Physical controls and a priori estimation of raising land surface elevation across the southwestern Bangladesh delta using Tidal River Management

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Abstract. The Ganges-Brahmaputra-Meghna delta in Bangladesh is one of the largest and most densely populated deltas in the world and threatened by relative sea level rise (RSLR). Renewed sediment deposition through tidal river management (TRM), a controlled flooding with dike breach, inside the lowest parts of the delta polders (so-called 'beels') can potentially counterbalance RSLR. The potential of TRM application in different beels across southwestern Bangladesh has been estimated previously but requires further exploration. Neither the seasonal and spatial variations in physical drivers nor the non-linear character of physical drivers and several sensitive parameters for sediment deposition have been taken into account so far. We used a 2D morphodynamic model to explore the physical controls of five parameters on total sediment deposition inside the beels during TRM: river tidal range (TR), river suspended sediment concentration (SSC), inundation depth (ID), width of the inlet (IW) and surface area of the beel (BA). Our model results indicate that these five parameters and their interactions are significant for sediment deposition per day (SPD) where SSC and BA have high impact, TR and ID have moderate impact and IW has low impact on sediment deposition. Non-linear regression models (NLMs) were developed using the results of 2D models to quantify how sediment deposition inside the beels depends on these parameters. The NLMs have an average coefficient of determination of 0.74 to 0.77. Application of the NLMs to 234 beels of southwestern Bangladesh indicates that TRM operation in beels located closer to the sea will retain more sediment as a result of decreasing SSC further inland. Lower average land surface elevation is one of the reasons for the beels in the western part to retain more sediment. Smaller beels have higher potential to raise land surface elevation due to nonlinear increase of sediment deposition per day (SPD) with beel area. Compartmentalization of larger beels may increase their potential to raise land surface elevation. Thus, the length of time of TRM application in cyclic order will need to vary across the delta from one to multiple years to counterbalance RSLR, depending on current beel land surface elevation and local TRM sediment accumulation rates. We found that operating TRM only during the monsoon season is sufficient to raise land surface in 96% and 80% of all beels by more than 3 and 5 times the yearly RSLR, respectively. Applying TRM only seasonally offers huge advantages as to keeping the land available for agriculture during the rest of the year. The methodology presented here applying regression models based on 2D

morphodynamic modeling may be used for the low-lying sinking deltas around the world to provide an a-priori estimation of sediment deposition from controlled flooding to counterbalance RSLR.

1 Introduction

Bangladesh contains one of the largest and most populated deltas in the world (Darby *et al.*, 2015). The coastal areas of Bangladesh are low-lying and flat: 62% of the coastal zone lies less than 3 m above mean sea level (AMSL) (Mohal *et al.*, 2007). Sea level rise (SLR) is an imminent threat to the livelihood of millions of people and Bangladesh can lose one fourth of its livable land due to flooding (Ericson *et al.*, 2006). Sea level projections for the year 2050 indicate a rise by 0.17–0.32 m under the representative concentration pathway (RCP) 2.6 scenario and 0.23–0.40 m for the RCP 8.5 scenario (Oppenheimer *et al.*, 2019). Goodwin *et al.* (2018) analyzed the effect of the Adjusting Mitigation Pathway (AMP) on global warming and SLR in the future and projected that the sea level rise can be 0.21 m by 2050 for the AMP4.5 scenario. The average rate of land subsidence for the Ganges-Brahmaputra-Meghna (GBM) delta is 2-3 mm/year (Krien *et al.*, 2019). This increases the vulnerability of the low-lying delta to SLR (Brown *et al.*, 2018). Therefore, the rate of relative SLR (RSLR) for the GBM delta can range from 7.6 mm/year for AMP4.5 to 10 mm/year for RCP8.5 in 2050.

To protect the low-elevation coastal zone from tidal flooding and to increase food productivity, polders with earthen dikes were constructed in the 1960s and 1970s (Van Staveren *et al.*, 2017). Initially, these polders increased food production (Nowreen *et al.*, 2014). However, the rivers in the GBM delta carry more than a billion tons of sediment per year (Islam *et al.*, 1999) and the constructed polder dikes interrupted the sediment flow from the tidal rivers to the former floodplain. This obstruction of sediment flow to the floodplains in combination with reduction of water flow from upstream areas due to anthropogenic changes silted-up the rivers. Sediments are now deposited in the river channel itself leading to bed levels being higher than the low elevation areas inside the polders. This causes drainage congestion inside those polders especially during the monsoon season with intense rainfall and high water levels in the rivers. Moreover, being starved from the yearly inflow of sediment, the land surface elevation of the polders decreased by as much as 1.5 m due to compaction, whereas the elevation of the nearby unprotected and regularly flooded Sundarbans mangrove forest remained unchanged (Auerbach *et al.*, 2015).

Problems with prolonged water logging led to deliberate breaching of the dike of Polder 25 (located northwest of Khulna city) by the local community in 1990. This restored the tidal dynamics between the river and the floodplain (van Staveren *et al.*, 2017) allowing sediment-rich water to enter the Dakatia Beel inside the polder. Beels are the lowest part of the floodplain in the polder formed by land erosion and subsidence (Amir and Khan, 2019) where surface runoff accumulates through internal channels (Chakraborty, 2009). 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). The breaching of the dike restored the drainage capacity of the river and as a result of sedimentation, the land surface elevation of Dakatia Beel increased.

This concept of re-opening of a section of the dikes to restore the drainage capacity of the river and raise the land surface elevation inside the polder through sedimentation is called 'Tidal River Management' (TRM) (van Staveren *et al.*, 2017). If

implemented properly, controlled flooding like TRM may potentially counteract the yearly sea level rise and subsidence within polders through sedimentation inside the polders (Shanmpa and Pramanik, 2012; Gain *et al*., 2017). Tidal river management

65   (TRM) has been applied to several polders by the Bangladesh Water Development Board (BWDB) since the late 1990's (Van Staveren *et al.*, 2017).

Sediment deposition inside a beel through TRM is determined by its surface area, inlet width and lay-out, as demonstrated by Gain *et al.* (2017) who evaluated previous TRM operation in Bhaina Beel, Khuksia Beel and Pakhimara Beel. Furthermore, deposition patterns within the beels showed large spatial differences (Amir and Khan, 2019). Satellite image analyses and field

70   surveys indicated that sediment deposition is larger close to the inlet of Pakhimara Beel, while one third of the beel situated farthest from the inlet hardly experienced any sedimentation (Islam *et al.*, 2020). Uneven sedimentation inside Bhaina resulted in water logging in some parts of the beel after TRM was implemented (Gain *et al.,* 2017). An additional inlet was introduced through dike breach of the Khuksia Beel, which increased the spatial uniformity of sedimentation inside the beel (Van Minnen, 2013). Amir and Khan (2019) proposed to achieve a more equal sedimentation over a beel through compartmentalization,

75   thereby first feeding the more distal parts of a beel. Through stepwise removal of embankments along the feeding canal inside the beel towards the compartment near the inlet, sufficient sediment deposition can be achieved over the entire beel over a period of 4 years. However, this compartmentalization likely requires large investments and an adequate regulation scheme. Islam *et al.* (2020) demonstrated how regulation of flow into a beel combined with multiple inlets connecting different river channels may increase the rate of sedimentation and enhance spatial uniformity of sediment distribution. Finally, Talchabhadel

80   *et al.* (2018) suggested multiple inlets for effective utilization of Khuksia Beel and inferred that the tidal basin size should be limited depending on tidal prism. These studies indicate that a better understanding of the physical controls of TRM sediment dynamics inside the beel is needed for effective and efficient TRM operation.

The boundary conditions provided by the river channel to which a beel is connected are major, external factors for deposition (e.g., Talchabhadel *et al.* (2017; Islam *et al*., 2020, 2021). The river flow, flood stage, tidal range, inundation depth of a beel

85   and suspended sediment concentrations in the feeding tidal channels together determine the amount of suspended matter that can enter and settle inside the beel. Since these external boundary conditions may vary across the southwestern (SW) Ganges-Brahmaputra delta in Bangladesh, these may result in considerable regional variation in potential success of TRM application. Islam *et al.* (2021) explored the applicability of TRM in southwestern Bangladesh for different river flow regimes. The tidal-dominated river zone near the sea in the south and the mixed tidal-river flow regime about 60 km inland were found to be most

90   suitable for raising land level with TRM.

Adnan *et al.* (2020) determined the effect of geomorphological parameters on sediment deposition for 234 beels in the southwestern region of Bangladesh. They selected 14 flood conditioning factors to derive a flood susceptibility map and identified through regression analysis five predictive geomorphological parameters for sediment deposition inside a beel, which were: land elevation, distance from the canal, topographic wetness index, topographic slope and curvature of the land.

95   Adnan *et al.* (2020) used tidal prism, river salinity, flood-prone areas, crop production and size of the beel to identify suitable TRM sites. Although their regression model for flood susceptibility had a coefficient of determination (R^2) of 0.88, it

remarkably did not include tidal range (TR) and suspended sediment concentration (SSC). TR and SSC vary seasonally and spatially and directly affect the amount of sediment delivered and deposited inside the beel (Islam *et al.*, 2020). Another problem of this regression is its linear character and the positive residual, suggesting sediment deposition under conditions of zero value for all parameters.

To evaluate how TRM may help to raise the land in polders in southwestern Bangladesh, a quantitative understanding is needed on how different boundary conditions, beel topography and geographical setting determine sediment deposition, and how these vary across the SW Ganges delta. This understanding is currently lacking. In this study we aim to determine the effect of physical controls related to the hydrodynamics of the river and how geo-morphodynamics of beels control the sediment deposition in those beels using TRM. We evaluate the possibility to raise the land surface elevation of the beels in the southwestern region of Bangladesh through sediment deposition using TRM to counterbalance yearly RSLR. We explore the effect of five parameters on the total sediment deposition inside a beel using a calibrated 2D hydro-morphodynamic model: river tidal range (TR), river suspended sediment concentration (SSC) are the two physical controls related to hydrodynamics of the river, inundation depth (ID), the width of the inlet (IW) and the surface area of the beel (retention basin, BA) are the three physical controls related to geo-morphodynamics of the beel. Through multiple-regression analysis we correlate beel characteristics and boundary conditions to total sediment deposition as calculated by the hydro-morphodynamic model, and subsequently apply the regression model obtained to the 234 beels identified by Adnan et al. (2020) to perform an priori assessment of the potential of raising the land surface elevation in beels inside the polders across the southwestern Bangladesh delta using Tidal River Management.

