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Research papers

Enhancing effectiveness of tidal river management in southwest Bangladesh polders by improving sedimentation and shortening inundation time

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ABSTRACT

Bangladesh, one of the countries most vulnerable to climate change, is threatened by sea level rise (SLR) and land subsidence. The tidal river management (TRM) practised in coastal regions of Bangladesh has the potential to raise the land by sedimentation, to counteract SLR and subsidence. TRM is an indigenous method in which dikes are breached to readmit sediment-rich water into a polder, which results in sediment being deposited in depressions in the polder called 'beels', while simultaneously preventing silting-up of the tidal rivers. However, after several years of continuous sedimentation from TRM, deposition has been uneven and less than expected.

To study the effectiveness of TRM, this research analyses different scenarios to identify which operation schemes most effectively trap sediment to raise the land surface. The scenarios developed considered the number of inlets, flow regulation through the beel using open inlets or gated inlets with different operation schemes, and seasonality. The study area was Pakhimara Beel in southwest Bangladesh, where TRM is ongoing. To simulate the scenarios, a two-dimensional (2D) morphodynamic model with variable cell size was set up, calibrated and used. The simulation results were analysed for total sediment deposition, uniformity of spatial distribution of sediment deposition and trapping efficiency.

Sediment deposition shows clear seasonal variability, with greatest deposition in the pre-monsoon period, less during monsoon and least in the dry season. Greatest deposition combined with high spatial uniformity was found for TRM that uses two inlets located at opposite sides connected to different watercourses. Regulated flow using successively opened gates resulted in highest sediment deposition in all seasons, about double that of the existing situation without gate. However, given the complexity and cost of gate operation, TRM with two inlets located at opposite sides of the beel without flow regulation may be considered more feasible, and still effective despite 20–30% less sediment deposition. To also increase acceptability by local affected stakeholders we propose to restrict this improved TRM to the monsoon period, to allow crops to be grown on the land in the dry and pre-monsoon periods, and ensure salinity is minimized. Such well-planned TRM has the potential to also counteract sea level rise in sinking deltas elsewhere in the world by enhancing sedimentation.

1. Introduction

Bangladesh is one of the most natural disaster-prone countries in the world (Ali et al., 2012). According to the Long-Term Climate Risk Index, it is the sixth most affected country worldwide (Kreft et al., 2016), with cyclones, floods and droughts occurring almost yearly (Ha and Ahmad, 2015). Climate change will intensify and aggravate the situation in the Ganges-Brahmaputra-Meghna (GBM) delta of Bangladesh even more, as under the RCP (Representative Concentration Pathways) 8.5 scenario, the sea level rise (SLR) for the coast of Bangladesh is expected to increase to 0.3 m by 2050, relative to global mean sea level (GMSL) between 1986 and 2005 (Davis et al., 2018). Land subsidence rates of more than 5 mm/year (Brown and Nicholls, 2015) for the coastal areas will further exacerbate the rate of relative SLR. The coastal zone of Bangladesh has an area of about 47,201 km^2 (Ahmad, 2019), of which 62% is less than 3 m above MSL (mean sea level) and 86% is less than 5 m above MSL (Mohal et al., 2006). The population in the coastal zone was 35 million in 2003 and is projected to have increased to 58 million by 2050 (Dasgupta et al., 2014). Relative SLR will therefore directly affect tens of millions of people (Ericson et al., 2005) by increasing flood risk, intensifying saltwater intrusion and reducing agricultural production (Brown and Nicholls,

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2015).

In the coastal areas of Bangladesh there are over 100 polders, all created in the 1960s and 1970s (Ali, 2002) with the primary objective of affording protection against tidal flooding (Mondal et al., 2006). Ishtiaque et al. (2017) found that before the dikes enclosing the polders were built in the 196s, the land in the southwest delta of Bangladesh was subsiding by 5–7 mm/year, which was compensated by sedimentation during seasonal flooding of the delta plain. Since the 1960s, the polders have lost up to 1.5 m elevation relative to the mean water level of the surrounding water bodies because the dikes have interrupted sediment accretion and subsidence has occurred (Auerbach et al., 2015). In contrast, the elevation in the southern Sundarbans (an area of unprotected mangrove forest) kept up with the mean water level of the surrounding water bodies owing to sedimentation during tidal floods (Auerbach et al., 2015). As dikes interrupt the natural tidal flow and associated overbank deposition, the adjacent tidal rivers have silted up, causing prolonged water logging and drainage congestion in the polders (Rashid et al., 2013). Due to the elevation loss of the polders and siltation of river channels, the dikes have become increasingly prone to failure through breaching and overtopping (Ishtiaque et al., 2017).

In the lowest parts of the polders, called 'beels', surface runoff accumulates through the internal polder drainage channels (Chakraborty, 2009). Beels are formed by land erosion and subsidence, and are located close to the river channels (Amir and Khan, 2019). They are commonly used for agriculture in the dry winter season and for aquaculture during the monsoon, when they are flooded by surface runoff (Chakraborty, 2009). Dakatia Beel, northwest of Khulna city, is the largest beel in southwest Bangladesh and is located in polder 25 (Fig. 1), which was constructed in the 1960s (van Staveren et al., 2017). It has faced severe water logging problems since 1982. A mass community mobilization in 1990 resulted in non-authorized breaching of the dike of polder 25 to drain the water from inside the polder (van Staveren et al., 2017). The breaching of the dike restored the tidal dynamics between the river and Dakatia Beel and increased the beel's surface elevation, due to renewed sedimentation. This event led to the introduction of the concept of 'Tidal River Management' (TRM). TRM involves re-opening the connection between the channel and its polder, so-called depoldering, aiming at controlled flooding of polders to re-establish sediment accretion (Auerbach et al., 2015). Since the rivers in the GBM delta carry more than a billion tons of sediment per year (Islam et al., 1999), TRM, if implemented properly, may have great potential to restore sediment accretion in the polders. With TRM, the surface elevation will rise, reducing the flood risks from SLR and subsidence (Rogers and Overeem, 2017). Accordingly, the Bangladesh Water Development Board (BWDB) has initiated several TRM projects (van Staveren et al., 2017).

Depoldering and controlled flooding are not new concepts. The Netherlands, the inspiration for the polders in the coastal areas of Bangladesh, has used depoldering in the 'Room for the River' project to facilitate river discharge for flood prevention (van Staveren et al., 2014, van der Deijl et al., 2018, Verschelling, 2018). Controlled flooding is also used in the Mekong delta to reduce the peak discharge in the river and bring sediments and nutrients to the flood plain (van Staveren

