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Student data:

Name: Josephien Lingbeek

Registration number: 5683149

Date:

03-11-2021

Signature:

The Effect of Sea Level Rise on Estuarine Morphology

Of Natural and Dredged Estuaries in Experimental Setup

Author:

Josephien Lingbeek BSc, 5683149

Supervisors:

Prof. dr Maarten Kleinhans, Jana Cox, MSc & Steven Weisscher, MSc

Utrecht University

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Abstract

Many estuaries are of great economic importance as they are home to large harbours and provide passage to large container ships when extensively dredged. Estuaries are also typically rich in mudflats and marshes that provide flood protection and are home to biodiverse ecosystems. The impact of Sea Level Rise (SLR) on these estuaries and the functions they provide may be large. Therefore, it is important to understand how all the different morphological features of estuaries (e.g., channels, tidal zonation) form and interact in natural and dredged systems and how they will respond to future SLR in order to develop sustainable management strategies. To research the effect of future SLR, two experiments were conducted in the Metronome tidal flume, one with a natural estuary and SLR and one with a dredged estuary and SLR. The results show that the natural system is better able to keep up with SLR than the dredged system. In the upstream regions of the natural system, channel mobility decreased and bank stability increased relative to natural estuaries without SLR, and thus SLR stabilises upstream estuarine morphology. In the upstream regions of the dredged system, the channel mobility significantly increased due to a strongly meandering channel that eroded the banks in the outer bends. As a result, the bank stability decreased in the dredged system with SLR relative to natural and dredged systems without SLR. While dredging on its own stabilises estuarine morphology, it destabilises estuarine morphology in combination with SLR. In the downstream regions of the estuary, bank stability decreases under influence of SLR for both the natural and dredged system. In dredged systems like the Western Scheldt, the results show that current dredging strategy is not sustainable with SLR, because total dredging volumes will increase as SLR and dredging continue and the most heavily dredged areas move upstream due to transgression.

Keywords: Estuary, Morphology, Sea Level Rise, Dredging, Scale-Experiments, Tidal Zonation, Bank Stability

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1 Introduction

1.1 Estuarine shape and significance

Estuaries are bodies of water with river inflow on one end and an open connection to the sea on the other (e.g. Leuven, et al., 2016). The consequences of Sea Level Rise (SLR) on estuaries and the functions they provide may be large, it is important to understand how all the different morphological features of estuaries form and interact in natural and dredged systems and how they will react to future SLR to develop sustainable management strategies.

Tides are able to enter estuaries from the open connection with the sea and shape the morphology within. While shape and channel patterns of estuaries vary a great deal, a large subset of estuaries have a single channel and a convergent funnel shape. This led to the concept of an ideal estuary, which narrows in the landward direction and has a constant depth, such that the tidal wave maintains the same amplitude along the estuary despite energy loss due to bed friction (Savenije, 2005).

Most natural estuaries are not ideal but amplify or dampen the tidal wave as it moves through the estuary. This has implications for the estuarine morphology. An estuary will narrow due to sedimentation when the tidal amplitude decreases through the estuary. When the estuary narrows, the width-depth ratio changes and the tidal wave will be dampened less in this negative feedback loop and sedimentation will decrease. When tidal amplitude increases, the opposite will happen, and the banks will be eroded to widen the estuary. When the tidal wave is amplified, the estuary widens, because the relative bottom friction will increase as width-depth ratio changes. This leads to less amplification of the tidal wave in another negative feedback loop. From this concept it is derived that when an estuary is not an ideal estuary, the estuary is not yet in equilibrium, but it is still adapting to eventually become an ideal estuary (Friedrichs, 2010).

Estuarine morphology is often more complex than an ideal funnel and is characterized by bars, tidal flats, marshes and channels. These are connected by flow and by transported sediment. Estuaries provide ecologically valuable habitats and many important ecosystem services including flood protection and food production, but also have great economic value to societies (Jeuken, 2000). They are home to major ports and are used for navigation by large containerships that require the estuary to be dredged. In this thesis the focus lies on scaled experiments of sandy estuaries of which many real life examples can be found around the world. Many of these estuaries lie in densely populated areas and provide us with the services described above where changes due to SLR might have large consequences. A well-studied estuary like this is the Western Scheldt in the south of the Netherlands at the border with Belgium, and it will be used as and illustrative example in this thesis.