2 Methods

2.1 Study area

The southwestern GBM delta of Bangladesh is a 41,900 km^2 large delta plain bounded by the Ganges and Padma Rivers in the north, the Meghna River in the east, the Bay of Bengal in the south, and the international border between Bangladesh and India in the west (Fig. 1). The southwestern region comprises 64 polders, located in the southern part of the study area (Fig. 1). The average land elevation of the polders of the southwestern delta obtained from the Coastal DEM (Kulp and Strauss, 2018) is 0.58 m AMSL and 45% of the areas within polders are below 1 m AMSL. The average land elevation of polders of southwestern GBM delta located east of Pasur River (Fig. 1) is about 0.62 m higher than the polders located in the west.

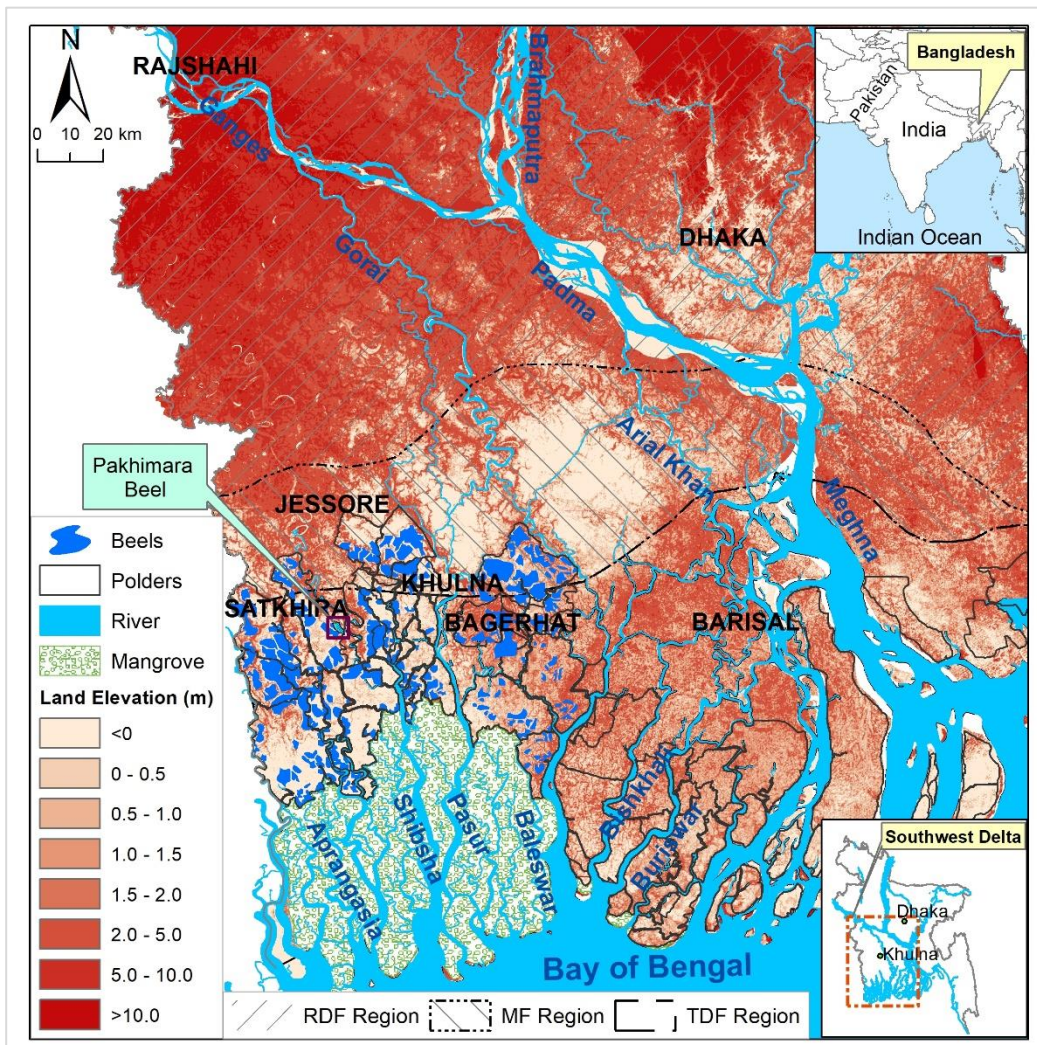
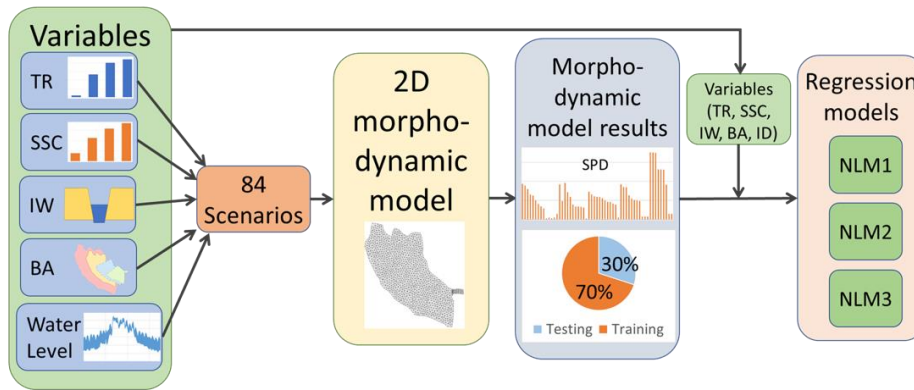



Figure 1: Polders and beels of southwestern Bangladesh. Elevation data from Coastal DEM (Kulp and Strauss, 2018). Beel data from Adnan et al., 2020.

2.2 General approach

125   The approach to evaluate the potential of raising land surface elevation of the beels in southwestern Bangladesh by sedimentation through controlled flooding is presented in Fig. 2 and described in the following sections.

Development of Regression models from 2D morpho-dynamic model results

Application of the Regression models: assessment of potential to raise land surface elevation

Potential of raising land surface elevation

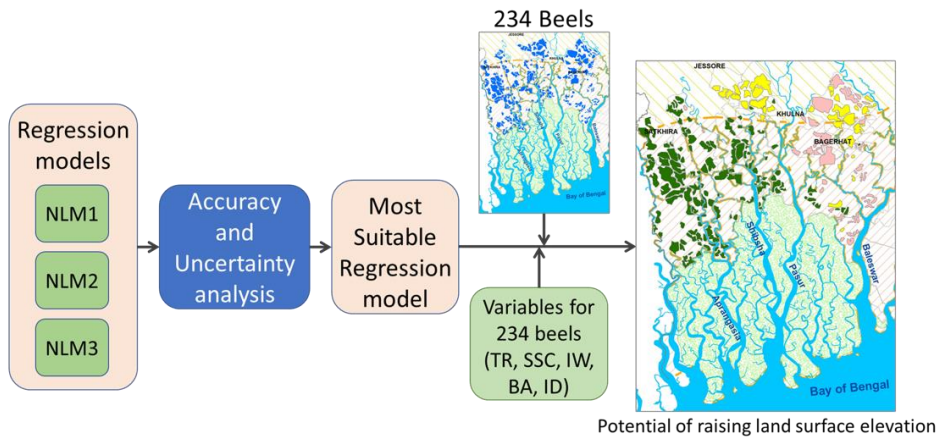



Figure 2: General approach used to establish the regression models for sediment deposition from physical control parameters, and their subsequent application to estimate potential of raising land surface elevation throughout the southwestern Bangladesh delta.

2.2.1 Beel template for 2D hydro-morphodynamic model simulations

To estimate total sediment deposition in beels resulting from TRM operation, we used a two-dimensional (2D) hydro-morphodynamic numerical model that was implemented and calibrated for Pakhimara Beel by Islam et al. (2020) as a reference. Tidal river management (TRM) has been operational since 2015 in Pakhimara Beel and monitoring data on water level, discharge and suspended sediment concentration have been collected by Institute of Water Modelling (IWM) (IWM, 2017a), which makes it an appropriate reference situation (cf. Islam *et al.* 2020). Here, this model was used as a template for beels across southwestern Bangladesh by adapting the surface area of the beel and the boundary conditions to different local conditions that occur within the SW delta. The area of Pakhimara Beel is about 700 ha, which is comparable to the average surface area of the beel (656 ha) as described by Adnan *et al.* (2020). Model simulations were carried out using Mike 21FM in which hydrodynamic processes and sediment transport are simulated dynamically to account for hydro-morphological interactions (DHI, 2012a). The three-dimensional incompressible Reynolds-averaged Navier-Stokes equations are solved by

Mike 21FM (DHI, 2012a). The tool uses an approximate Riemann solver to calculate the convective fluxes at the interface of the cells of the 2D mesh (DHI, 2012a). The MT module uses the advection-dispersion equation (ADE). The ADE is solved using the third-order finite difference scheme, known as the ULTIMATE scheme, which is based on the QUICKEST scheme (DHI, 2012b). For morphological simulation, the bathymetry is updated for each time step according to net sedimentation (DHI, 2012b).

To represent the bathymetry of Pakhimara Beel, a flexible cell size was used. A finer mesh was opted to represent the canal inside the beel, and a coarser mesh was used for the flood plain to reduce calculation costs (Islam *et al.*, 2020). The surface area of the mesh cells varied from 170.5 m^2 to 5000 m^2 (Islam *et al.*, 2020). The model of Pakhimara Beel was supplied by time varying water levels and SSC data. As the grain size of the sediment is fine (less than 63 µm) for the study area (Datta and Subramanian, 1997; IWM, 2010), the MT (mud transport) module of Mike 21FM for cohesive sediment transport was used.

Islam et al. (2020) calibrated the 2D hydro-morphodynamic model for Pakhimara Beel by comparing the observed water level, discharge and SSC with simulated ones. Manning's coefficient, shear stress and settling velocity were the primary parameters for calibrating the hydrodynamic and morphodynamic models. Sensitivity analysis of the model was carried out with varying Manning's coefficient from 0.1 s m$^{-1/3}$ to 0.01 s m$^{-1/3}$, shear stress from 0.01 N m^{-2} to 0.1 N m^{-2} and settling velocity from 0.0001 m s^{-1} to 0.001 m s^{-1}. To understand the uncertainty of the model, the coefficient of determination (R^2) and the normalized root mean square error (NRMSE) were calculated by comparing the modelled results with the observed data for the different input variables. Best model performance was obtained using a spatial average value of 0.032 s m$^{-1/3}$ for the Manning's coefficient, shear stress of 0.08 N m^{-2} and settling velocity of 0.0005 m s^{-1}. The related 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). Islam *et al.* (2020) also captured the effect of spring and neap tide during different seasons by running simulations for three tidal conditions and time periods of -14 days. For this study, we carried out simulations for a similar period of 14 days and similar parameterizations to capture the full range of tidal cycles for three flow seasons. The resulting sediment deposition in a beel was calculated in tons per day.

