The effect of polder and inlet size on sediment trapping using Tidal River Management in Bangladesh

BSc Thesis Earth Sciences

Faculty of Geosciences

Utrecht University

Author:
Marijn Engelen
5743109

Supervisors:
Prof. dr. Hans Middelkoop
Md. Feroz Islam

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Universiteit Utrecht

Faculty of Geosciences

Table of contents

1 Introduction

The country of Bangladesh, Asia, consists for a large part of the delta of the Ganges, Brahmaputra and Meghna rivers, which are part of one of the largest catchments on Earth. Together, they create one of the most dynamic deltas in the world (Dewan et al., 2015; Van Staveren et al., 2017). Apart from this, Bangladesh is one of the most densely populated countries in the world (Our World in Data, 2019). The dynamic delta provides its inhabitants with fertile ground, but also creates large problems. Attempts to tame the dynamic system through the construction of dykes has resulted in siltation of the rivers, the subsequent floods caused by the congestion, a loss in biodiversity, and waterlogging of agricultural land (Gain et al., 2017). These problems are aggravated by the continuously subsiding land with a median rate of 2.9 mm/year (Brown and Nicholls; 2015).

The cause for the excessive deposition in the rivers can be found in the polderisation of the land as part of the Coastal Embankment Project (CEP) and a decrease in freshwater discharge because of the construction of the Farakka Barrage, just a few kilometres over the border with India (Serageldin, 2015). The construction of the embankments of the CEP was meant to protect the land against flooding, but it also prevents the tides from depositing sediment on the floodplains. The decrease in freshwater discharge means that the large amounts of sediment brought in with the tides cannot be flushed out again. These processes combined cause the sediment to be deposited in the rivers, creating a congestion.

1.1 Historical development

Before the CEP, the water management was done by so-called *Zamindars*, which were local landlords. They ordered the common folk to construct relatively low embankments, to protect the crops grown during the dry season for the first month of the flood season. After the harvest, the embankments were overflown and the so-called *beels,* which are bowl-shaped depressions in the landscape that accumulate water, were flooded. The flooding water would bring in sediment, which was deposited and would make sure the land remained fertile. After the flood season, the embankments were restored, and the land could be cultivated again (van Minnen, 2013; Dewan et al., 2015; Van Staveren et al., 2017).

In the 18th century, Bangladesh became part of the British empire. The focus of the British was much less focused on agriculture and flood protection, and more focused on the navigation of the rivers (van Minnen, 2013). More priority was given to the structural embankments to reclaim land from the water. These embankments were also used for the construction of a vast network of railroads. While the Zamindars remained in some form of power, the larger scale maintenance of the rivers was neglected and by the end of the 19th century, the area was socio-environmentally in decline (Van Staveren et al. 2017).

After India became independent from the United Kingdom, Bangladesh became part of Pakistan. After several large floods occurred in the following years, the United Nations recommended the government intervened in the management of the system. Because of this, the Coastal Embankment Project (CEP) was started and polders were constructed throughout the entire area (Gain et al., 2017). The result was an increase in food production and a large growth in population due to a larger sense of security (Awal, 2014). However, the construction of the embankments made the rivers unable to deposit their sediment on the floodplains, causing the rivers to congest, raising the overall water levels. This led to an increased tidal range and an eventual decrease in biodiversity. Lack of maintenance led to the siltation of the rivers and drying up of water bodies due to the irrigation needed for the increased food production. Since the water is unable to efficiently leave the polders, waterlogging has become a big problem. With climate change and the rising sea levels, this problem has become urgent, and it is thus important that a solution is found.

The following decades, several other organisations were formed to manage the delta. However, conflicting interests between the stakeholders made it so none were successful. A promising solution is Tidal River Management (TRM) in which the *beels* are opened during flood, so the water carrying the sediment can enter, and closed during the following ebb, so the sediment can settle. However, the problem is that the *beels* are used for food production on which the local people are dependent. To assess the effectivity of the TRM system and how the both the *beel* and the water affects this, several experiments have already been done and models are used.

1.2 Tidal River Management

The concept of TRM is not entirely new. The local population has previously suggested breaching the polders to allow tidal flow to bring in sediment. In 1990 they demonstrated this idea, with promising results: 1050 ha of land was made free from water-logging (Tutu, 2005). However, it also caused salinity intrusion and large areas to be inundated, resulting in the destruction of crops (de Die, 2013)

In 1997, the local population created a breach in another *beel*, namely *Beel* Bhaina. The results of this were promising as well, as both the depth and the width of the adjacent Hari River increased significantly (Gain et al., 2017). The cut remained open for several years and after it was closed, the bed of the Hari River rose by approximately 6 metres in one year (de Die, 2013).

Current TRM in the Pakhimara *beel* (see figure 1) is an ongoing project that started in 2015. Monitoring of the area shows that this project is working effectively, as the *beel* no longer experiences waterlogging, the tidal prism of the Kobadak river has increased, and the width & depth of the river is increasing (IWM, 2017). However, the people living along the Kobadak River experienced severe erosion of their land and the associated economic damage and social problems (Gain et al., 2017).

1.3 Study goal and area

Since the concept of TRM will be practiced in many places in Bangladesh, it is important to be able to predict the outcome of such a project. To do this, a wide variety of variables need to be taken into consideration. This thesis aims to study some of the aspects affecting the efficiency of TRM, namely the effect of the size of the *beel* and the size of the

Figure 1 - The Pakhimara beel.

inlet on the amount of sediment that is trapped. This, in turn, gives rise to the following research question:

What is the effect of beel and inlet size on the amount of sediment trapped?

To do this, one of the *beels* was modelled to study these effects, namely the Pakhimara *beel*. The modelled *beel* for this study is located to the southwest of Khulna, Bangladesh (see figure 2). It is connected to the Kobadak River, which flows into the Kholpatua River near Khulna, via a small channel. As the study area lies in the southwestern part of Bangladesh, it has a strong tidal influence. The differences between the different *beel* and inlet sizes are studied throughout the year, so for the dry season, the pre-monsoon season and the monsoon season.

1.4 Thesis outline

After this introduction giving a brief history of the management of the delta and presenting the goal of the study, the thesis continues with some information regarding the hydrodynamic (river discharge, tides) and climatic (seasons) conditions at the study area. Following this, the methods used are described. The results are then presented by dividing them into separate sections for the different seasons. The discussion tells how the different scenario's compare, what may cause these differences and what scenario is the most applicable. Lastly, a conclusion is reached.

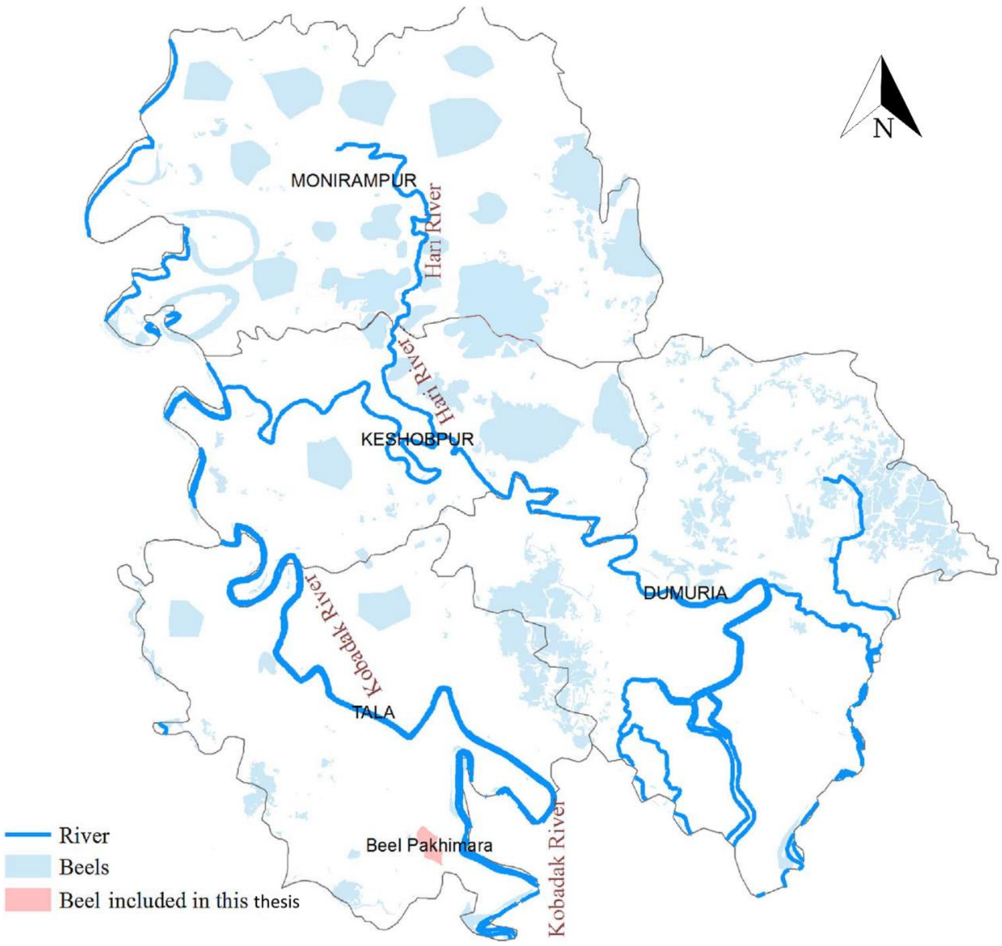

Figure 2 - Map of the study area consisting of the Khulna-Jessore-Satkhira districts, with the Kobadak river and the Pakhimara beel. Taken from Gain et al. (2017)

2 Hydrodynamic and climatic conditions

To get a better understanding of the different conditions used in the model, the following section provides some information regarding the hydrodynamic and climatic conditions. The modelled *beel* lies in the southwest of Bangladesh, with a mostly tidal flow regime. The upstream influence is only small. Bangladesh knows several climatic seasons, which will be discussed.