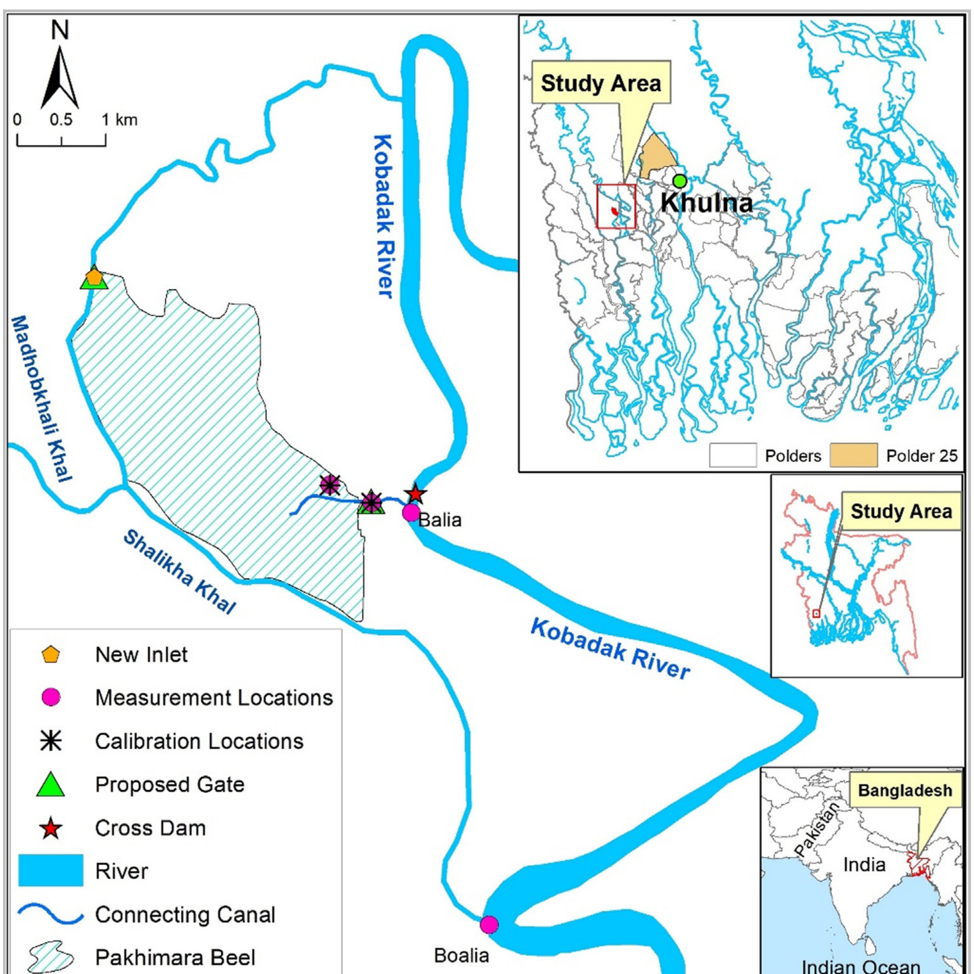

Fig. 1. Location map of Pakhimara Beel.

et al., 2018). An additional benefit is that as a result of the controlled flooding, pests and acid in the soils are flushed away (Kosmas, 2014), as demonstrated by the higher food productivity and household income from livestock at former TRM sites compared with elsewhere in the region (Masud and Azad, 2018; Masud et al., 2018).

A remaining major challenge for TRM is to ensure that the polder captures adequate amounts of sediment and the sediment is distributed evenly over the polder (cf. Gain et al., 2017; Amir et al., 2013). A recent survey conducted at Pakhimara Beel (since 2015, an area in southwest Bangladesh with active TRM) revealed that sedimentation mostly occurred close to the inlet (IWM, 2017). Parts of a polder where less sediment accumulates will remain low and experience prolonged flooding during the monsoon. The prolonged flooding and uneven sedimentation, as well as the lack of alternative livelihoods, lack of proper compensation and lack of participation of local residents during the flooding all challenge the effectiveness of TRM (de Die, 2013).

To achieve a more uniform spreading of sediments inside a beel, Amir et al. (2013) modelled the effects of compartmentalization of a beel with dikes, and a gradual removal of the dikes along the connecting canal with unregulated flow. Additional canals were simulated that connect the beel with the adjacent river network in order to bring water containing suspended sediment into part of the beel further away from the inlet. These simulated interventions showed positive results with elevation inside the beel rising more evenly. However, implementing this scenario would require large investment in compartmentalizing with dikes, developing of connecting canals and modifying the dikes along the canal banks. It would also require TRM to operate continuously for at least 4 years. The dependency of sedimentation inside the beel on inlet width and river discharge has been numerically simulated by Talchabhadel et al. (2017). Varying the width of an inlet did not affect the amount of sediment deposition in a beel, but more important controls for sedimentation were the angle of flow entering the beel and the water discharge into the beel (Talchabhadel et al, 2016). Using two inlets connected to the same river and located several kilometres apart did not increase the amounts of sediment deposition within a beel (Talchabhadel et al, 2018). More generally, sedimentation inside a beel was shown to depend on flow velocity, particle size (van Rijn, 1993), river discharge (Verschelling et al., 2017) and location of the inlet (Talchabhadel et al., 2017). In spite of these previous studies, some critical controls of effectiveness of TRM in a beel remain to be investigated. These are the effect of using multiple inlets located in opposite corners of the beel and connected to different feeding channels that regulate the flow into and out of the beel by means of gates.

Enlarged and uniform sedimentation combined with making land available during a part of the year may increase the effectiveness of TRM and its acceptance by local residents. Our study therefore aimed to determine whether sediment accumulation in beels of the GBM delta can be optimized using multiple inlets and flow regulation using gates. We investigated this for a beel in the southwest GBM delta where TRM is currently ongoing, using a 2D morphodynamic model to simulate sediment deposition as a function of number of inlets and flow regulation. We analysed the effects of these scenarios on sediment deposition in the beel for different seasons, to explore whether regulated flooding can be limited to a single season so that the land may be available for the rest of the year.

2. Study area

Pakhimara Beel, located in the southwest of Bangladesh, has been subjected to TRM since 2015 (Gain et al., 2017), and was selected as study area for this research. Pakhimara Beel is under the administrative jurisdiction of Tala Upazila (sub-district) within Satkhira District, which is located inside the Khulna Division in the southwestern region of Bangladesh. The study area stretches from 22°41′45.27″N, 89°13′33.02″E to 22°39′33.93″N, 89°15′16.64″E and covers 730 ha (Gain et al., 2017). The river Kobadak flows along the beel on the eastern side and a canal called Sarulia-Shalikha Khal flows along the western side of the area (Fig. 1). At present, Pakhimara Beel is connected to the Kobadak river through an inlet and a connecting canal (IWM, 2017). The flow through the canal into the beel is not regulated by gates. Entire Pakhimara Beel is influenced by tidal cycles. The Sarulia-Shalikha Khal meets the Kobadak river about 10 km downstream of the beel (Fig. 1).

Before TRM started, the mean elevation of Pakhimara Beel was 0.57 m PWD (PWD is the datum for the Public Works Department of Bangladesh with the zero datum at 0.46 m below MSL; Sarwar, 2013) and the beel had an average slope of 0.2% (survey conducted by IWM (Institute of water modelling); IWM, 2010). Pakhimara Beel is surrounded by dikes, and a 1.5-km long connecting canal with maximum bottom width of 40 m was constructed for this TRM project (IWM, 2010; 2017). A cross dam on the Kobadak river was constructed just upstream of the inlet of Pakhimara Beel, to ensure that during the dry season and pre-monsoon, the tidal water flow coming from the south through the Kobadak river enters the beel. The cross dam was removed during monsoon to drain the flood water from upstream.

After 1.5 years of TRM, the land level of Pakhimara Beel was surveyed by IWM and compared with the pre-TRM situation, which revealed uneven sedimentation and areas with less surface level increment (IWM, 2017). A land levelling survey by IWM and satellite images made during TRM operation demonstrated that most of the suspended sediment entering the beel had settled close to the inlet and had not reached the other side of the beel. Consequently, about 200 ha in the beel with least sediment deposition will remain flooded for a long time during the wet season even after TRM has ended.

3. Methods

3.1. Data collection

Data for understanding and developing of the present situation and for establishing the future scenarios were collected from secondary sources such as governmental and non-governmental research organizations, reports and published literature (Table 1). TRM started officially in Pakhimara Beel in August 2015 (Gain et al., 2017). At the inlet canal, water level, discharge and suspended sediment concentration (SSC) were recorded by IWM (IWM, 2017). IWM also carried out a land level survey of Pakhimara Beel after 1.5 years of TRM operation, to document the spatial distribution of sediment accumulation. The average land level of the study area was 0.57 m PWD before TRM and had increased to 1.17 m PWD after 1.5 years of TRM. Although water level data were collected for most of the 1.5 years of TRM operation at several locations (Fig. 1), discharge and SSC were measured periodically on only a few days, covering one complete tidal cycle (12 h) for each day of measurement. The water level, discharge and SSC monitoring locations of IWM are presented in Fig. 1.

