Hydraulic and morphological response to Tidal River Management in Bangladesh

Bachelor Thesis

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Abstract

In the southwestern region of Bangladesh, severe drainage problems occur within the polders due to relative sea level rise and accumulated sediment within the tidal channels. In order to counter this, a method based on ancient water management, called 'Tidal River Management' (TRM) is implemented. By restoring the natural tidal regime by temporarily inundating the polder, sediment is brought into the polder, which initiates land raise while the drainage capacity of the tidal channel improves. In this research, a 1D-hydraulic model was used to investigate the hydraulic response inside the river and in the inlets of polders to TRM operation. This was done for six polders connected to the same tidal river in the south-western region of Bangladesh. Results were compared for performing TRM separately or for all polders simultaneously. With these results, the effect of TRM operation on drainage capacity of the tidal channel and the rate of land raise in the polders, is estimated. The results indicate that land raise for opening all beels simultaneously will likely not be enough to keep up with relative sea level rise. However, if a polder is opened separately, the individual polder will likely keep up. Furthermore, drainage congestion in the tidal river will slightly improve near the four most seaward polders but will worsen near the two most landward polders if all polders are opened simultaneously.

1. Introduction

The country of Bangladesh is located in the downstream area of the mighty Ganges, Brahmaputra and Meghna rivers. It is surrounded by the Rajmahal Hills in the west, Himalayas and the Meghalaya Plateau in the north, and Tripura–Chittagong hills in the east. The country itself consists of a flat, low-laying alluvial plain (Huq & Shoaib, 2013) with a mean elevation range up to 1m in the tidal floodplains in the south and south-west, 1-3m on the main river floodplains and up to 6m in the north-east. The Ganges, Brahmaputra and Meghna rivers join in Bangladesh and together bring 1.05 trillion m^3 of water and transport the world highest sediment load of 1.0 to 1.4 billion tons each year from the surrounding elevated areas to Bangladesh (Khan, 2014). This makes the delta, where Bangladesh is part of, the largest and one of the most dynamic, in the world.

91 percent of the water in the river systems originates from catchments outside of Bangladesh, the rest of it is added as annual rainfall (Parvin et al., 2013). In the coastal area, tidal rivers have shape and dominate the landscape for millennia. These morphodynamically very active rivers determine the drainage pattern and morphology of this region by frequent flooding and both transport and distribution of sediment from the Bay of Bengal.

The seasons are characterized by a sub-tropical, humid, moderately warm climate. The seasons distinguish mostly on broadly varying precipitation quantities. Not only temporal, but also extreme spatial differences in rainfall are present. Variation from 1400mm in the west to more than 4300mm in the east. The seasons are classified in four different meteorological seasons: Pre-monsoon, monsoon, (post-monsoon) and the dry season. The largely temporally varying precipitation rates are responsible for extreme weather events causing floods during the wet seasons and scarcity during the dry season and pre monsoon. These extreme events are projected to increase due to climate change (Shahid, 2011).

While once the tidal rivers shaped the landscape in the coastal area, humans have taken over this task and implemented large scale geo-engineering projects such as the construction of polders. In the coastal area 41 out of the total 150 million Bengals are situated. (The World Bank, 2017). According to (The World Bank, 2017) the population will grow significantly, increasing the number of inhabitants in the coastal area by about 20 million in 2050. In this region, the average population density is 743 inhabitants per km^2. Fishing, agriculture, shrimp farming, salt farming and tourism are the main source of income. (Sarwar, 2005). This high population density and agricultural dependency causes dramatic economic and social consequences for natural hazards such as flooding and cyclones.

Climate change does not only increase the number of extreme precipitation events, but also induces sea level rise. According RCP 2.6, global sea level rise (SLR) is projected to be between 0.18-0.33m (90% confidence interval) by 2050. According to RCP 8.5, this might be between 0.21m and 0.38m. (Strauss & Kulp, 2017). Due to compaction of the sediment and tectonic processes, land subsidence already reaches a rate of 5 mm/y enhancing relative sea level rise (RSLR). The increased RSLR amplifies the frequency of flood events.

Due to the densely populated area and the high dependency on agriculture, the consequences for these flooding events are high. (Davis et al., 2018) predicts that 0.9 to 2.1 million people from the southern part of the country will be displaced by 2100, causing mass migration in the area. This will have severe economic consequences as people lose their land and sources of income. With this loss of land, food security is at stake, risking future famines.

All these demographic, geographical, physiographic and hydro-climatologic elements cause Bangladesh to have a long history of flood management approaches. From 1958 the coastal embankment program (CEP) was initiated. Polders in Bangladesh were constructed and the tidal rivers were embanked. The old floodplains were used for construction and agriculture and, as a consequence, the intertidal area decreased. Due to this reduced volume of water storage, the tidal prism decreased and sediment accumulated within the tidal channels. As a result, the tidal channels partly silted up while the polder area did not receive enough sediment and lowered due to land subsidence. As a consequence, drainage congestion problems are now widespread throughout the south west of Bangladesh.

Some polders experienced waterlogging problems as the drainage channels were located higher than the lowest parts of the polder. These depressions collect surface run-off water and become static water bodies. The local name for such a low land adjacent to the river is called a 'beel'.

A method to improve the drainage of the polders is Tidal River Management (TRM). In this method, the embankment surrounding the polder is breached and the natural tidal regime is restored within the polder and both water and sediment can freely flow into the polder during high tide. By adding tidal basins and therefore increasing the volume of the system, the tidal prism increases. As the tidal prism increases, the cross-sectional area of the tidal channels increases with it (Ibne Amir et al., 2013). Deposition takes place in the opened polders and raises the land while the tidal channels are lowered and widened due to erosive processes. This improves the drainage capacity of the polders. After some years of operation, the breach is closed and the raised land can be drained and becomes habitable again.

Rotational schemes for tidal basins adjacent to tidal rivers have been made in order to alternate the TRM method between different tidal basins (IWM, 2016). In this way, tidal basins are not flooded for too long and farmers will not suffer for too long. This concept is known as tidal basin management (TBM)

1.1 Problem

Although TRM has been a successful way of raising the level of the beel and lowering the tidal channels, physical and social-economic challenges remain. Physical challenges include sediment management problems, such as the non-uniform spatial and temporal sediment distribution within the tidal basin. From experience and model results (Islam et al., 2020) (Talchabhadel et al., 2018), most sedimentation takes place near the cut point, creating drainage congestion problems in the far end of the basin. Compartmentalization and rotation of the openings is proposed (Ibne Amir et al., 2013) to spread the sediment more uniformly.

Next to physical challenges, TRM encounters social problems (Gain et al., 2017) as not all local stakeholders favour TRM and sometimes prefer the CEP method. In order for TRM to operate, people (often farmers) are displaced and lose their land and source of income. This in combination with non-transparent crop compensation by the government and insufficient consultation with the local people results in small public support. These social conflicts have effect on the physical results (Gain et al., 2017). For example, shrimp farmers that did not leave their land had left fields constructions in place that obstructed the uniform spreading of sediment. This caused water-logging problems to remain and the TRM method to end earlier. In the three TRM examples sketched by (Gain et al., 2017), the most successful scenario was the one where local conflicts were resolved before TRM was implemented.

Time is a very important factor that comes in play in order to conduct TRM successfully. Shorter duration of inundating the area for TRM leads to smaller economic loss and broader public support. Conversely, flood protection is urgently needed to prevent great potential future damage. In order to reduce the duration, effectiveness of TRM should be maximized. Furthermore, if the TRM method is poorly planned but still put to action, results disappoint and more damage than good may be done. Poor implementation will negatively affect the public support. Therefore research on both the most effective and successful way should be done before implementing TRM. This all means that, there is an urgent need to research on the physical effects of TRM in order to improve its effectiveness.

1.2 Objective

This study aims to determine the hydrodynamical response to TRM operation on six beels in the Tala Upazila (subdistrict), Satkhira district, Khulna division (figure 1). With these results, an indication on the morphodynamic response, such as sedimentation rates, channel geometry and land raise will be provided.

1.3 Research questions

To achieve this goal, the following research questions were formulated to be answered in this study:

1. How much sediment is demanded per beel to raise the land quick enough to keep up with RSLR
2. What happens to the hydrodynamics (stage, discharge and tidal prism) in the area if one or multiple beels are opened?
3. What will happen to the drainage capacity of the tidal river?
4. How long will TRM have to be in practise in this area in order for it to be effective?
5. Because the temporal differences in precipitation, sedimentation rates will differ per season. How does the hydrodynamic and morphodynamic behaviour change per season?
6. What happens if we open multiple beels simultaneously compared to when we open them separately with regard to hydrodynamics and sedimentation?

In this research, literature, existing hydrologic data, and a hydraulic model were used in order to answer the research questions. Data is derived from fieldwork by IWM (2017).

Figure 1. Geographic map Bangladesh

2. Water management in South-West Bangladesh

2.1 Water management history

2.1.1 Early embankments

The local rulers, the Zamindars, used embankments in order to store irrigation water. The Zamindars controlled the construction of temporary embankments that operated between October and May to prevent the tidal water to enter the rice fields during these seasons. Around June to September, during the monsoon, the water was allowed to enter the previously enclosed areas. This way, sediment accumulated and the land was raised, fertilized and could be used for fishing. This also allowed the water to be distributed more evenly during the flood season. (Van Staveren et al., 2017). During the colonial times, the policy was less focused on irrigation but more on redirecting the rivers for navigational purposes.

During this period, water management was neglected. Embankment and reservoir tanks were in a poor state and the rivers silted up as they were not properly dredged anymore. As a consequence, frequent flooding and crop damage became a mayor problem.

2.1.2 Systematic embankment programme

From 1958 the coastal embankment program (CEP) started (van Minnen, 2013). The CEP program was initiated by the UN Krug mission after the large flood in 1954. In 1964 the East Pakistan Water and Power Development Authority (EPADC) with help of the International Engineering Company (IECO) constructed the so called 'Master Plan' for water resources. This plan focussed mainly on reducing flooding events and decrease salinity (de Die, 2013) for the purpose of increasing agricultural production by constructing dikes and polders and drainage sluices in order to reclaim land in the coastal area. The so called 'polders' came into existence. The CEP was initially successful and flood security increased. This meant an upturn in food security as the single crop areas changed from two to three crop areas. (Gain et al., 2017). However, negative side effects became soon apparent.

2.1.3 Changing conditions

Because the area of the floodplain reduced by the construction of dykes, the tidal prism decreased as well. As a consequence, the sediment transport capacity reduced and the tidal rivers collected the sediment that would naturally be deposited on the floodplain. As a consequence, the tidal channels silted up (figure 2). These two events led to more and more land being waterlogged. However, several other reasons are under debate as causes for the amplified drainage congestion problems. Two of them are the construction of the Farraka barrage and the change in land use. The construction of the Farraka Dam at the Ganges, 19km east of the border in 1975, decreased the fresh water supply, that had not only irrigational purposes but also functioned as a flushing mechanism for the accumulated sediment in the tidal channels. Now the downstream tributaries of the Ganges became more tidal dominated and less river dominated. Another factor was the local change of land use. While the CEP project was constructed for rice and jute production, the shrimping business came into existence after the jute market disappeared. While the CEP's goal is to keep the brackish tidal water out, the shrimping companies needed this brackish water to breed certain kind of shrimps. This change in land use increased the waterlogging problems as water was allowed to penetrate more deeply into the land.

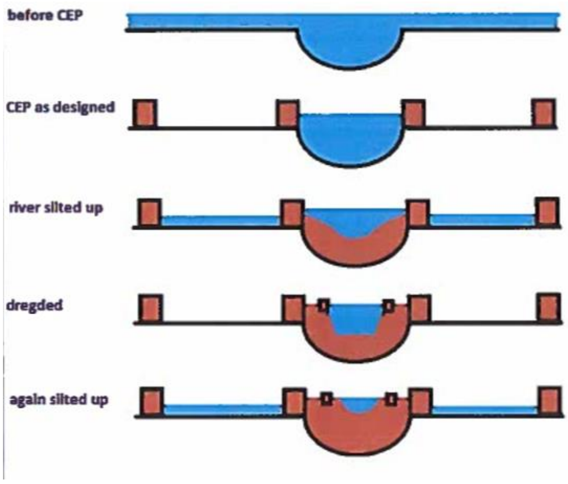

Figure 2. Schematization of siltation problem caused by the CEP program. 1: situation before CEP program, large intertidal area. 2: Construction of polders and embankment of the tidal rivers, decreased intertidal area, decreased tidal prism. 3: Due to decreased intertidal area and tidal prism, siltation of the tidal rivers. 4: To avoid further siltation, dredging of the tidal channel is commonly practised. 5: After a while, the river silts up again. (van Minnen, 2013).

The Bangladesh Water Development Board (BWDB) initiated the Khulna-Jessore Drainage Rehabilitation Project (KJDRP) in order to restore the drainage capacity.

As dissatisfaction about the CEP project and the shrimping companies grew, a local committee was founded called the ‘Paani committee’. In 1990, without governmental approval, the dikes of ‘beel Dakatia’ were breached and water was allowed to enter the beel. Sediment that had accumulated in the tidal channels could enter the beel and within two years 1050 ha of land was raised and freed from waterlogging (Gain et al., 2017). It was here where the important discussion on poldering and de-poldering started.

2.2 TRM

The intended dike breach in 1990 was an example of TRM, based on the Zamindars water management concept explained above. TRM restores the natural tide movement in the beel and could be seen as an example of building with nature. During flood, the water enters the beel and is trapped by embankments surrounding it. This causes flow velocities to decrease and therefore sediment to be deposited. During ebb, the suspended sediment concentration (SSC) has reduced greatly and the water leaves the beel, leaving sediment behind. In the course of seasons and years this deposition raises the land and reduces the waterlogging problems. During the dry season and pre monsoon, a cross dam is constructed inland of the beel to direct the tidal water into the beel. During the monsoon it is removed in order drain water from land (Islam et al., 2020). Due to an increase in intertidal volume, the tidal prism increases as well. This causes higher discharges increased cross sectional area of the tidal channel. In figure 3, a laboratory relationship between tidal prism and cross-sectional area of the tidal channels is given. The increased cross section of the tidal channels improves the drainage capacity. (Ibne Amir et al., 2013). Besides mitigating the waterlogging and siltation problems, TRM thus also improves the navigability of the tidal channels.