2.1 Upstream conditions

Bangladesh consists for the most part of the delta of the Ganges, Brahmaputra and Meghna rivers, which is a dynamic tidal delta of which approximately 6% is actually part of Bangladesh. The three rivers originate in the Himalayas and end in the Bengal Basin.

The river to which the modelled *beel* is connected, the Kobadak river, is not influenced by the major rivers, as it is cut off on the upstream side (IWM, 2017). Instead, it drains an area of approximately 1067 km^2 that surrounds it (Jahid, 2016). Human intervention has greatly decreased the water pressure from upstream by the construction of embankments. For the study area of this thesis, the upstream conditions are thus relatively small.

2.2 Seasons

Bangladesh is a country that knows four climatic seasons: 1) the dry season in winter, 2) the pre-monsoon season around spring, 3) the monsoon or wet season in summer, and 4) the post-monsoon season (Shahid, 2010). These seasons are in part characterised by the amount of precipitation the land receives in these periods (see figure 3) and the resulting suspended sediment concentrations in the rivers. For this thesis, the post-monsoon season is not included separately. Instead, it is split in two and added to the monsoon and dry season. The reason for this is that the post-monsoon season is relatively short. For simplicity, it is combined with the other seasons.

2.2.1 Dry season

During the winter, the climate of Bangladesh is determined by dry winds coming from the northeast. The air above the land cools relatively quickly, while the sea is still relatively warm, causing a high-pressure area pushing the air towards the sea. This air carries only little moisture, resulting in low amounts of precipitation and low river discharge. It is characterized by a low-hanging fog that can persist for several days (Barry and Chorley, 2003; Ahmed and Alam, 2016).

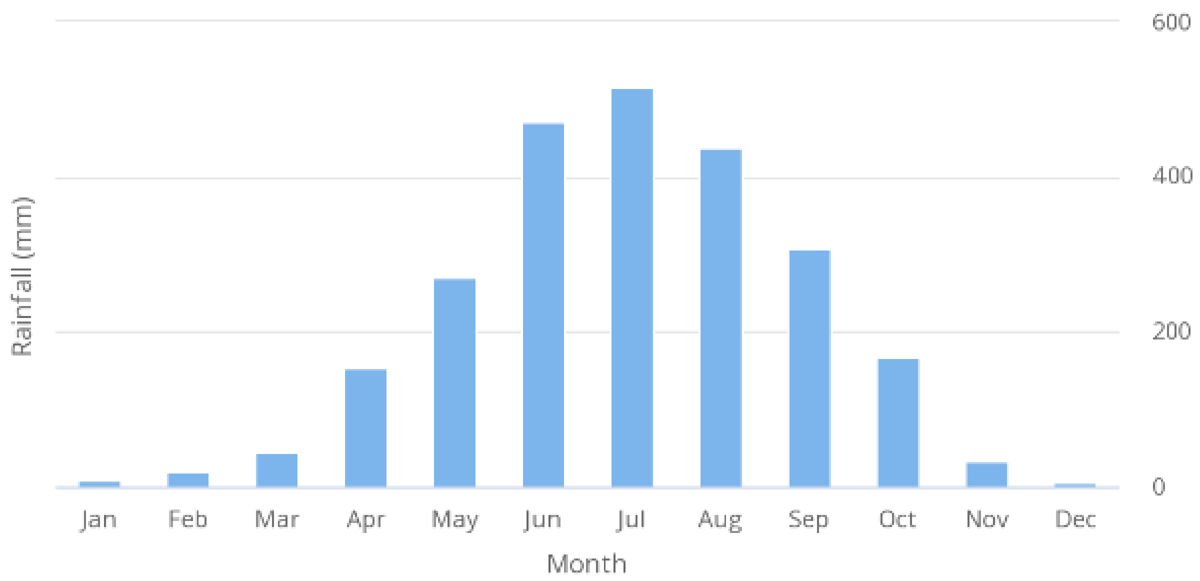

Figure 3 - Average rainfall per month in Bangladesh for the period 1901 – 2016. (World Bank, 2016)

The dry season lasts generally from around mid-November to late February. Average precipitation rates are generally below 2 mm/day, as seen in figure 3 The dry season amounts to only 5% of the total annual rainfall, with rainfall ranging from 10-20 mm for the western and 40-60 mm for the eastern region. (Ahmed and Alam, 2016).

2.2.2 Pre-monsoon

Between the dry winter and the monsoon season lies the transitional pre-monsoon season. This season is characterized by convective storms that bring relatively short, but intense rainfall events. These intense rainfall events cause large amounts of sediment to be brought downstream. The pre-monsoon approximately lasts from March to May and accounts for 10-20% of the total annual. The rainfall generally varies between 200-250 mm in the western central part of the country and 750-800 mm for the eastern part (Ahmed and Alam, 2016).

2.2.3 Monsoon

During the summer, Bangladesh receives large amounts of rain due to the quick warming of the land. This is the monsoon, or wet, season and it lasts from June to September. The rapid warming of the land causes the air to rise, creating an area of low pressure. The moist air from the Gulf of Bengal flows towards the land, warms up and rises, causing the large amounts of water to condense into rain. Together with the presence of the Himalayas, which help push the moist air up, this causes large amounts of precipitation (Barry and Chorley, 2003). In comparison to the pre-monsoon season, this season is characterized by a more continuous rainfall and discharge, but with less sediment. During the monsoon period, about 80% of the total annual precipitation falls.

After the monsoon season, the post-monsoon season lasts from October to November, but since this season is relatively short, it has not been included separately in this thesis. Instead, the first half was included with the monsoon season and the second half was included with the dry season.

2.3 Tides

The coastline of Bangladesh is greatly influenced by the movement of the tides. (Brammer, 2014). The tidal ranges vary from relatively small in the western part to quite large in the eastern part (Ahmed and Louters 1997). The effect of the tides can be felt far into the rivers; the distance depends on the season and the amount of precipitation that is transported by the rivers. The larger influence of the river during the monsoon period results in a smaller tidal range in the upstream region (Horrevoets et al., 2004; van Minnen, 2013). However, since

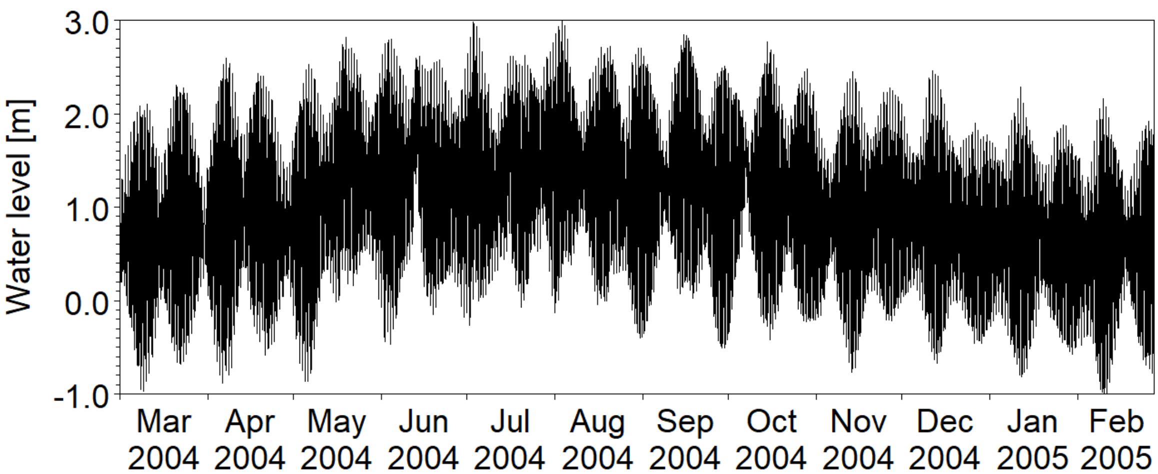

Figure 4 - The water level as recorded in the Kobadak river, with the tidal cycle clearly visible.

the rivers transport more water, the overall water level is higher during the monsoon season. The Kobadak river, to which the modelled *beel* is connected, is a tidal river (IWM, 2017). Figure 4 shows the tides at the *beel*. The tidal range at the modelled *beel* for this thesis is approximately 2 metres during the dry season, and 1.5 during the monsoon, averaged out over spring and neap tide.

A tidal wave moves faster through deeper water, since in shallow water it is hindered by the friction exerted on the water by the bottom and sides of the river. This causes the tidal wave to be distorted and become asymmetrical, meaning that the time in which the water rises is shorter than that of the lowering water (Airy, 1982; Dronkers, 1986; Chernetsky et al., 2010). Since the amount of water that moves in and out remains the same, this means that the flow velocities are much higher during the rising tide. Higher flow velocities can transport more sediment and with a larger grain size, resulting in a net transport of sediment in the landward direction. Because of this phenomenon, the tides are able to bring sediment into the *beels*, without taking all of it out again.

3 Method

The results were gathered using a model. In this model, boundary conditions determined with earlier research were used. Using ArcGIS, the total amount of sediment accumulation was calculated.

3.1 The model: MIKE21 FM

To calculate and visualise the changes in a *beel*, a 2D model called MIKE21 FM, developed by DHI, was used. This is a tool to model coastal or marine regions, simulating physical, chemical and biological processes, using a flexible mesh. For the modelled *beel*, the faces of the mesh had a surface area of approximately 1000 m^2, distributed quite equally. The model is based on the solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations. For the scientific documentation of how the model works, see the scientific manual (DHI, 2017) found on DHI's website.