1.2 Morphological features of estuaries

1.2.1 Channels and sediment transport

Estuarine channel and bar morphology and channel behaviour were already described by Van Veen in 1950. Flood and ebb channels are mutually evading each other. This means that they are dead-ended, with a shallow sill at the end over which the flow diverges and flow velocity decreases leading to sedimentation that keeps the sill in place. These sills form obstructions for large container vessels that navigate up the estuary. In a system like the Western Scheldt, where the width of the system is not larger than about 3 to 5 times the width of the main channel, one large meandering ebb channel formed with the flood channels on the bars in the inner bends of this channel. In this system sediment is not simply transported back and forth in every tidal cycle. Sediment starts to cycle, on average moving in upstream direction in the flood channels and downstream in the ebb channels (Jeuken, 2000; Van Veen, 1950).

1.2.2 Bars, flats and marshes

Typically, estuarine tidal flats and marshes, are on the fringes of the estuary (Eisma et al., 1998) and bars and shoals lie between channels. Empirical research has been done on the patterns, shape and depth of these bars (Leuven et al., 2016; 2018a; 2018b), and shows that bars in estuaries have very similar dimensions to river bars. However, estuarine sand bars are typically slightly more elongated (Leuven et al., 2016). Experimental research by Leuven et al. (2018a) concludes that bars in estuaries occur in the wider parts of the estuary and do not migrate due to alternating tidal flow. In Leuven et al. (2018b) it is shown that the presence and size of bars is dependent on the excess width of the estuary relative to what the ideal estuary shape would be.

1.2.3 Tidal zonation

The estuarine system can be divided in three tidal zones that have conceptually different properties and dynamics: the subtidal, intertidal and supratidal zones. Subtidal areas are always submerged and convey most of the tidal flow momentum (Friedrichs, 2010). An example of subtidal area are the channels in an estuary, of which migration causes bar and bank deformation. Intertidal areas are submerged during high water but are emerged during low water. Tidal flats and most parts of bars are examples of intertidal areas. And they respond to mud sedimentation and vegetation settling, and affect the tidal water levels (Friedrichs, 2010). Supratidal areas are nearly always above water level and only flood at times of extremely high waters during storms a few times per year (Eisma et al., 1998). Examples of supratidal areas are marshes on the fringes of the estuary and sometimes the highest parts of bars. Species diversity is relatively high in estuaries due to the presence of these many different environments that are created by gradients in the previously discussed water depths and tidal influence, and salinity (Baeyens et al., 1997).

1.3 Effects of dredging on channels and bars

Deep channels typically in the mouth grant passage to the large containerships while for instance tidal flats, bars and marshes typically have very high ecological value. These same shallow areas also provide flood protection. But human or nature induced changes that will benefit one of these functions does not necessarily benefit the other functions.

Dredging is one of the alterations made by humas to benefit the economic use of the estuary. Since container ships are so big these days, navigation can only be possible if there is a continuous deep channel. As this rarely exist in the natural situation, channels are dredged (Cox, 2018; Van Dijk et al., 2021). The morphology directly changes in the subtidal channels because of the deepening and in the shallower intertidal and supratidal areas morphology directly changes, because the dredged sediment is dumped back into the system in these places.

Changes in morphology also have implications for the hydrodynamics in the system. Winterwerp et al. (2013) have studied four small estuaries in Western Europe (Elbe, Ems, Scheldt and Loire). In their comparison they find that tidal range is amplified and the point of maximum tidal range has moved further upstream during the twentieth century as a result of dredging in combination with land reclamation and embankment. When channels are deepened, bottom friction decreases which causes the tidal amplitude to increase. This makes the tidal wave able to penetrate further upstream (Temmerman et al., 2013). In combination with dumping dredged material on intertidal area, this increases flood dominance (Friedrichs, 2010).

Another effect of dredging is that the tidal flow is focussed into the dredged channel, causing the channel to start deepening itself. This means that in other parts of the estuary tidal energy decreases and with that the amount of erosion decreases. This effect causes a stabilisation of the channel into the newly imposed morphology that can persist long after dredging has ceased as was shown in scale experiments in the Metronome flume (Cox, 2018; Van Dijk et al., 2021).