For TRM, Pakhimara Beel was connected to the river via a connecting canal and a cross dam was constructed across the river just north of the inlet of the connecting canal, to ensure that during high tide, the incoming flow through the lower river channel from the coastal zone enters the Beel (IWM, 2017). The connecting canal has a bottom width of 40 m at −1.1 m PWD and is 1.5 km long (IWM, 2010). The flow through the connecting canal inside the beel is not regulated by gates (IWM, 2017).

Flow regimes in Bangladesh show seasonality in three periods (Ahmed et al., 2016): pre-monsoon (March to May), monsoon (June to October) and dry (November to February). The observed water levels indicated that the river's tidal range varies greatly between seasons. Average tidal ranges are 2.4 m during the pre-monsoon, 1.5 m during the monsoon, and 2 m during the dry season. The SSCs measured at Balia on Kobadak River demonstrate that the SSC also varies with season (average SSC is 0.84 kg/m^3 during the pre-monsoon, 0.58 kg/m^3 during the monsoon, and 0.37 kg/m^3 during the dry season), with the

Table 1
Overview of the collected data.

Type of Data	Monitoring Period	Method of data collection	Reference
Land surface elevation	2010 and 2017	DGPS; levelling instrument	IWM (2010; 2017)
Land use	2011	Field survey	Ministry of Land, Bangladesh
Hydrometric: Water level	September 2015 – October 2016; January – April 2017	Staff gauge and pressure cell	IWM (2017)
Hydrometric: Discharge	August – September 2016; February – April 2016; March – April 2017	ADCP	IWM (2017)
Suspended sediment concentration	November – December 2015; February – April 2016; August – September 2016; March – April 2017; all from 06.00 h to 18.00 h daily at 1 hourly intervals	Pump bottle sampler	IWM (2017)
Salinity	September 2015 – October 2016; January – April 2017	EC meter	IWM (2017)
Canal and river alignment and cross sections	January, March, June, August, November 2016	Echo-sounder	IWM (2017)
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

highest SSC occurring in April. SSCs were measured by IWM over a two-week period to capture the effect of spring and neap tides. The suspended sediments are cohesive with a median grain size less than 63 µm. Average salinity of the water inside Pakhimara Beel was 8.5 PSU during the pre-monsoon, 1.7 PSU during the monsoon and 5.1 PSU during the dry season.

3.2. Setup of the 2D mathematical model

A two-dimensional (2D) numerical morphodynamic model was set up for the study area using Mike 21FM, developed by DHI, in which hydrodynamic processes, sediment transport and changes in bed topology are simulated dynamically using a flexible mesh (DHI, 2012a, 2012b). Mike 21FM uses an approximate Riemann solver to calculate the convective fluxes at the interface of the cell of the 2D mesh. For the calculation of cohesive sediment transport, Mike 21 FM uses Mud Transport (MT) module. This module is used for transport of sediment with grain size less than 63 µm (DHI, 2012b). It uses the advection-dispersion equation (ADE), which is solved using the third-order finite difference scheme known as the ULTIMATE scheme based on QUICKEST (DHI, 2012b). For morphological simulations, the bed topography is updated for each time step by taking account of net sedimentation (DHI, 2012b).

A 2D model with the bed topography of Pakhimara Beel was setup in Mike 21FM, where the 2D cells are triangular. The surface area of the mesh cells varied from 170.5 m^2 to 5000 m^2. To reduce computational costs, finer mesh was used to represent the inlet canal and coarser mesh was used for the floodplain (Fig. 2). As the grain size of the sediment conveyed into the beel is less than 63 µm (IWM, 2010), the MT module for cohesive sediment transport was used as the mathematical modelling tool. Settling and re-entrainment of fine sediments are simulated using the concepts of Krone (1962) and depend on the ratio between actual shear stress of the flow and critical shear stress for deposition and re-entrainment of sediment particles. The model setup was used for simulating the period for which data were available (Table 1). The Manning coefficient, sediment settling velocity and critical shear stress for settling were determined by calibration. From the available data (Table 1), three consecutive 14-day periods were selected, representing pre-monsoon (April), monsoon (August) and dry (February) seasons. For these three periods, measured hourly water levels and SSC at the Balia measurment point (Fig. 1) were used as input for the model to determine sediment deposition during each of the main hydrological seasons. After calibration, the model was used for different scenarios, to study the sediment dynamics inside the beel and to identify the scenario with maximum sedimentation, maximum trapping efficiency and most spatially uniform sediment distribution.

3.3. Sensitivity analysis and model calibration

A sensitivity analysis was carried out to understand how different parameters affect the model results. For the hydrodynamic module, the sensitivity of discharge and water level to varying roughness coefficient (Manning coefficient) was investigated. The hydrodynamic model was simulated by varying the Manning coefficient within the range of 0.1 s/$m^{1/3}$ to 0.01 s/$m^{1/3}$. For the morphodynamic module, the effects of varying critical shear stress and the settling velocity on the suspended load were determined. The critical shear stress for settling was varied from 0.01 N/m^2 to 0.1 N/m^2 and settling velocity was varied from 0.0001 m/s to 0.001 m/s. These ranges were selected considering the values presented by Barua et al. (1994) for the sediments in the Meghna Estuary.

The model was calibrated for the present-day situation by comparing observed water levels, discharge and SSC at the connecting canal to the beel, and water levels inside the beel ('calibration' locations in Fig. 1) to simulated values by the model. This was complemented by visual comparison of patterns observed in field surveys (IWM, 2017) with those generated by the model. Due to the lack of available observation data, no further validation of the model could be performed.

To quantify the model performance, the coefficient of determination (R^2), normalized root mean square error (NRMSE), percentage model bias (PB) and Nash-Sutcliffe model efficiency (ME) were calculated by comparing the modelled results with the field data for the different variables (Table 2), and observed vs modelled data were plotted (Fig. 3). The calculated goodness of fit and the plots of observed vs modelled data for the developed model indicate that the calibrated model resulted in good agreement between the observed and simulated data (Allen et al., 2007) and therefore the calibrated model was subsequently used to simulate sediment deposition in the beel for the scenarios.

3.4. Development of scenarios

21 scenarios were developed to determine how the sediment dynamics inside Pakhimara Beel depend on the number of inlets (one or two), the control of water flow and the amount of suspended sediment entering the beel. This was investigated for the three main hydrological seasons. The scenario matrix developed considering the combination of the different conditions is presented in Table 3.