3.2 Initial and boundary conditions

The initial shape and bathymetry of the modelled *beel* can be seen in figure 5, together with the different locations at which the data was collected and where the weirs were simulated to change the size of the *beel*. The gate through which the water enters and leaves the *beel* is located at location 4. To make sure that the boundary conditions are set correctly, a connecting channel was added, which is not depicted in figure 5 but is visible in the other figures depicting the model. The surface elevation and suspended sediment concentration for the different seasons at the inlet are shown in figure 6 and figure 7 respectively.

For this thesis, three different widths were used for this inlet: one equal to the width of half the river, one equal to the width of the river and

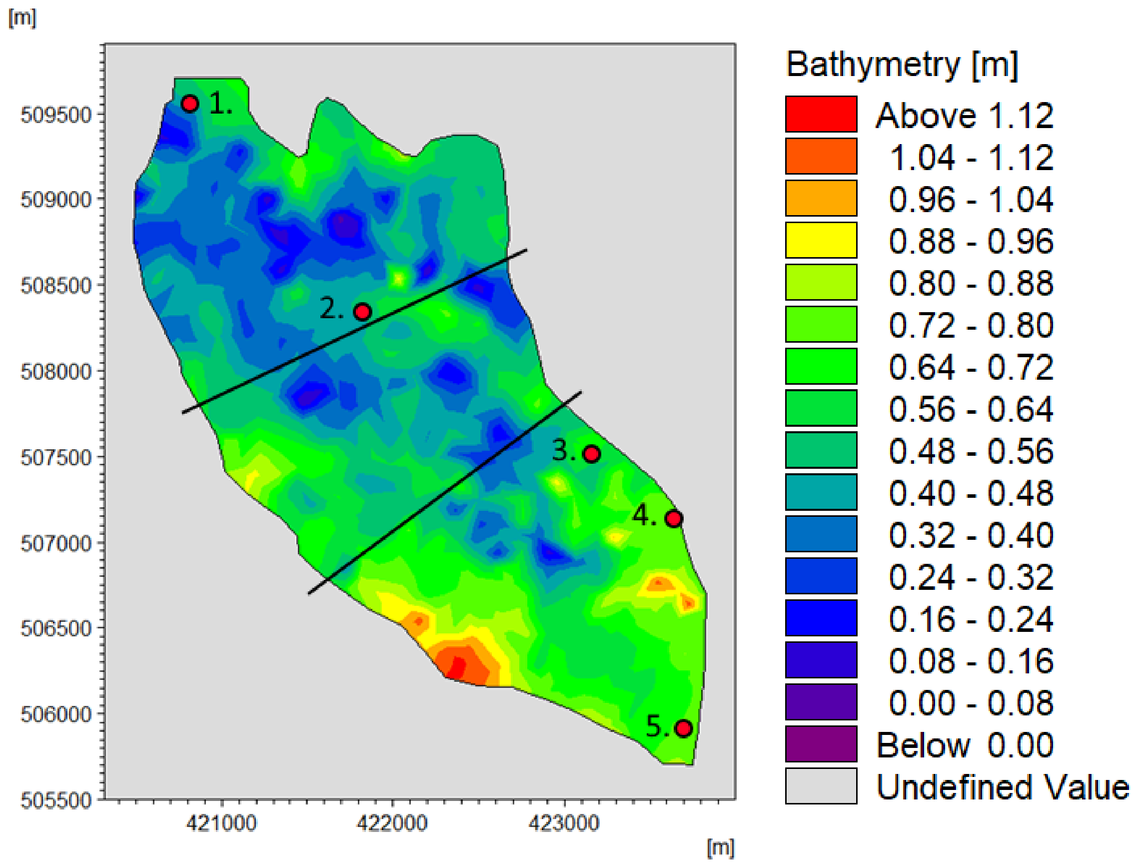

Figure 5 - The bathymetry of the beel, with indication for where the weirs were constructed and for the points of measurement: 1.) Far from inlet; 2.) Middle of the beel; 3.) Close to inlet; 4.) End of link channel and 5.) Lower right corner.

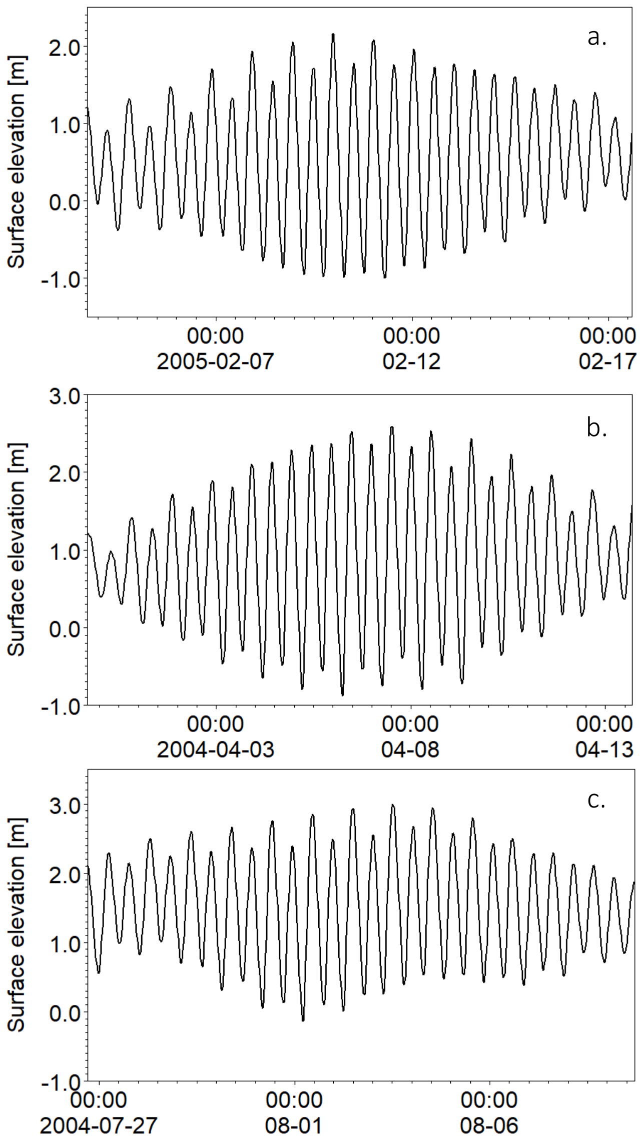

Figure 6 - Water surface elevations at the inlet for a.) the dry season, b.) the pre-monsoon, and c.) the monsoon.

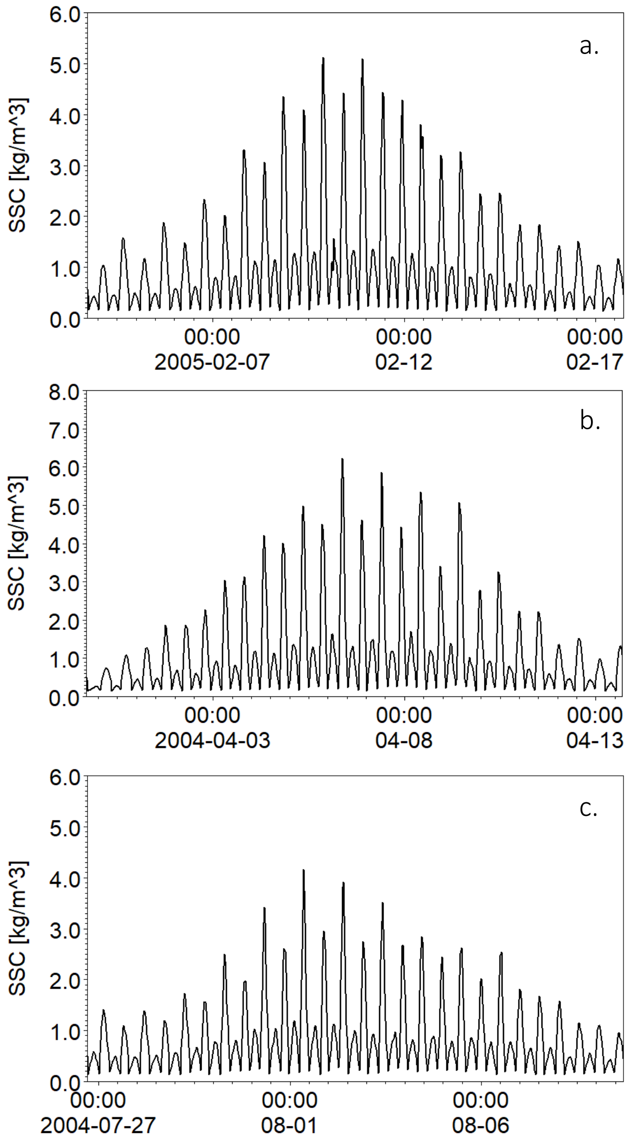

Figure 7 - The suspended sediment concentration (SSC) at the inlet for a.) the dry season, b.) the pre-monsoon, and c.) the monsoon.

one twice the width of the river. The river in question is assumed to have a width of 60 metres. Going forward, the different widths are indicated as *hrw* (half-river width), *frw* (full-river width) and *trw* (two-river width).

For the size of the *beel*, three different sizes have been used as well. Apart from the full size, which has an area of approximately 7.4 x 10^6 square

metres, a size of one-third of the total *beel* and two third of the total *beel* have been used. The different sizes were created by having the model construct a weir at the appropriate location. From here on out, the different sizes will be referred to as *bs1/3* (*beel* size one third), *bs2/3* (*beel* size two third) and *bsf* (*beel* size full).