2.2.2 Scenario matrix for hydro-morphodynamic modelling

We explored five parameters which affect the total sediment deposition inside a beel: river tidal range (TR), river suspended sediment concentration (SSC) are the two physical controls related to hydrodynamics of the river, inundation depth (ID), the width of the inlet (IW) and the surface area of the beel (retention basin, BA) are the three physical controls related to geo-morphodynamics of the beel. We have selected the parameters that are the primary controls of the sediment trapping within a beel. The ID and the TR determine the volume of water and sediment that may enter a beel. The SSC in the river water then linearly determines the sediment load conveyed into the beel. The IW and BA are controls of the actual volumes entering a beel and the residence time of the water, determining the time for sediment settling. We have explored the physical drivers, and the parameters considered take into account geomorphic conditions as well. The variable ID is the difference between the

average land elevation and water level, as such it takes geomorphic parameters proposed by Adnan et al. (2020) such as land elevation, topographic slope and curvature of the land into account. Additionally, two of our proposed parameters TR and SSC take water and sediment dynamics of the river into account.

For our analysis, we adjusted the hydro-morphodynamic model of Pakhimara Beel with different values for the input parameters that represent the physical control variations across the SW delta. A scenario matrix of those boundary conditions was developed considering varying IW, BA, TR and SSC. Inundation depth (ID) was determined for each scenario as the difference between the average land level inside the beel and the average water level from 2D hydro-morphodynamic model results. The land elevation data were obtained from the coastal DEM generated by Kulp and Strauss (2018).

The inlet width (IW) of beels of previous TRM projects reported by Gain *et al.* (2017) varied from 30 m to 60 m. We, therefore, used inlet widths of 30 m, 60 m and 120 m for the scenarios. The study of Adnan *et al.* (2020) was used to determine a relevant range in surface areas of the beels (Fig. 1). The average area of the beels of southwestern Bangladesh is about 656 ha (Adnan *et al.,* 2020), and 90% of the beels are smaller than 1400 ha. The beels are located within the catchments of Pasur, Shibsa, Kobadak and Kholpetua rivers and their tributaries (Fig. 1). For our scenarios, 230 ha, 460 ha, 700 ha and 1400 ha were considered as the surface area of the beel.

Tidal range (TR) and SSC vary spatially for different flow regions and seasons. Islam *et al.* (2021) divided the southwestern delta into three regions based on the flow regime of their rivers: river-dominated flow (RDF), mixed river-tide flow (MF), and tide-dominated flow (TDF) regime in the coastal area. Following Islam *et al.* (2020) and Lázár et al. (2015), we distinguished three flow seasons: the dry season (November to February), pre-monsoon (March to May) and monsoon (June to October). For all flow regions, TR is highest during the pre-monsoon season and lowest during the monsoon season (Islam *et al.*, 2021). Tidal range is generally higher for the rivers in the TDF region than for the rivers in the RDF region of the southwestern delta. Suspended sediment concentration (SSC) in the river is highest during the monsoon and lowest during the dry season for RDF and MF regions. For the TDF region, SSC in the river is highest during the pre-monsoon and lowest during the dry season (Islam *et al.*, 2021). For the scenarios, we used the TR and the SSC that occur within the three flow regime regions during the different seasons as defined by Islam *et al.* (2020, 2021) (Table 1). Islam *et al.* (2021) used sediment rating curves when measured SSC were not available.

To simulate and analyze the effect of different scenarios, the calibrated model of Pakhimara Beel developed by Islam *et al.* (2020) was adjusted for different inlet widths and surface areas of the beel (Fig. 3), and for different TR, SSC and inundation depth where the last results from the flood water level in the feeding river channel. The boundaries of the beels were selected for different scenarios in such a way that the surface area of the beel met the criteria of the scenarios presented in Table 2. It was assumed that the adjusted models represent the sediment dynamics inside the beel as if the beels were located within different parts of the delta. Ground level of the model was adjusted for different regions within the delta following Islam *et al.* (2021). The average altitude of the RDF region is 5.6 m AMSL which is higher than the average river water level for pre-monsoon and dry seasons. During the monsoon season, the average water level in the rivers of the RDF region is high enough to flood the land. Therefore, only the monsoon season is considered for the RDF region in the scenario matrix. In total we

developed 84 scenarios considering the seasonality of water level and SSC, different inlet width and the surface area of the beel (Table 2).

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Table 1: Overview of data used in this study

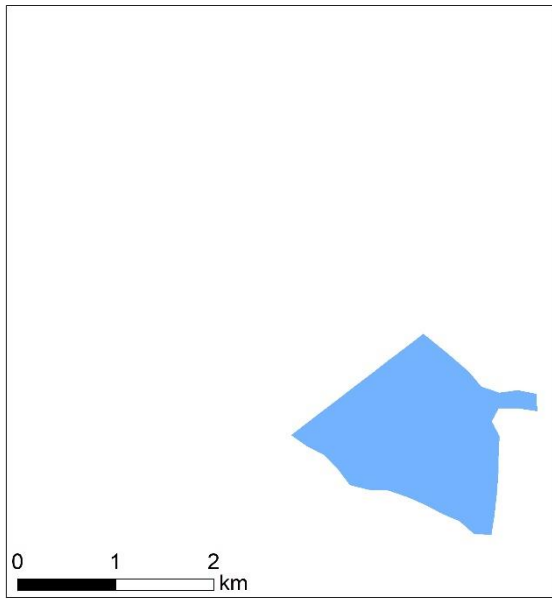
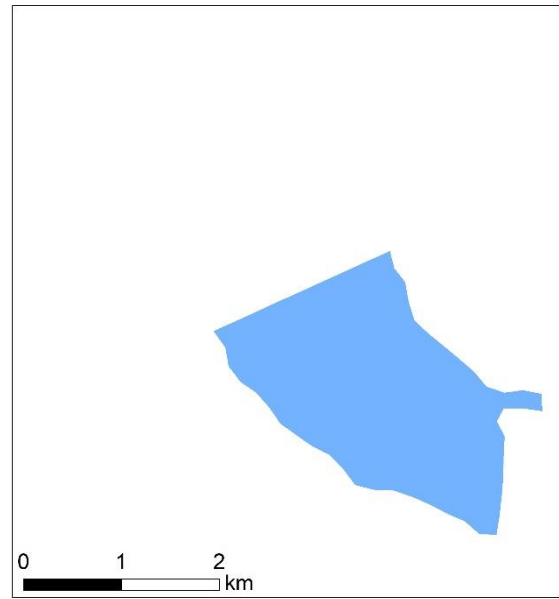
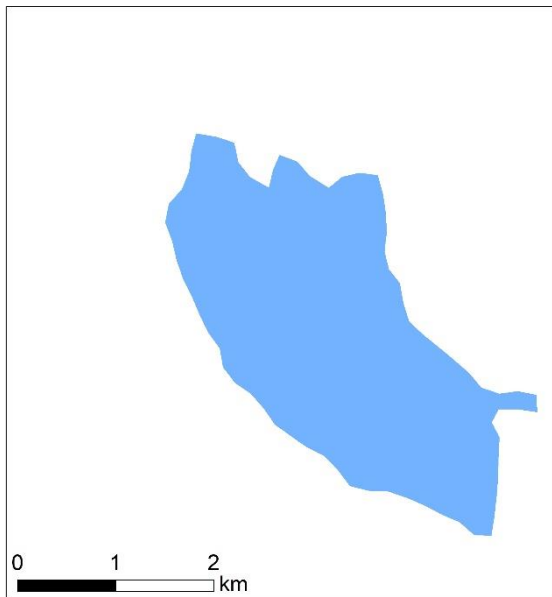
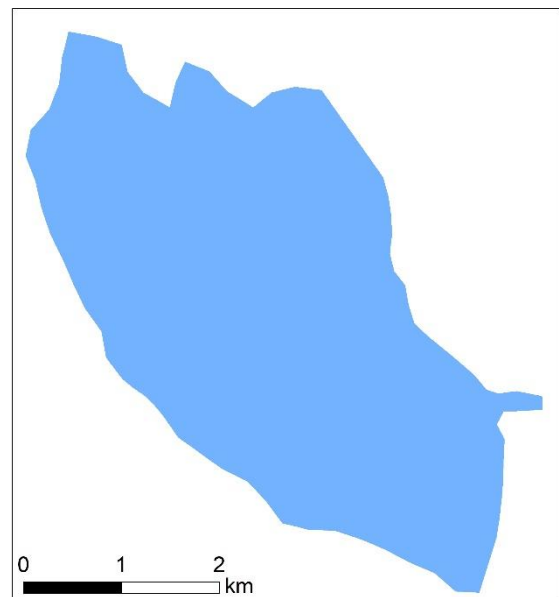
Type of Data	Monitoring Period	Method of data collection	Reference / source
Land surface elevation	2000, 2010 and 2017	DGPS; levelling instrument	IWM (2010; 2017a; 2017b)
	2018	Shuttle Radar Topography Mission (SRTM), Lidar and artificial neural network	Kulp & Strauss (2018)
Land use	2011	Field survey	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 (2017a; 2017b) and BWDB
Hydrometric: Discharge	Kobadak (August - September 2016; February - April 2016; March - April 2017); Gorai (1980 - 2016); Nabaganga (1983 - 2006);	ADCP	IWM (2017a; 2017b) and BWDB
Suspended sediment concentration	Kobadak (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); Gorai (sporadically between 1989 – 1998 and 2010 - 2018); Nabaganga (sporadically between 2012 - 2016); Pasur (sporadically between 2012 - 2016)	Pump bottle sampler	IWM (2017a; 2017b) and BWDB
Salinity	September 2015 – October 2016; January – April 2017	EC meter	IWM (2017a; 2017b)
Canal and river alignment and cross sections	2016 and 2017	Echo-sounder	IWM (2017a; 2017b) and Google earth
Alignment of the dike surrounding Pakhimara Beel and its design cross-section	2017	Field survey	IWM (2017a; 2017b)
TRM operation rules	2017	Consultation of documents and experts	IWM (2017a; 2017b)
Satellite imagery	2009, 2013 and 2016	Image analysis	Google Earth

(a)

(b)

(c)

(d)

Figure 3: The beels with different surface areas considered for scenario development, (a) 230 ha, (b) 460 ha, (c) 400 ha and (d) 1400 ha.