We considered the situation with a single inlet, at the existing location or at a new location. The new inlet was positioned at the opposite side of Pakhimara Beel farthest away from the existing inlet (Fig. 1), adjacent to the river network with no connecting canal. The dimensions of the new inlet were the same as those of the existing inlet. Moreover, the same time series data of water level, discharge and SSC

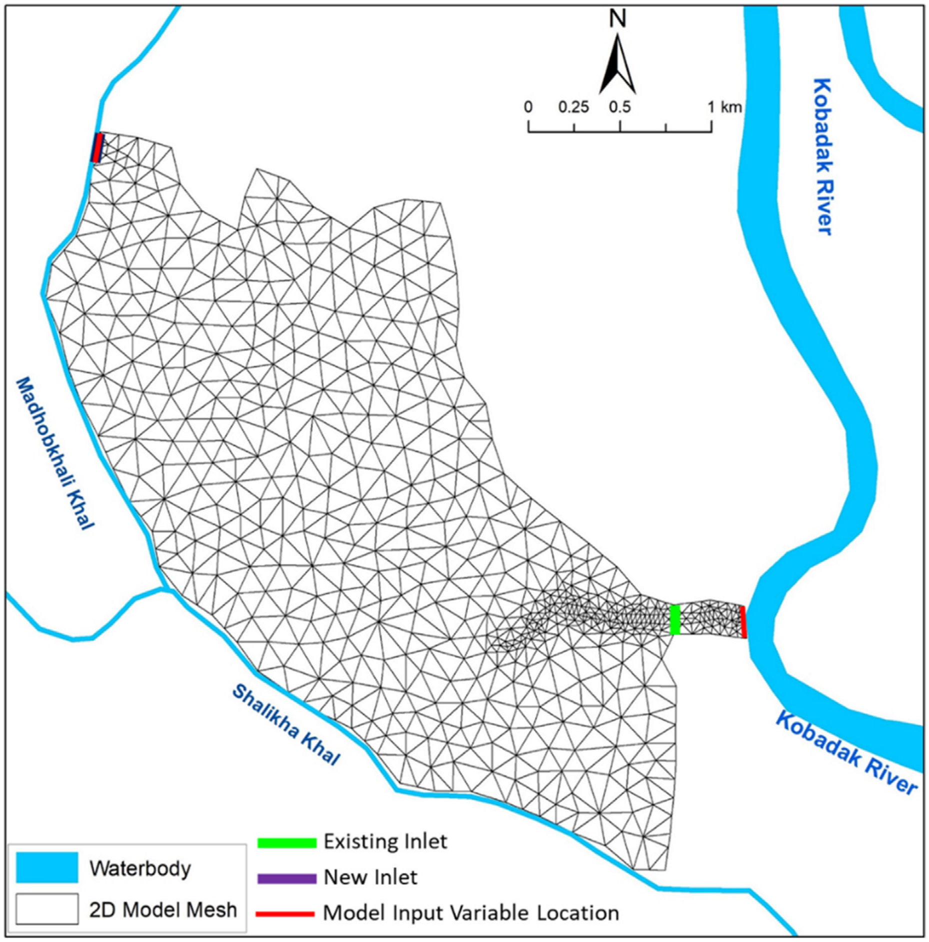

Fig. 2. The extent and mesh of the 2D mathematical model.

Table 2
The goodness of fit of the 2D model for water level, discharge and SSC.

	Connecting Canal			Pakhimara Beel
	Water Level	Discharge	SSC	Water Level
R^2	0.87	0.88	0.84	0.85
NRMSE (%)	9.7	16.6	18.3	11.6
Percentage model bias (PB)	0.28	17.3	17.9	0.43
Nash-Sutcliffe model efficiency (ME)	0.87	0.89	0.56	0.85

was applied for both inlets. For the existing inlet, a canal 1.5 km long into the beel was assumed to represent the actual situation. We also considered a situation with these two inlets working in combination.

We analysed the regulation of opening of the inlets by assuming there were gates in the inlets and that these remain open for 12 h to allow sediment-rich water to flow into the beel, and are then closed during the next 12 h so that during the 12 h that the floodwater remains stagnant in the beel the sediment can settle. Two gate operation schemes were utilized for the scenarios with two inlets: simultaneous and successive. For simultaneous gate operation, the gates were opened and closed simultaneously at both inlets (Fig. 4). For the successive gate operation of two inlets, first one gate was opened to admit inflow and then closed to retain the water, and later the other gate was opened to release the water (Fig. 5). Allowing inflow through one inlet and releasing through the other was done to ensure through flow across Pakhimara Beel. For both situations, the water was retained for 12 h in the beel before it was released (Fig. 5). As gates are operated manually in Bangladesh, in the simulations it was assumed that the opening and closing of the gate requires 1 h.

3.5. Analysis of the results

The existing operation of the TRM for Pakhimara Beel was simulated to calibrate the model. Further, the model results were analysed for different scenarios and compared in terms of i) the total mass of sedimentation for the seasons, ii) trapping efficiency, iii) the spatial distribution of sediments, and iv) uniformity of sedimentation. Sediment deposition for different seasons was estimated using the results of the representative 14 days of simulation and extrapolated for the total number of days in a season. Trapping efficiency was calculated as the fraction of the incoming suspended sediment that is retained or deposited within the beel (cf. Verschelling et al., 2017). The spatial distribution was evaluated using maps of sediment deposition. Spatial uniformity of sedimentation was analysed by plotting sediment deposition against cumulative percentage of total area covered.

4. Results

4.1. Sensitivity and calibration of the model

The sensitivity analysis was carried out by varying the roughness coefficient, critical shear stress and settling velocity. Discharge and water level are clearly affected by the roughness coefficient (Manning coefficient) (Fig. 6). The SSCs show little variation for varying critical shear stress (Fig. 7a), but show a stronger dependency on settling velocity (Fig. 7b).