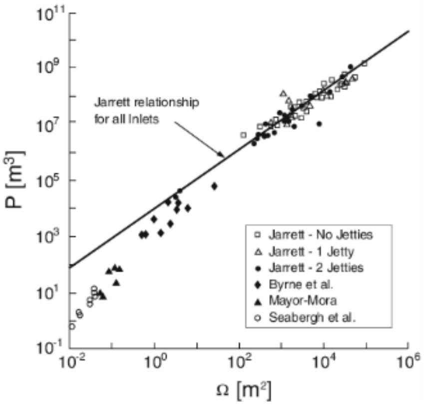

Figure 3. Relationship between tidal prism and cross-sectional area of the tidal channel (D'Alpaos et al., 2009)

2.2.1 Past examples of TRM

The TRM method has been applied several times to different sites. One was the unauthorized public embankment cut in beel Bhaina in 1997 by the Paani committee (Gain et al., 2017). Within three years the river was deepened by 10-12m near the EC and widened 2-3 times. On average, 600ha of land raised by 1m, 1.5-2m near the cut point and 0.2m in the far end of the floodplain. After 4 years in 2001, TRM operation stopped and the beel was closed.

Another case was the east Beel Khukshia in 2006, monitored by IWM. It covers an area of 800ha and unlike beel Dakatia, the embankment cut was formally planned. Here, the area received 0.9 million m^3 of sediment and heightened the beel by 1.2m on average in seven years (1.5-2m near the cut points and 0.5m in the far end during the first 5 months of operation (Gain et al., 2017). Also, near the cut point, the river lowered by 10-11m.

3. Study Area

3.1 Location

The study area is located in the south western region of Bangladesh in the administrative jurisdiction Tala Upazila in the Satkhira district of the Khulna division between N22°43’30 – N22°37’30 and E89°18’0 - E89°13’0 (WGS 84, 45N) (figure)

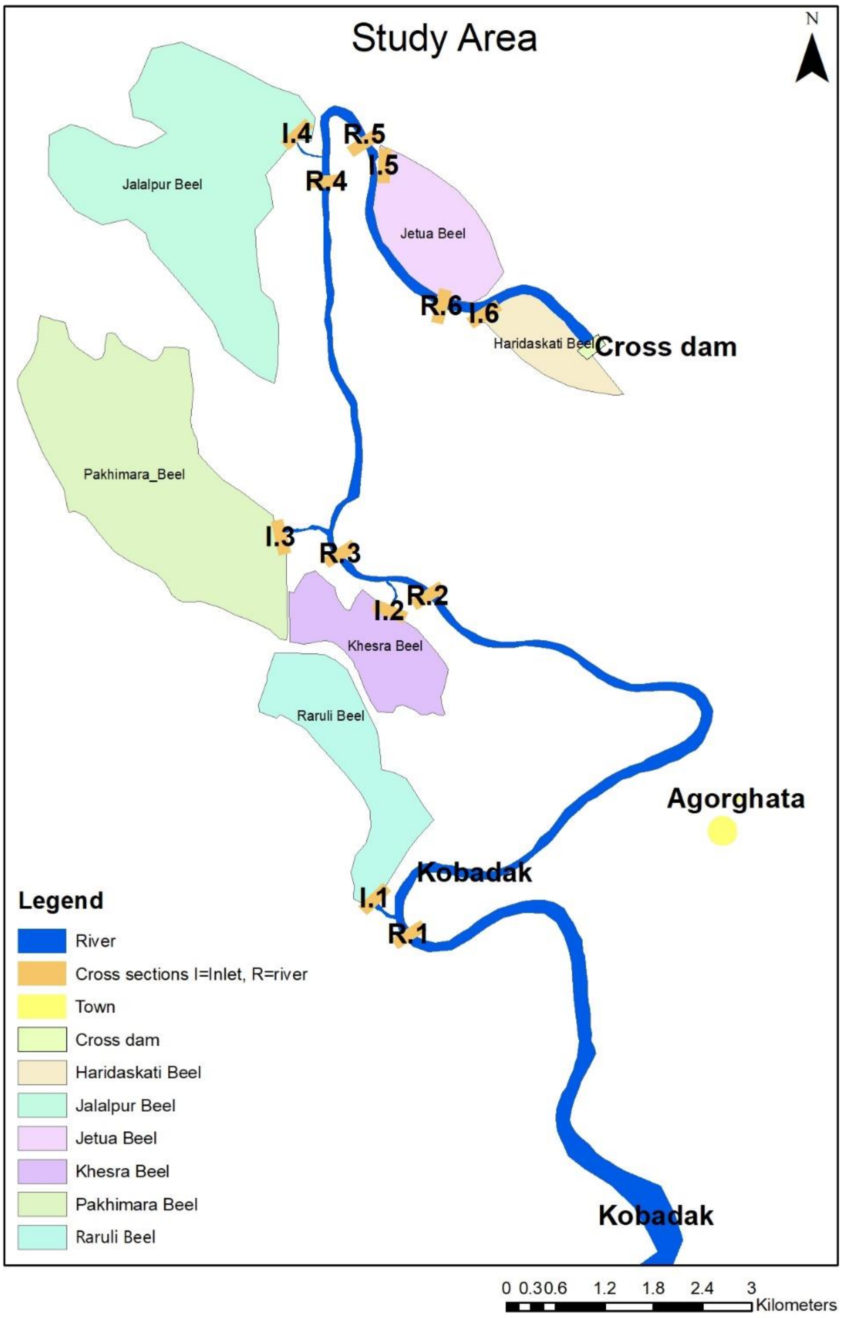

Figure 4. Schematization study area. Location of modelled cross sections (I=inside inlet, R=inside river)

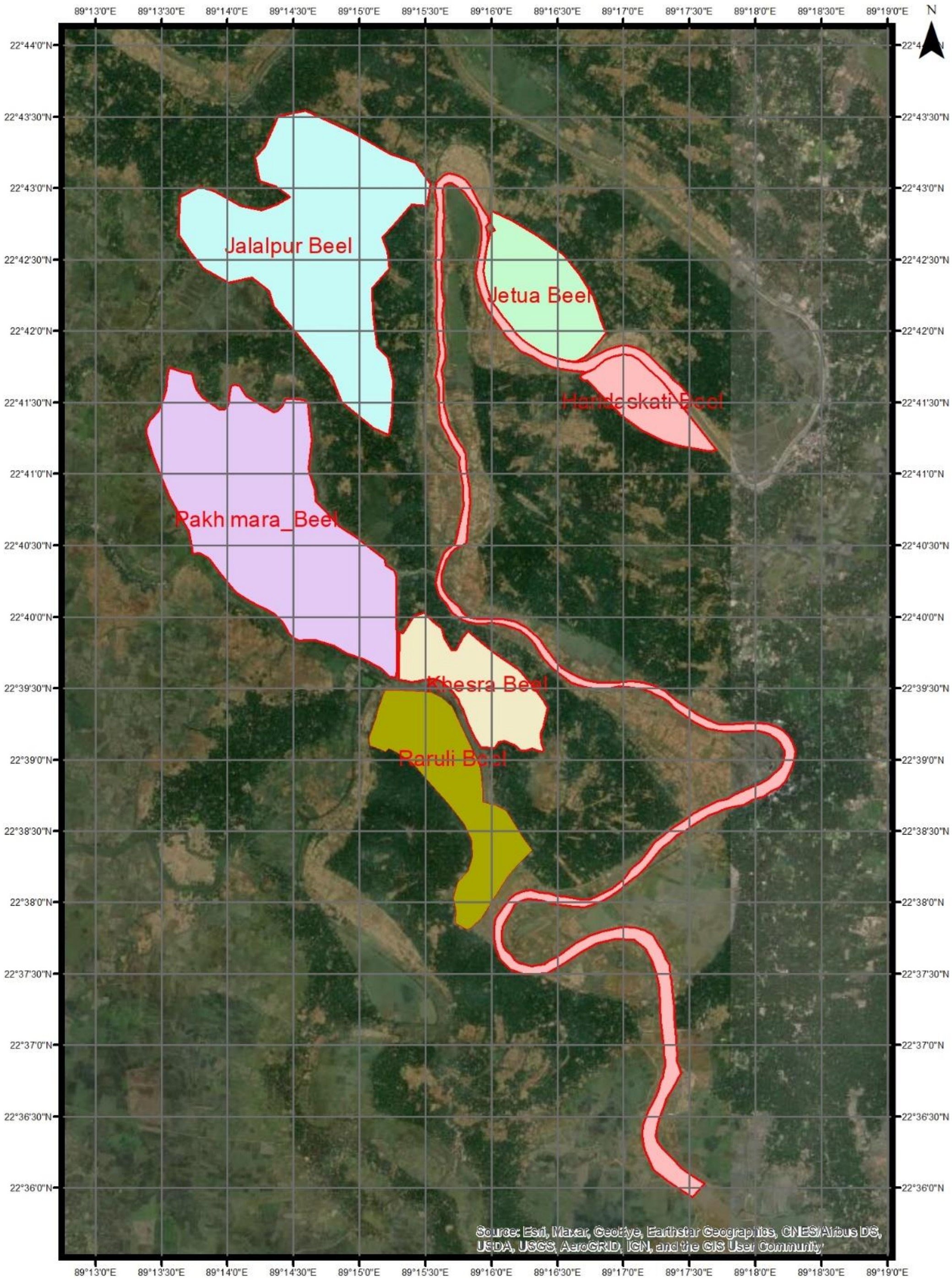

Figure 5. Satellite Imagery study area with WGS84/UTM zone 45 grid (Esri DigitalGlobe)

3.2 Local climate

In figure 6, the annual normal maximum and minimum temperatures and average rainfall per month are shown. The hot summer pre-monsoon is apparent from March to May. The high temperatures causes high evaporation rates. It is also the time when tropical cyclones occur most frequently. On average the area receives around 350mm of rainfall during this period. During the rainy monsoon (*Khariff*) from June to September, tropical depressions on the land cause prevailing landward winds from the Bay of Bengal. During this time the most extreme precipitation rates are reached. More than 1000mm (around 60% of the total annual precipitation) of rain is measured in the area during this period. Meteorologists also distinguish the short post-monsoon from October to November when

150mm of rain is recorded. In this paper, this period is equally split up in the rainy monsoon and the dry season. During the dry season *(Rabi)* from December to February, only 100mm of rain is measured (Huq & Shoaib, 2013).

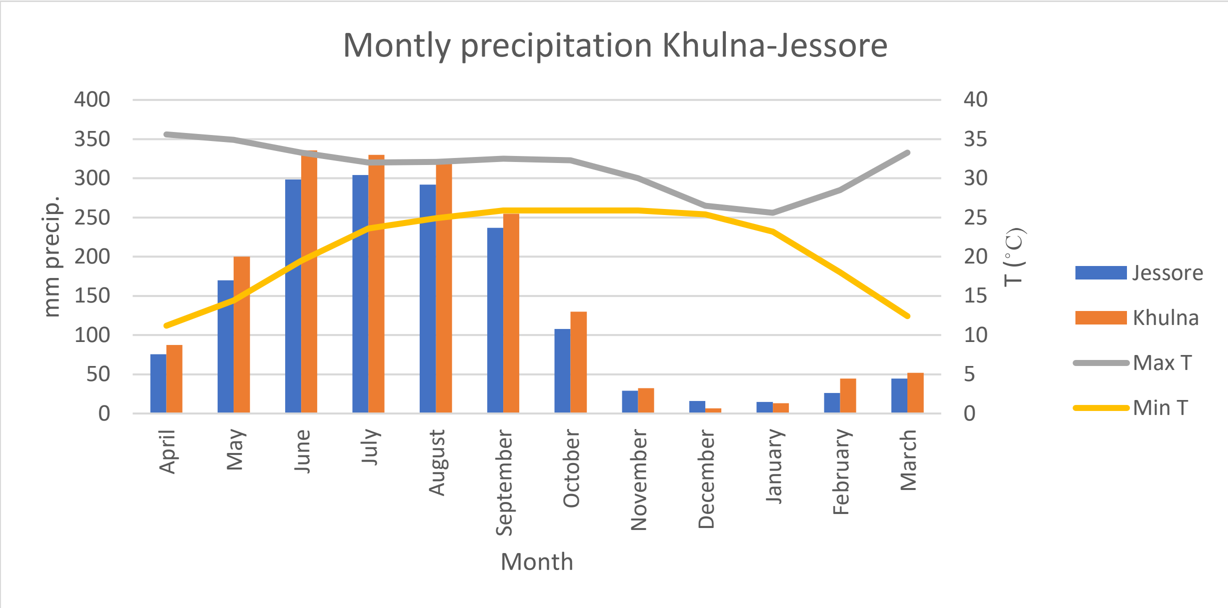

Figure 6. Monthly average precipitation rates and monthly minimum and maximum normal temperatures (IWM, 2016)

3.3 Hydrodynamical characteristics

The investigated beels are connected to the Kobadak river which flows through the Jessore, Satkhira and Khulna districts (IWM, 2017). This tidal dominated river used to be part of the Ganges river system. It was anthropogenically disconnected from the Mathabhanga river, which is located south of the study area and flows along the border of India. This in combination with the reduced fresh water inflow from the Ganges due to the construction of the Farraka barrage, caused decreased fresh water inflow into the Kobadak river. The Kobadak river now only receives fresh water during monsoon from the Ganges system. Extra water is added by the BWDB that pumps water from the Ganges to the Kobadak river to prevent it from drying out and providing irrigation water (Banglapedia, 2016). Due to the reduced fresh water inflow and embankments of the floodplain, the Kobadak river silted up and experiences drainage congestion problems.