Since river discharge and suspended sediment concentrations are largely dependent on the climatic season, the model was run for three different time periods. The model calculated time steps of 5 minutes for 14 consecutive days, giving a total of 4032 timesteps. The reason for running the model for 14 days was to include a full tidal cycle, with both neap tide and spring tide. The used time periods are:

- Dry season: 3/2/2005 17:30:00 to 17/2/2005 17:30:00
- Pre-monsoon: 30/3/2004 16:30:00 to 13/4/2004 16:30:00
- Monsoon: 26/7/2004 17:00:00 to 9/8/2004 17:00:00

All in all, this gives a total amount of 27 model runs. All model runs can be seen in table 1.

3.3 Sediment calculations

The total mass of the accumulated sediment in the polder was calculated using the MIKE Zero Toolbox to create the shapefiles and ArcGIS to use these files to determine the total mass. This was done using the *"Calculate Geometry"* function to determine the area of every individual face of the mesh. Multiplying this with the sediment accumulation as given by the model for every face of the mesh gives the sediment accumulation per face. Summing these together gives the total mass.

	Inlet width 0.5	Inlet width 1	Inlet with 2
Beel size 1/3	*Dry season* *Pre-monsoon* *Monsoon*	*Dry season* *Pre-monsoon* *Monsoon*	*Dry season* *Pre-monsoon* *Monsoon*
Beel size 2/3	*Dry season* *Pre-monsoon* *Monsoon*	*Dry season* *Pre-monsoon* *Monsoon*	*Dry season* *Pre-monsoon* *Monsoon*
Beel size full	*Dry season* *Pre-monsoon* *Monsoon*	*Dry season* *Pre-monsoon* *Monsoon*	*Dry season* *Pre-monsoon* *Monsoon*

Table 1 – All 27 modelled scenarios. The different variables are the beel size, the inlet width, and the season.

4. Results

The results are presented by dividing it into separate sections for the different seasons. Per season, the differences between the *beel* sizes and the inlet widths are presented. The total sediment accumulation was visualized in figures similar to figure 8. One of these is included in the main text; the rest has been included as an appendix at the end of this thesis.

It is important to note that all results are from a 14-day period, somewhere in the middle of the respective season.

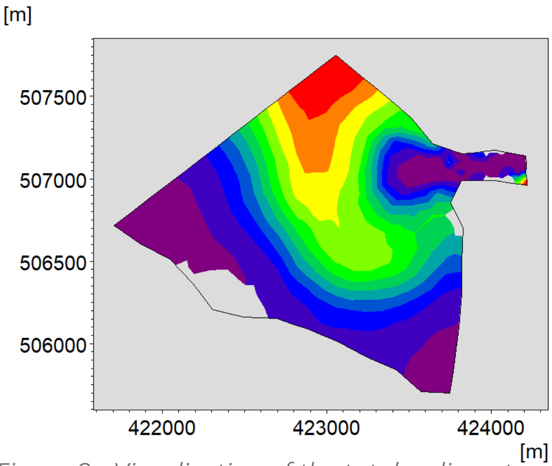

Figure 8 - Visualization of the total sediment accumulation. This example has an inlet width equal to the river width. The season is the dry season. Red is 1200 g/m² and purple 0 g/m².

4.1 Dry season

4.1.1 Beel size

During the dry season, increasing the size of the *beel* results in a larger amount of sediment accumulating in the *beel* overall, regardless of inlet width. However, the accumulation per unit area decreases with beel size. Figure 10 shows a decrease from approximately 40 gram per square metre for *bs1/3* to 25 gram per square metre for *bs2/3* for the dry season with a constant inlet width of 1 river. The decrease in accumulated sediment per unit area from *bs2/3* to *bsfull* is much smaller, only a few grams.

However, the spatial distribution of the sediment changes. Figure 9 shows that with an increase in *beel* size, the amount of sediment

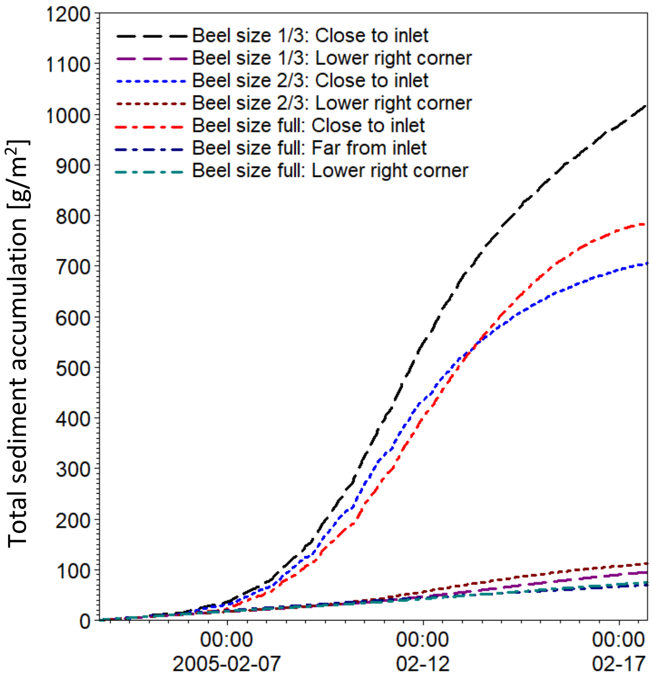

Figure 9 - Total sediment accumulation close to the inlet, in the lower right corner and far from the inlet during the dry season. The river width is kept constant at frw.

accumulated close to the inlet is reduced, as the sediment has a larger area to be deposited on. In the lower right corner, the sediment accumulation changes only slightly, indicating that the additional sediment is brought further into the *beel* and not towards the lower right corner. The amount of sediment accumulated far from the inlet is approximately the same as in the lower right corner, so apart from the area close to the inlet, it is distributed quite equally over the entire *beel*. This can also be seen in figure A….

Something of note is the shape of the lines representing the location close to the inlet, which have a concave shape in the first half and then change into a convex shape later. This shape remains somewhat constant with an increase in *beel* size, but the change from concave to convex shifts to a later date. For *frw*, the accumulation close to the inlet for *bs2/3* slows down faster than for *bsfull*, which means that in the end, more sediment has accumulated at this location for *bsfull*.

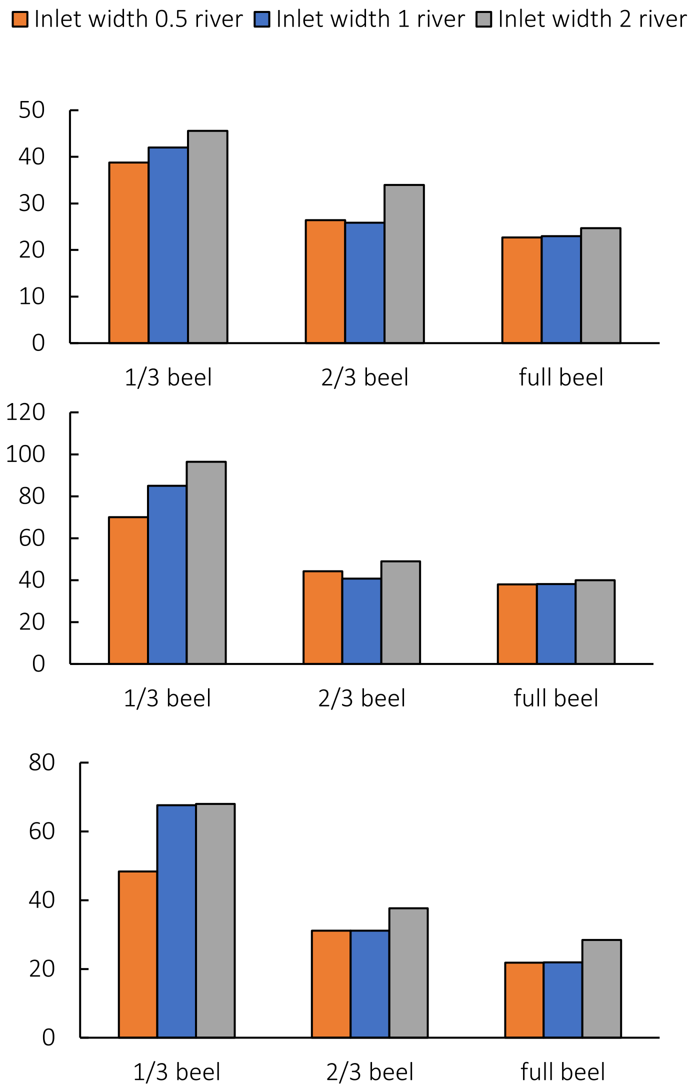

Figure 10 - Sediment accumulation per unit area (g/m^2) for a) the dry season; b) the pre-monsoon season; and c) the monsoon season.

Flow velocities

For *frw*, the flow velocities at the end of the link channel generally decrease when the *beel* size becomes larger than *bs1/3*, mostly in the positive direction (into the *beel*), as seen in figure 11. For *bs2/3* and *bsfull*, it varies when the flow velocities are the largest. In general, they increase more for *bs2/3* going from neap to spring tide. It is also evident that the flow velocities for *bs2/3* reach their maximum sooner, but it lasts for a shorter period of time.