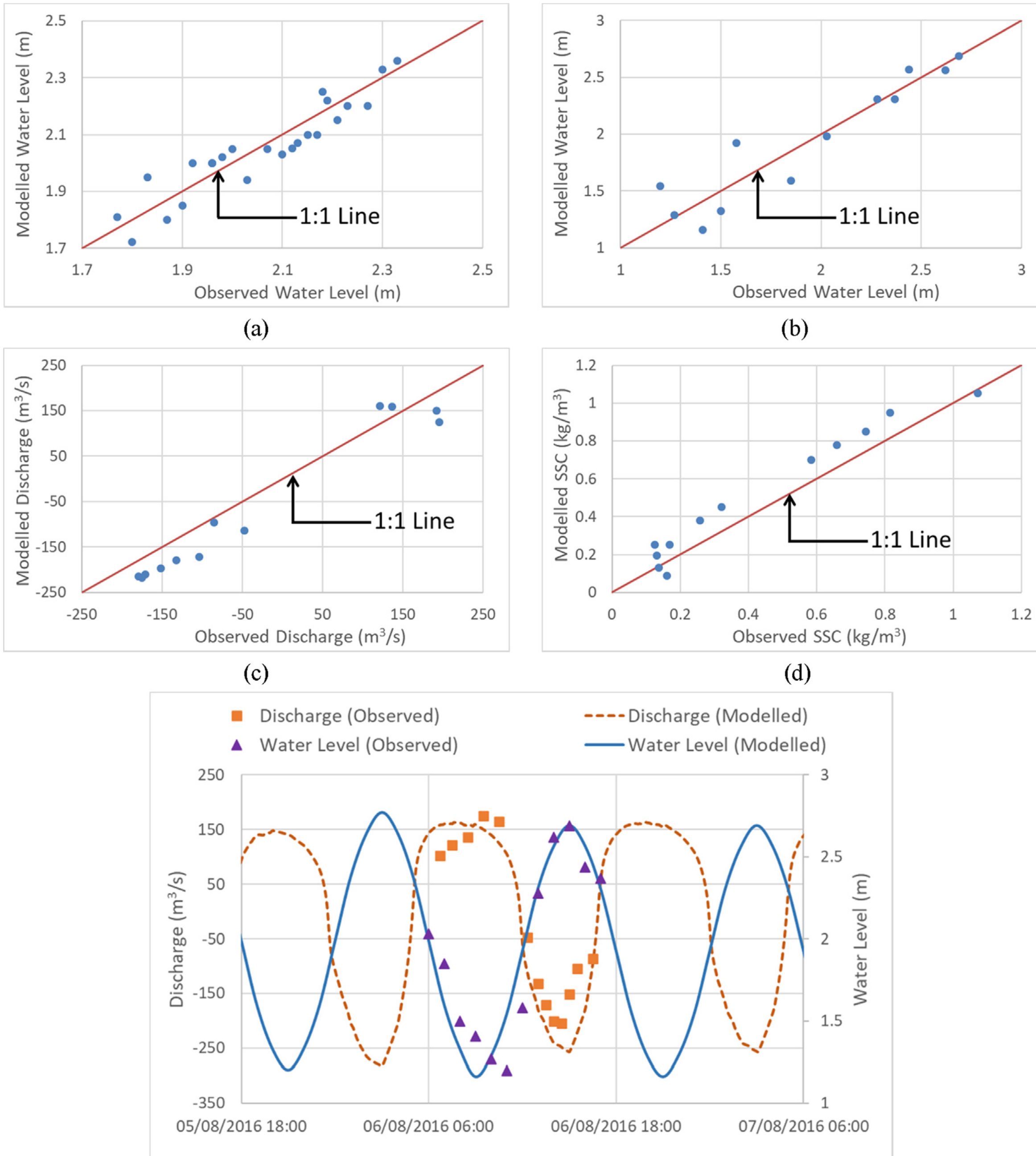

Fig. 3. The observed data vs modelled water levels inside Pakhimara Beel (a), and water level (b), discharge (c), SSC (d) and time series of water level and discharge (e) at the connecting canal.

Table 3
Scenario matrix with respect to season, number of inlets and gate operation modes.

Season	Inlet Conditions						
	Single inlet				Two Inlets		
	Existing		Proposed (New)		Permanent	Regulated	
Pre-monsoon	Open	Regulated	Open	Regulated	Open	Simultaneous	Successive
Monsoon	Open	Regulated	Open	Regulated	Open	Simultaneous	Successive
Dry	Open	Regulated	Open	Regulated	Open	Simultaneous	Successive

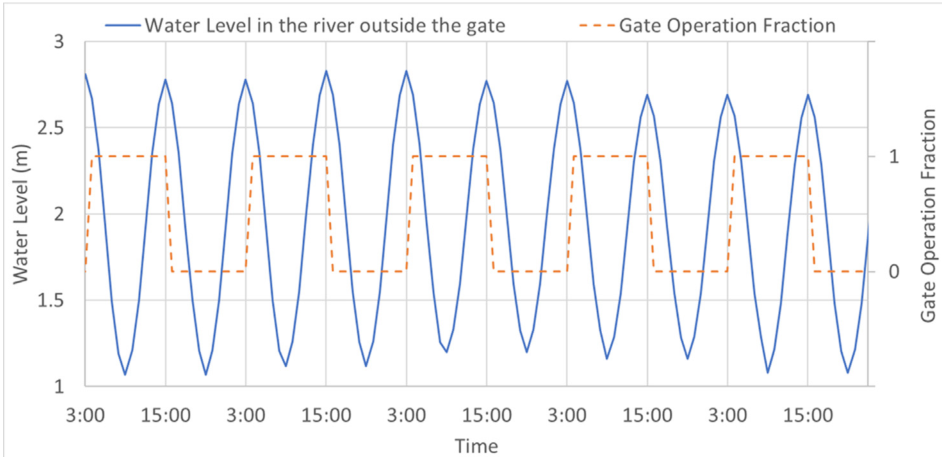

Fig. 4. The cyclicity of water level in the river outside the gate and operation of the gates (1 = Open, 0 = Closed) for the scenario with both gates operating simultaneously.

The best model performance was obtained for a Manning coefficient equal to 0.04 s/m$^{1/3}$ and settling velocity equal to 0.05 cm/s. The Manning coefficient used is consistent with the value suggested by Talchabhadel et al. (2018) for Khuksia Beel which is adjacent to our study area and the settling velocity used is within the range suggested by Hale et al. (2019) for the southern GBM delta. Subsequent model simulations were done using these parameter settings. With ± 10% change in the calibrated value of the Manning coefficient, the ranges of calculated R^2 were 0.57 to 0.63 for water level, 0.56 to 0.62 for discharge and 0.75 to 0.78 for SSC. With ± 10% change in the calibrated value of the settling velocity, the ranges of R^2 were 0.78 to 0.80 for water level, 0.77 to 0.79 for discharge and 0.57 to 0.65 for SSC.

4.2. Sediment deposition

The simulated sediment deposition in the beel for different seasons shows clear seasonal variability, with the greatest deposition in the pre-monsoon period and the least in the dry season (Fig. 8a). Simulated total sediment deposition for the pre-monsoon scenarios is 20 to 30% more than for the monsoon scenarios. In the scenario of two inlets with successive gate operation sediment deposition is about double that of the existing situation without gate for all three seasons (Fig. 8). The location of the inlet does not affect total sediment deposition. Sediment deposition increases with two inlets, regardless of flow regulation with gates. However, flow regulation results in more sediment deposition, with most deposition occurring when using two inlets with successive gates. Two inlets without gates and simultaneous gates result in similar estimated sediment deposition.

4.3. Trapping efficiency

To understand the differences in potential of sediment deposition among the scenarios, trapping efficiency was calculated as the ratio of the amount of sediment retained by the beel over the suspended sediment load delivered into the beel (Fig. 8b). Calculated trapping efficiency indicates that for the scenarios with flow regulation using gates only 7–23% of the suspended sediment entering the beel is retained. The highest value (23.2%) is found for the scenario using two inlets with simultaneous gate operation during the dry season. Using one or two inlets without gates does not affect trapping efficiency, but flow regulation increases the trapping efficiency substantially. Gate operation also affects the trapping efficiency, with the simultaneous gate operation scenario resulting in higher efficiency than the scenario with successively opening the gates.

4.4. Spatial distribution of sediment deposition

The spatial variation in simulated sediment deposition for the monsoon scenarios is illustrated in Fig. 9. Sediment deposition occurs in about two-thirds of the beel when a single inlet is used, regardless of its location or whether flow is regulated. When using two inlets, sedimentation occurs over the entire Pakhimara Beel. For the two-inlet

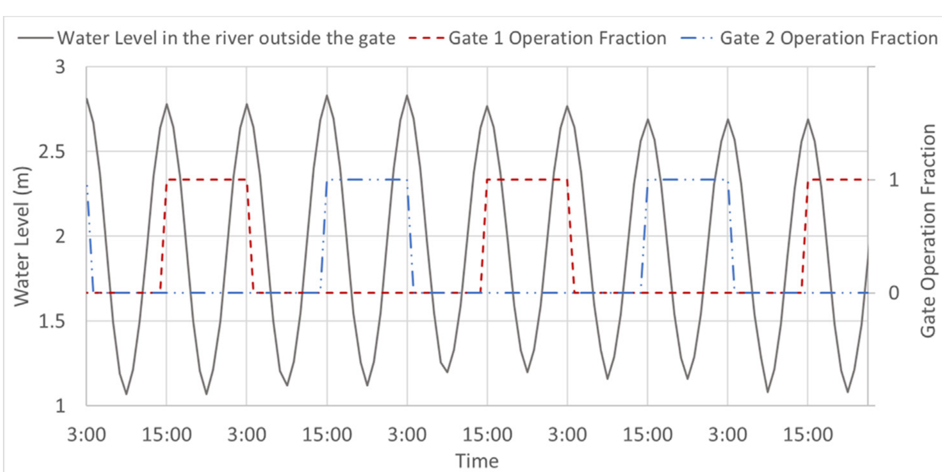

Fig. 5. The cyclicity of water level in the river outside the gate and operation of the gates (1 = Open, 0 = Closed) for the scenario with "successive" gate operation.

