year respectively.

Rogers and Overeem (2017) indicated that in the GBM delta the aggradation rates 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 Paramanik (2012), Talchabhadel et al. (2018) and van Staveren et al. (2017) investigated the beels within polders along the river reaches with TDF 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 TDF and MF region. As the polders designated by BWDB are within the tide-dominated and MF regions (Figure 1), controlled flooding by re-opening the polder during monsoon can potentially enable the polders to maintain the height to overcome projected RSLR and ESLR for the worst case scenario. However, if controlled flooding like TRM is carried out continuously for several years, the incremental land elevation inside the beel will increasingly cause the annual sediment accumulation to reduce over time (Adnan et al., 2020). However, the rate of SLR as well as the rate of subsidence have large uncertainties and wide ranges. As the average land elevation of RDF region is about 5–6 m AMSL with lowest land subsidence rate, it can safely be assumed that the associated polders in this region will not become flooded due to relative SLR by 2050. However, the region of tide-dominated and MF regimes will presumably shift upstream with SLR making TRM effective for larger areas in the future.

5 | CONCLUSIONS

We explored the potential of re-establishing sediment deposition in low-lying polder sections – 'beels' in the SW GBM delta to raise their land surface elevation. There are more than 100 polders in the SW GBM delta, whereas large parts of the river-dominated floodplain have been protected from flooding by embankments as well, which has turned these into forms of polders as well. To explore the sediment deposition potential inside the beels through breaching of its protecting dike, we carried out scenario analyses representing the seasonal variability of river discharge, SSC and tidal range in river branches across the delta, and applying different flow regulation operations for the beel. Our scenario analyses demonstrate that:

- Flow regimes and associated SSCs in the feeding river channels are the primary controls of sediment deposition inside a beel where TRM is operated. Total sediment deposition inside beels increases considerably along the downstream gradient from a river-dominated (north) to a tide-dominated (south) flow regime towards the coast. Sediment accumulation within beels along the reaches with a TDF regime is 28 times higher than along the reaches with RDF regime and 1.3 times higher than along the reaches of MF regime during the monsoon season. The higher average land elevation and lower SSC in the rivers of RDF regime results in much lower sediment deposition compared to tide dominated flow regimes. Even though sediment deposition during monsoon inside a beel along a river stretch with MF regime is comparable with deposition under a TDF regime, sediment deposition during pre-monsoon and dry seasons is substantially lower for a MF regime. Therefore, the potential for TRM is much higher in the region where the rivers have a TDF regime. With SLR the extent TDF regime will presumably shift inland making TRM effective for larger areas in the future.
- Seasonality of sediment deposition is evident for all three flow regions. Highest sediment accumulation inside the beel by re-opening the polder occurs during the monsoon season for all regimes of the southwestern GBM delta. Tidal range, SSC and river discharge varies seasonally and govern the sediment dynamics and sediment deposition inside the beel. Increase in river discharge, SSC along with relatively high tidal range result in larger sediment deposition inside the beel. Sediment accumulation is highest during monsoon owing to the highest river discharge and relatively higher SSC in the rivers providing highest sediment load, and lowest during dry season when river discharge and SSC in the feeder river is lowest. In the tide-dominated region the seasonal variation of sediment deposition is smaller compared to other regions, due to the strong tidal effect and small variation of SSC in all seasons.
- Sediment trapping efficiencies are low (order 10%), which is due to the small grain size of the sediment and inherently low settling rates, in combination high flow velocities associated with tidally filling and draining of the beel, only interrupted with brief periods of flow stagnancy that allow sediment to settle.
- Regulation of flow into the beel considerably affects total sediment deposition in the beel, as the associated 12-h period of water retention greatly increases trapping efficiency. However, flow regulation allows water to enter the beel for fewer tidal cycles than without flow regulation. This results in total sediment deposition being lower with regulated flow compared to unregulated flow. Unregulated flow results in highest sediment accumulation during monsoon for all the regions. Thus, it is potentially an effective means to increase sediment deposition.
- All the polders in the southwestern GBM delta are situated within the low-lying mixed and TDF regions. The average land elevation of the floodplain in the river-dominated region is several metres higher than the coastal region. The total sediment deposition inside the beel results in an increment of land elevation in all three regions, especially in tide-dominated and MF region during monsoon. For both mixed and TDF regions this annual rise of land elevation is larger than the projected RSLR and ESLR. In spite of the uncertainties inherent to projections of RSLR and ESLR until 2050 and beyond, the RDF region will remain situated above sea level, because the average land elevation is about 5–6 m AMSL.

The application of indigenous practice like TRM to re-introduce sedimentation inside beels through breaching of the dike of the polders, can effectively counteract the combined effects of projected SLR and land subsidence, even for the low elevation coastal zone of Bangladesh. This study illustrates that TDF region of SW Bangladesh has highest potential for sedimentation with flooding through dike breaches owing to the large tidal range and high sediment loads in the estuaries. Flooding the polders and tidal wetlands are currently being practiced in Rhine and Meuse delta of Netherlands, Scheldt Estuary of Belgium and Mekong delta of Vietnam. In other deltas worldwide with similar boundary conditions Practices like TRM may be an effective strategy to prevent the delta plain from drowning due to sea level rise.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

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

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