215 **Table 2: Scenario matrix, combining beel surface area and inlet width with different flow regimes and seasons. TR = tidal range, SSC = suspended sediment concentration in the feeding river.**

Inlet width (m)	Surface area of the beel (ha)	Flow regions						River dominated flow (RDF)
		Tide dominated flow (TDF)			Mixed river tide flow (MF)			
		Season			Season			Season
		Dry (TR=2.42 m SSC=1.52 kg m^{-3})	Pre-monsoon (TR=2.47 m SSC=1.85 kg m^{-3})	Monsoon (TR=2.02 m SSC=1.13 kg m^{-3})	Dry (TR=1.41 m SSC=0.54 kg m^{-3})	Pre-monsoon (TR=1.45 m SSC=0.53 kg m^{-3})	Monsoon (TR=0.33 m SSC=1.58 kg m^{-3})	Monsoon (TR=0.11m SSC=0.39 kg m^{-3})
30	230	TD11	TP11	TM11	MD11	MP11	MM11	RM11
	460	TD12	TP12	TM12	MD12	MP12	MM12	RM12
	700	TD13	TP13	TM13	MD13	MP13	MM13	RM13
	1400	TD14	TP14	TM14	MD14	MP14	MM14	RM14
60	230	TD21	TP21	TM21	MD21	MP21	MM21	RM21
	460	TD22	TP22	TM22	MD22	MP22	MM22	RM22
	700	TD23	TP23	TM23	MD23	MP23	MM23	RM23
	1400	TD24	TP24	TM24	MD24	MP24	MM24	RM24
120	230	TD31	TP31	TM31	MD31	MP31	MM31	RM31
	460	TD32	TP32	TM32	MD32	MP32	MM32	RM32
	700	TD33	TP33	TM33	MD33	MP33	MM33	RM33
	1400	TD34	TP34	TM34	MD34	MP34	MM34	RM34

2.2.3 Identifying the effect of TR, SSC, ID, IW and BA on sediment deposition

The calculated amounts of sediment deposition per day (SPD) in the beel using the 2D hydro-morphodynamical model for all
220 scenarios were compared with each other to determine and understand how these depend on the five parameters studied (TR, SSC, ID, BA and IW). Using an analysis of variance (ANOVA), we identified which of these five parameters and their interconnectivity significantly correlate to sediment deposition per day (SPD). A Pearson correlation matrix was calculated to determine the strength of the correlations among the parameters.

2.2.4 Non-linear regression analysis

225 Previous studies (Islam *et al.* 2020; Islam *et al.,* 2021, Talchabhadel *et al.,* 2017; Gain *et al.,* 2017) indicated that the relations are non-linear between SPD and TR and between BA and IW. Moreover, linear multivariate regressions (LMs) usually include a residual term, which would predict sediment deposition even when all variables have zero value, such as in the empirical

equation used by Adnan *er al.* (2020). We, therefore, applied a non-linear multivariate regression (NLM) analysis between the beel characteristics (BA, IW), boundary conditions (TR, SSC, ID) and sediment deposition in the beel (SPD, in tons per day) calculated by the hydro-morphodynamic model for these inputs and considered them as variables of NLMs (Fig. 2). The regression equation has the following form as Eq. (1):

$$SPD = a * SSC^b * BA^c * TR^d * ID^e * IW^f, \tag{1}$$

where a, b, c, d, e and f are statistically obtained coefficients.

The results of the model simulations for the 84 scenarios were divided into two groups, 56 (70%) of them were used as training set and 28 (30%) as testing set for the regression analysis (Fig. 2). The regression coefficients were determined from the training set, after log-transformation of the equation and correction for bias resulting from this transformation. In accordance with the way Mike 21FM simulates sediment deposition from suspended sediments, SSC affects sediment deposition linearly (DHI, 2012b). Therefore, the exponent for SSC in the regression analysis was fixed to "1". We calculated the coefficient of determination (R^2) and normalized root mean square error (NRMSE) for different combinations of predictive variables to identify which predictors should be included to estimate sediment deposition per day. To explore the sensitivity of regression analysis related to dividing the results of the model simulations to training and testing samples, 10 sets of training and testing samples were randomly generated.

2.2.5 Application of the regression model to estimate potential sediment deposition and land surface elevation in the beels of southwestern Bangladesh

The regression model established was applied to estimate sediment deposition per beel under TRM using IW, BA, ID, average SSC and average TR for the 234 beels identified by Adnan *et al.* (2020). For each beel, we first determined the associated flow regime of the feeding river branch (cf. Islam *et al.*, 2021). To estimate sediment deposition for the beels using the regression model, we used the TR and SSC for the flow regions and different seasons defined by Islam *et al.* (2021). Inundation depth (ID) was determined from the difference between the average local land surface elevation and the average water level inside the beel. The surface area (BA) was determined for all beels, and a standard inlet width (IW) of 60 m was used. To estimate the total sediment deposition for each of the 234 beels, sediment deposition per day (SPD) was multiplied for each season by the number of days per season, and the results were summed to obtain the annual deposition. From these estimated seasonal and annual sediment depositions, land elevation increase was calculated using the beel area and sediment dry bulk density of 1300 kg m^{-3} as suggested by Allison and Kepple (2001) and Rogers and Overeem (2017) for the GBM delta. The estimated land elevation increase was compared with the relative sea level rise (RSLR) per year to define the potential of raising land surface elevation to counteract RSLR. The potential is considered as "low" when the land height increase is lower than maximum anticipated RSLR of 10 mm yr^{-1} for RCP8.5 in 2050; as "medium" when the land elevation increment is between 1 and 3 times RSL; "high" with increment between 3 and 5 times RSLR and "very high" when elevation increment is more than 5 times RSLR. In the latter case TRM can potentially be applied to the beel once every five years to counteract RSLR.

3 Results

3.1 Sediment deposition for different beel lay-outs and boundary conditions

The results obtained by the hydro-morphodynamic models for the different scenarios indicate that average sediment deposition per day (SPD) varies seasonally and spatially with varying tidal range (TR) and suspended sediment concentration (SSC) (Fig. 4). Highest SPD occurs during the monsoon season along river branches with a mixed flow (MF) regime. During the dry and the pre-monsoon seasons, the highest SPD occurs in the tide-dominated flow (TDF) region. During the dry and pre-monsoon seasons, deposition cannot occur in the river-dominated flow (RDF) region, and even during the monsoon season the SPD in the RDF region is substantially lower than in the other two regions.

Sediment deposition per day (SPD) generally increases for larger beels, but the increase varies among the regions and seasons (Fig. 4). For the monsoon season, the beels with surface area (BA) of 1400 ha have 1.5, 5.2 and 5.4 times higher SPD compared to the SPD of 230 ha BA in the TDF, MF and RDF regions, respectively. For the pre-monsoon, this ratio is about 2 in the TDF region and about 4 in the MF region. The results of the morphodynamic model also indicate that inlet width (IW) of the beel has very little effect on SPD (Fig. 4). According to the morphodynamic model results the considered inlet widths are apparently not a limiting factor for deposition, the channel capacity becomes the limiting factor to convey the larger flow of water towards the beel for the wider inlets.

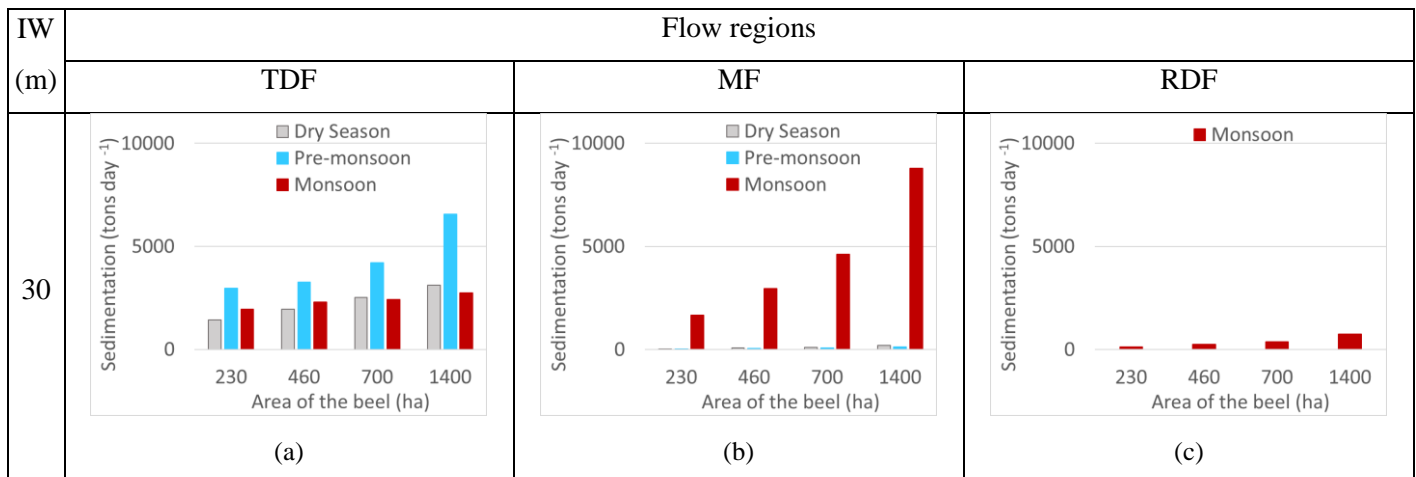
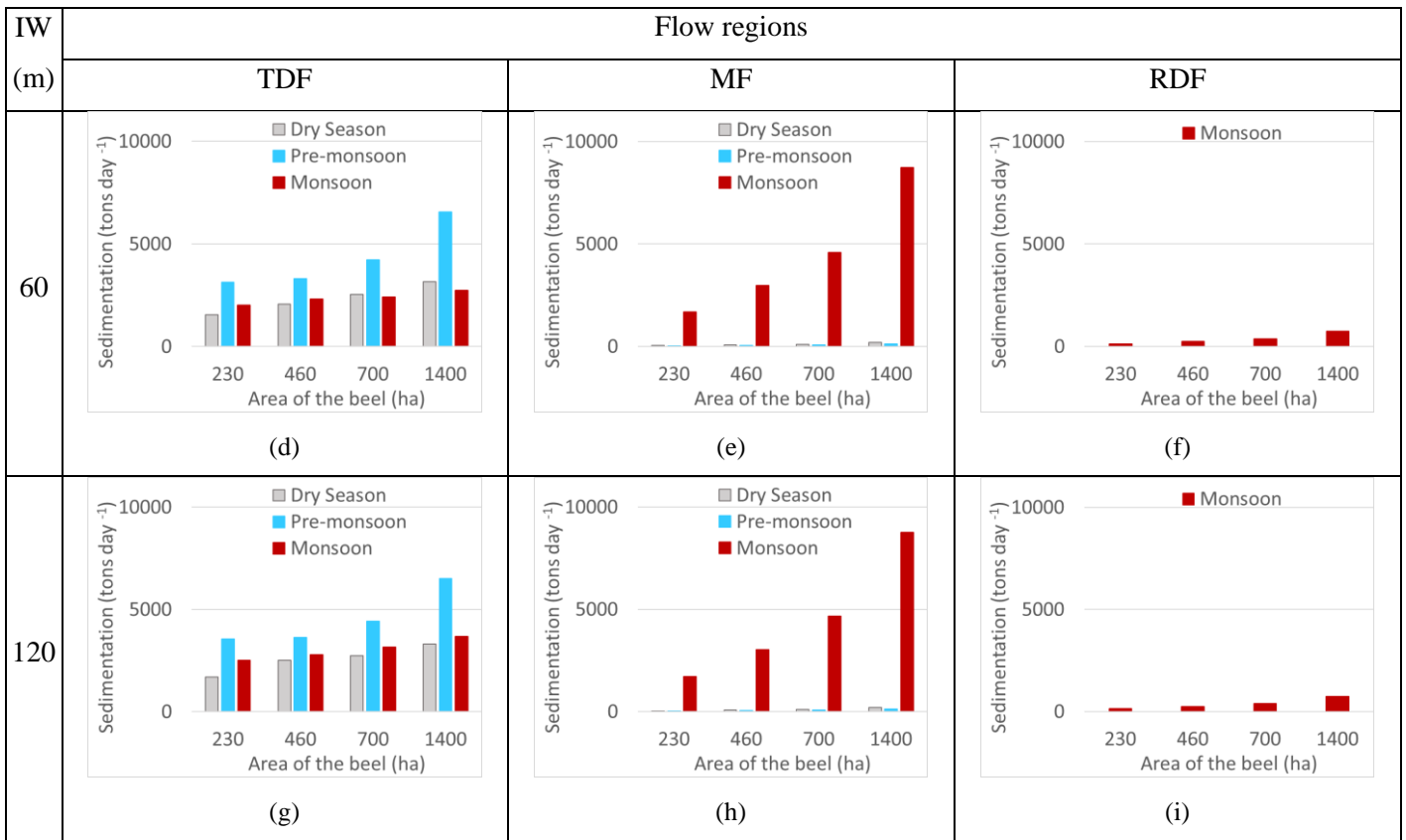