In the negative direction (out of the *beel*) the flow velocities are almost the same for *bs1/3* and *bs2/3* but smaller for *bsfull*. Close to the inlet, flow velocities are largest for *bs2/3,* although they are much smaller than at the end of the link channel. It can be noted that close to the inlet, the difference between the flow velocities in and out of the *beel* is relatively large, so the water flows back much faster. In the lower right corner, the flow velocities decrease relatively quickly with *beel* size, as the water is now able to flow further

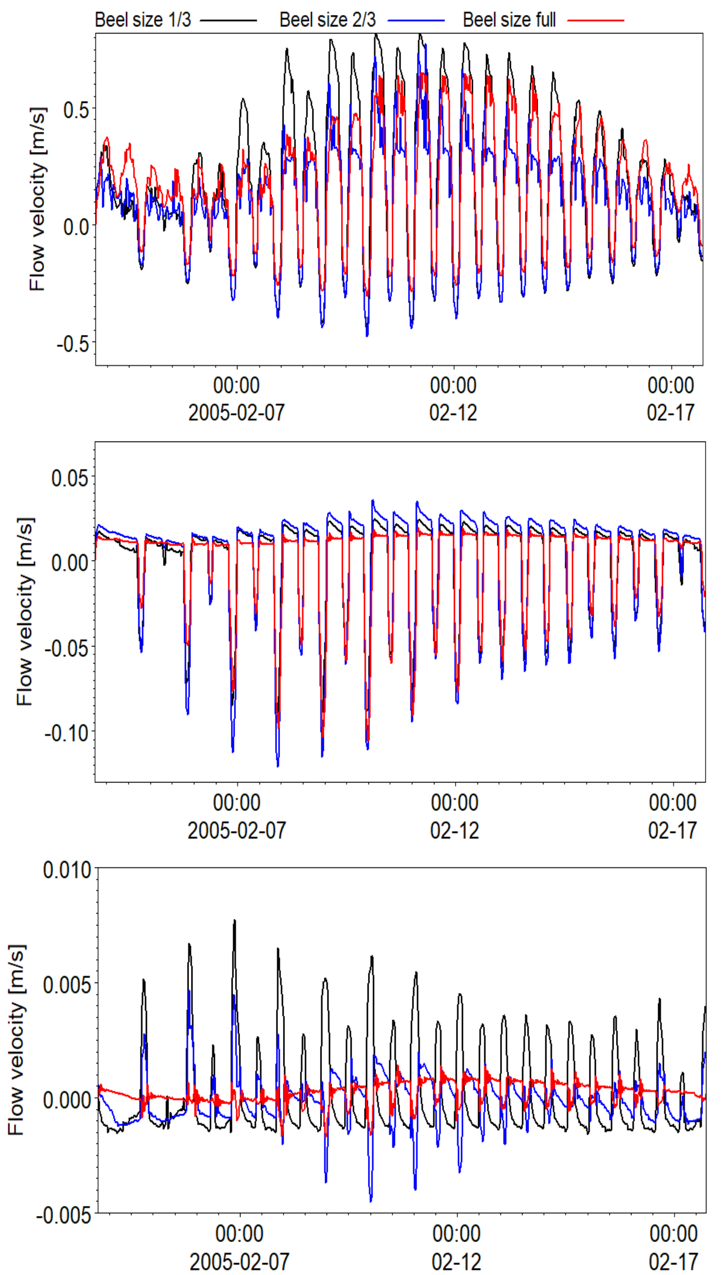

Figure 11 - The variation in flow velocity for the different beel sizes. The data was collected at 3 different locations: a) End of link channel; b) Close to the inlet; and c) Lower right corner.

towards the north. However, the flow velocities are close to zero, so it does not have a large influence.

Decreasing the inlet width to *hrw* results in a substantial decrease in flow velocities at the end of the link channel for *bs2/3*. They are now noticeably lower than for both *bs1/3* and *bsfull*. Increasing the inlet width to *trw* has the opposite effect; now the flow velocities for *bs2/3* are closer to those for *bs1/3* and *bsfull*. Out of the *beel*, all three become almost identical for *hrw* and *trw*.

4.1.2 Inlet width

Decreasing the width of the inlet results in a smaller amount of accumulated sediment in *bs1/3* and *bsfull* but seems to cause slightly more sediment to accumulate in *bs2/3*. The difference between *hrw* and *frw* for *bsfull* is close to zero, while that for *bs1/3* is relatively large. Increasing the width of the inlet shows an increase in the sediment accumulated per unit area. The increase is the largest for *bs2/3*, going from approximately 25 gram per square metre to approximately 35 gram per square metre. The increase is much smaller for *bs1/3* and *bsfull*.

During the dry season, varying the width of the inlet does not influence the distribution of the sediment much. As the area in the north gets filled up in *bs1/3*, the sediment starts to be deposited more in the southern area. Close to the inlet, the sediment accumulation throughout time is almost the same for *hrw* and *trw*, while it is slightly higher for *frw*. Figure 12 shows the sediment accumulation for *bsfull*. The larger inlet results in the sediment to be transported further into the *beel,* causing the sediment accumulation close to the inlet to lessen with increasing *beel* size. The general shape of the lines is similar to those of figure 9, with a change from a concave to a convex shape. It can be noted that the line representing the *trw* shows some small-scale variations, as the amount of sediment accumulated first increases to then decrease.

The different inlet widths influence the way in which the size of the *beel* affects the sediment accumulation throughout time. The *frw* inlet results in sediment accumulation as seen in figure 9, where the accumulation close to the inlet for *bs2/3* is eventually surpassed by that for *bsfull*. With a smaller inlet, this never happens and the total sediment accumulation close to the inlet remains higher for *bs2/3* than for *bsfull* during the whole period. The same happens for *trw*, but now the same small-scale variations seen in figure 12 are present.

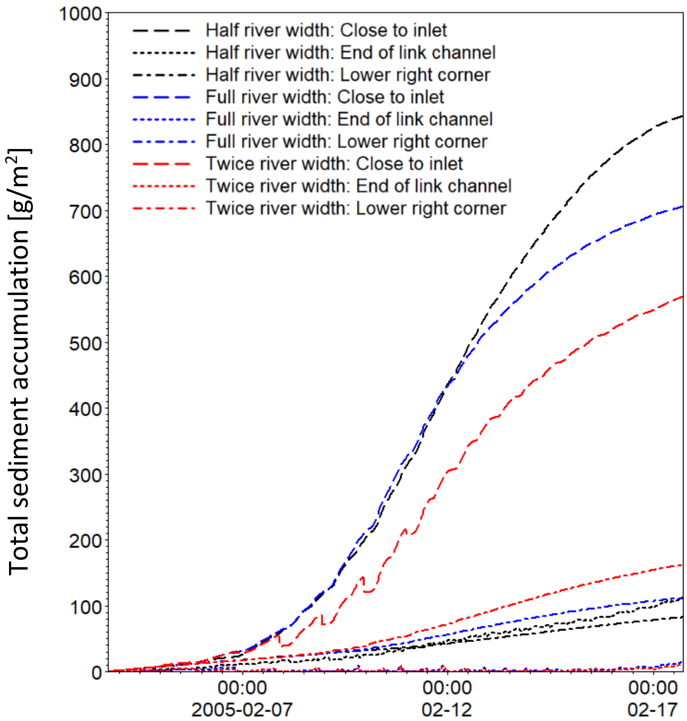

Figure 12 - Total sediment accumulation close to the inlet, in the lower right corner and far from the inlet during the dry season for different inlet widths. The beel size is kept constant at bsfull.

Flow velocities

The flow velocities at the end of the link channel vary with a varying inlet width as they did with the different *beel* sizes. The way they vary through time is similar. However, while an increase in *beel* size results in a decrease in flow velocities, an increase in the width of the inlet results in an increase of the flow velocity. The time over which the maximum positive flow velocity takes place is shorter for the *trw* inlet during spring tide.

For a larger *beel* size, the flow velocities for the *hrw* and *frw* become more similar and for the full *beel*, they are approximately equal, regardless of location in the *beel*. The way in which the flow velocities close to the inlet vary for the different widths is similar to that seen in figure 11. For *bs1/3*, the smaller inlet width results in the smallest flow velocities in both directions, while the larger inlet results in the largest. For *bsfull*, the same as close to the inlet happens and *hrw* and *frw* become the same. This happens in the lower right corner.

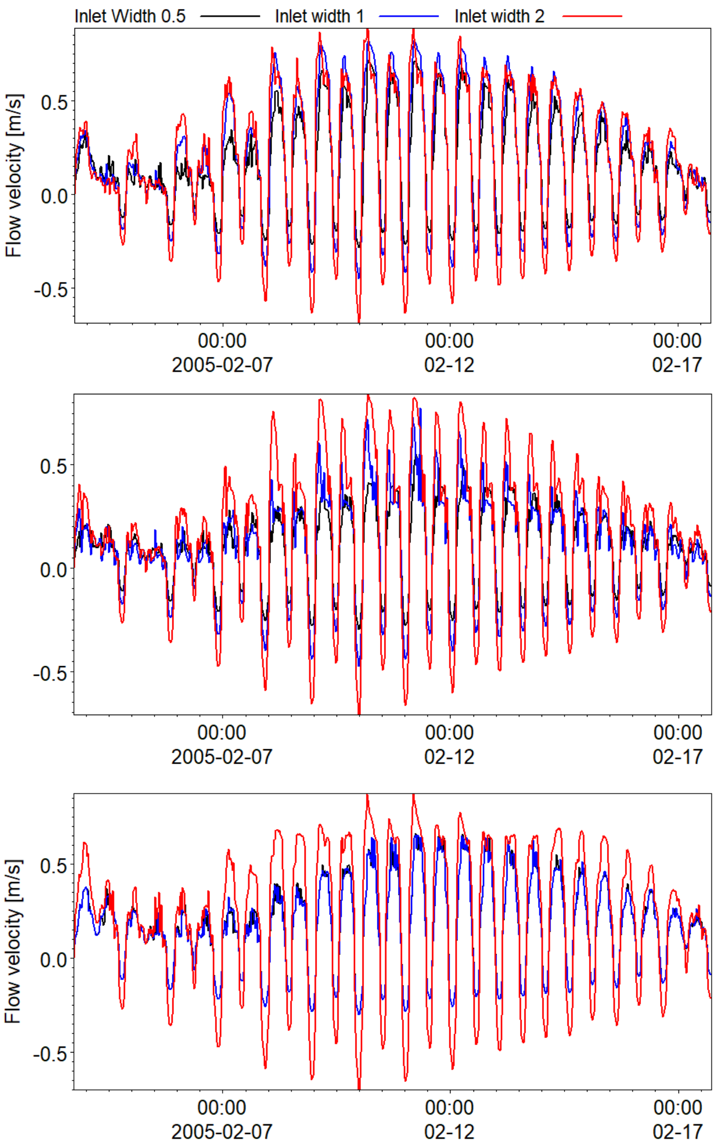

Figure 13 - Flow velocities different beel sizes, varying inlet width.