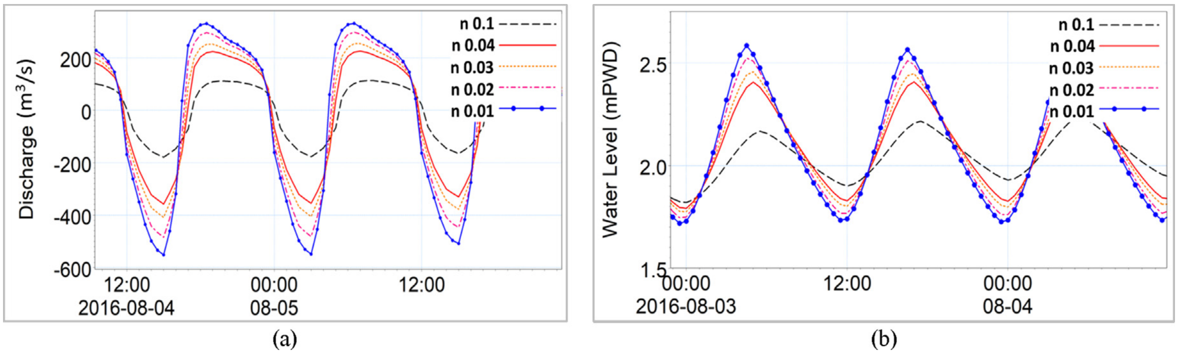

Fig. 6. The effect of the Manning coefficient on the discharge (a) and water level (b) in the beel.

situation, flow regulation using gates leads to more sediment deposition (Fig. 8a), with a similar extent of sedimentation (Fig. 9).

The plot of sediment deposition against cumulative percent area indicates that with a single inlet about 30% of the total area experiences no or little sediment deposition, regardless of the inlet position or the flow regulation using gates (Fig. 10). For two inlets, about 5% of total area experiences no or little sediment deposition, and sediment deposition increases and almost doubles by comparison with the situation with a single inlet (Fig. 8a). Remarkably, applying two inlets with successive gates increases total sediment deposition (Fig. 8a), but the spatial uniformity decreases (Fig. 10). Two inlets without gates and with simultaneous gates result in similarly uniform sediment accumulation.

5. Discussion

This research explored how to optimize TRM to improve its efficiency in trapping sediment. A calibrated 2D morphodynamic model was used to simulate multiple scenarios considering the seasonality, number of inlets, non-regulated and regulated flow using gates and different operating regimes for the gates.

Our model results show that there is a strong seasonality in sediment deposition, with the greatest deposition occurring during pre-monsoon (Fig. 8a). This is related to the seasonal variation of the discharge and the SSC of the Kodabak river at the inlet, which is in accordance with the findings of Talchabhadel et al. (2016). The tidal range and the SSC in the rivers are highest during the pre-monsoon, resulting in the water that enters the beel being more sediment-rich. Although the SSC is lower in the monsoon than pre-monsoon, the total sediment load in the river and into the beel is higher. This is due to highest discharge and water level, and relatively high SSC in the river during monsoon season. However, due to tidal range being less in the monsoon than in the pre-monsoon season, the daily amounts of water and sediment entering the beel were are during the monsoon than during the pre-monsoon, and therefore sediment deposition in the beel is greatest during pre-monsoon.

The number and location of inlets, and the water body that feeds them, play a critical role in sediment deposition inside the beel. Both Amir et al. (2013) and Talchabhadel et al. (2018) have indicated that multiple inlets connected to the same river do not substantially increase the sedimentation inside the beel. Amir et al. (2013) show that multiple inlets connected to the same river resulted in a more uniform spatial distribution of sedimentation even though total sedimentation was not substantially higher. Talchabhadel et al. (2018) suggest exploring whether an additional inlet close to the zone of the lowest sedimentation inside the beel would achieve more sediment deposition and a more uniform spatial distribution of deposition. Our results confirm that using two inlets located at opposite sides of the beel and connected to different watercourses increases both the total sediment deposition (Fig. 8a) and the spatial uniformity of sediment deposition (Fig. 9 and Fig. 10). With a single inlet, suspended sediment from the river cannot reach the areas far from the inlet during a tidal cycle.

Our results show that flow regulation into the beel with gates can increase total sediment deposition (Fig. 8a). As long as flow velocities and inherent shear stresses in the flow exceed the critical values for deposition, the sediment particles will remain in suspension (Unal 2018). When shear stress decreases as a result of decreasing flow velocity (Mehta, 1988), deposition will start to occur (Unal, 2018). This is particularly the case in the scenarios with gate operation that causes the floodwater to stagnate for 12 h in the beel, resulting in high trapping efficiency (Fig. 8b). In contrast, with two inlets and unregulated flow, the water inside the beel is constantly moving with the tides, rendering

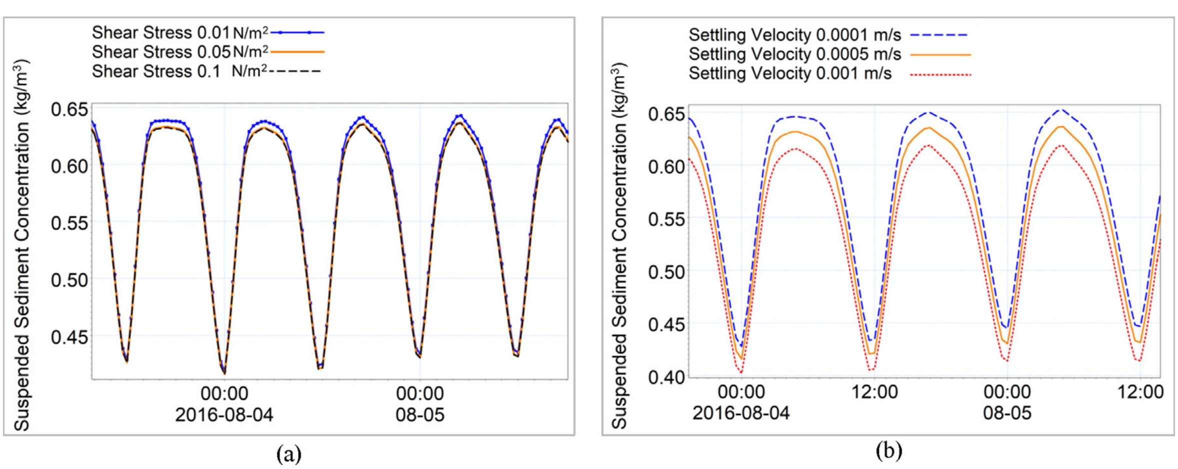

Fig. 7. Effect of varying critical shear stress for deposition (a) and settling velocity (b) on the suspended sediment concentration of the flood water within the beel.