Figure 4: Sediment deposition simulated with the 2D hydro-morphodynamic model for three different inlet widths (IW), three different flow regions (TDF= tide dominated flow, MF= mixed flow, RDF= River dominated flow), four different beel surface areas (BA) and three different seasons.

280   With larger tidal range, larger volumes of water and sediment become transported inside the beels. Moreover, the effect of TR on SDP is highest close to the inlet and the effect decreases when moving away from the inlet. The effect of tide also decreases further inwards the beel as those beel sections are much wider and the tidal energy dissipates. For the subareas where the effect of TR is high especially near the inlet, the flow remains dynamic and active which results in lower SPD. Furthermore, the velocity inside the beel decreases with increasing distance from the inlet. Therefore, water flow velocities in the distal areas

285   located farthest from the inlet of larger beels are considerably lower than those in the distal parts of smaller beels. Sediment deposition rates increase at lower flow velocity. Combining the effect of having larger volumes of sediment delivered into a beel and lower flow velocities in the distal areas of the beel results in higher sediment trapping efficiency and higher SPD for larger beels (Fig. 4). However, sediment deposition per unit area is generally higher for smaller beels. As TR and SSC govern the sediment load delivered by the river, the seasonality of TR and SSC results in seasonal and spatial variation of SPD inside

290   the beel. Sediment deposition per day (SPD) is higher when TR and SSC are higher. The velocity and shear stress are higher close to the inlet for narrow inlets which prevent sedimentation near the inlet. Therefore, suspended sediment tends to settle

close to the inlet with increasing inlet width resulting in different spatial distribution of sediment deposition for different IW even though IW has minimal effect on SPD.

3.2 Controls of sedimentation

295 The ANOVA test demonstrated a significant effect of TR, SSC, BA, IW and ID on modelled SPD (Table 3). Also, most of the interactions between TR, SSC, ID, BA and IW are significant for SPD as the p-value is smaller than 0.05 (Table 3).

Table 3: ANOVA test p-value for sediment deposition per day (SPD) with tidal range (TR), suspended sediment concentration (SSC), beel surface area (BA), width of the inlet (IW) and inundation depth (ID) and their interaction. Rows with p-value less than 0.05 are highlighted as they are statistically significant.

Individual Variables	p-value	Interaction between two variables	p-value	Interaction between three or more variables	p-value
TR	$< 2 \times 10^{-16}$ ***	TR:SSC	$< 2 \times 10^{-16}$ ***	TR:SSC:BA	3.8×10^{-1}
SSC	$< 2 \times 10^{-16}$ ***	TR:BA	$< 2 \times 10^{-16}$ ***	TR:SSC:IW	2×10^{-1}
BA	$< 2 \times 10^{-16}$ ***	SSC:BA	$< 2 \times 10^{-16}$ ***	TR:BA:IW	5.5×10^{-1}
IW	$< 2 \times 10^{-16}$ ***	TR:IW	4.9×10^{-5} ***	SSC:BA:IW	7.6×10^{-3} **
ID	$< 2 \times 10^{-16}$ ***	SSC:IW	2.7×10^{-4} ***	BA:IW:ID	1.9×10^{-3} **
		BA:IW	9.6×10^{-1}	TR:SSC:BA:IW	2.6×10^{-2} *
		BA:ID	1.2×10^{-2} *		
		IW:ID	4.3×10^{-6} ***		

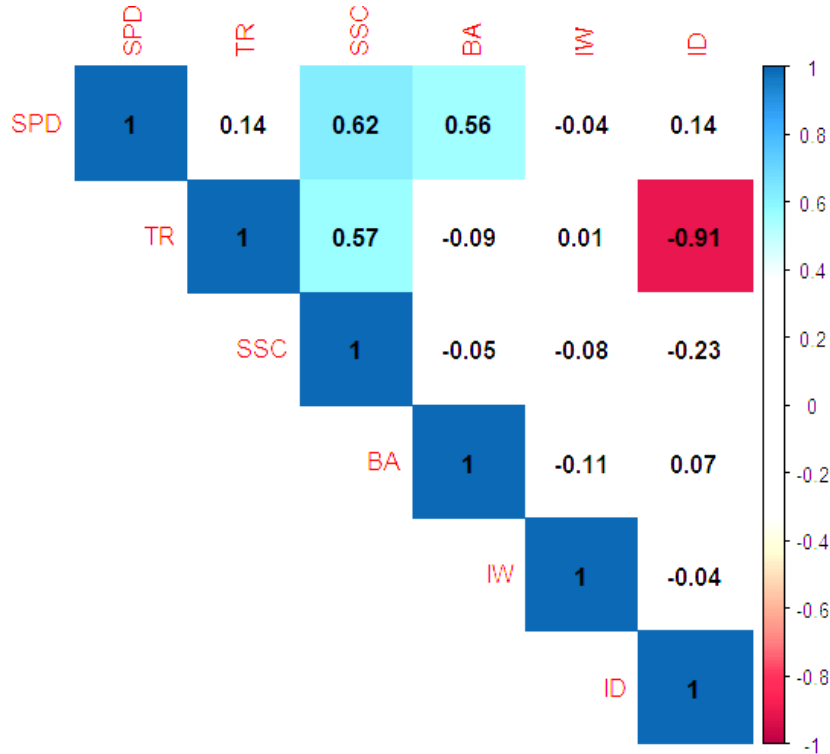
300 Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '

Tidal range (TR), SSC, ID and BA positively correlate with SPD, with highest correlations for SSC and BA (Table 4). These correlations reflect the higher TR and SSC in the TDF region (Table 2) resulting in high SPD, when compared to the other flow regions (Fig. 4). Conversely, the lowest SPD in the RDF region reflects its lower SSC and TR (Table 2; Fig. 4). The

305 strong correlation of SSC with SPD is evident for the MF region during the monsoon season because SSC is higher in this region than in the TDF region (Fig. 4). TR is higher during the monsoon season in the TDF region than that in the MF region, while SSC is lower (Table 2). Similar to TR and SSC, larger BA and ID result in larger volumes of water and sediment entering a beel, and hence higher SPD (Fig. 4), which is reflected in their positive correlation with SPD (Table 4). The large ID in the MF region during the monsoon season results in the positive correlation of ID with SPD. The correlation matrix also indicates

310 that TR and ID have a very strong negative correlation (Table 4). Tidal range (TR) is lowest during the monsoon season when

water level in the river is highest and TR is high during the dry and the pre-monsoon season when water level in the river is low (Table 2). This results in the negative correlation between TR and ID. Suspended sediment concentration (SSC) and BA have stronger effect on SPD as the correlation of SPD with these are highest. Tidal range (TR) and ID have moderate effect on SPD and IW has minimal to no effect of SPD.

315   **Table 4: Pearson correlation coefficients between sediment deposition per day (SPD), tidal range (TR), suspended sediment concentration (SSC), beel surface area (BA), width of the inlet (IW) and inundation depth (ID).**

3.3 Multivariate regression model for prediction of sediment deposition

Based on the correlation between the controlling factors and SPD as well as the significance of the controlling factors for SPD (Table 3 and Table 4), we set-up a multivariate regression model to estimate SPD. Sediment deposition per day (SPD) has
320   strong to moderate positive correlation with SSC, BA, TR and ID, and weak negative correlation with IW (Table 4). Although IW has minimal effect on SPD, IW is found as statistically significant for SPD (Table 3). The interconnectivities between TR, SSC, ID and BA are also identified as statistically significant for SPD (Table 3). Therefore, we considered all the control factors (TR, SSC, ID, BA and IW) as variables for the regression analysis to estimate SPD and compared the results to identify the most suitable empirical equation for the regression model.