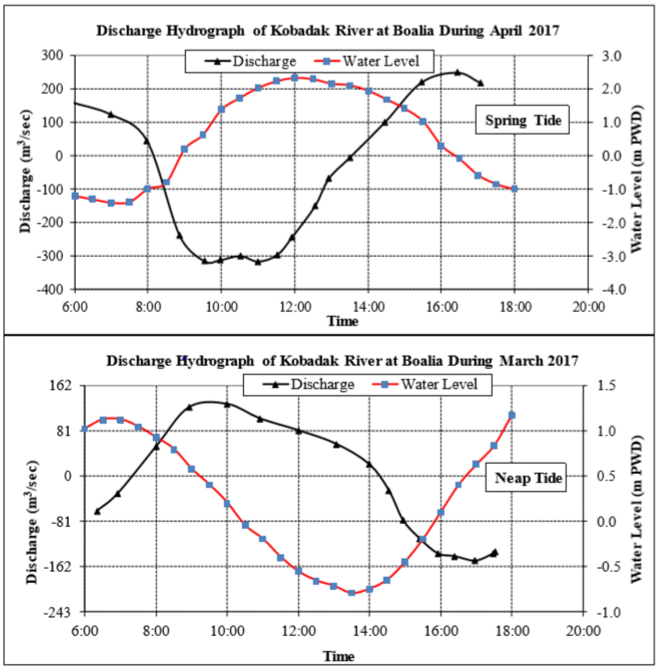

Figure 7. Discharge at Boalia (negative during flood, positive during ebb)

Because the Kobadak river is tidal dominated, the area faces intrusion of saline water. In beel Pakhimara this is about 8.5 PSU during the pre-monsoon, 1.7 PSU during the monsoon and 5.1 PSU during the dry season (IWM, 2017) . Saline water is harmful for agriculture but useful for shrimp farming.

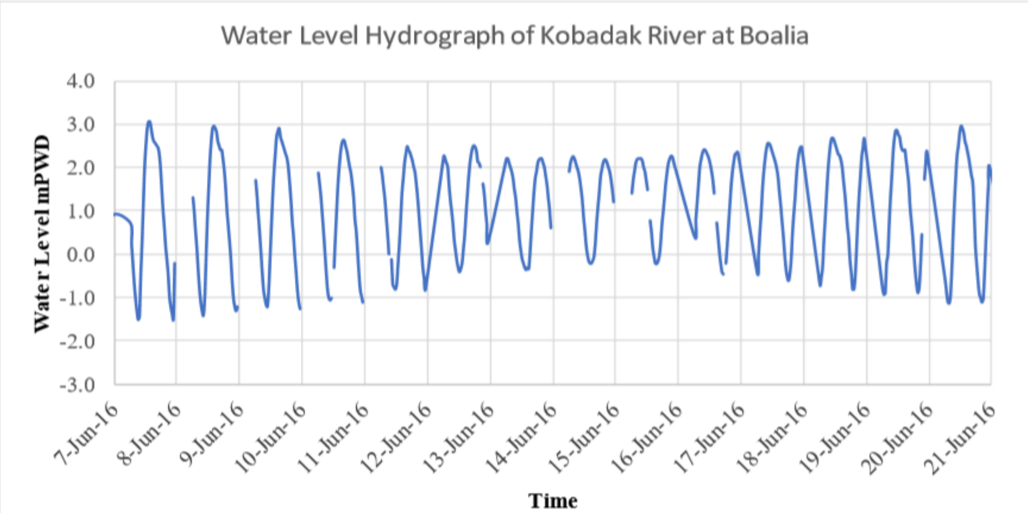

Figure 8. Water levels Boalia (20km south-west of the Raruli beel) (data: IWM)

In figure 7 and 8, stage and discharge at Boalia (20km south-west of the Raruli beel) is displayed, presenting a semidiurnal tide regime. Highest discharge is measured during monsoon. The highest SSC is measured in April (Islam et al., 2020),

Table 1. Numerical characteristics of the study area

Beel	**Area (km^2)**	**Elevation (m.a.s.l.)** (CoastalDEM)	**Population (inhabitants)** (Bangladesh Population Census 2001, Bangladesh Bureau of Statistics)	**Estimated size of inlet of the beel (m^2)**
Haridaskati	0.9	-1.3 - 2.7	n.a	16
Jalalpur	6.2	-3.8 - 2.3	22501	1400
Jatua	1.9	-1.9 - 1.8	n.a	2464
Khesla	1.7	-2.9 - 0.9	25603	1780
Pakhimara	6.3	-3.9 - 1.3	n.a	400
Raruli	2.2	-1.4 - 1.6	n.a	2664
Total	19.2	-3.9 – 2.7	n.a	x

3.4 Socio economic conditions

In 2001 about 70 % of the population in the Tala subdistrict had agricultural practises as the main source of income (Bangladesh Population Census 2001, Bangladesh Bureau of Statistics). The population is very young: less than 6% of the inhabitants is above 61 years old. (Dey et al., 2019). Poverty is widespread, 63% of the population in the Tala Upazila earn $1.90 USD or less per capita per day. This was based on a survey among 4100 households within the Tala Upazila district by (Dey et al., 2019).

3.5 Practise of TRM in the area

TRM has been practised in beel Pakhimara since 2015 (Gain et al., 2017). A cross dam was constructed directly inland of the beel during dry season, in this way, more water was directed into the beel. During monsoon this cross dam was removed to drain flood water from land (Islam et al., 2020). By the year 2017, sediment deposition had resulted in a land raise between several centimetres and more than a meter above the pre-TRM elevation in 2010 (figure 9) (IWM,2017). The TRM practise also increased the cross-sectional area of the Kobadak river due to the increased tidal prism. This had a positive effect on the drainage of adjacent beels, including beel Jalapur. However, most sedimentation occurred near the embankment cut (figure 9). This enhanced elevation differences within the beel and after TRM practise, 200 ha remained water-logged (Islam et al., 2020). Another reason was that locals had not removed fishing nets that obstructed the uniform spreading of sediment (IWM, 2017). These factors caused TRM in beel Pakhimara to be only partially successful.

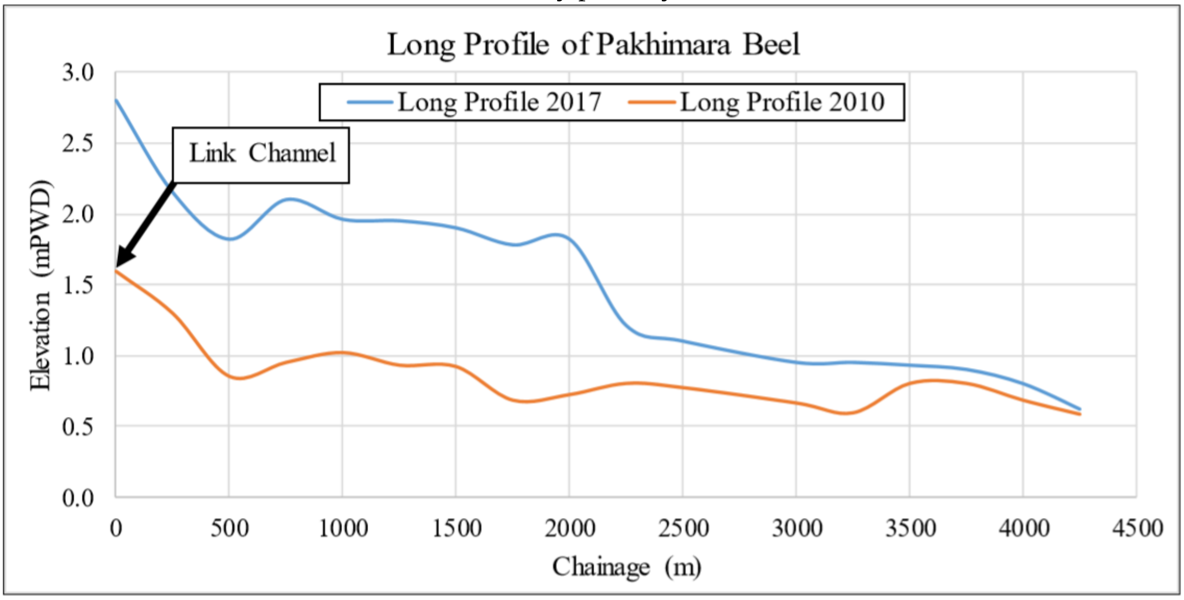

Figure 9. Cross section beel Pakhimara from 2010-2017. Before and after TRM operation (inlet is located on the left) (IWM, 2017)

4. Method

This sections is divided into *data collection*, *model description*, *hydrodynamics*, *morphodynamics* (retrieved from the hydrological model output) and the *development of the scenarios*. A short overall strategy is described below.

The 1D hydraulic model HEC-RAS was used to calculate stage, (cumulative-)discharge and flow velocities at cross sections displayed in figure 4. From the cumulative-discharge during one tidal cycle, the tidal prism was calculated, using the difference between the maximum volume of water accumulated during flood minus the minimum volume of water accumulated during ebb for one spring tide.

Knowing the tidal prism in the inlet, the total water volume entering each beel during one tidal cycle was determined. From this, sediment inflow into each beel was calculated by multiplying: tidal prism of the inlet with SSC and a trapping efficiency. Knowing the sediment input, estimates were made on rate of land raise. Tidal prism and flow velocity in the channel were used to predict whether sediment transport increases or decreases and if the channel cross sectional area would increase or decrease. All of these results were tested for different scenario's where beels were opened separately, simultaneously or all closed.

4.1 Data collection

Stage, discharge, SSC and geometric data of the channel was collected by IWM field research. Stage, discharge and SSC were collected for three seasons. A regional, hydraulic model was adjusted for the Living Polders project. From this adjusted model stage and channel geometry was retrieved for this study. Satellite imagery also contributed to the channel and beel geometry of the model.

Table 2. Data collection

Type of data	***Monitoring period***	***Method of data collection***	***Source***
Hydrometric: Stage	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 (SSC)	August - September 2016; February - April 2016; March - April 2017	Pump bottle sampler	IWM (2017)
Elevation data	x	Corrected SRTM data	CoastalDEM
Geometry	x	Satellite Imagery	*(personal communication)*

4.1 Model description

In order to research the hydrological response to TRM operation in the study area, the 1D hydraulic model HEC-RAS was used. HEC-RAS (Hydrologic Engineering Centers River Analysis System) is developed by the Hydrologic engineering centre of the US Army Corps of Engineers (Kowalczuk, 2018). Its user-friendly interface, minimal amount of input data and relatively fast computation speed makes it a suitable choice within the scope of this research. The schematization and input of the data were done by (Islam, 2020). The model bases its flow characteristics on the St. Venant/Shallow water equations, geometry and the Manning's roughness equation. (Pappenberger et al., 2005). 1D flow characteristics are measured at cross sections displayed in green in figure 10. The cross sections chosen to display in this paper are found in figure 4. Data from table 2 is used as input. Boundary conditions such as stage and discharge were located where the Kobadak river ends up in the Shibsa river (roughly 20km seaward from Raruli beel). In order to model TRM practise, the model allows water from the tidal river to enter the wider beel via an inlet. The area of the inlets of the beels are provided in table 1. From here on, the (simplified) practise of TRM is named as the opening of a beel.

Input	**Output (at cross sections in inlet and in river)**
Geometry	Modelled Stage
Measured Stage	Modelled Discharge
Measured Discharge	Modelled cumulative discharge
Manning coefficient (=0.05)	

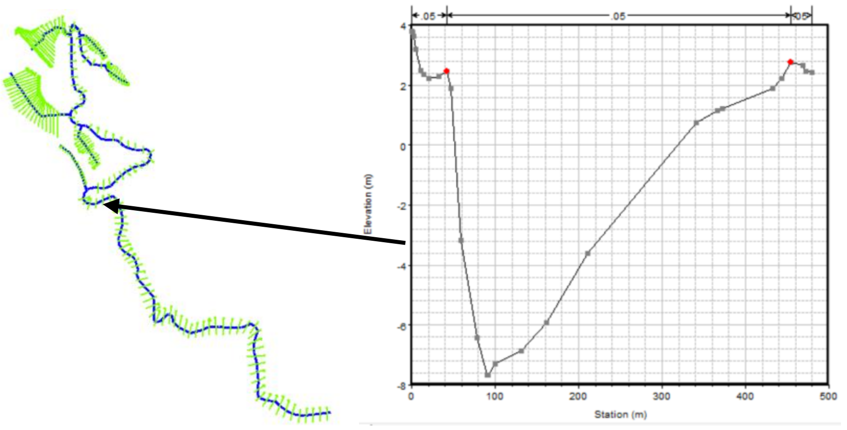

Figure 10. Plan view of the modelled area (left), model cross section near Raruli beel (location indicated by the arrow) (right)

In figure 10 , a cross section of the tidal river and the plan view of the modelled area is shown (schematized in figure 4). The beels are modelled as widened and shallow channels. Landward of beel Haridaskati, a cross dam is modelled that prevents the water from penetrating further landward (figure 4). The model runs use a computational time of 5 minutes. The output is aggregated to intervals of 1 hour. One model run covers a period from the first of January to 30th of December. The model is capable of computing hydrodynamic results but is not capable of retrieving sedimentation results for a tidal regime as the direction of water reverses. Therefore, the sedimentation results are manually calculated with help of the hydrodynamic results.

4.1 Hydrodynamics

In order to show the hydrodynamic response to TRM, hydrodynamic results were generated from HEC-RAS for cross sections in the river near and in the inlet of every beel (figure 4). Stage and discharge results were only taken for every beel's inlet. These were measured in order to show tidal range and peak discharge during flood and ebb. Flow velocity results were only retrieved from the cross sections in the river.

Cumulative-discharge was retrieved both for cross sections in the inlets and in the river. From cumulative discharge, tidal prism was calculated (equation 1) for one spring tide in each season. Therefore, results for tidal prism were known for both cross sections in the river and in the inlets.

Equation 1. Calculated tidal prism. This was done during spring tide.

$$Tidal\ prim = cum.discharge\ flood - cum.discharge\ ebb$$

Stage was measured in order to show what happens to the water levels and tidal range when TRM is practised.

Table 3. Result (Stage, (cumulative-)discharge and flow velocity) and location (river and inlet).

	River cross section (R) (figure 4)	**Inlet cross section (I) (figure 4)**
Stage	No	Yes
Discharge	No	Yes
Cumulative-discharge (Tidal Prism)	Yes	Yes
Flow velocity	Yes	No

4.3 Morphodynamics

From the tidal prism and the relationship between tidal prism and cross sectional area of the tidal channel (figure 3), estimates are made on whether the cross sectional area of the tidal channel increases or decreases. Furthermore flow velocities were used for estimations in sediment transport capacity and direction of sediment transport.