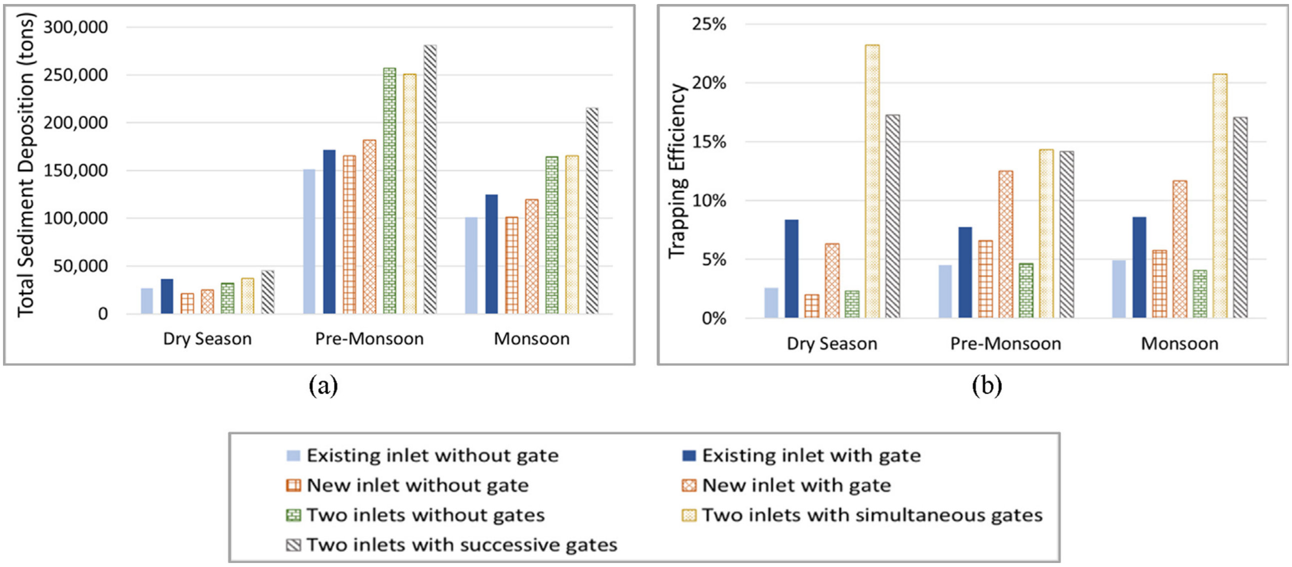

Fig. 8. Estimated total sediment deposition (a) and trapping efficiency (b) for different seasons and scenarios.

trapping efficiency low. Still, as gates prevent flow from the river from entering the beel for 12 h in cyclic order, the total sediment load delivered inside the beel becomes lower than when flow is unregulated. The resulting total deposition for two inlets with unregulated flow is roughly the same as that for two inlets with regulated flow with gates operated simultaneously. The scenario of two inlets where flow is regulated with successive gate operation results in the lowest average velocity and consequently the greatest total deposition. For the successive gate operation schemes, the suspended sediment-rich water enters through one inlet gate, and after a 12-hour period of water stagnancy to allow the sediment to settle the water drains through the other gate. It seems that the flow velocities during the drainage stage of the beel are too low for deposited sediment to be resuspended, resulting in large sediment deposition. However, constructing gates is resource-intensive and the gates require regular maintenance. Constructing gates for an inlet 40 m wide may cost over 1 million euros, assuming the rates paid for construction work in Government of Bangladesh development projects (GoB, 2005). Ensuring that regular maintenance is carried out may also prove difficult, as during the field visits several existing gates were found non-operational or in need of maintenance.

Verschelling et al. (2017) explored the effect of different variables, such as inlet discharge, wind speed and direction on the trapping efficiency of a depoldered area similar to a beel with unregulated flow. They found that the sediment trapping efficiency in their study area depended largely on the inlet discharge. Their study indicated that larger inlet discharge results in increase of total amount of sediment retained and reduction in trapping efficiency. The larger inlet discharge corresponds to increased influx of sediment and more sedimentation on the tidal flats. However, the increase of shear stress during high discharge events cause most of the fine sediments to stay in suspension and result in reduction of trapping efficiency. In our study area, inlet discharge varies seasonally. Accordingly, trapping efficiency from our model results also shows considerable seasonal differences generally ranging from 5 to 15% and with the highest value of 23% for two inlets with simultaneous gates during the dry season (Fig. 8b). Under current TRM practice, the flooding of land occurs for several years, which dramatically restricts the livelihoods and economic activities of the local people. Seasonal operation of TRM with flow regulation by gates would provide the opportunity to flood the land for only part of the year, making the land available for agriculture during the rest of the year. Although pre-monsoonal TRM would yield the most sediment deposition, monsoonal TRM would minimize the salinity of inflowing water and sediment, which would have positive effects on crop production. Sediment deposition would still be high and only 20–30% less than during the pre-monsoon. Making the land available for crop production in the dry and pre-monsoon period (October to May) would greatly enlarge the effectiveness of TRM. Seasonal TRM operation was already being practised in the pre-polder era in the southwest region, referred to as “Ostomasi Badh” (van Staveren et al., 2017).

Data collected throughout the year, especially while the TRM was ongoing, would have provided essential information on the impact of TRM on the river and the beel. Nevertheless, our model simulations provide a first understanding of this process and its impacts. All the simulations in this research were done for 14 consecutive days covering spring and neap tides. Furthermore, taking 14-day time windows representing different seasons allowed us to quantify and understand seasonality effects. In reality, sediment deposition will also vary during the seasons, along with the variations in SSC and river flow. If long-term data become available, the simulation should be done for at least an entire year. The analysis of the reliability of model results revealed that the model was able to replicate the existing conditions fairly well (Table 2). As the results indicate that the tidal range plays a vital role in sediment dynamics, the next step should be to explore more areas closer to the sea as well as inland to study the effects on sediment deposition in beels. And as the SSC is an important variable, it is essential to further explore the sediment dynamics in the river in relation to seasonality and sediment availability. Finally, it should be investigated to what extent reintroducing of sediment trapping in de-poldered areas of the lower GMB delta would affect sediment loads and further silting-up of the lower delta river channels.

Converting the simulated amounts of deposition during pre-monsoon season to estimates of increase in land elevation, thereby assuming an effective soil density of 1300 kg/m^3, the re-introduction of sediment deposition in this beel would result in a rise of the landsurface in the order of 18 mm and 20 mm per year for the scenarios of single inlet without and with flow regulation using gate, and 28 mm/yr for the scenarios of two inlets without flow regulation, 28 mm/yr and 31 mm/yr for two inlets with simultaneous and successive gate operation. These values are about two times (for the scenarios of single inlet) to three times (for the scenarios of two inlets) as high as the relative sea level rise considering the yearly rates of subsidence (Brown and Nicholls, 2015) and sea level rise (Davis et al., 2018). This implies that seasonal operation of TRM indeed may be an efficient strategy to raise the polder land surface to counteract relative sea level rise.