1.4 Expected effects of SLR on estuarine morphology

Dealing with SLR due to human induced climate change is one of the greatest challenges of this century. SLR caused by anthropogenic forcing has been observed over the last century. From 1970 to 2015, Global Mean Sea Level Rise (GMSLR) was 3.2 mm/yr and even faster between 1993 and 2015 (Oppenheimer et al., 2019). Towards the end of the century GMSLR is expected to be even faster in all Representative Concentration Pathway (RCP) scenarios.

1.4.1 Large scale effects of SLR on estuaries

A lot of research has been done on the consequences of future SLR in coastal areas. Galbraith et al. (2002) showed in a modelling study using field data that projected SLR will inundate large amounts of tidal flats around the US, causing serious loss in shorebird habitats. Craft et al. (2009) also showed with field data and modelling that loss of marshlands in coastal area affects the provision of ecosystem services by the marsh systems. Alizad et al. (2016) showed in another modelling study that SLR under lower RCP scenarios affected mainly water levels and gradients in rivers and creeks in coastal marshland in the Gulf of Mexico, but higher RCP scenarios would lead to extensive inundation of marshland at this location.

The effect of SLR on estuary morphology has already been researched using computer modelling (Leuven et al., 2019). It showed that SLR has the potential to cause increased tidal amplification, because bed friction is decreased by the increased water levels. Small shallow estuaries are most likely to be able to adapt to SLR in comparison to large deep estuaries, but the ability to adapt depends largely on the availability of sediment in the system. One of the proposed sources for this sediment is from the floodplains that are now often embanked (Jeuken, 2000; Leuven et al., 2019).

1.4.2 Effect of SLR on hydrodynamics in estuaries

Du et al. (2018) did numerical modelling on the effect of SLR on the tide itself. They investigated the expected deformation of the tidal wave in ideal estuaries and estuaries on the U.S. East Coast and concluded that it is not a given that tidal range increases with SLR due to reduced bottom friction. They found that a tidal range reduction is expected especially in short estuaries (shorter than resonance length) and estuaries of which the bathymetry contains a relatively large amount of shallow areas next to the channels that would become inundated as a result of SLR.

Apart from estuary length and bathymetry, Leuven, et al. (2019) showed that estuary depth overall also plays a role in whether tidal range is amplified with SLR. They found that natural large deep estuaries will not face tidal amplification, but small shallow estuaries will.

1.5 Effect of SLR on estuaries in the Metronome flume

This research will focus on the potential effect of SLR on the morphology of natural sandy estuaries and dredged sandy estuaries using the Metronome research facility to examine if findings from literature and modelling can be confirmed in scale experiments. The Metronome is a tilting tidal flume that performs in scale experiments of sandy estuaries such as those found on the Dutch coast (Kleinhans et al., 2017). In these scale experiments the two previous experiments that researched funnel shaped estuaries will be used as control experiments for the experiments to study the effects of SLR. The experiment run by Leuven et al. (2018a) will be repeated so SLR can now be applied to the naturally formed estuary. Secondly the experiment run by Cox (2018) and Van Dijk et al. (2021) with a dredged estuary will also be repeated with SLR.

1.5.1 Channel mobility hypothesis

In the Metronome there are several features that can be watched to give information on how the estuary is responding to SLR. Channel mobility is one of these. Lentsch, Finotello, & Paola (2018) researched the channel mobility in deltas with an experimental setup for a natural situation. They suggested that the influence of tides stabilizes the channel and this effect will be enhanced with future SLR as tidal influence will grow when water levels rise. As discussed before it depends on the length, depth and bathymetry of the estuary if tidal influence will indeed increase and the tidal range will be amplified more due to SLR or not. In the Metronome the estuary is expected to respond like a long overall shallow estuary where the tidal range is amplified.

In dredged estuaries this would mean that channel stability will increase with SLR on top of the stabilization that already occurs with dredging (Van Dijk et al., 2021). Van Dijk et al. (2021) also finds that in dredged estuaries, SLR will likely have less effect on estuary morphology than dredging. They suggest more channel mobility will occur in side channels, but not in the dredged main channel.

From this the hypothesis is that in the Metronome main channel mobility will decrease with SLR in both natural and dredged systems. The focus will be on the dredged system since this will impact an already stressed system where channel mobility would influence the ability to navigate up the estuary and the stability of the existing estuary shape.