325 Since the interconnectivities between TR, SSC, ID and BA are significant for SPD (Table 3) and since the effect of TR and BA on SPD is non-linear (Fig. 4), we developed three non-linear multivariate (NLM) regressions with increasing number of variables. Suspended sediment concentration (SSC) and BA were considered as variables for NLM1 as SSC and BA have higher correlation with SPD (Table 4). Tidal range (TR) and ID were included as variables along with SSC and BA for NLM2 as TR and ID have moderate correlation with SPD (Table 4). All the variables SSC, BA, TR, ID and IW were included in

330 NLM3. The range and standard deviation (STD) of the parameters of the NLMs for 10 sets of training and testing sample are presented in Table 5. Note that the exponential coefficient for suspended sediment concentration was fixed to 1. The variation in regression coefficients obtained using the different training sets is generally low, with higher variation for the scaling factor a and the exponential coefficient f related to IW.

Figure 5 shows the estimated SPD by Mike 21FM models versus the calculated SPD by regression models for both the training

335 and testing datasets. NLM1 shows a larger spread and seems to overestimate SPD for low and higher values when compared to the other two regression models. The coefficient of determination (R^2) of the three regression models ranges between 0.61 to 0.84 for the training sets and 0.29 to 0.94 for the testing sets (Table 6). The averages for the two sets are, however, highly comparable. The predictive skill of the models generally increases with increasing number of variables. NLM1 using only BA and SSC as predictors for SPD, results in relatively moderate average R^2 of 0.61 and 0.71 for the training and testing data sets

340 respectively (Table 6). NLM2 using TR, SSC, ID and BA and NLM3 using TR, SSC, ID, BA and IW produce better results. The mean R^2 for NLM2 are 0.77 and 0.74 for training and testing data sets respectively and the mean R^2 for NLM3 are 0.77 and 0.76 for training and testing data sets respectively (Table 6). Although IW correlates statistically significant with SPD in the ANOVA test (Table 3), it hardly contributes to better prediction of SPD with exponential coefficients of 0.02 - 0.14 (Table 5). The normalized root mean square error (NRMSE) ranged between 0.3 to 0.5 for the training datasets and 0.15 to 0.49 for

345 the testing datasets (Table 6). The mean of NRMSE for NLM1 for the training samples is higher than obtained for NLM2 and NLM3. The mean NRMSE obtained for the testing dataset is almost similar for all three NLMs.

Since NLM3 yielded the highest mean R^2 and the lowest mean NRMSE for both the training and testing dataset (Table 6), it was selected as most suitable regression model to estimate SPD for the beels of southwestern Bangladesh. As a separate test, we applied NLM3 to the Bhaina Beel and the Khuksia Beel where TRM was operated previously. Van Minnen (2013) reported

350 that 6.45 million m^3 and 8.2 million m^3 of sediment were deposited in Bhaina Beel and Khuksia Beel, respectively, after five years of TRM operation. Sediment deposition per day (SPD) estimated with the NLM3 regression models for Bhaina Beel and Khuksia Beel had an average error of about 12-17% relative to the observed value which can be considered as moderate. This supported our confidence that the regression model NLM3 can be applied as a simple regression model for evaluating TRM potential on the basis of estimated sediment deposition in beels in the southwestern GBM delta.

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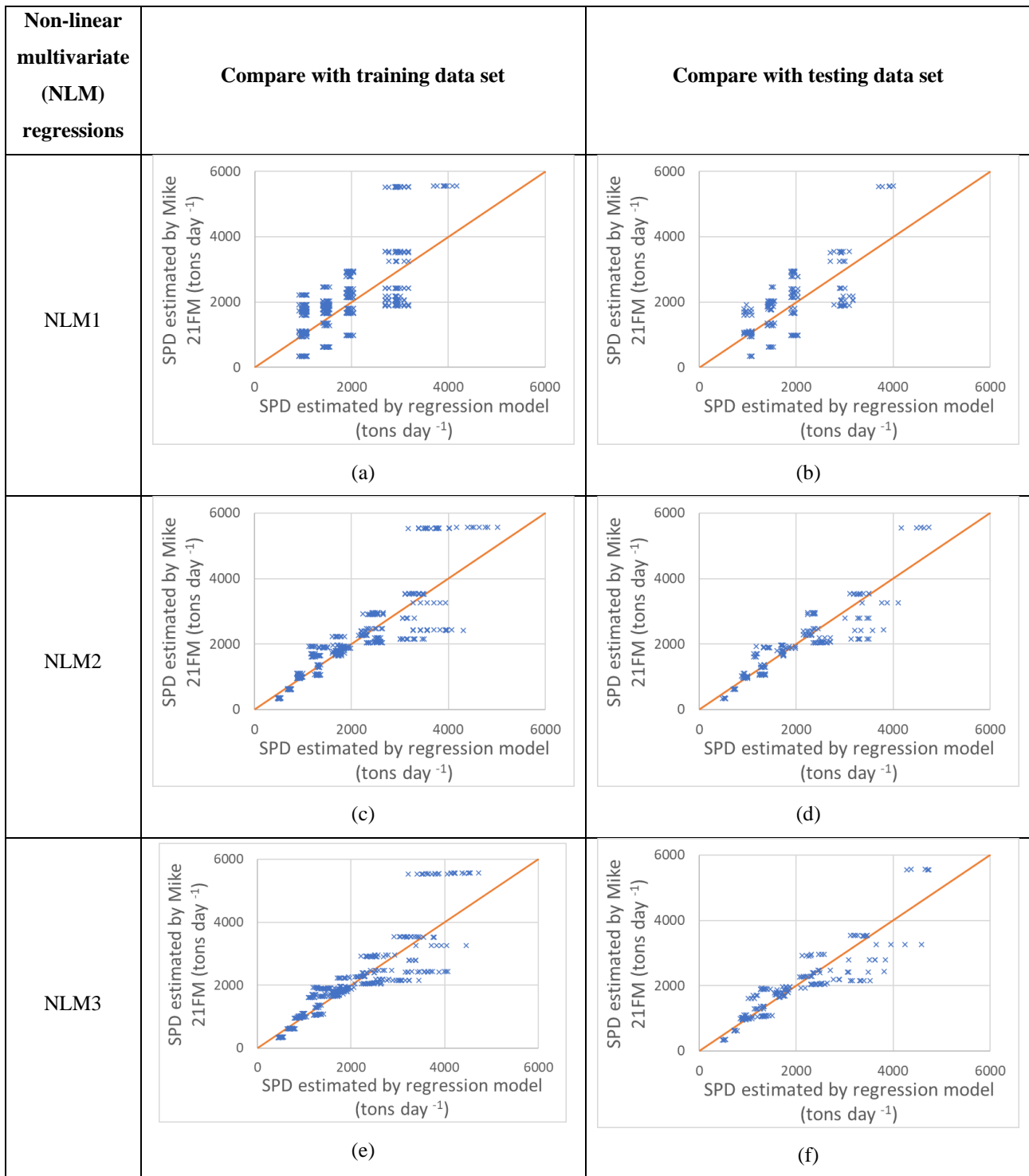


Figure 5: Calculated SPD using the hydro-morphological model against estimated SPD using NLM regressions for all 10 sets of training and testing data samples. The line depicts the 1:1 line.

Table 5: The range and standard deviation (STD) of the parameters of NLMs. Note that exponent b was fixed to 1.

Non-linear multivariate (NLM) regressions		Factor and exponents of the regression equation					
		a	b	c	d	e	f
NLM1: $SPD = a*(SSC)^b(BA)^c$	Range	0.03-0.40	1	0.53-0.69	-	-	-
	STD	0.13	0	0.05	-	-	-
	Mean	0.17	1	0.61	-	-	-
NLM2: $SPD = a*(SSC)^b(BA)^c(TR)^d(ID)^e$	Range	0.10-0.45	1	0.53-0.63	0.53-0.62	0.57-0.74	-
	STD	0.11	0	0.03	0.04	0.05	-
	Mean	0.20	1	0.59	0.57	0.65	-
NLM3: $SPD = a*(SSC)^b(BA)^c(TR)^d(ID)^e(IW)^f$	Range	0.06-0.38	1	0.53-0.62	0.53-0.63	0.58-0.75	0.02-0.14
	STD	0.09	0	0.03	0.04	0.05	0.04
	Mean	0.15	1	0.59	0.57	0.65	0.08

Table 6: The accuracy and sensitivity of the non-linear multivariate (NLM) regressions with different variables.

Non-linear multivariate (NLM) regressions		R^2		NRMSE	
		Training	Testing	Training	Testing
NLM1	Range	0.61-0.71	0.29-0.77	0.39-0.50	0.25-0.46
	STD	0.03	0.14	0.04	0.08
	Mean	0.65	0.65	0.44	0.30
NLM2	Range	0.71-0.82	0.54-0.93	0.30-0.40	0.15-0.49
	STD	0.03	0.12	0.03	0.01
	Mean	0.77	0.74	0.36	0.31
NLM3	Range	0.71-0.84	0.44-0.94	0.30-0.40	0.15-0.49
	STD	0.04	0.08	0.03	0.09
	Mean	0.77	0.76	0.35	0.30