4.2 Pre-Monsoon season

4.2.1 Beel size

Increasing the size of the *beel* during the pre-monsoon season results in a decrease in the sediment accumulation per unit area, similar to the dry season. Interestingly, increasing the *beel* size from *bs1/3* to *bs2/3* results in a decrease in the total sediment accumulation for *frw* as well. For *trw*, the total accumulation is larger than *frw*, but smaller than for *hrw*. The *trw* inlet only shows a significant increase from *bs2/3* to *bsfull*. There is practically no change from *bs1/3* to *bs2/3*.

Figure 14 shows that the spatial distribution of the sediment is similar to that of the dry season. Close to the inlet, *bs2/3* has less accumulation than *bs1/3* and for the most part more than *bsfull*. The biggest difference is in the lower right corner, where more sediment accumulates during the pre-monsoon. An increase in the *beel* size means less sediment at this location. For *hrw*, the differences close to the inlet are much smaller and *bs2/3* and *bsfull* are almost identical. In the lower right corner, there is now more sedimentation for the full *beel* size. For *trw*, the accumulation

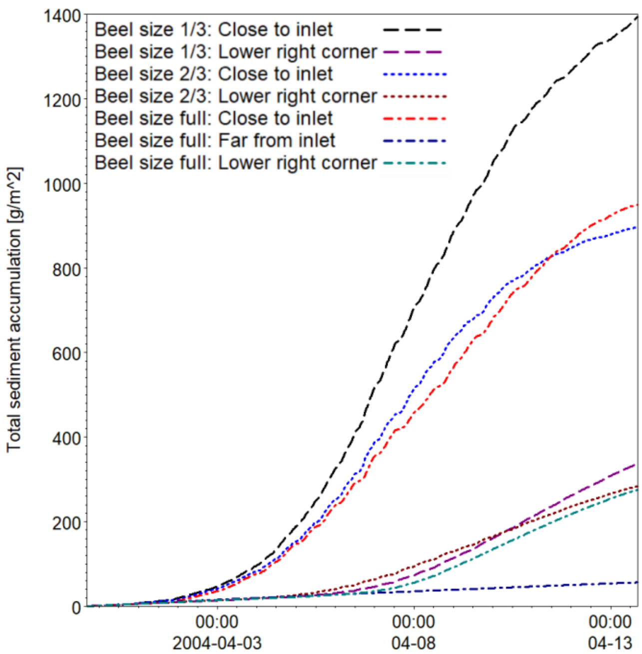

Figure 14 - Sediment accumulation pre monsoon

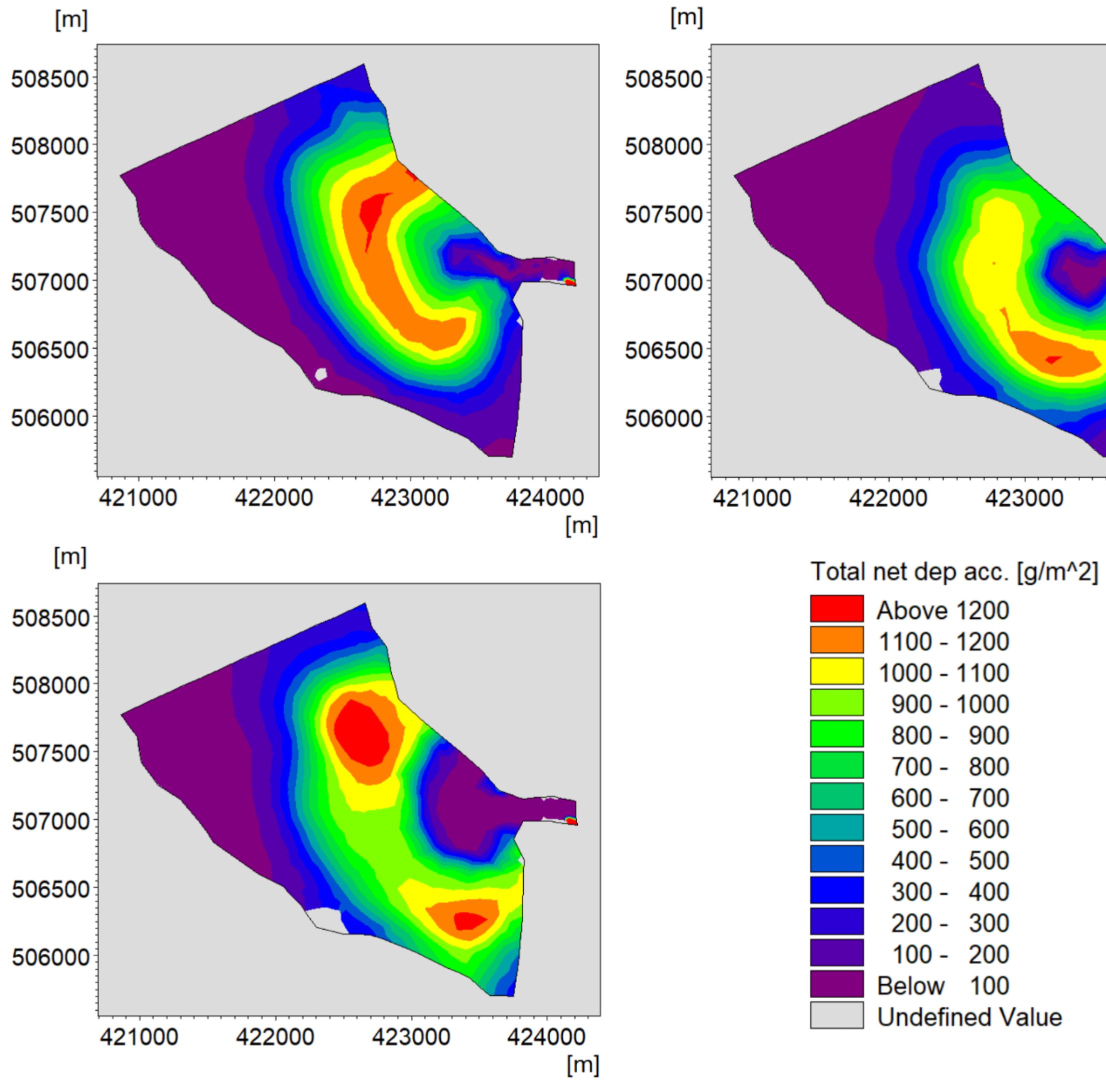

Figure 15 - Visualization of the total sediment accumulation during the pre-monsoon. The size of the beel is kept constant at bs2/3. The width of the inlet is a.) hrw, b.) frw, and c.) trw.

close to the inlet starts to show small-scale variations, similar to those seen in figure 12 For *bs1/3*, the line remains approximately the same, while the lower right corner receives an even larger portion of the sediment.

Figure 15 shows a visualisation of how the sediment distribution changes with inlet width.

Flow velocities

The flow velocities at the end of the link channel are slightly larger during the pre-monsoon season, as seen in figure 16. They become more similar for *bs1/3* and *bs2/3* during spring tide. However, just after neap tide, they are clearly larger for *bs1/3*. Like during the dry season, the flow velocities for *bs1/3* and *bs2/3* are larger than for *bsfull*, in both directions. The biggest difference is that

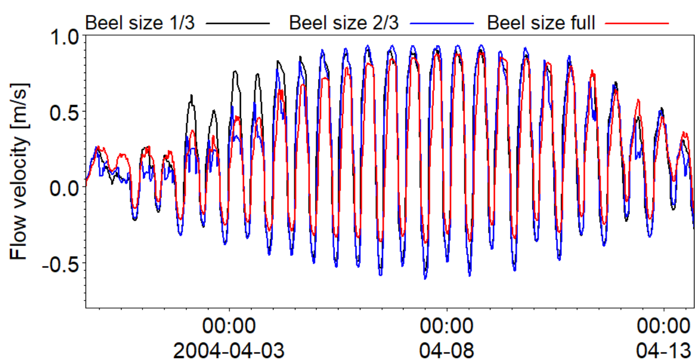

Figure 16 - Flow velocities at the end of the link channel during the pre-monsoon.

the duration of the maximum flow velocities is larger during the pre-monsoon season.

Either decreasing or increasing the width of the inlet removes the influence the *beel* size has on the outgoing flow velocities, as they become equal for all three sizes. However, the outgoing flow velocities for *trw* are significantly larger. The flow into the *beel* is larger for *bs1/3*.

4.2.2 Inlet width

Decreasing the width of the inlet from *frw* to *hrw* results in a decrease of the total sediment accumulation of approximately 18% for *bs1/3*, while it results in an increase of almost 10% for *bs2/3*. The full *beel* is not affected much by a change from *frw* to *hrw*, as the inlet does not permit the sediment to be transported far enough. Increasing the size of the inlet results in an increase in total sediment accumulation for all different *beel* sizes, with the largest increase being for *bs2/3*. The full *beel* shows the smallest increase, with only 5%.