With the tidal prism, estimates were also made on sediment inflow inside the beels. Tidal prism is multiplied by: the trapping efficiency (table 3) (derived from previous literature (Islam et al., 2020)), SSC and number of tides per season (153 during monsoon, 120 during pre-monsoon and 152 during the dry season) (equation 2). For the trapping efficiency, the lowest values and highest values obtained by (Islam et al., 2020) are compared (table 3).

Equation 2. Calculated sedimentation per beel for each season (kg/season).

$$\boldsymbol{Sedimentation} \left(\frac{\boldsymbol{kg}}{\boldsymbol{season}}\right) = Tidal\ Prism \left(\frac{m3}{tide}\right) * Trapping.eff * SSC \left(\frac{kg}{m3}\right) * number\ of\ tides\ per\ season$$

Table 4. Numerical values for: minimum/maximum trapping efficiency, SSC and tides per season.

Season	**Minimum Trapping efficiency**	**Maximum Trapping efficiency**	**SSC (mg/m^3)**	**Number of tidal cycles** (F.Islam, personal communication).
Monsoon	5%	21%	1375	153
Pre-Monsoon	5%	15%	929	152
Dry season	2.5%	23%	784	120

In order to calculate the rate of land raise per beel, an average is determined, thereby ignoring that sediment does not spread uniformly throughout the beel, and assuming that sediment input remains constant as long as TRM is in practise. A soil density for deposited sediment of **ρ**=1300kg/m^3 was used to convert mass into elevation.

Equation 3. Calculated land raise for each beel (m/season)

$$\boldsymbol{Seasonal\ land\ raise}\ (\frac{\boldsymbol{m}}{\boldsymbol{season}}) = \frac{sedimentation\ \left(\frac{kg}{season}\right)/\rho}{area\ beel\ (m2)}$$

This calculation was done for three seasons. For the annual rate of land raise, the three seasonal land raises were added.

4.2 Scenarios

To evaluate the interaction between hydrodynamics of the channel and beels, several scenarios were developed in which a single or multiple beels were opened.

Two scenarios were analysed for stage and (cumulative-)discharge for three seasons: The ‘beels opened separately’ (BOS) and ‘all beels opened’ (ABO) scenario. Flow velocity was analysed only for the dry season as flow velocity was only calculated for this season by the model. The BOS and ABO scenario were developed to show the hydraulic effects if TRM is practised separately on one beel or simultaneously on six beels. For the BOS scenario, the model was run six times, one for each beel opened. For the ABO scenario, the model was run with all beels opened. Only for the tidal prism, a reference model run was done with no beels opened (NBO) in order to show how tidal prism changes if only one beel is opened. In total, eight model runs were done.

Results from the same cross sections (in the inlet and in the river) for different scenarios, were compared afterwards for each subject. All runs retrieved results for one year, from this year one week in every season was used for evaluation. In all three weeks, spring tide is recorded in the middle of the week.

Table 5. Scenarios. For the BOS scenario, the model was run six times. For the ABO and NBO scenario, the model was run once. For the ABO and BOS scenario, cross sections in the inlet and in the river near the beels (figure 2) were analysed for stage and (cumulative-)discharge. For the NBO scenario, only cumulative-discharge (from which tidal prism is calculated) in the cross sections in the river were analysed

Pre monsoon	**Dry season**	**Monsoon**
Beels Opened Separate (BOS)	Beels Opened Separate (BOS)	Beels Opened Separate (BOS)
All Beels Opened (OBA)	All Beels Opened (OBA)	All Beels Opened (OBA)
No Beels Opened (NBO)	No Beels Opened (NBO)	No Beels Opened (NBO)

Table 6. Weeks used for each season. Spring tide is recorded in the middle of the week.

Pre monsoon	**Dry season**	**Monsoon**
30/03/2000 to 13/04/2000	16/01/2000 to 30/01/2000	25/07/2000 to 08/08/2000

Table 7. This table shows which result is retrieved for which scenario.

	NBO	**BOS**	**ABO**
Stage	No	Yes	Yes
Discharge	No	Yes	Yes
Cumulative-discharge (tidal prism)	Yes (only in tidal river)	Yes	Yes
Flow velocity	No	Yes (only dry season)	Yes (only dry season)
Sedimentation	No	Yes	Yes
Land raise	No	Yes	Yes

5. Results

The results are split up in two parts, the hydrodynamic results (stage, discharge and tidal prism) and the sediment transport results that are assessed from the tidal prism in the inlets.

5.1 Hydrodynamics of the channel-beel system

For all eight simulations, the results for stage, (cumulative-)discharge and the resulting tidal prism were extracted from the model runs. In order to reduce the number of figures, the results that are compared and shown in the figures are only for the monsoon season. Results for the other seasons are added to the appendix. The BOS scenario is described first and afterwards compared to the ABO scenario. In the last part of every section, differences between seasons are described. Positive discharge is in landward direction (during flood tide), negative in seaward direction (during ebb tide).

5.1.1 Stage per inlet

5.1.1.1 BOS scenario

Stage results from every beel's inlet from six model runs for the BOS scenario show what happens to stage in each inlet without interaction of other beels (solid lines of figure 11) and are elaborated in the following section.

The peak of the tidal wave propagates landward with its peak in stage reaching each inlet further landward later in time. The vertical tide is asymmetrical and flood dominated. Two apparent decreases in the tidal ranges are visible between Raruli to Khesla (up to -0.89m) and between Khesla and Pakhimara (up to -1.0m). The further inland, the shallower the tidal wave becomes, likely due to the increased friction area. Between Khesla and beel Pakhimara, the tide is dampened by the greater size of beel Pakhimara (6.3 km^2) which allows the lateral spreading of the water volume. This is also the case in beel Jalalpur (6.2km^2). Furthermore, in the inlet of beel Haridaskati, tidal range increases compared to the inlet of Jatua even though beel Haridaskati is further inland. This could be caused by narrowing due to its smaller volume (0.9 km^2 compared to 2.2km^2 for Jatua). These results show that location and size of the beel influences the tidal range.

Not all differences can simply be explained according to size and location of the beel. Comparing Jalalpur and Pakhimara (figure 11, grey and green solid lines) one would except the tidal range for Jalalpur to decrease as both these beels have approximately the same size and Jalalpur is further landward. However, tidal range is larger for Jalalpur than for Pakhimara. One reason for this could be the geometry of the channel which shallows and narrows in landward direction. Higher stages are also found for the most inland beel Haridaskati. This is likely caused by water that is blocked by the modelled cross dam inland of beel Haridaskati.

5.1.1.2 ABO scenario

The dotted graphs in figure 11 show the results assuming all beels are opened (ABO) simultaneously. This illustrates the interaction between beels, and effect of the increased volume of the tidal basin on stage becomes visible. For most inlets, lower stages are found during flood and higher stages are found during ebb. This means a reduction in tidal range in these inlets. The greatest decrease in tidal range (-0.7m) occurs at the inlets of the most landward beels: Jatua and Haridaskati. The smallest decrease in tidal range is modelled for the inlet of beel Pakhimara, which shows higher stages during both ebb and flood. In the inlet of Raruli beel, stage increases during flood and decreases during ebb.

Reduced tidal range can be explained by the greater volume of the tidal basin caused by the opening of all beels. Greater lateral spreading of water is possible during high tide which results in more constant stages. During ebb, water levels remain more constant due to the larger water volume that is stored inside the beels that has a buffering function on stage.

5.1.1.3 Seasonal differences

The overall lowest stages can be found during the end of the dry season (second half of February), stages increase during the pre monsoon and are, on average, highest during mid-monsoon (first half of August) (appendix 1). The tidal range shows the same trend: Lowest during dry season, increases during pre-monsoon and highest during the monsoon.

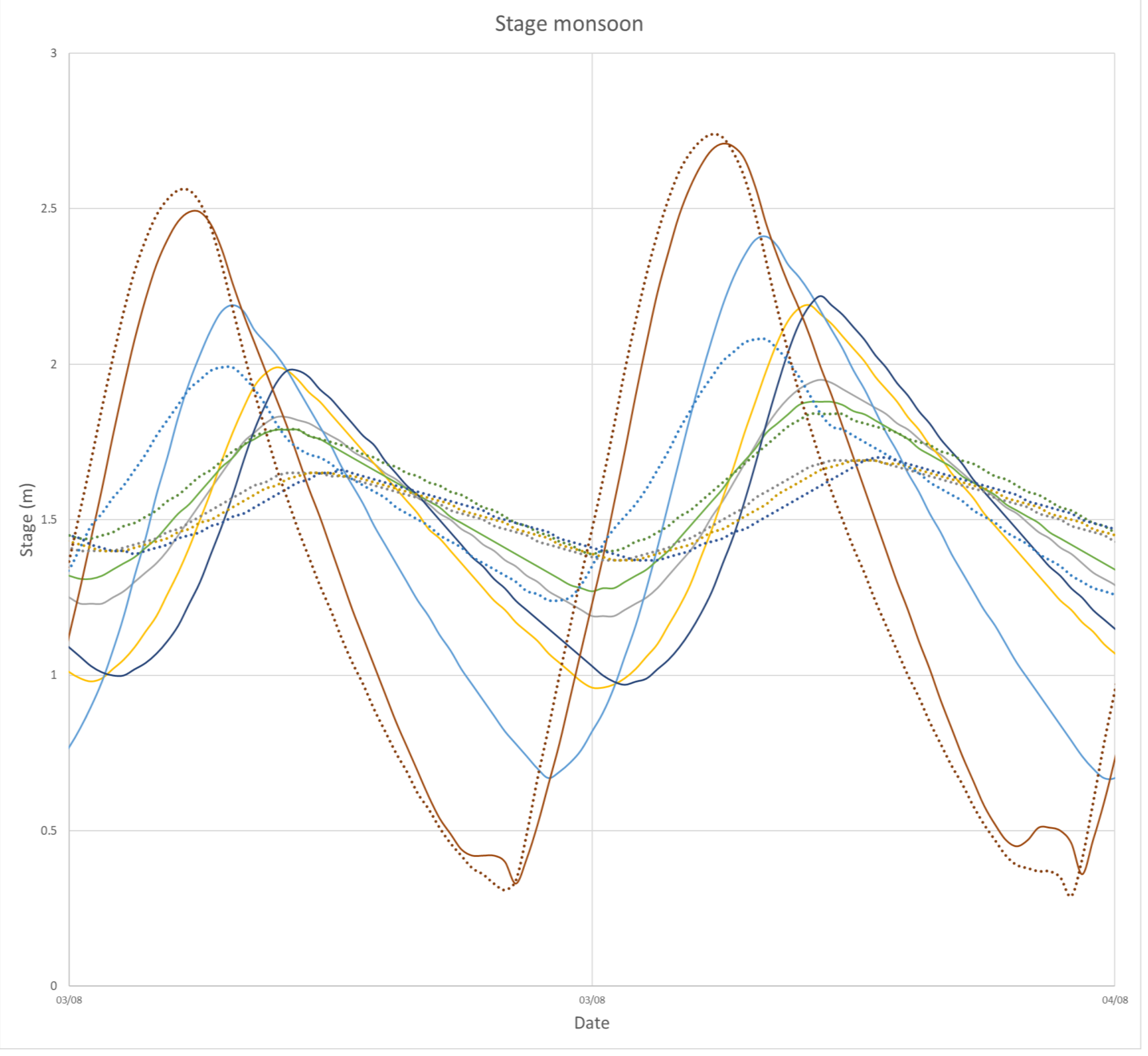

Figure 11. Stage in the inlet for every beel during the monsoon period. In the figure, two tidal cycles are displayed. The dotted lines indicate the stage for the ABO scenario.

5.1.2 Discharge per inlet

5.1.2.1 BOS scenario

The solid lines in figure 12 show the discharge for every beel's inlet for the BOS scenario during the monsoon. Discharge at the inlet depends on its inland location and size of the beel. A position further seaward and a greater volume of the beel leads to higher discharges at the inlet. Horizontal tidal asymmetry is visible as the peak discharges are present during flood and a smaller discharge for a longer time period is present during ebb (figure 12). At the cross section in the inlet of Raruli beel, the largest discharge of all beels is simulated (+360 m^3/s during flood and -225/s during ebb). Landward of Raruli beel, in the inlet of Khesla beel, discharge declines significantly to 210 m^3/s during flood and -80m^3/s during ebb. The discharge increases in the inlet of beel Pakhimara because of its large volume. Beel Haridaskati receives very little water due to its location far inland and its small size.

5.1.2.2 ABO scenario

Overall, the asymmetry of the horizontal tide weakens for all inlets as peak discharges during high tide reduce substantially more than peak discharges during ebb. Of all beels, peak discharge during high tide declines most in Jatua beel (up to -125m^3/s). The highest decline in peak discharge during ebb is found for Raruli beel (-85m^3/s). The relative decrease in discharge is greatest for Jatua beel. Little delay in peak discharges are visible for the ABO scenario due to the increased fill volume and acquired filling time of the added beels. Overall, lowest values for discharge are modelled during the dry season, with increasing discharge during the pre-monsoon and highest values occurring during the monsoon period (appendix 2).

Figure 12. Discharge Inlet during the monsoon period. Dotted lines are for the ABO scenario

5.1.3 Tidal prism

Figures 13 and 14 show the tidal prism at several cross sections seaward of each beel. The figures show results from cross sections in the river (figure 13) and cross sections in the inlets of the beels (figure 14). For the cross section in the river, the BOS, the ABO and the NBO scenario was run. For the cross sections in the inlets, only the BOS and the ABO scenario was run.

5.1.3.1 BOS scenario

In the BOS scenario, the relative importance of size and position becomes visible. This relative importance between size of the beel and position of the beel changes with the position of the cross section's location. In the river sections near the beels, the relative importance of location is greater than the size of the nearby beel. Tidal prism decreases significantly in landward direction. Comparing river sections near Jalalpur (R.4) (6.3km^2) with Pakhimara (R.3) (6.2km^2) , the tidal prism near Jalalpur (R.4) decreases with 2.5Mm^3 compared to the river section near Pakhimara (R.3) while both beel's sizes are comparable. Jalalpur is only 5km further landward. This decrease in tidal prism between Jalalpur and Pakhimara is more than 80% of the total tidal prism in the river near beel Jalalpur (R.4).