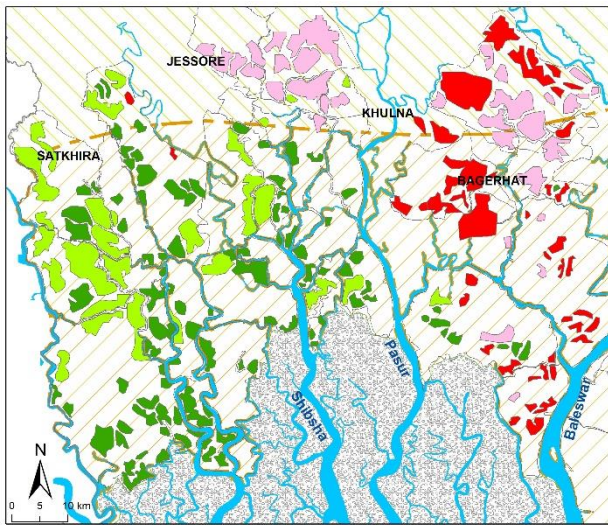
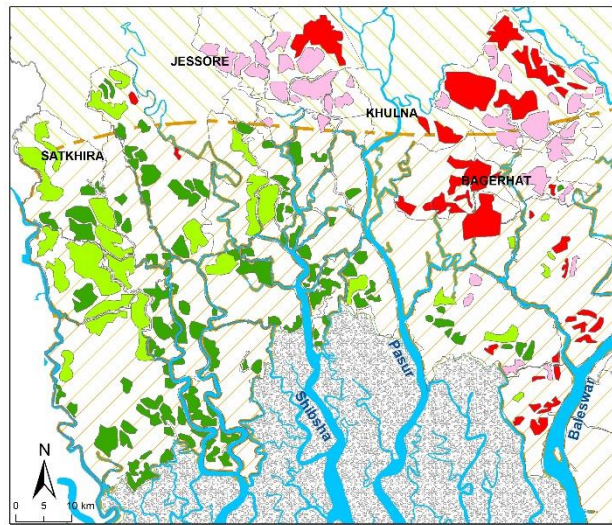
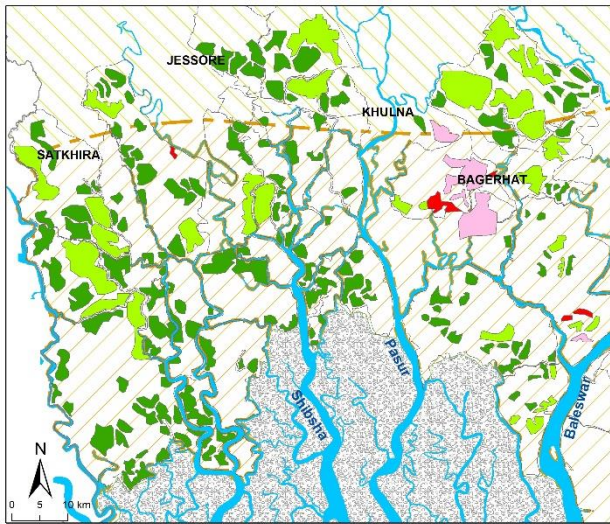
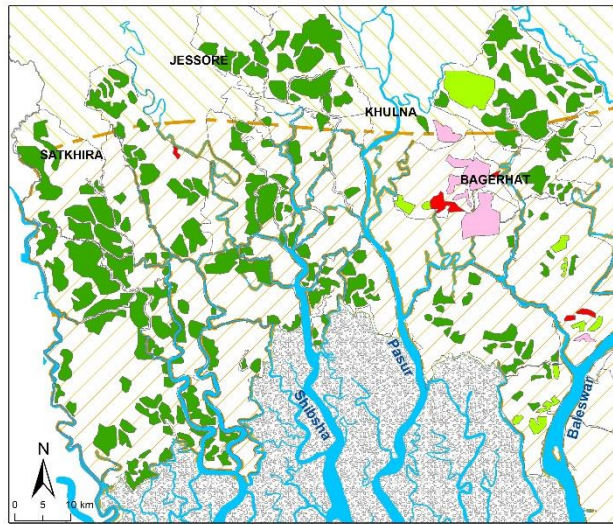
3.4 Estimation of potential of the beels to stay above sea level through renewed sedimentation using the regression model

The potential of sediment deposition to raise the land surface of the beels of southwestern Bangladesh was assessed using the empirical equation of the NLM3 regression model, assuming a beel inlet width of 60 m for all cases. The estimated potential of raising land surface elevation shows considerable seasonal and spatial variability (Fig. 6). Seasonal estimated SPD for all beels varies from 4 mm yr $^{-1}$ (0.4 times RSLR) during the dry season to 150 mm yr $^{-1}$ (15 times RSLR) during the monsoon

season. Spatially the beels located west of the Pasur River of the study area have a high potential for TRM for all scenarios, while the beels east of the Pasur River generally have lower potential (Fig. 6). Generally, smaller beels have higher potential to raise land surface elevation than larger beels (Fig. 6). Out of the 234 beels, 32, 31 and 35 have high, and 115, 120 and 187 have very high potential to raise the land surface elevation during the dry season, pre-monsoon and monsoon, respectively.

375   This means TRM operation during the monsoon season only is sufficient to raise the land surface by more than 3 times yearly RSLR (> 30 mm yr^{-1}) for 96% of all beels and by more than 5 times the RSLR (>50 mm yr^{-1}) for 80% of all beels. Applying TRM around the year increases the potential to raise land surface elevation from high to very high in 22 additional beels.

A number of beels located east of the Pasur River remain having low to medium potential even with around the year operation of TRM. The beels within the MF region have low to medium potential to raise land surface elevation when TRM is operated

380   during the dry and pre-monsoon seasons (Fig. 6a and Fig. 6b).

(a)   (b)

(c)   (d)

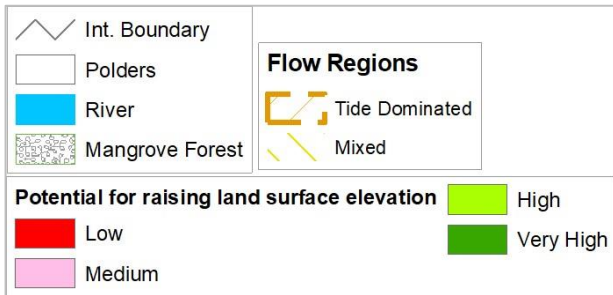



Figure 6: The potential of raising land surface elevation of beels in southwestern Bangladesh using TRM operation during a) Dry, b) Pre-monsoon, c) Monsoon seasons and d) round the year.

Very high potential is > 5* RSLR; High 3-5*RSLR; Medium 1-3 *RSLR; Low potential < 1*RSLR (RSLR = 10 mm yr^{-1})

4 Discussion

4.1 The effect of physical controls on sediment deposition per day (SPD)

We explored how sediment deposition per day (SPD) in beels having a single inlet under active operation of Tidal River Management (TRM) depends on boundary conditions associated with flow regime of the feeding river and season (tidal range (TR) and suspended sediment concentration (SSC)), and on various beel dimensions (surface area (BA), width of the inlet channel (IW) and inundation depth (ID)).

The physical controls TR and SSC which are related to hydrodynamics of the river have a positive correlation with SPD. SPD depends on the sediment load in the feeding rivers for which TR and SSC are primary drivers resulting in positive correlation of SPD with TR and SSC (Table 4). This is similar to the findings of Islam *et al.* (2020; 2021). Of the two physical controls TR and SSC, SSC has the highest correlation with SPD (Table 4). This means that sediment deposition in beels depends mostly on SSC in the feeding river, which in turn shows a high correlation with TR (0.57). The physical controls TR and SSC are deemed statistically significant by the ANOVA test p-values (Table 3). Islam *et al.* (2021) found that seasonal and spatial variation of SSC and TR in the rivers result in a large seasonal and spatial variation of sediment deposition in beels indicating that TR and SSC are primary physical controls of SPD. The scientific document provided by DHI for Mike 21FM indicates that SPD increases linearly with increasing SSC (DHI, 2012b). Talchabhadel *et al.* (2017) indicated that high sediment deposition occurs inside the beel with stronger tide in the river. According to Talchabhadel *et al.* (2017) and DHI (2012b), SPD will vary seasonally with seasonality for SSC and TR, which is confirmed by our findings.

Statistical analysis of our 2D hydro-morphodynamic model results indicates that among the physical controls BA, ID and IW which are related to geo-morphodynamics of the beels, SPD has highest correlation coefficient with BA (0.56) (Table 4). SPD increases with larger beel surface area, which is in accordance with Van Minnen (2013) who reported 6.45 million m^3 of sediment deposited in Bhaina Beel (600 ha) compared to 8.2 million m^3 in the larger Khuksia Beel (1100 ha) during 4 years of TRM operation. With larger surface area of a beel, a larger volume of suspended sediment can be delivered inside. We found that SPD has positive correlation with ID and BA (Table 4) which is similar to Talchabhadel *et al.* (2017) who indicated that more sediment deposition occurs when larger volumes of water enter the beel with tide. We found low correlation between IW and SPD (Table 4) which is consistent with the findings of Talchabhadel *et al.* (2017). They suggested IW has minimal effect on SPD, although the spatial distribution of sediment deposition varies between different IWs, which is similar to the results of our 2D hydro-morphodynamic model. As BA and ID vary among the beels of SW Bangladesh, this causes variations in SPD among the beels. All three physical controls related to geo-morphodynamics of the beels, BA, ID and IW, and their interactions are statistically significant for SPD as indicated by the ANOVA test p-values (Table 3).

4.2 Estimation of SPD with multivariate non-linear regression models (NLMs)

We developed non-linear regression models from the 2D morphodynamic model results to provide an a priori estimation of sediment deposition inside the beels of southwestern Bangladesh if they would be subjected to TRM practice. Adnan *et al.* (2020) used linear regression modelling with geomorphological parameters as variables which were mostly related to land elevation to calculate sediment deposition. They did not consider TR and SSC to estimate sediment deposition, but Islam *et al.* (2020) found sedimentation inside the beel depends strongly on the SSC and TR in the rivers. The coefficient of determination (R^2) of the linear regression model of Adnan *et al.* (2020) is stated as 0.88 even though their empirical equation had a residual which will yield sediment deposition with all the variables set to zero. We used non-linear regression models to include the effects of non-linearity between SPD and the steering physical factors TR, BA, ID and IW and their interaction as described by Islam *et al.* (2020), Talchabhadel *et al.* (2017), Gain *et al.* (2017), Van Minnen (2013) and DHI (2012b). The accuracy and uncertainty analysis of our regression models for 10 sets of training and testing samples indicate that the regression model NLM3 may be applied to estimate sediment deposition.

Of the parameters considered in the non-linear regression models as variables, SSC is the most difficult one to have measured data across time and space, and hence it has large uncertainty. Tidal range (TR) and ID also vary in time and space and are estimated from observed water level which has lower uncertainty compared to SSC. The width of the inlet (IW) and BA are related to the geographic setting of the beels and have well-defined values when a TRM is operated. Therefore, SSC has the largest uncertainty while it is a major parameter with the highest correlation with SPD.

4.3 Estimated sediment deposition, potential to raise land surface elevation and their implication for the beels of southwestern GBM delta

Our estimation of potential sediment deposition and associated land surface elevation increment inside beels using the regression models indicates that TRM shows high potential to counterbalance RSLR in southwestern Bangladesh. When operated year-round, in 228 out of 234 beels (97%), the land surface elevation can be raised by more than 3 times the RSLR as predicted under the RCP 8.5 scenario (10 mm yr^{-1}) for southwestern Bangladesh (Oppenheimer *et al.*, 2019). When operated only during monsoon, land surface elevation can be raised in 96% of all beels by more than 3 times RSLR and in 80% of all beels by more than 5 times RSLR, indicating that TRM operation only during monsoon is almost as effective as year round operation.