The spatial distribution of the sediment does not change much with a varying inlet width for *bs1/3* and *bsfull*. The only change is that the amount of accumulated sediment increases. For *bsfull*, this means that the sediment can reach slightly further into the *beel*. For *bs2/3*, the location where the most sediment accumulates changes with inlet width. This can be seen clearly in figure 15. For *hrw*, the sediment accumulates mostly on the location close to (a little north of) the inlet. For *frw*, the most sediment is deposited closer to the lower right corner. And finally, for *trw*, the sediment accumulates in both areas, with a depression in between.

Flow velocities

Flow velocities at the end of the link channel are largest for an *hrw* inlet if the *beel* is small. Increasing the inlet width causes the flow velocities into the *beel* to decrease during spring tide. However, during neap tide, the opposite happens and increasing the inlet width results in larger flow velocities. For *bs2/3*, a large inlet width generally results in larger flow velocities, most notably in the outward direction. Like the dry season, for the *bsfull*, the flow velocities for *frw* and *trw* are approximately the same. Further away from the inlet (i.e. close to the inlet or in the lower right corner), a similar trend to the dry season is observed.

4.3 Monsoon season

4.3.1 Beel size

Changing the *beel* size during the monsoon season does not affect the total sediment accumulation much for *frw*. However, it should be noted that the total accumulation is largest for *bs1/3*. For *hrw*, increasing the *beel* size from *bs1/3* to *bs2/3* results in an increase in the total sediment accumulation of approximately 30%. Increasing it further results in only a small increase of 5%. For *trw*, both increases result in an increase of approximately 12%.

Per unit area, the decrease in accumulation for the monsoon differs from the accumulation during the pre-monsoon. While during the pre-monsoon, there is almost no change between *bs2/3* and *bsfull*, there is a slightly larger difference during the monsoon season.

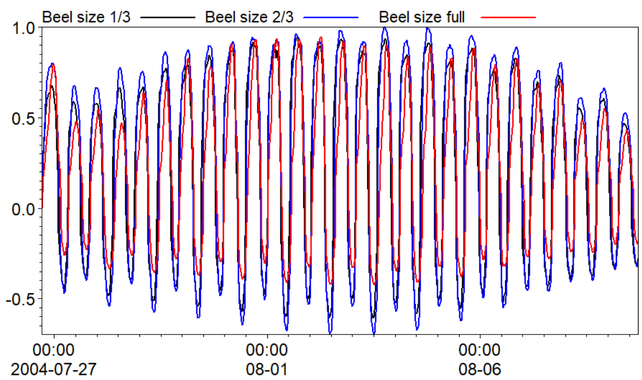

Figure 17 – Flow velocities at the end of the link channel for the monsoon.

Flow velocities

The flow velocities during the monsoon are much more consistent than during the dry season and the pre-monsoon, as seen in figure

17. Close to the inlet, the flow velocities become larger in both directions going from *b1/3* to *bs2/3*, but they are smaller for *bsfull*. They also seem to shift slightly to a later time.

4.3.2 Inlet width

For *bs1/3*, decreasing the width of the inlet results in a significant decrease in the amount of accumulated sediment, while increasing the width has almost no effect. For *bs2/3*, the opposite is true: decreasing the width results in almost no change, while increasing the width results in a relatively large increase. The same can be said for *bsfull*.

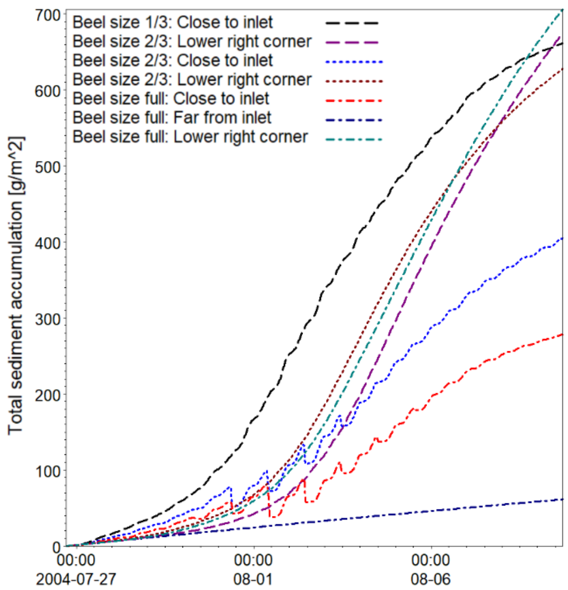

Figure 18 - Total sediment accumulation close to the inlet, in the lower right corner and far from the inlet during the monsoon season for different beel sizes. The inlet width is kept equal to the river width.

The main difference between *hrw* and *frw* for *bs2/3* lies in the spatial distribution of the sediment. Figure 18 shows that sediment that was first deposited in the northern half of the *beel* now accumulates in the southern half. Increasing the inlet width further results in the sediment being accumulated in both regions. The full *beel* shows something similar: the sediment is moved more towards the lower right corner.

Figure 18 also depicts this. The sediment accumulation close to the inlet reduces rapidly, while the accumulation in the lower right corner increases. The largest sediment accumulation at this location occurs for *bsfull*, followed by *bs1/3*. Far from the inlet, the sediment accumulation rate remains constant throughout the entire period.

Flow velocities

Increasing the width of the inlet during the monsoon results in an increase in flow velocities in both directions for bs1/3. For bs2/3, it results in a similar increase in the negative direction, but for the flow into the beel, trw results in slightly smaller flow velocities during spring tide. The flow velocities for hrw and frw become identical when the beel size increased to the full size.

5. Discussion

From the results, it follows that a change in *beel* or inlet size results primarily in changes in the flow velocities and, as a consequence, the sediment accumulation in the *beel*. In this section, the effect on flow velocities will be discussed first and the effect on sediment accumulation thereafter. To reach a final recommendation, the thesis from Davie Vuurboom (2019) is used to link this thesis to previously acquired results regarding different gate operations.

5.1 Flow velocities

Varying either the *beel* size or the inlet width results in a change in flow velocities. Increasing the size of the *beel* generally results in a decrease at all locations, as seen in figure 11. The decrease is most noticeable during the dry season, where the flow into the *beel* varies strongly with *beel* size. Interestingly, the flow out of the *beel* is a lot less affected by the change in *beel* size.

This difference between the in- and outgoing flows is possibly a consequence of the asymmetry of the tidal wave. The flow velocities into the *beel* are higher, since the water enters in a relatively short time, and are more variable. The flow out of the *beel* takes place over a longer time period and is more consistent, showing fewer small-scale variations. The asymmetry becomes clearer further away from the inlet, due to the friction of the *beel*. This is represented in the way the water surface elevation changes with time, as seen in figure 19

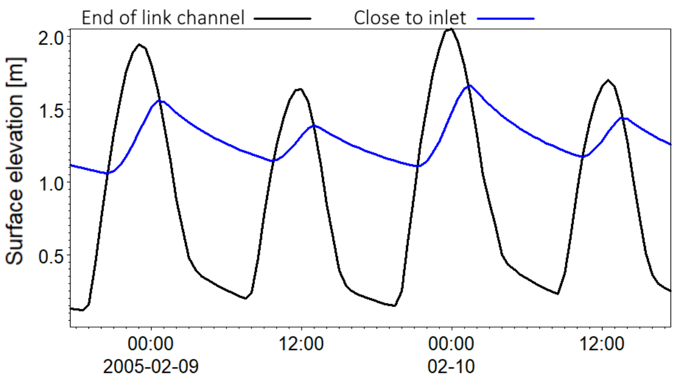

Figure 19 - Asymmetry in the water surface level, during spring tide. River width 1, 1by3, dry season.

The differences in flow velocity change significantly with the seasons, as the upstream conditions change because of the difference in precipitation. The additional water results in overall larger flow velocities, in both directions. They are also more consistent with *beel* size, as the asymmetry dampens out as a consequence of the smaller tidal influence, which is, in turn, an effect of the more consistent river discharge (Horrevoets et al., 2004). During the monsoon, this results in only little influence from changing the *beel* size on the flow velocities into the *beel*, making it evident that it is the tides that create the differences in flow velocity. Out of the *beel*, the effect of a change in *beel* size seems to be comparable to the dry season, although with larger flow velocities.

At the location close to the inlet, the contrast between the in- and outgoing flows is much larger. Here, it is the outgoing flows that are short and much faster. It may be that this is an effect of the bathymetry of the *beel*, as the water favours other paths. In the lower right corner, the flow velocities are only small. However, the change in *beel* size is clearly visible here, since the water now flows towards the newly available space.

The influence of the inlet width is of a similar magnitude. Increasing the width of the inlet generally results in larger flow velocities during the dry season, while decreasing it reduces the flow velocities. During the pre-monsoon, this effect is a lot smaller. A larger *beel* size results in smaller differences in flow velocities between *hrw* and *frw*. During the monsoon, they become almost identical for the full *beel* size.