1.5.2 Tidal zonation, area and elevation hypothesis

If supratidal, intertidal and subtidal area would be able to keep up with SLR this would mean that they would all gain height without losing surface area. For this to happen in the Metronome experimental setup, there would have to be enough sediment available in the system as discussed by Leuven et al. (2019). In the Metronome sediment can only be added to the system when material is eroded from the subsurface or banks. However, Van Dijk et al. (2021) models showed that under SLR intertidal flat elevation will increase, while its volume will decrease, meaning that surface area is decreasing. Therefore in the Metronome it is expected that intertidal area elevation will increase, while surface area will decrease.

Due to SLR, tidal prism will increase as a consequence of the increased tidal range, which will result in more erosion. Since most tidal energy is concentrated in the subtidal area, subtidal areas are expected to be affected most by erosion. The hypothesis is therefore that channels and subtidal area will either deepen or widen with SLR.

Since intertidal area and subtidal area are losing sediment volume, this might be compensated by an increase in supratidal area volume. This would happen if supratidal area elevation is able to increase and keep up with SLR and possibly also by maintaining surface area.

For dredged systems sediment starvation might be an even bigger problem than for the natural system, since channel mobility is also decreased by dredging and enhances the effect of decreased channel mobility by SLR.

1.5.3 Bank stability hypothesis

Bank stability can be derived from width development of the estuary, because the more stable the banks are, the slower the estuary will widen. In the Metronome the subsurface and banks only consist of sand; the stability is not influenced by plants, mud or even embankment. The banks are therefore in general easily erodible.

In the dredged system experiment without SLR, channel and morphology fixation occurs that causes the estuary to stay narrower than a natural system (Cox, 2018). As discussed in the section above, channels are expected to become even more stable due to SLR and it is thus expected that SLR will have the same effect on bank stability as dredging. This means that SLR will not reduce bank stability, and might even increase it.

1.5.4 Dredging volumes hypothesis

Since it is expected that channels become more stable due to SLR on top of the higher channel stability caused by dredging, it is also expected that total dredging volumes will decrease even further as dredging continues under SLR. Largest volumes are dredged in the middle of the Metronome between 8 and 12 metres (Figure 1,Van Dijk et al., 2021). SLR has caused transgression in tidal systems during the Holocene (de Haas et al., 2018). Future SLR might again cause transgression, also in the experimental setup in the Metronome. The transgression in the Holocene only occurred in completely natural systems, but transgression in a dredged system might imply that dredging patterns will also transgress. This would mean that the most heavily dredged area moves further upstream.

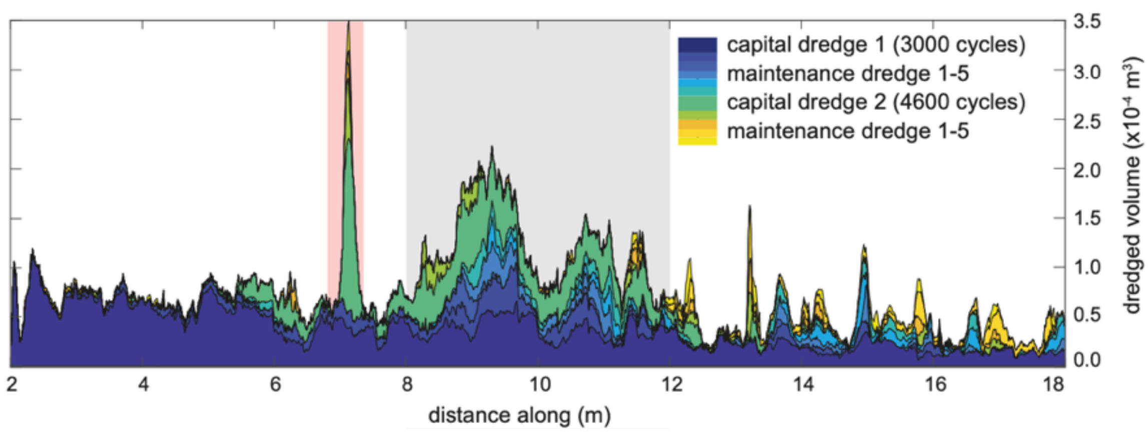


Figure 1 Cumulative dredged volumes per dredging event of experiment 023 along the Metronome. With downstream on the left and upstream on the right. The grey marked area is the location where most dredging took place (Van Dijk et al., 2021).