The sediment carried by Ganges, Brahmaputra and Meghna rivers discharges through the Meghna estuary (Anisul and Munsur, 2016). These sediments re-enter the western sea arms where the beels identified by Adnan *et al.* (2020) are located due to clockwise estuarian circulation (Anisul and Munsur, 2016). Derby *et al.* (2018) indicated that due to anthropogenic and climate change the supply of fluvial sediment to the apex of the GBM delta is likely to increase substantially, by around 50 percent by 2090s. In contrast, Higgins *et al.* (2018) projected that due to anthropogenic changes upstream, both the Ganges and the Brahmaputra rivers will experience reduction in the annual suspended sediment load by 39-75% and 9-25%, respectively. The increase or decrease in sediment supply in the rivers will impact the potential of the beels for sediment deposition in the future.

The overall effect is dependent on the future climate and connected socio-economic scenarios. With our method a priori

445   estimation of sediment deposition and potential of TRM can be achieved for different future scenarios.

Beels close to sea and to the west of the Pasur River in the tide dominated flow region show highest potential for sediment deposition and raising their land surface elevation by means of TRM. However, Adnan *et al.* (2020) indicated that the beels close to the sea have a low potential to reduce flood susceptibility. The tidal range (TR) and SSC are high in the rivers close to the sea all around the year (Islam *et al.* 2021) resulting in a high potential to raise the land surface elevation with sediment

450   deposition for the beels of southwestern Bangladesh. Thus, our results indicate the natural flood vulnerability of these polders may be sustainably reduced by application of TRM using controlled flooding.

According to our estimation smaller beels generally have higher potential to raise land surface elevation than larger beels. Van Minnen (2013) reported that 6.45 million m^3 and 8.2 million m^3 of sediment deposited in Bhaina Beel and Khuksia Beel during TRM operation, with surface areas of 600 and 1100 ha respectively (Gain *et al.*, 2017). Although surface area of Khuksia Beel

455   was 1.8 times that of Bhaina Beel, sediment deposition was only 1.3 times higher. Therefore, the average land elevation increment was higher in smaller Bhaina Beel which is in line with our findings. As suggested by Amir *et al.* (2019), the rise of land surface elevation in larger beels may be achieved by compartmentalizing the beel into smaller part.

The land elevation east of the Pasur River is higher (Fig. 1), resulting in lower ID for the beels even within the same flow regions. Suspended sediment concentration (SSC) and TR are generally lower for the mixed flow (MF) region when compared

460   to the TDF region during dry and pre-monsoon seasons (Islam *et al.*, 2021). Therefore, SPD and potential to raise land surface elevation with sediment deposition are also generally lower for beels in the MF region during dry and pre-monsoon seasons when TR and SSC for the river stretches in the MF region are lowest. However, the water level in the rivers is generally higher during the monsoon season (Islam *et al.*, 2021), increasing the ID and consequently the SPD and potential to raise land surface elevation is high for almost all the beels. The beels having low to medium potential to raise land surface elevation during

465   monsoon season and annual operation of TRM, have high average land level (Fig. 1) reducing the ID and causing low SPD.

Adnan *et al.* (2020), Amir and Khan (2019) and Talchabhadel *et al.* (2018) considered uninterrupted operation of TRM for several years. In addition to annual operation of TRM we have considered seasonal operation of TRM as well. Our analysis shows that the potential is higher when TRM is operated during monsoon than during pre-monsoon and dry seasons (Fig. 6). Monsoon season is longer and sediment load is higher in the rivers compared to the pre-monsoon and dry seasons resulting in

470   higher sediment deposition and higher potential to raise land surface elevation than in other seasons. This is an important finding as continuous and lengthy operation of TRM may not be accepted by local communities. Farmers living in Khuskshia Beel where TRM was operated continuously for 7 years have a negative impression of TRM due to such a long period of operation and lack of compensation, and questioned its effectiveness (Gain *et al.*, 2017). When TRM is only operated in the monsoon season, the land inside the beel will remain available to local stakeholders for the rest of the year. This may potentially

475   increase the acceptability of TRM to the local stakeholders.

4.4 *Using tidal river management (TRM) as a way to keep up with relative sea level rise (RSLR)*

Controlled flooding like TRM can potentially be applied in rotation to the beels with high potential to counteract yearly RSLR through sediment deposition and thus raise the coastal areas of the GBM delta. This would entail two main phases. First, the land surface in the beels, as well as the polders they are in, should be raised to get equal to the current average sea level of the region. After that TRM should be applied such that the land surface is raised at least at the pace of RSLR to remain equal or above to sea level. TRM may be operated once in every few years to achieve these goals and keep the land available for agriculture in between. Gain *et al.* (2017) indicated that rotational operation of TRM is suggested by experts and local communities. Talchabhadel *et al.* (2020) explored the rotation of TRM in 4 beels of southwestern Bangladesh and concluded that TRM can be applied sequentially in one beel at once continuously for 4 years. They also suggested that TRM should initially be applied in beels located downstream and gradually shift towards the beels located upstream, regardless of the surface area of the beels. IWM (2017a) also proposed sequential operation of TRM in the beels along the Teka-Hari-Teligati River system of southwestern Bangladesh where TRM can be applied in one beel at once and continuously for 7 years in each beel. However, physical constraints as well as socio-economic aspects of TRM operation should be considered to determine an optimum flood rotation scheme for the beels in southwestern Bangladesh. At this point in time, however, there is no master plan indicating how a rotational scheme should be devised to raise the GBM delta effectively with TRM against RSLR.

Our study may present a method to work out such a plan in future to raise the land with sedimentation and to offset yearly RSLR. However, it must be noted in our study only total sedimentation inside the beel was explored and spatial distribution of sediment deposition was not considered. As Islam *et al.* (2020), Talchabhadel *et al.* (2017) and Gain *et al.* (2017) indicated, spatial distribution of sediments inside the beel is also important for the operation of TRM. For this more location specific detailed studies will be required to understand the effect of TRM inside a specific beel. Implementation of several previous TRM operation included excavation of the adjacent river supplying sediments inside the beel (IWM 2017a; 2017b). Water and sediment dynamics of the river are affected by the change in river bathymetry. Therefore, the effect of dredging and exaction of the river should be explored in the future.

Socio-economic aspects such as conflict between the stakeholders, lack of proper compensation, lack of livelihood opportunities, lack of stakeholders' participation during planning and implementation phase of the TRM, lack of cooperation between stakeholders and government agencies, divergence in common interest, imbalance between expectation and outcome and unequal distribution of benefits of TRM challenged the effective implementation of previous TRM operations (van Minnen, 2013; van Staveren *et al.*, 2017; Gain *et al.*, 2017; Mutahara *et al.*, 2018). Therefore, next to the physical considerations the socio-economic aspects and social acceptability of TRM should get ample attention in order to fully reap the potential of the method we have explored.

To understand how the sediments delivered by the tide inside the beels affects the soil fertility and food productivity, De Bruin (2019) collected samples of new and old sediment deposits from three different locations. The locations were: the beel where TRM was operated in the past (Khukshia Beel), the beel where TRM operation was ongoing (Pakhimara Beel) and an area

which received much sediment during a dike breach as a result of a cyclone induced storm surge (Polder 32). Sediment samples

510   were also collected from the areas which are protected from tidal flooding. The rice variety preferred by local farmers was cultivated by De Bruin in the collected sediment samples following traditional and local practices. The results indicate that the sediments delivered by tide had similar fertility and food productivity as the old sediment deposits which were not flooded in recent years. Therefore, the sediments delivered by the rivers of southwest Bangladesh is as good as old sediment deposits if not better.

515   Our study also considers operation of TRM in one beel within a river reach at once. More detailed studies will be required to reflect on the changes in sediment availability in the river section during a basin wide operation and shifting of TRM in several beels as suggested by Talchabhadel *et al.* (2016 and 2020). As our study considers TR and SSC of the river sections, the changes in sediment availability for such TRM operation can be taken into account. Moreover, similar to our study, Talchabhadel *et al.* (2016 and 2020) also explored the shifting of TRM operation considering TRM in one beel at once.

5 Conclusion

The Ganges-Brahmaputra-Meghna delta in Bangladesh is severely threatened by sea level rise. Tidal River Management (TRM) may offer a solution by raising the land surface in polders through re-sedimentation by controlled river flooding using deliberate dike breach. Previous studies such as Adnan et al. (2020) determined the potential of TRM to raise the land in 234 beels in southwestern Bangladesh using five geomorphological parameters and identified 106 beels (26%) as suitable for TRM operation but did not take into account seasonal and spatial variations in physical drivers, nor the non-linear character of physical drivers and several sensitive parameters for sediment deposition. We used non-linear multivariate regression models (NLM) with five parameters as variables to determine sediment deposition potential of TRM operation in the 234 beels in southwestern Bangladesh, of which tidal range (TR) and suspended sediment concentration (SSC) are related to hydrodynamics of the river, and inundation depth (ID), width of the inlet (IW) and surface area of the beel (BA) are related to geo-morphodynamics of the beel.

In contrast to Adnan *et al.* (2020), who considered geomorphological parameters to determine suitability for TRM operation, our NLM results indicate that beels located closer to the sea, where tide dominates river flow, have higher potential for TRM. Furthermore, the potential to raise land surface elevation using TRM is high (elevation rise > 3 times yearly RSLR) for 97% of the beels with year round operation of TRM, but almost as effective (96% of all beels) when operated only during monsoon (Fig. 6). 80% of all beels have very high potential (elevation rise > 5 times RSLR) when operated only during monsoon. Smaller beels show higher potential to raise the land surface elevation than larger beels. Higher land surface increments in larger beels may be achieved by compartmentalizing them into smaller compartments. TRM operation during monsoon showing virtually the same high potential as year-round operation is an important finding, since restricting TRM to the monsoon season implies the land will remain available for agriculture during the rest of the year. This may increase acceptability of TRM to stakeholders in the beels and polders.

Our regression model provides a priori estimation of the potential to raise land surface elevation for the beels in southwestern Bangladesh, which may assist decision makers to prioritize the location of TRM operation, for example as part of the Bangladesh Deltaplan 2100. TRM may be implemented, restricted to monsoon periods, involving a flood rotation scheme of different polders being raised during different years, over a prolonged period of time, to keep up with continuing sea level rise. However, since TRM operation is not only dependent on physical constraints, planning should also give adequate attention to socio-economic aspects to get acceptance by stakeholders affected.

Data availability.

550   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 do not have the authority to share the data publicly.

Author Contribution

All the authors contributed to the conceptualization, development of methodology, writing and editing of the manuscript. In addition to these Md Feroz Islam carried out the model simulation and analysis, and Paul P. Schot, Stefan C. Dekker, Jasper

555   Griffioen and Hans Middelkoop supervised the research.

Competing interests

The authors declare that they have no conflict of interest.

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