5.2 Sediment accumulation

The higher positive flow velocities relative to the lower negative flow velocities caused by the tidal asymmetry results in more sediment to be transported in compared to out of the *beel*, as less energy is available in a certain amount of time. The resulting net sediment deposition is what causes the change in total sediment accumulation. Figure 15 and the figures in Appendix A show the result of this process after one tidal cycle of 14 days. The sediment accumulates mostly relatively close to the inlet with less sediment far from the inlet, but at the end of the link channel, the accumulation is close to zero. This crescent shape is caused by the asymmetry in the flow velocities for the different locations, as discussed in the previous section. The increased asymmetry further from the inlet

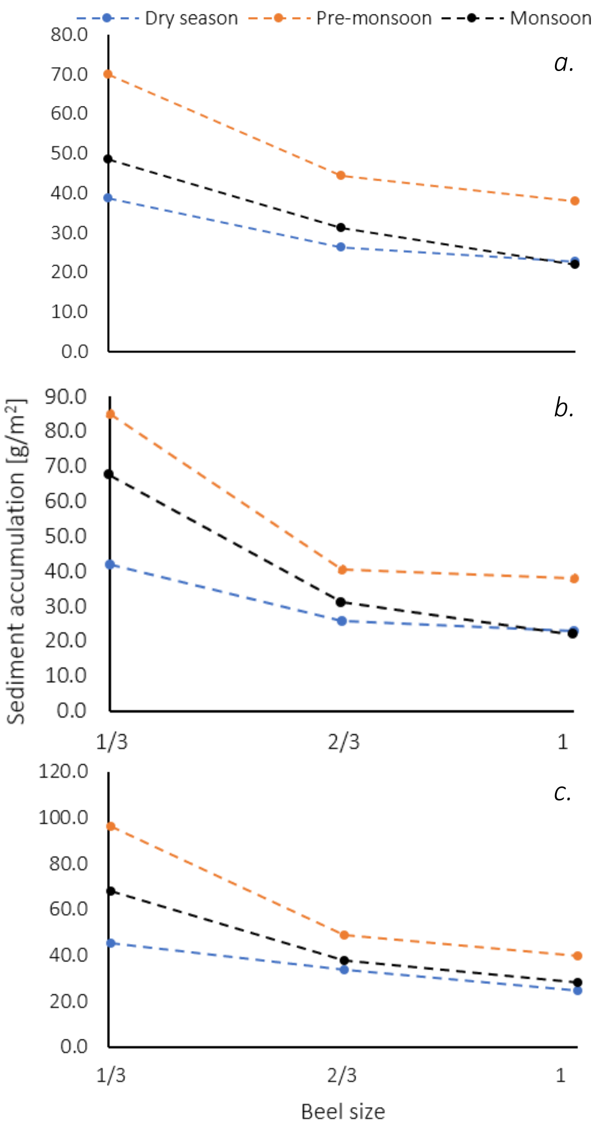

Figure 20 - The change in sediment accumulation per unit area for a.) inlet width ½ river, b.) inlet width 1 river, and c.) inlet width 2 river.

causes more sediment to be left behind. After a certain point, most of the sediment has already been deposited, which is why the sediment accumulation far from the inlet is relatively low.

Beel size

It seems logical that increasing the size of the *beel* results in an increase of the accumulated sediment, as there is more space for the water to flow to and thus for the sediment to be deposited. The tidal prism increases, and more sediment is brought into the *beel*. This is certainly the case for the dry season. However, this is not what occurs during the pre-monsoon and monsoon seasons when the inlet width is equal to the width of the river. In this case, the total sediment accumulation decreases at first for *bs2/3* to then increase again for *bsfull*.

Per unit area, the increase in the size of the *beel* results in a lower sediment accumulation. This is also visible in figure 10, where the accumulation close to the inlet decreases significantly as the water is now able to move further into the *beel*. It is thus evident that the increase in the total sediment accumulation is not enough to keep up with the increase in *beel* size. Figure 20 shows that the effect of increasing the *beel* size becomes less after a certain point. The decrease in accumulation per unit area is relatively large going from *bs1/3* to *bs2/3*, but a lot smaller going to *bsfull*.

The shape of figures 12, 14 and 18 indicate that at first, the sediment accumulates slowly. After multiple days, the accumulation rate increases and then reduces again. As these model runs were 14 days long, which constitutes one tidal cycle, a logical explanation can be found in the difference between neap and spring tide. More evidence for this can be found by looking at the flow velocities, which seem to be larger at the same time as the sediment accumulation rate is highest. During the monsoon, when the flow velocities are much more consistent throughout the tidal cycle, the graph for the sediment accumulation is more linear.

Inlet width

The effect of the width of the inlet strongly depends on the size of the *beel*. For *bs1/3*, the effect is quite significant for all three seasons. A change in inlet width results in a change in the tidal prism, which in turn results in the change in the total amount of sediment trapped. The only exception to this is the increase to *trw* during the monsoon season. The effect of changing the inlet width decreases as the *beel* gets larger. For *bs2/3*,

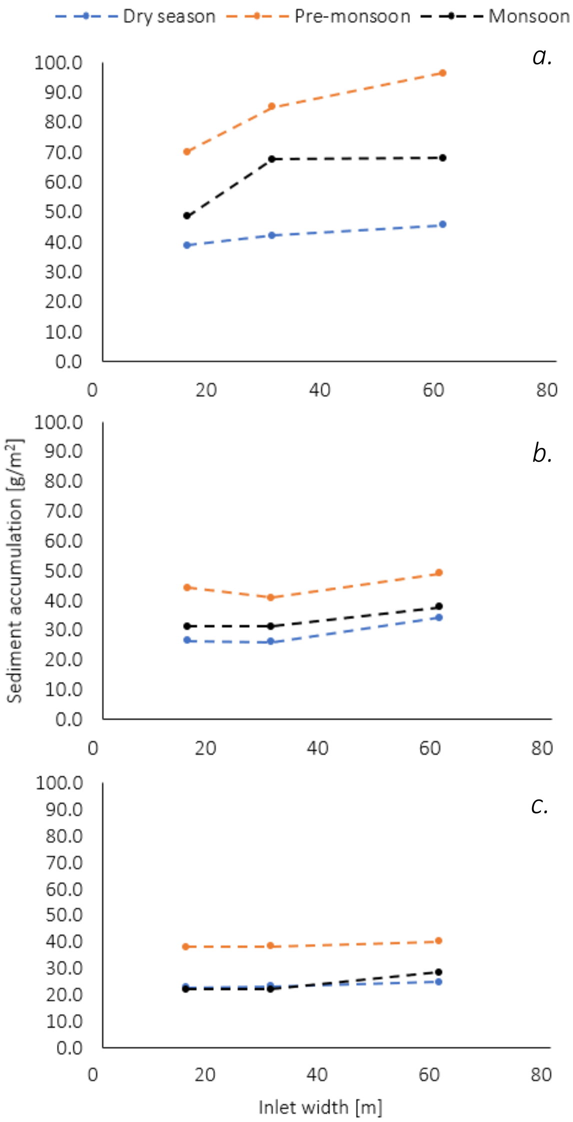

Figure 21 - The change in sediment accumulation per unit area for a.) beel size 1/3, b.) beel size 2/3, and c.) beel size full.

the effect is most noticeable when increasing the inlet width from *frw* to *trw*. When the full *beel* is used, the effect becomes small for the most part, with the exception of making the inlet width *trw* during the monsoon season.

For a smaller *beel* size, there is practically no change when making the inlet wider than the river during the monsoon. In this case, the most change can be seen during the pre-monsoon. There is however a large increase in sediment accumulation when increasing the width from *hrw* to *frw*.

When the inlet width becomes *trw*, sediment that is first put into the *beel* during flood is later removed during ebb, as the flow velocities are high enough. This causes the fluctuations in the graphs and results in less accumulation close to the *beel*. In figure 21, it is visible that *trw* results in a larger area with little sediment accumulation, as the sediment erodes.

5.3 Recommendations

From earlier work by Vuurboom (2019), the effect of different gate operations for the different seasons was determined for several flow regimes. It was found that when the river is dominant, the different gate operations have only little influence. For the intermediate and tidal flow regimes, the different gate operations did influence the sediment accumulation. Since the *beel* studied in this thesis lies in a tidal setting, the focus will be on this.

In the tidal regime, it was found that during the dry season, the largest sediment accumulation occurred when only one of the gates is operated. During the pre-monsoon and monsoon seasons, the highest amounts were found when operating the gates parallel to each other, either keeping them both open throughout the entire tidal cycle or opening and closing them simultaneously. It is clear that there is a peak in sediment accumulation during the pre-monsoon.

From this thesis, it follows that while increasing the *beel* size increases the total sediment accumulation, it decreases the accumulation per unit area. It depends on the *beel* in question how this affects it. The inlet width was found to influence the sediment accumulation as well. It was found that increasing the inlet width further than the width of the river adjacent to the *beel* has little influence. Since doubling the inlet width takes a lot of work, time and money, it is recommended to not increase it further than the width of the river.

To build further upon the research done for this thesis, the influence of the *beel* and inlet size should be studied for the different flow regimes. Currently, all scenarios were modelled in a tidal regime. The results may differ for the river and intermediate regime.

6. Conclusion

This thesis has presented 27 different scenarios for tidal river management, with different *beel* sizes, inlet widths and seasons. It was shown that for effective tidal river management, it is important to consider the size of the *beel* and the width of the inlet. A larger *beel* size generally means more sediment accumulation overall, but less per unit area. Increasing the width also increases the amount of sediment accumulation but becomes less effective when it is increased beyond the width of the adjacent river. This is the most evident for the monsoon. In the pre-monsoon, it does have an effect on the sediment accumulation, depending on the size of the *beel*.

As was clear from earlier studies, the best season for tidal river management is the pre-monsoon. This season brings in the most sediment for all *beel* sizes and inlet widths. During the dry season, the crops can grow and after the harvest in the pre-monsoon, the *beel* can be opened to let the water and sediment in. This process is similar to that before the CEP, before the construction of the polders.

Depending on the desired result, the size of the *beel* may be decreased to increase the sediment accumulation per unit area. However, since constructing weirs to decrease an already existing *beel* in size is costly, it is better to adjust the width of the inlet to the size of the *beel*. Increasing the width of the inlet results in more sediment accumulation and is recommended to a certain extent. Increasing the width further than the width of the river increases the sediment accumulation only slightly at best. During the pre-monsoon for example, the effect is noticeable. However, the cost of doing so is too high for this to be feasible and it is, therefore, better to keep the inlet width approximately equal to the width of the river.

Since this thesis was conducted for a tidal flow regime, it is not yet clear how things change further upstream, where the influence of the river is larger.

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