For the tidal prism in the inlets for the BOS scenario, the size of the beel becomes relatively more important than the location of the beel. Figure 14 shows that beel Pakhimara's size (large beel) and position (not too far landward) causes it to collect most water of all beels.

5.1.3.2 ABO scenario

In the ABO scenario, the interaction and increased volume of the tidal basin can be analysed.

When comparing the ABO scenario with the BOS scenario in the river, tidal prism decreases at all river sections. The simulations show a decrease in tidal prism for the ABO scenario compared to the NBO scenario for the river sections near Khesla, Jatua and Haridaskati. This suggests that if all beels are opened, the smallest three beels' effect on the tidal prism in the river decreases while the larger beels collect relatively more water. Again comparing Pakhimara with Jalalpur, a decrease of 0.5Mm^3 is visible for Pakhimara and a decrease of 0.9Mm^3 is visible for Jalalpur. This shows that the more inland the beel is located, the greater the tidal prism decreases as water is being trapped by other beels. This is visible for Jatua and Haridaskati as well. This effect causes a stronger decreasing landward gradient in water volume for the four most landward beels. However, the figure also shows that more landward beels effect the tidal prism seaward as well, as less water is collected by (the most seaward) Raruli beel. Still, the tidal prism decreases relatively more for the inland beels. One could say that for this scenario, the landward position of the beel has a greater effect on the tidal prism in the river than the size of the beel due to an already decreasing landward trend in water volume and the added trapping of water in more seaward beels.

5.1.3.3 Seasonal differences

The tidal prism is highly variable per season (appendix 3). During the monsoon, the tidal prism for the inlets of the beels doubles compared to the dry season. During the pre-monsoon, values for tidal prism are found in between the values for the monsoon and dry season.

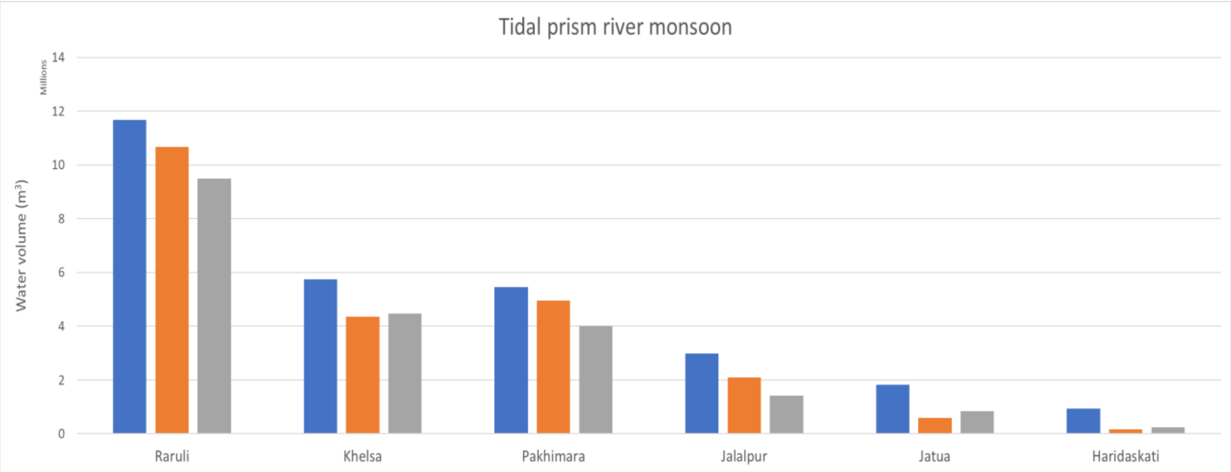

Figure 13. Tidal prism during the monsoon period for all river sections near each beel. Same scenario's as the previous graph with the addition of the NBO scenario (grey)

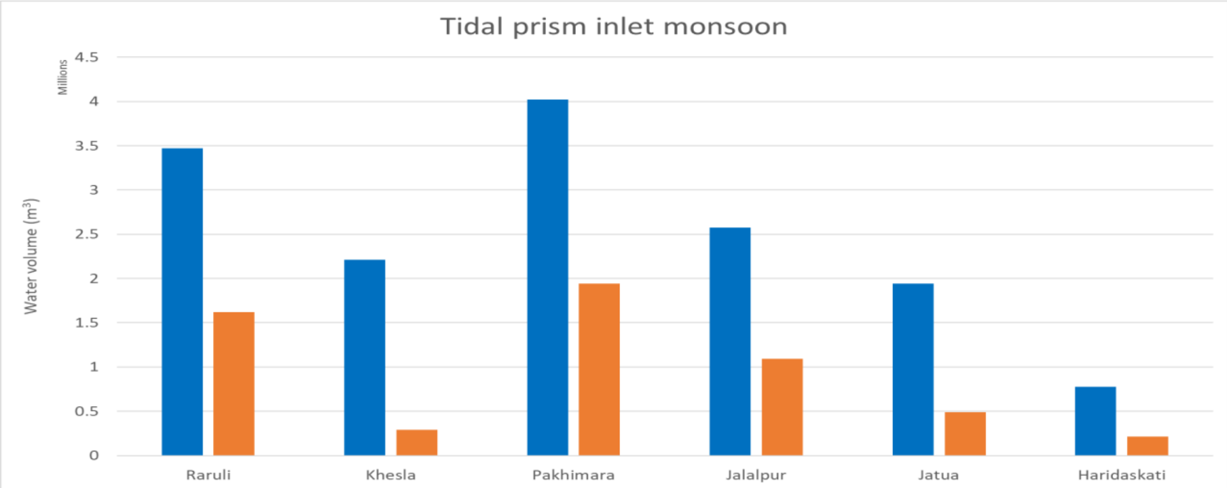

Figure 14. Tidal prism during the monsoon period in the inlet of every beel. Blue indicates the BOS scenario, orange the ABO.

5.2 Sediment dynamics

5.2.1 Sediment demand

In figure 15, the volume of sediment needed for increasing, uniform land raise is presented(V=A*dh). The highest sediment demand is seen for Pakhimara and Jalalpur due to their large sizes which is around 6.5 times larger than for the smallest beel, Haridaskati. The larger the beel, the greater the sediment demand.

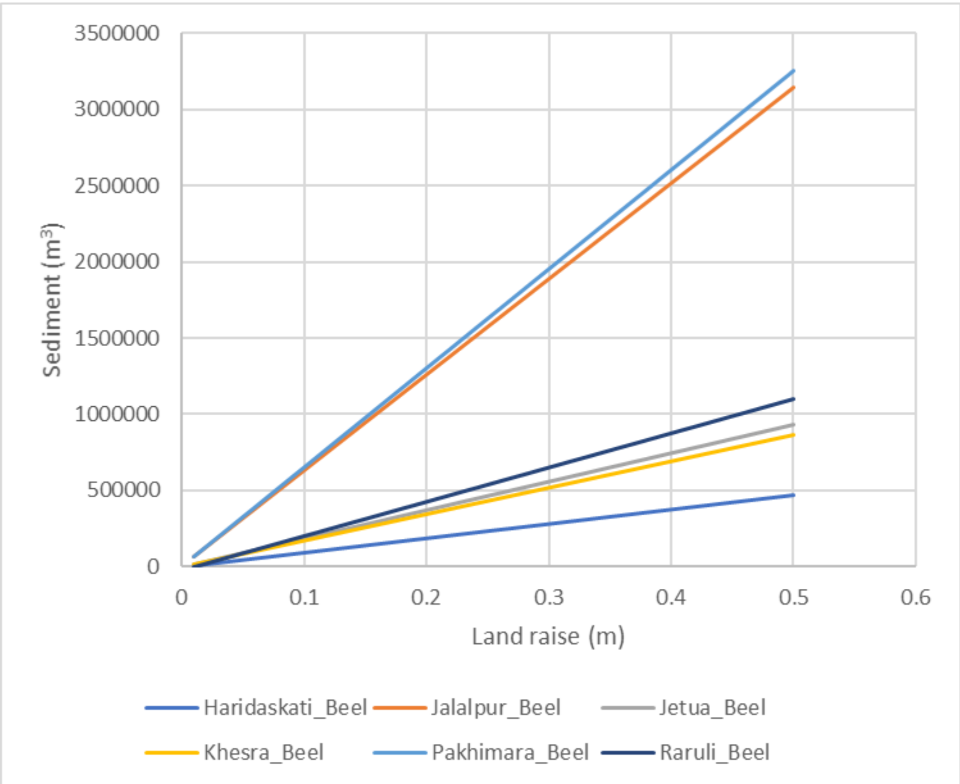

Figure 15. Sediment demand per beel per land raise of the total beel.

5.2.2 Sediment load and land raise

In figure 16 the annual sedimentation load that enters each is presented based on the volume of water that enters each beel. Pakhimara's location and size causes it to collect most sediment of all beels. The opposite is true for beel Haridaskati which shows far lower values. According to figure 16, the sediment input will drop by half (Pakhimara, Jalalpur, Raruli), to a third (Khesla, Haridaskati and Jatua) if all beels are opened. The smaller beels collect relatively less sediment than the larger beels as a larger fraction of the water ends up in the larger beels which is, according to the calculations, therefore also true for the sediment.

The hydrodynamic analysis demonstrated that the size of the beel is the most important factor for the magnitude of the tidal prism in the inlet of the beel. As the sediment load is directly derived from the tidal prism, the same is true for the annual sediment load that enters the beel. However, even though a large beel collects more sediment than a smaller beel, the rate of land raise is higher for smaller beels as is shown in figure 17. This is because a smaller beel's sediment demand is less than for a larger beel to reach the same height.

5.2.2.1 Seasonal differences

Because the tidal prism is highly variable per season, the same is true for sediment influx inside the beels. During the monsoon and pre monsoon, not only tidal prism but also SSC and trapping efficiency are higher than during the dry season. This results in 3 to 7 times more sediment deposition. In the larger beels, variation in seasonality is relatively greater than in small beels.

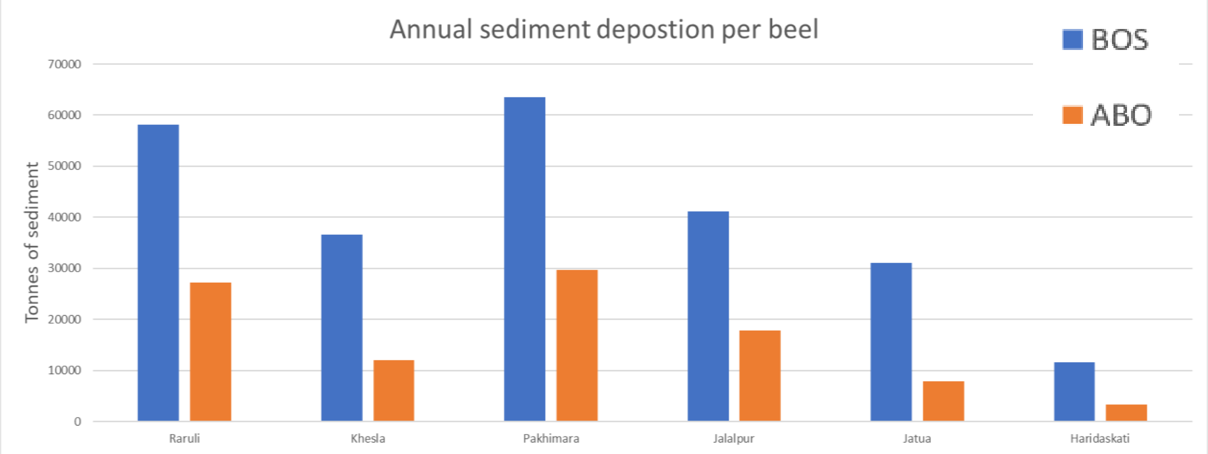

Figure 16. Annual sediment deposition per beel for the BOS (blue) and ABO (orange) scenario. This is the sum of sediment deposition for three seasons.

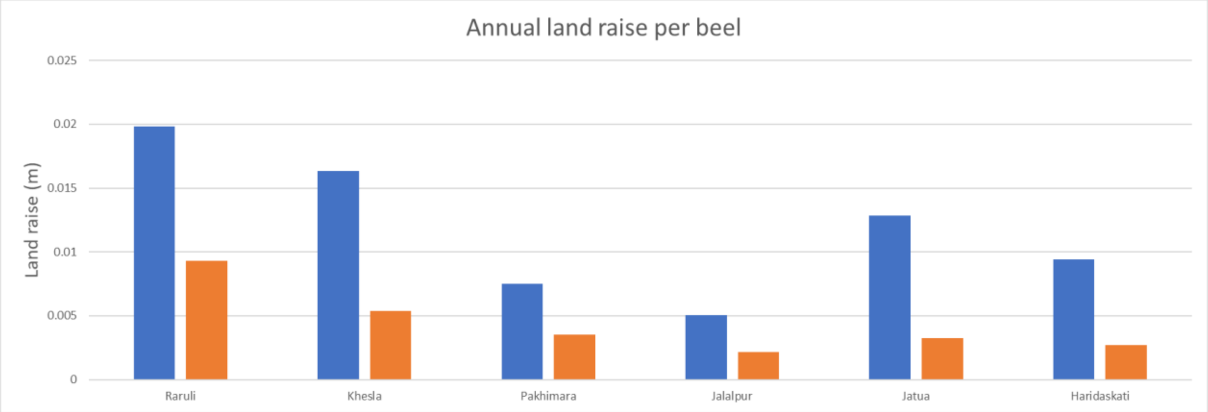

Figure 17. Annual land raise per beel for the BOS (blue) and ABO (orange) scenario.