2 Methods

To research the effect of SLR on sandy estuaries with the Metronome, two experiments were designed. These are based on previous experiments, from Cox (2018), Van Dijk et al. (2021) and Leuven et al. (2018a). These are respectively experiment 006 (exp006) and experiment 023 (exp023) and will hereafter be referred to as such.

The first experiment of this thesis (experiment 042, exp042) is based on exp006. Exp006 is a naturally developed estuary with the same water (sea) level throughout the experiment. Exp042 was done with the same settings, except that between 3000 and 6000 cycles sea level was elevated incrementally.

Exp023 is also based on exp006, but dredging was applied to the system. The second experiment of this thesis (experiment 043, exp043) takes exp023 a step further. Not only dredging was applied to the system but also SLR. SLR was applied in the same manner as in exp042. (See Table 1 for overview; experiment numbers are those in the experiments database of the Metronome.)

Table 1 Experiments in the Metronome with control on SLR, dredging or the combination.

Experiment	SLR	Dredging	Reference
Exp006	-	-	Leuven et al. (2018a)
Exp023	-	✓	Cox (2018) & Van Dijk et al. (2021)
Exp042	✓	-	Current thesis
Exp043	✓	✓	Current thesis

Before diving into a more detailed explanation of the experiments, a description of the lab facility is given. An explanation on the relevant settings of experiments and the equipment to gather data are also given below. Lastly there is a description of how raw data from the experiments was processed to produce results.

2.1 Metronome experiments

The settings discussed in this section apply to all four experiments (exp006, exp023, exp042 and exp043). Experiments are conducted in a tilting tidal flume in the Earth Simulation Lab at Utrecht University. The flume is called Metronome (see Figure 2). This is a research facility that enables scientific research on estuaries in scale experiments (Kleinhans et al., 2017).

The Metronome is 20 metres long, 3 metres wide and 40 cm deep and is lined with artificial grass of 3 cm in height. The Metronome is filled with a sand bed and water. The initial levelled sand bed is 18 metres long, the last two metres of the Metronome length is the sea. In the experiments the height of the sand bed is 7 centimetres from the top of the grass lining. To make sure the estuary forms properly an initial channel of 3 centimetres depth is dug in the levelled sand bed. For the experiments in this thesis, this channel is exponentially widening in the seaward direction. The initial channel is therefore a converging funnel shape in upstream direction.

The weir at the seaward end of the flume controls the water level in the flume. The water level is initially set to 65 millimetres from the bottom of the Metronome. A constant supercritical flow over the weir keeps the water level constant. The estimated thickness of this water layer over the weir with the used pump capacity is 5 millimetres.

The Tides are simulated in the facility by tilting the Metronome over the short axis. One tidal cycle (i.e. tilting the Metronome back and forth once) takes 40 seconds with an amplitude of 75 millimetres. On the far end of the sea a wave generator paddle simulates wave action. On the river end of the flume, where the initial channel is narrowest, there is a setup that can simulate a river input with water and sediment. For the experiments discussed in this thesis river discharge is 100 litre/hour of water and no sediment input. Since no sediment is added to the water stream, a sediment starved river is simulated. The changes from Table 1 were applied after 3000 cycles.