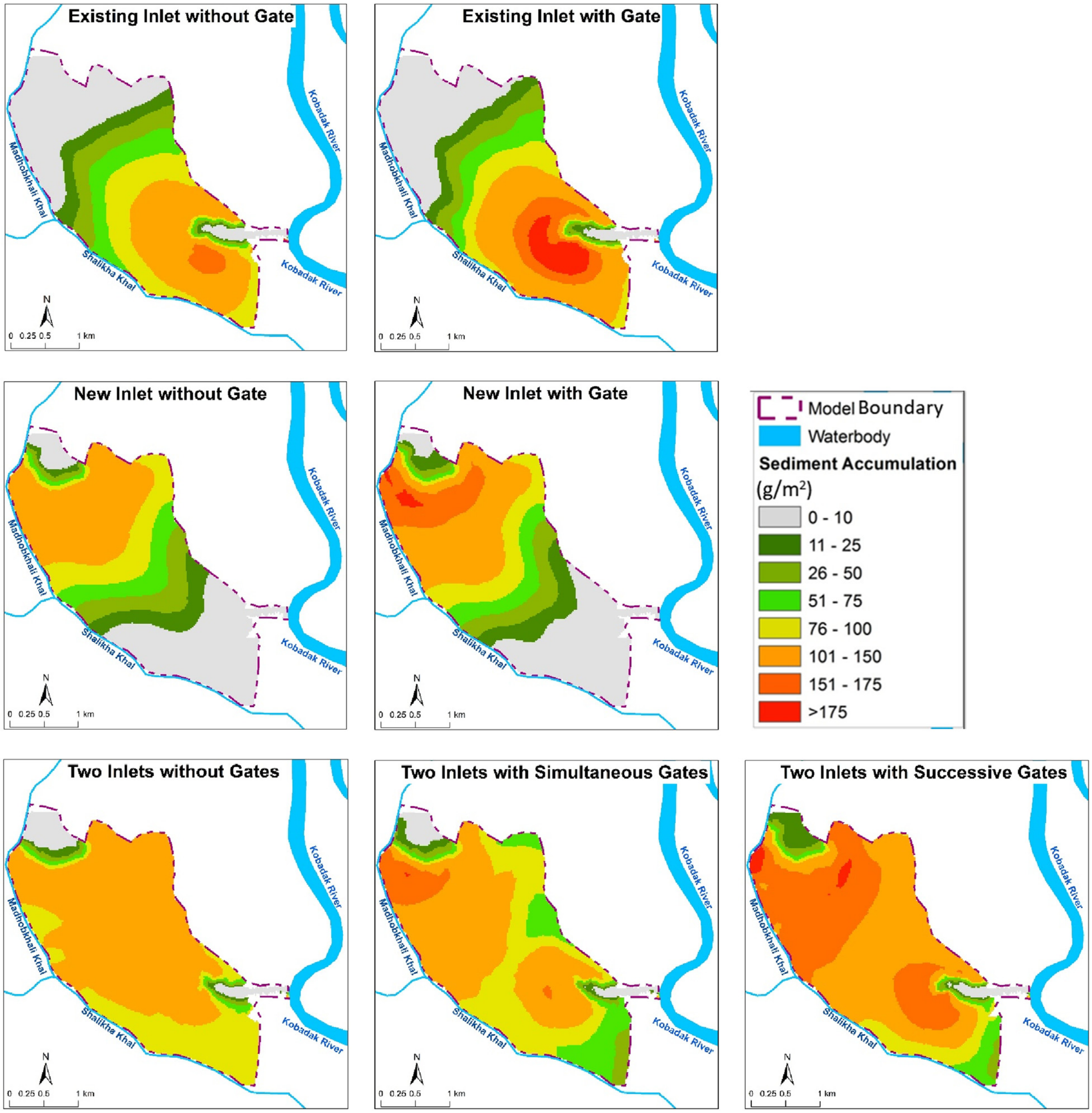

Fig. 9. Spatial pattern of sediment deposition for different scenarios during monsoon (Table 3).

6. Conclusion

To identify the options for improved TRM in de-poldered floodplain areas in the lower Ganges delta in Bangladesh, we investigated the effect of inlet regulation to enhance sediment trapping in a polder depression (a ‘beel’). Our numerical model simulations based on Pakhimara Beel, exploring different scenarios of gate operation and carried out for different hydrological seasons indicate that:

- The amounts and spatial variation of sediment deposition in a beel may differ widely, depending on the number of inlets and the flow regulation scheme applied to the beel;
- Regulated flow increases sediment trapping efficiency by about 10%, leading to larger total sediment deposition inside the beel by about 18%;
- Two inlets located at opposite sides of the beel and connected to different watercourses substantially increase both the spatial uniformity of sedimentation (by about 30%) and the total sediment deposition (by about 50%) compared to the scenario with one inlet;
- Using two inlets with successive gate operation, which ensures flow through the beel and provides sufficient time for the sediment to settle, further increases total sediment deposition by 25%;
- Sediment deposition varies seasonally, with the pre-monsoon period yielding the highest deposition because the SSC in the river is high, and there is large inflow of water and sediment into the beel as the tidal range is high;
- TRM during the monsoon period results in 20 to 30% less sediment deposition than during the pre-monsoon, but has the advantage that the incoming floodwater is much less saline, 1.7 PSU instead of 8.5 PSU during pre-monsoon;
- The land level increase as a result of estimated sediment accumulation during pre-monsoon season is in the order of 20 mm for single inlet and 30 mm for two inlets, which is two to three times as high as than the rate of yearly relative sea level rise up to the year 2050.

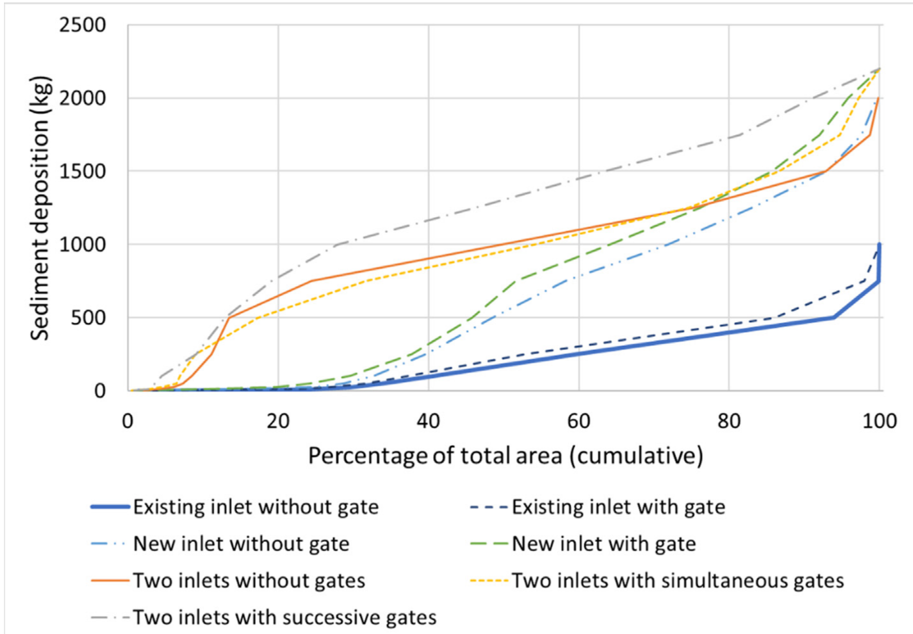

Fig. 10. Spatial uniformity of sediment deposition depicted as sediment deposition vs percent of total area (cumulative).

During monsoon, these values are about 5 mm lower, but still higher than relative sea level rise;

Our results suggest that using two openings (whether with or without flow regulation through gates) results in more enhanced total sediment deposition and uniformity of spatial distribution of sediment deposition than is achieved with current practice. Given the complexity and cost of gate operation, the most feasible TRM is to have two inlets at opposite sides of the beel without flow regulation, even though flow regulation with successive gate operation yields higher sediment deposition. Moreover, we propose TRM operation only during the monsoon, which is when the river water is least saline, thereby leaving the land available during the rest of the year thus enhancing TRM acceptability by local stakeholders. Although the results indicate that flow regulation is advantageous, it demands costly maintenance and operation of regulation structures. Nevertheless, as gates also may provide protection against flood hazards and can regulate flow if required, it is recommended that inlets include gates and the gates are maintained and operated properly.

Thus, well planned, effective, and stakeholder-acceptable (e.g. seasonal) operation of TRM with efficient sediment trapping and uniform spatial distribution as presented in this study has the potential of counteracting relative sea level rise through raising the land by re-introcuding sedimentation. This may be not only the case for the lower GMB delta, but might support the sinking deltas around the world to counteract SLR and land subsidence by utilizing the sediments delivered naturally by the rivers or from the estuary and sea.

Author contributions

All the authors contributed to the conceptualization, development of methodology, writing and editing of the manuscript. Md Feroz Islam carried out the model simulation and analysis, and Hans Middelkoop, Paul P. Schot, Stefan C. Dekker and Jasper Griffioen supervised the research.

CRediT authorship contribution statement

Md Feroz Islam: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Hans Middelkoop:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing - review & editing. **Paul P. Schot:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing - review & editing. **Stefan C. Dekker:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing - review & editing. **Jasper Griffioen:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data used in this research were provided by the Institute of Water Modelling (IWM) for research purposes only. IWM is the owner of the data. Therefore, the authors are not authorized to share the data publicly.

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