5.2.3 Transport capacity

Flow velocity profiles within the main channel near each beel during the dry season were compared for the ABO and BOS scenario, as a measure of sediment transport capacity (figure 18). Higher flow velocities allow for greater erosion and sediment transport. Not only magnitude but also direction of flow can tell something about sediment transport processes. Highest flow velocities are found during flood ranging from 0.81 m/s (Jalalpur) to 0.31 m/s (Haridaskati). Flow velocities during ebb range from 0.38 m/s (Raruli) to 0.1 m/s (Haridaskati). Flow velocities decrease for every section for both tides in the ABO scenario. For the three most landward beels, flow velocities decrease most for the ABO scenario. These results show that the flow velocities during flood decrease relatively more than during ebb, decreasing the velocity asymmetry of the tide.

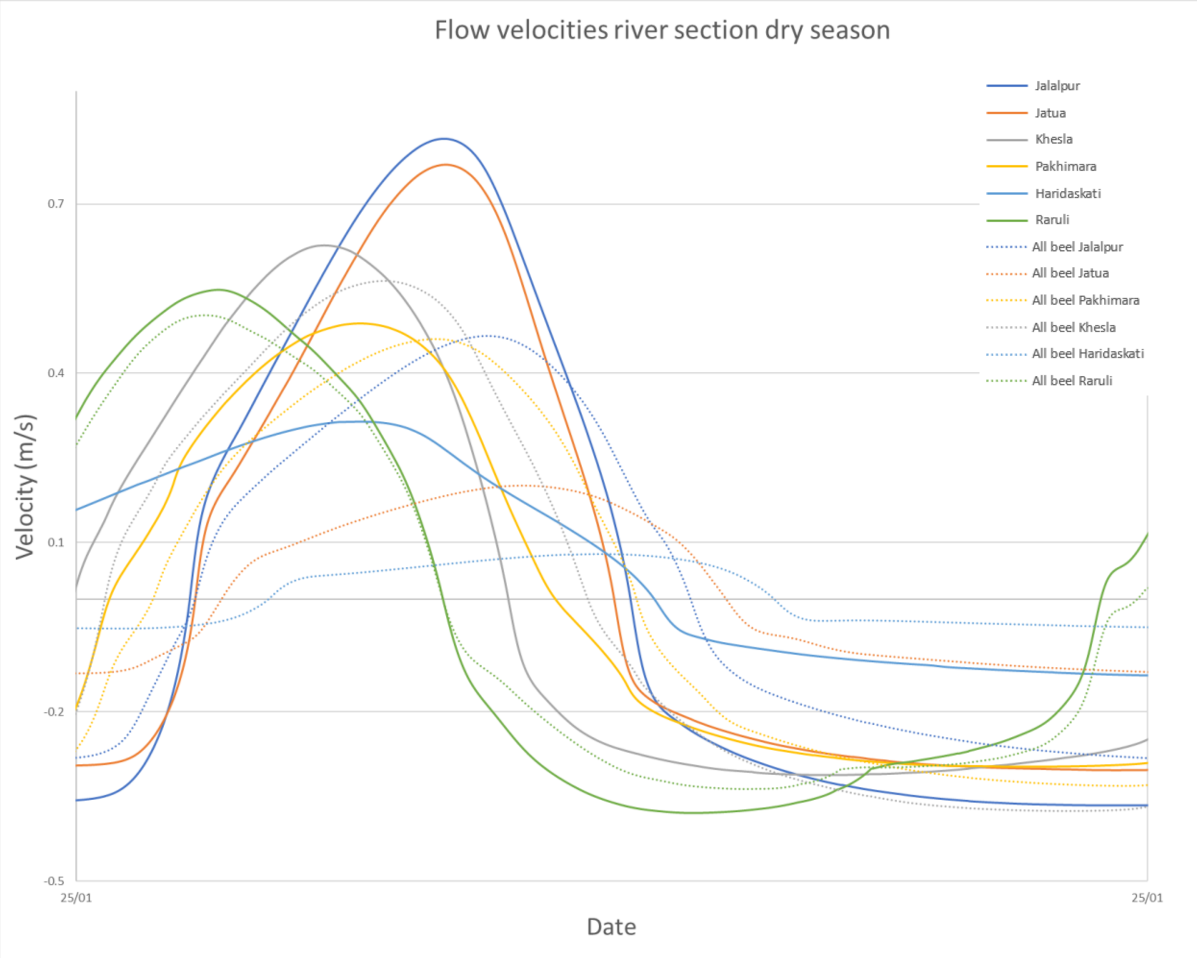

Figure 18. Flow velocities in the river sections during the dry season. Dotted lines represent the ABO scenario

6. Discussion

The results show that size and location are the most important factors explaining the hydrodynamics. Still the hydrodynamics of the area are complex with other factors such as channel geometry and size of the inlet that are also of influence. Increased tidal range between beel Pakhimara and Jalalpur could be explained due to channel geometry and increased tidal range for beel Haridaskati could be caused by interaction of the constructed cross dam. High, counter-intuitive values for tidal range, discharge and tidal prism were modelled for Raruli. One important factor is its (most seaward) location. However, its inlet's size could also be a reason for the large quantities of water entering the beel. This in combination with its small size could explain the large tidal range in the inlet.

Still, a 1D representation of this complex system could cause some discrepancies. The high values near Raruli beel could be overestimated by the model. One reason for this overestimation could be that the model shows results for Raruli beel that are too close to its boundary conditions (which, of all beels, are closest to Raruli). Another remarkable model result was the steep, landward decline in tidal prism for the NBO scenario. Tidal prism for the river section near Haridaskati is 30 times smaller than the tidal prism for Raruli, without any intervention of other beels in the system.

In the results for discharge, a reduction in tidal asymmetry for the ABO scenario occurs as discharge decreased relatively more during flood than during ebb. Due to tidal asymmetry, net transport of sediment is directed landward. In the velocity profiles for most cross sections, flow velocities decreased relatively more during flood than during ebb and even increased during ebb near Pakhimara and Khesla. These changes for flow velocity and discharge could decrease the relative landward transport and increase the relative seaward transport. This could be both beneficial and disadvantageous for TRM. Less sediment will be brought in the system that accumulates in the tidal channels which improves the drainage capacity. Disadvantageous is the fact that less sediment is transported landward that ends up inside the beels.

As was obtained from the results, the water volume that passes the inlets is mostly dependent on the size of the beel, but also depends on the local tidal range and inlet size. In the ABO scenario, a reduction in water volume passing the inlet of 52% to 87% is visible compared to the BOS scenario. The smallest beels collect relatively the least because a larger fraction of water is trapped inside the larger beels. However, unlike the water volume that enters the inlets, the water volume that passes through the river clearly decreases in an inland direction. Tidal prism decreases for the most landward beels and reaches below the NBO situation in beel Jatua and Haridaskati. If the tidal prism decreases in these locations, according to the relationship between tidal prism and cross-sectional area of the tidal river, the reduced tidal prism will cause a reduction the cross sectional area of the river here. This can also be concluded from the decreased flow velocities in the river in these sections. This could worsen the drainage capacity in this area. In order to avoid this, the two most landward beels (Jatua and Haridaskati) could be opened first. The results show that if these beels are opened separately, this will allow the tidal prism to increase in the river while these beels will be able to collect a reasonable amount of sediment. Whether it is possible to open these two beels simultaneously has not been researched. Figure 19 shows what happens to the tidal river in several steps further seaward of beel Jatua when it is opened. The first section is seaward of Jatua, the last near Raruli beel (20km further seaward). It shows that tidal prism increases nearby but this effect diminishes further seaward. From this result, a negative effect on drainage capacity seaward is not expected when opening the two most inland beels.

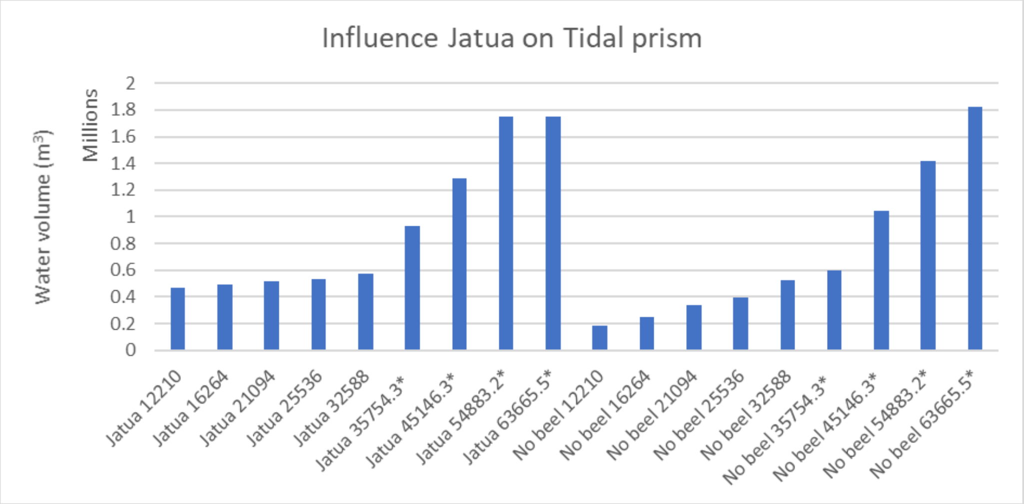

Figure 19. Influence of Jatua on tidal Prism. The BOS scenario for Jatua (9 most left) is compared to the NBO scenario (9 most right). The cross sections are the same for the NBO and BOS scenario and go from land (left) to sea (right)

Regarding improvement of drainage capacity, the four most landward beels could be opened simultaneously as the tidal prism increases in the river for all of these beels during the ABO scenario. However, according to figure 17, the rate of land raise will drop by half (Pakhimara, Jalalpur, Raruli), to a third (Khesla, Haridaskti, Jatua). Still, opening all beels separately will slow down the overall rate of land raise. If all beels are opened, sediment influx reduces for every individual beel. However, by opening all beels, the total rate of sediment influx inside the beels will increases to more than five times the number of the maximum sediment influx that can be reached when opening the beels separately. The great disadvantage for opening all beels simultaneously is the large area that remains unhabitable while rotating the beels will keep a larger area habitable.

In this model, a cross dam was placed directly at the inland side of the most inland beel Haridaskati. In the BOS scenario, this cross dam remained in place. In reality, a cross dam is often added directly inland of a beel. Adding a cross dam allows more to enter the beel. However, it does cut off the inland part of the tidal river. This has a decreasing effect on the tidal prism as the inland channel volume is removed. The cross dam could have a stimulating effect on sedimentation inside the beel but could also counteract the improvement of the drainage capacity of the tidal channel.

Another option is, what is now being done during the monsoon, the removal of the cross dam inland of beel Haridaskati. In this case, river water from land can enter the system. This will increase the tidal prism inside the tidal river and will decrease the relative effect on tidal prism by the opening and closing of the beel. During dry season, little flow from upstream is present therefore no much difference is excpected. Both options could be researched to discover the effect of a cross dam on the hydrodynamics inside the tidal channel and beel.

In the estimates for sediment accumulation inside the beels for the ABO scenario, SSC is assumed to remain the same for every beel. However 32% of the water that passes the cross section in the river near Raruli beel, enters Raruli beel. This means that 1.6% to 6.5% (depending on the trapping efficiency) of the total sediment load enters Raruli beel. If this reduction is true for six beels and no erosion on the main channel is assumed, this adds up to 9% to 33% after six beels. However, between Raruli and Khesla, the maximum fill volume of the tidal channel is 6x larger than what enters Raruli beel. In this river section, if flow velocities are high enough, sediment might be added to the water through channel erosion, which will be available for beel Khelsa. Whether one should take into account a decreasing trend in SSC caused by the trapping of sediment in the beels, depends on how much is added through local bed erosion in the river section between the beels. This has not been researched.

The seasonal variation in tidal prism is large (appendix 3). This directly has an effect on the total sediment load entering the beel. Even though for the dry season a shorter duration of only 120 tides is used, compared to 153 and 152 for the pre-monsoon and monsoon, the SSC during the dry season is also lower (F.Islam, personal communication). In contrast with what (Gain et al., 2017) suggests, who states that most sedimentation takes place during the dry season, these results suggest that most sedimentation takes place during the monsoon. Therefore, according to these results, TRM is most feasible during the monsoon.

The results for maximum trapping efficiency show that if all beels are opened, the rate of land raise will be between 10 mm/y to 20mm/y (and 40 mm/y for Raruli beel). According to (Strauss & Kulp, 2017) between 5mm/y to 13mm/y relative SLR is expected in the coming years for the Khulna district. These are rough estimates as local subsidence rates can vary greatly. Assuming the rate of land raise, due to the modelled TRM method, inside the beels to remain constant, this may just enough to keep up with sea level rise. If the minimum trapping efficiency is taken into account in the ABO scenario, the rate of land raise for all beels, expect Raruli (20mm/y), will be 5mm/y or less. According to these results, it will be unlikely that TRM, for the modelled ABO scenario, could keep up with RSLR. However, opening the beels separately, the rate of land raise for Jalalpur will be 5-23mm/y which will could be enough to keep up with RSLR. In the figures below, cross tables are shown with relative land raise (land raise due to TRM –RSLR) per beel, per scenario for maximum/minimum trapping efficiency and maximum/minimum RSLR. This shows that it will be hard for TRM to raise all beels fast enough to keep up with RSLR but it is likely to be sufficient to raise individual beels.

Figure 20 shows how long TRM is practised to how long it can be closed before RSLR catches up again for minimum/maximum RSLR and minimum/maximum trapping efficiency for 14 years. Its minimum y-value is zero therefore situations indicated in red in table 7, are not included. Only the situation with minimum RSLR and maximum trapping efficiency, shows that if all beels are opened, the time TRM is in practise will be shorter than the time RSLR catches up again for all beels. In all other cases, if all beels are opened, TRM has to be longer in practise than time it is not in practise or beels will not catch up with RSLR at all. If beels are opened individually, duration of TRM practise in Jalalpur and Jatua will still likely be longer than the time the beels can be closed but for beel Khesla, Raruli and Pakhimara this is the other way around. For beel Haridaskati this will be somewhere in between. These results show that, even for the beels that are raised fastest, 5 years of TRM practise is the absolute minimum in order to make it habitable again for a reasonable time.

Table 8. Relative annual rise of each beel a.m.s.l for minimum/maximum trapping efficiency and minimum/maximum RSLR

Raruli (ABO)	Max trapping efficiency	Min trapping efficiency
Max RSLR	+20 mm/y	-4 mm/y
Min RSLR	+36 mm/y	+4 mm/y

Raruli (BOS)	Max trapping efficiency	Min trapping efficiency
Max RSLR	+79 mm/y	+7 mm/y
Min RSLR	+87 mm/y	+15 mm/y

Khesla (ABO)	Max trapping efficiency	Min trapping efficiency
Max RSLR	+7 mm/y	-8 mm/y
Min RSLR	+15 mm/y	0 mm/y

Khesla (BOS)	Max trapping efficiency	Min trapping efficiency
Max RSLR	+63 mm/y	+3 mm/y
Min RSLR	+71 mm/y	+11 mm/y

Jalalpur (ABO)	Max trapping efficiency	Min trapping efficiency
Max RSLR	-3 mm/y	-11 mm/y
Min RSLR	+5 mm/y	-3 mm/y

Jalalpur (BOS)	Max trapping efficiency	Min trapping efficiency
Max RSLR	+10 mm/y	-8 mm/y
Min RSLR	+18 mm/y	0 mm/y

Pakhimara (ABO)	Max trapping efficiency	Min trapping efficiency
Max RSLR	+4 mm/y	-9 mm/y
Min RSLR	+12 mm/y	-1 mm/y

Pakhimara (BOS)	Max trapping efficiency	Min trapping efficiency
Max RSLR	+22 mm/y	-5 mm/y
Min RSLR	+30 mm/y	+3 mm/y

Jatua (ABO)	Max trapping efficiency	Min trapping efficiency
Max RSLR	+2 mm/y	-10 mm/y
Min RSLR	+10 mm/y	-2 mm/y

Jatua (BOS)	Max trapping efficiency	Min trapping efficiency
Max RSLR	+54 mm/y	0 mm/y
Min RSLR	+46 mm/y	+8 mm/y

Haridaskati (ABO)	Max trapping efficiency	Min trapping efficiency
Max RSLR	0 mm/y	-10 mm/y
Min RSLR	+8 mm/y	-2 mm/y

Haridaskati (BOS)	Max trapping efficiency	Min trapping efficiency
Max RSLR	+31 mm/y	-4 mm/y
Min RSLR	+39 mm/y	+4 mm/y

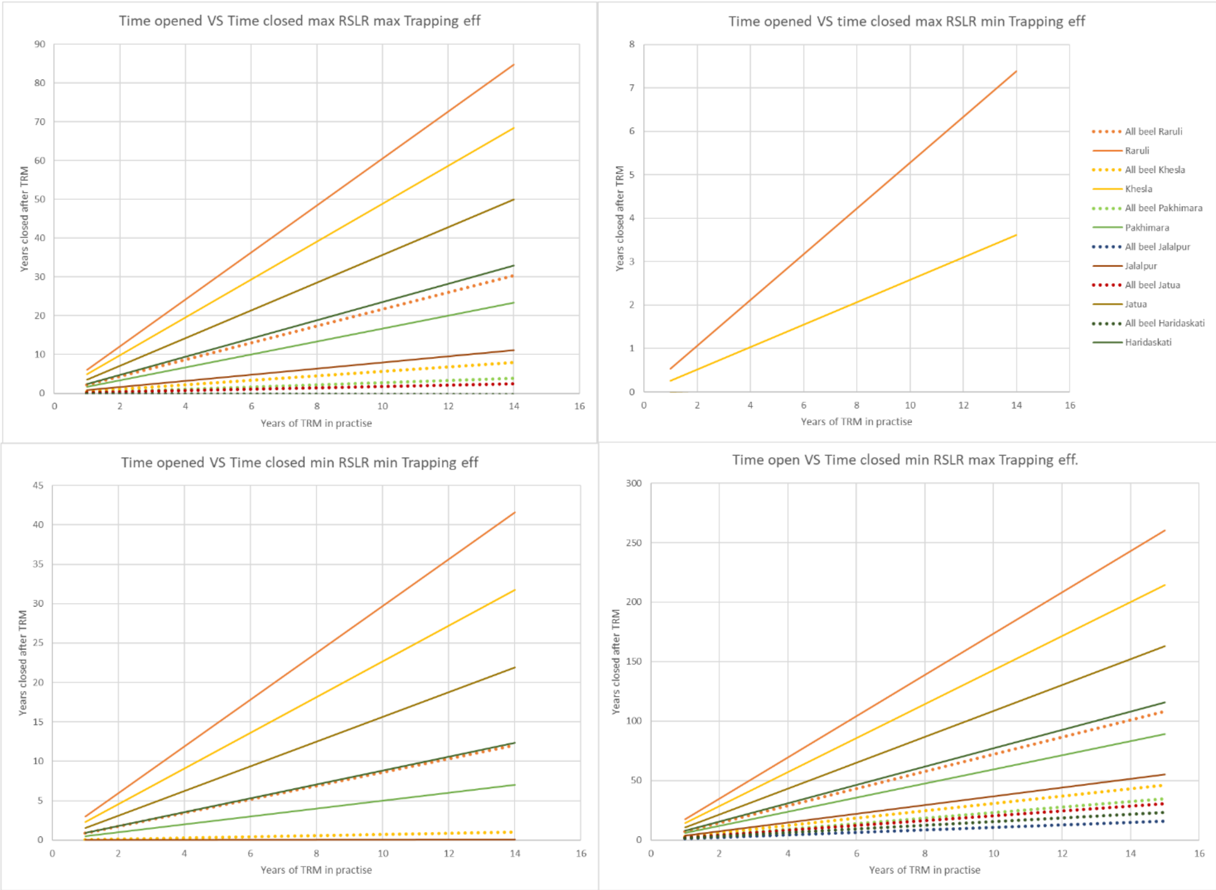

Figure 20. Time a beel is inundated for TRM purpose (x-axis), Time a beel can be closed until RSLR catches up again (y-axis)

7. Conclusion

This study showed the highly responsive-to-changes character of the hydrodynamics in the tidal dominated Kobadak river and in the inlets of the beels that are connected to this channel. Different responses are visible depending on whether all beels are opened separately or simultaneously.

- Under a scenario where all beels are opened tidal range and discharge in the inlets depend mostly on both the beel's size and the inland or seaward location.
- Tidal prism in the inlets is mostly determined by the size of the beel while tidal prism in the river sections persistently decreases away from the coast.
- Opening all the beels increases the volume of the tidal basin, which results in a decrease of tidal range, tidal prism and discharge in both the inlets and in the river sections.
- When all the beels were opened, a clear interaction between beels appears; the further a beel is located inland the greater the decrease in tidal prism became, therefore the relative importance of location increases as less water penetrated landward due to trapping of water in the more seaward beels.
- Even though size and location play a big role in the hydrodynamics, other factors such as channel geometry and inlet size of the beels make the hydrodynamic character of the area more complex.
- The interaction of a cross dam on drainage capacity in the tidal channel and sedimentation rate inside the beel could be part of future research.
- Differences in discharge, flow velocity and tidal prism were related to predicted changes in the morphodynamics of the river and inside the beels:
- In the situation where all beels were opened, a more symmetrical tide arises, which may reduce landward transport of sediment.
- Opening all beels also improves drainage capacity in the river sections near Raruli, Pakhimara and Jalalpur as tidal prism increases compared to the situation where no beels were opened.
- When all beels are opened, drainage capacity in the river near Jatua, Haridaskati and (very slightly for) Khelsa deteriorates due to their small size and/or far inland position. Therefore, in order to improve drainage capacity, it is suggested to open the most inland beels first.

The results suggest that, inside the beels, sediment input reduces drastically if all beels are opened compared to when they are opened separately. If operating TRM on multiple beels simultaneously it is likely that not all beels will be raised fast enough to keep up with RSLR, however if operating on an individual beel, it is likely that TRM could keep up RSLR for this individual beel. However, for beel Jatua and Jalalpur the duration of TRM operation is likely to be longer than the time it is free from water while for beel Khesla, Pakhimara, Raruli (and Haridaskati), TRM operation will be shorter, which makes it more feasible for these beels. Furthermore, if all beels are opened, most land is lost and most people are displaced. Therefore a selection of beels should be made to operate TRM on in this area. Possible future research could look for a favourable combination or sequence of TRM operation in the area with a more detailed 2D model. The results also show that most sedimentation can be deposited during the monsoon. However, TRM operation is not a matter of seasons, but on a timescale of years in order for it to be feasible.

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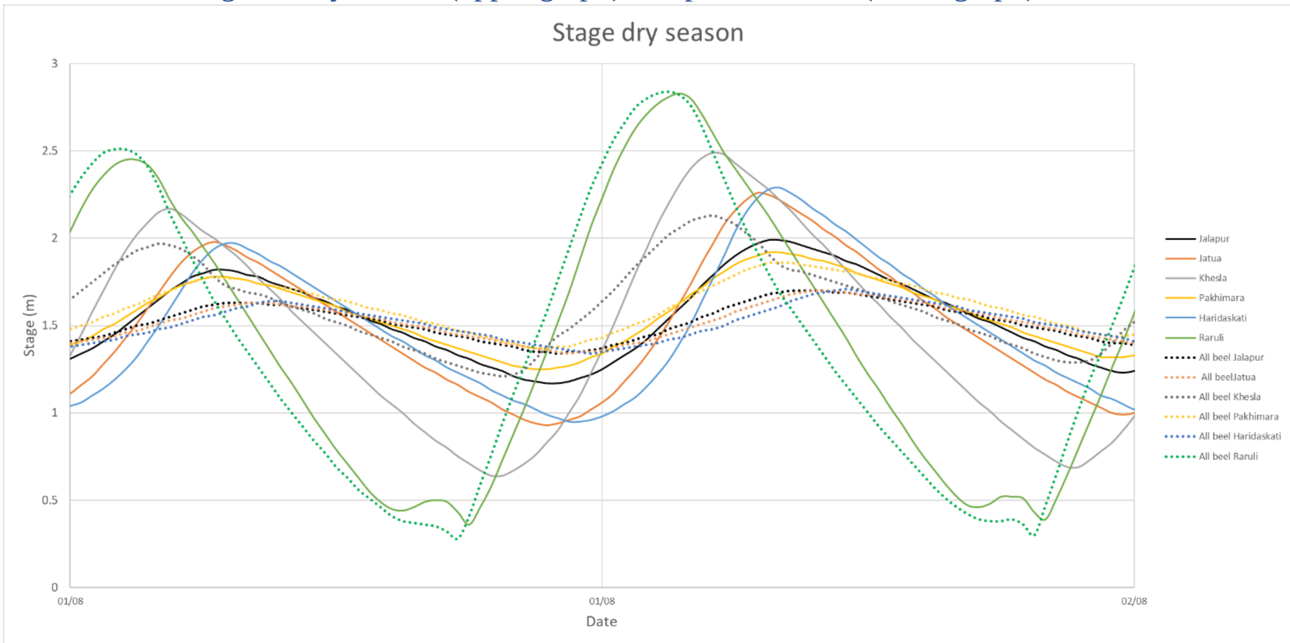
App. 1

Stage for dry season (upper graph) and pre-monsoon (lower graph)



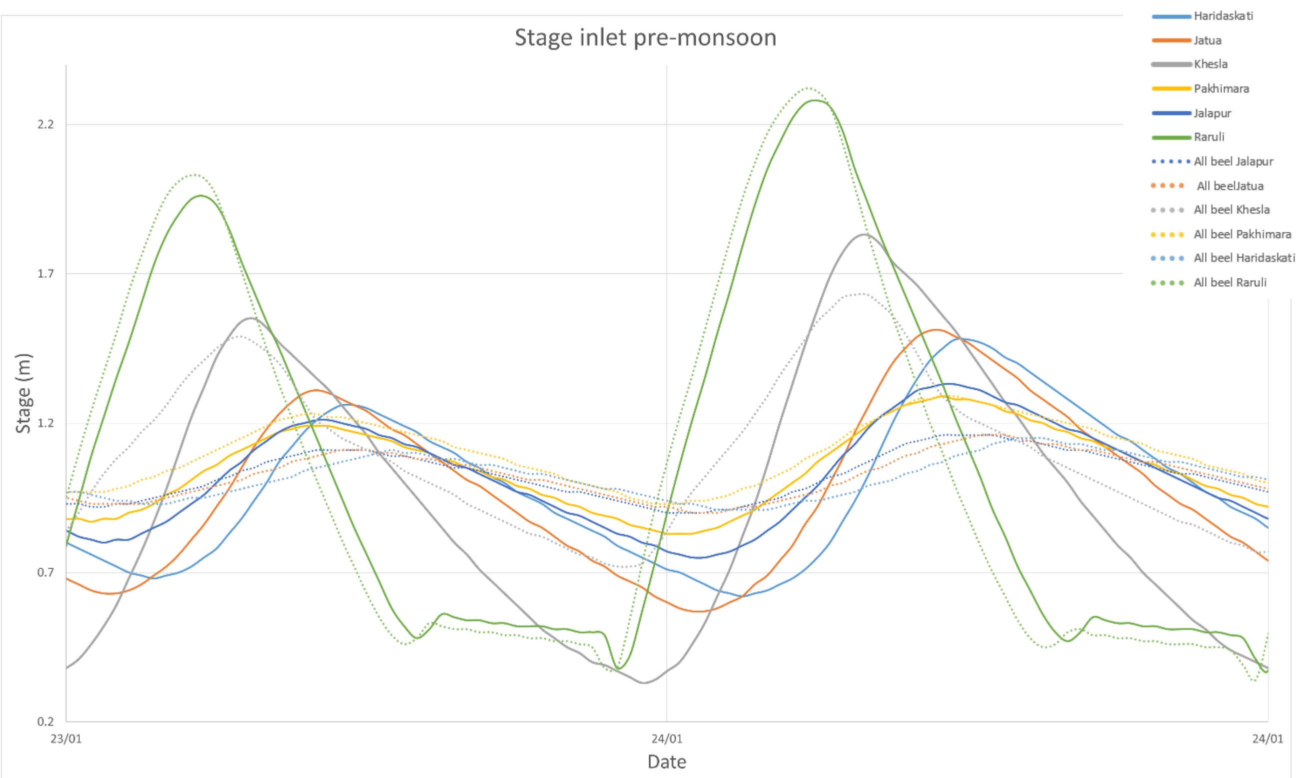
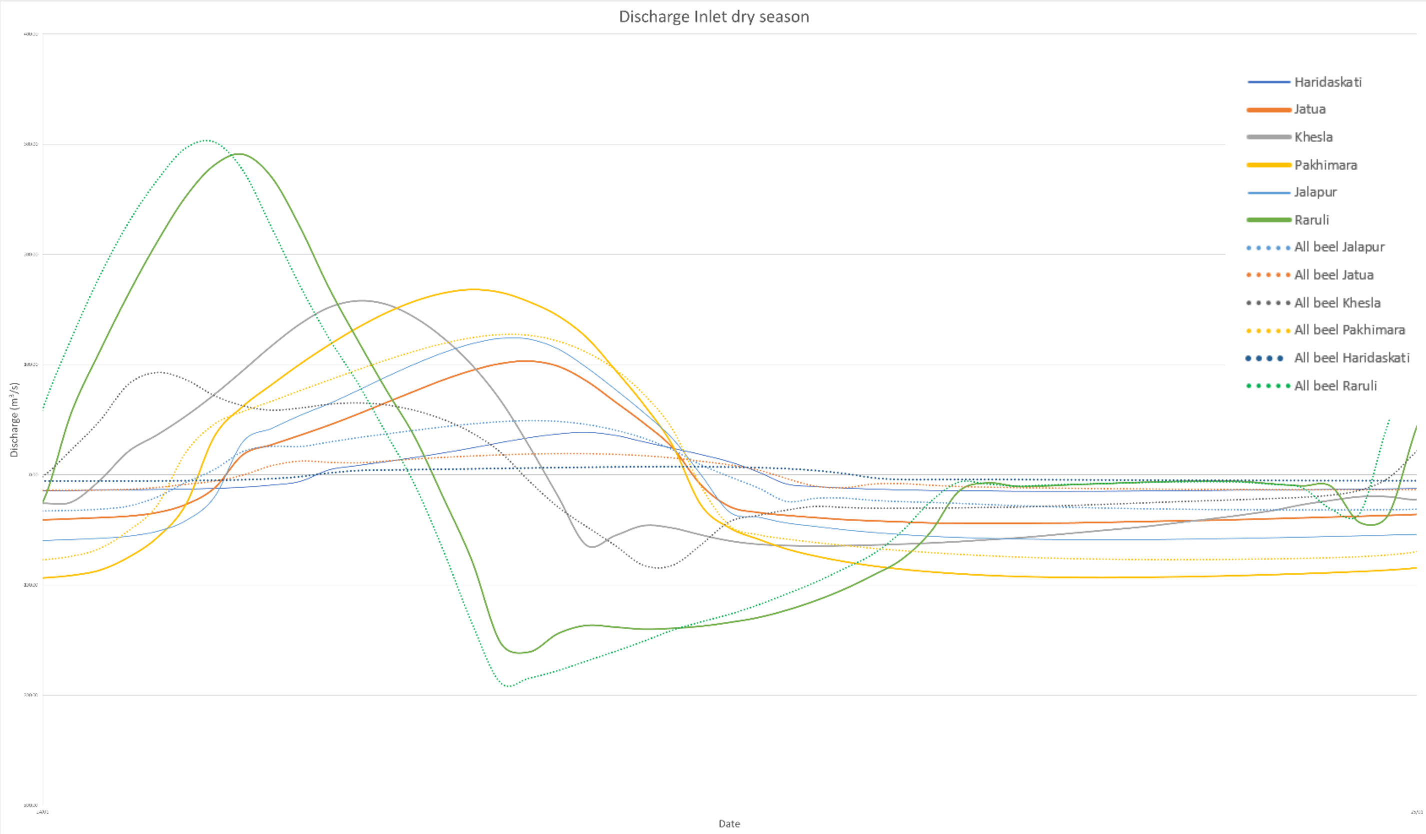


Figure 21 and 22. Stage for dry season and pre-monsoon. The dotted line indicates the ABO scenario, the solid line the BOS scenario

App. 2

Discharge for the dry season (upper) and pre-monsoon (lower)



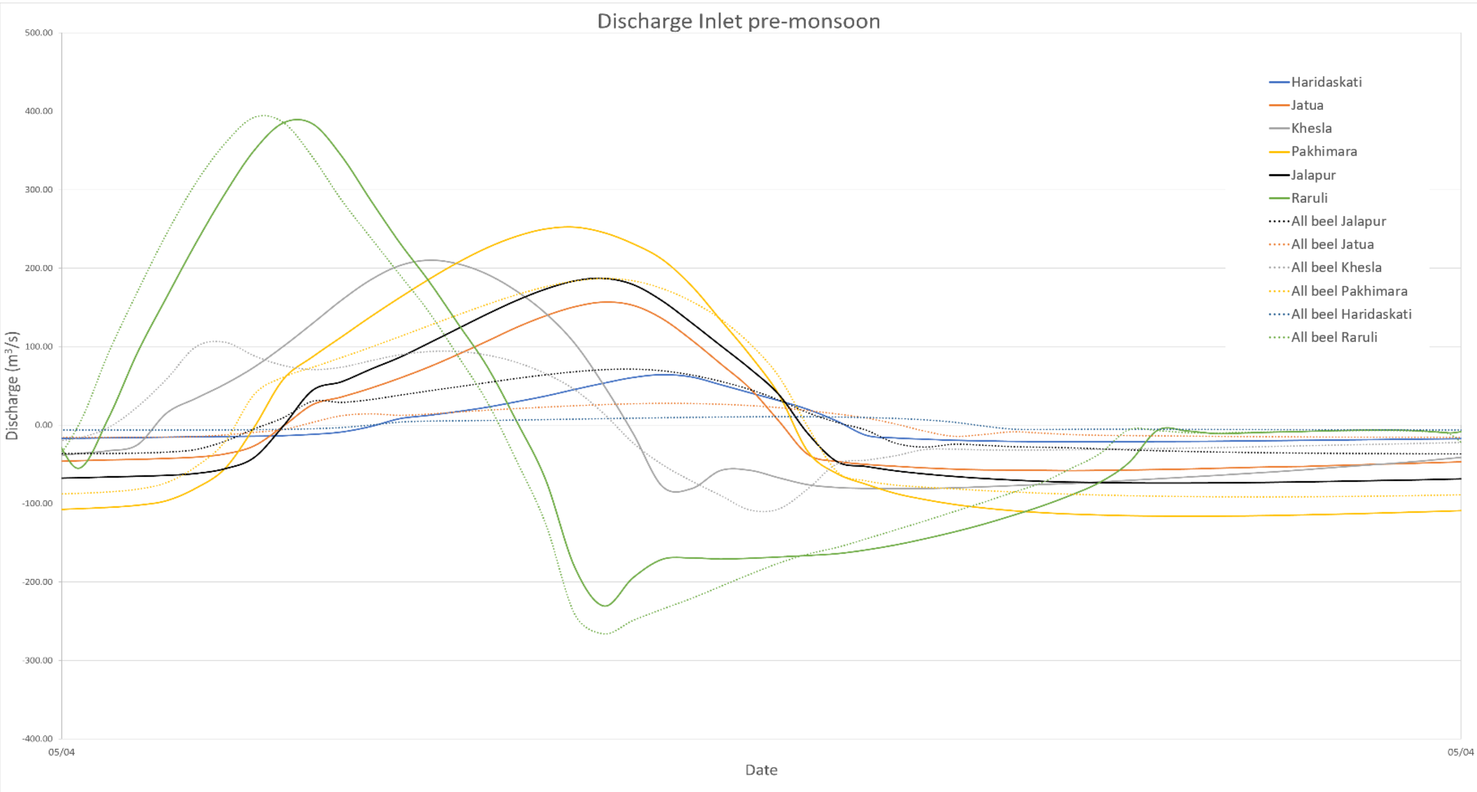
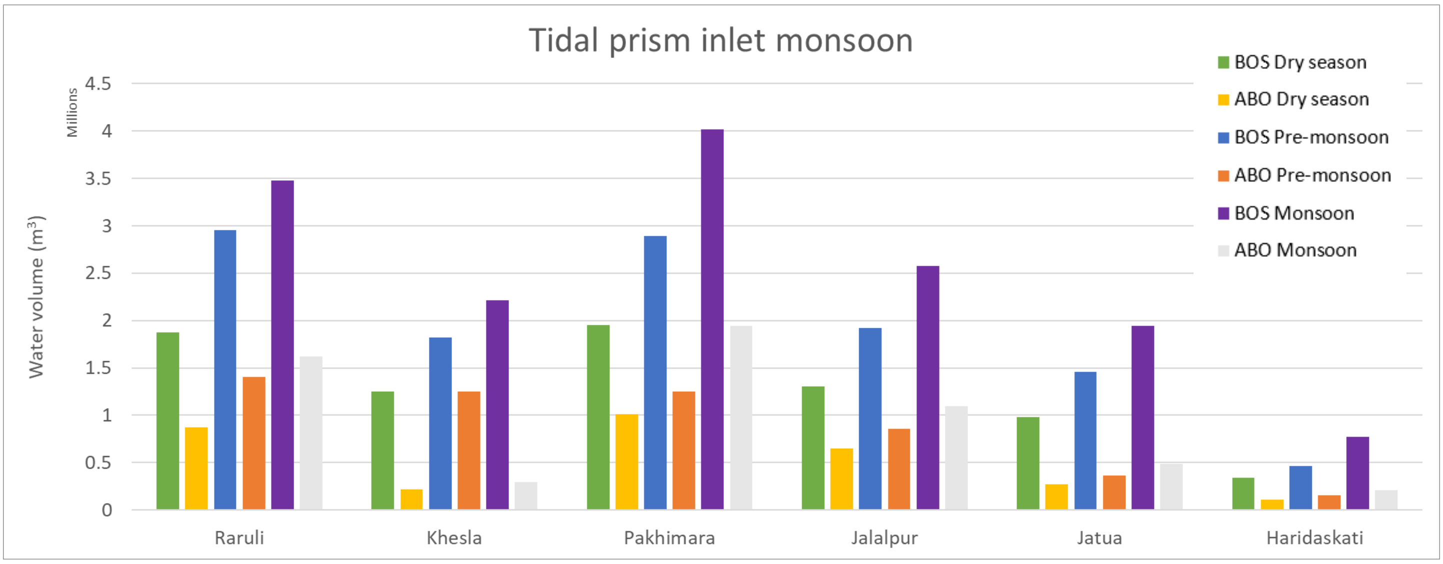


Figure 23 and 24. Discharge for dry season and pre-monsoon. The dotted line indicates the ABO scenario, the solid line the BOS scenario

App. 3

Tidal prism (upper) and sediment deposition (lower) for dry season and pre-monsoon



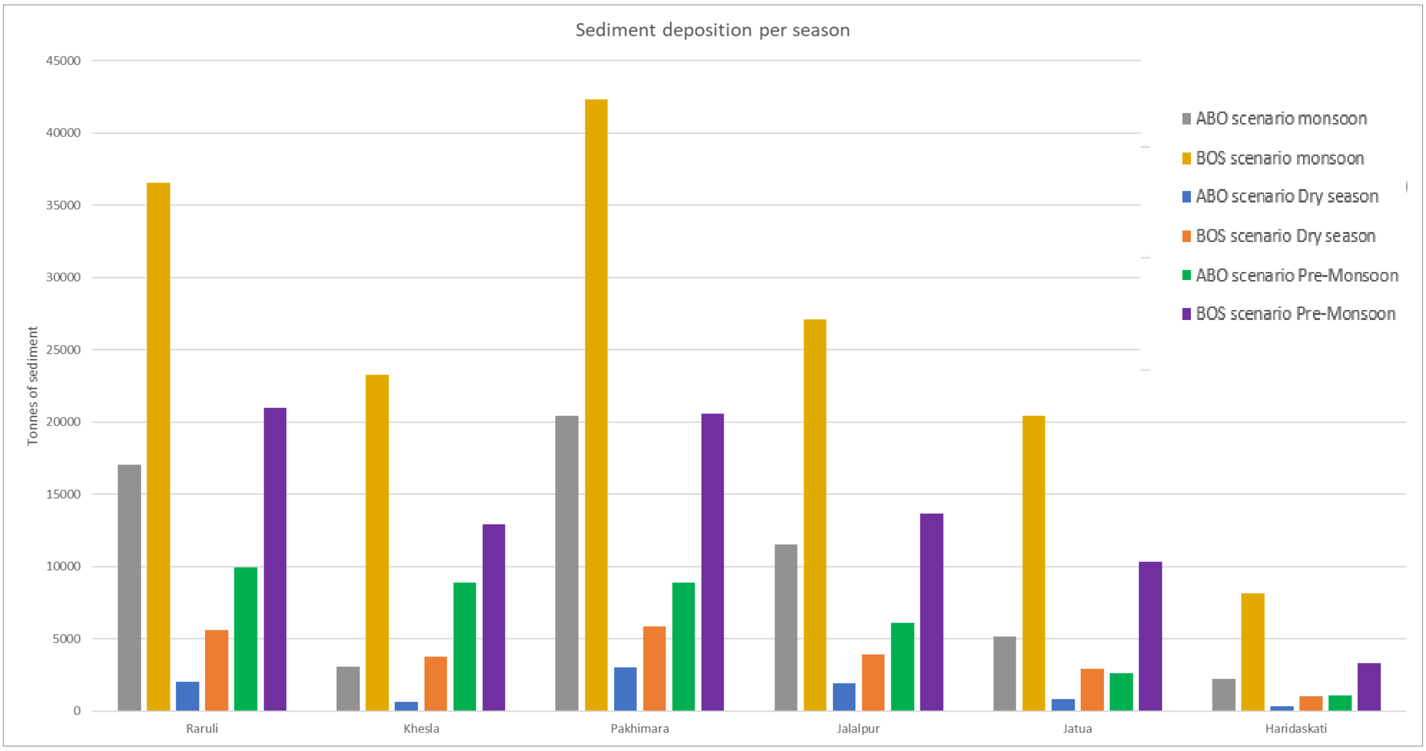


Figure 25 and 26. Tidal prism (upper) and sediment deposition (lower) for dry season and pre-monsoon for the ABO and BOS scenario.