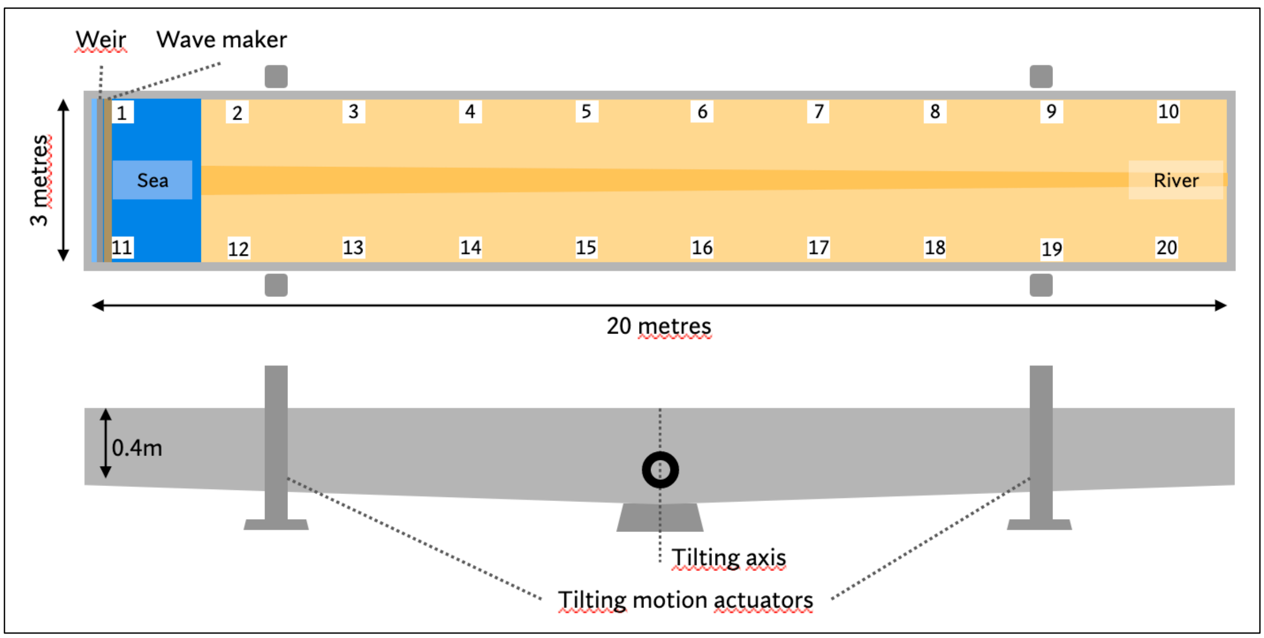


Figure 2 Schematic overview of the Metronome flume (based on Kleinhans et al., 2017) with top view of the Metronome (top) and side view of the Metronome (bottom). The numbers in white boxes in the top view are target numbers used to make DEMs in Agisoft Photoscan.

2.1.1 Pilot experiments

Prior to Exp042 and Exp043, a series of tests (Exp041) were undertaken to determine a suitable method of applying SLR. The first test was the application of instantaneous SLR of 1 centimetre. After that, SLR in smaller increments was examined. The best method was defined as the one which shows a gradual and "natural" pace of morphological response to SLR, without fully drowning the estuary. This turned out to be a SLR in increments of 2 millimetres every 1000 cycles with a total of 8 millimetres. This method was used in the two following experiments (exp042 and exp043).

2.1.2 Experiment 042: Natural estuary with SLR

In experiment 042 SLR is initiated after 3000 cycles up until that point exp006 and exp042 formed under the same conditions. From then on the SLR was applied with increments of 2 mm every 1000 cycles up to a total of 8 mm of SLR (see Table 2). The last SLR was thus applied at 6000 cycles, but the experiment was run to 11000 cycles in total to show long term morphological development.

Table 2 Still water level settings above the flume floor of the "weir" at the seaward end of the Metronome.

Cycle	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000
Water level (mm)	65	65	65	67	69	71	73	73	73	73	73	73

2.1.3 Experiment 043: Dredged estuary with SLR

In experiment 043 SLR was applied the same way as exp042 (Table 2). On top of this dredging was applied to the system. The dredging strategy is the same as in Cox (2018) and Van Dijk et al. (2021). The strategy was designed by Cox (2018) to simulate the dredging in the Western Scheldt. It consists of two dredging periods, that both start off with a large capital dredge at 3000 and 4600 cycles. These capital dredging events represent channel deepening events for shipping purposes. After the capital dredging events, the channel was maintained at depth with five follow up maintenance dredging events. In the first dredging period the channel was dredged to a depth of 3 cm measured from the top of the floodplains. In the second period the channel was dredged to a depth of 3.5 cm. In the first dredging period maintenance dredges were undertaken every 50 cycles and in the second period maintenance dredges were 100 cycles apart. The intervals between dredging in the second dredging period were longer because the estuary is now larger and more stable and takes longer to respond and to fill in. (The dredging schedule can be found in Table 3).

The width of the dredged channel is calculated from the width of the developed estuary. At the river end, the width of the dredged channel should be 10% of the estuary width, in the middle regions about 15% and at the seaward end 20%. At the first capital dredge this means 3 cm on the river end, 15 in the middle regions and 30 at the seaward end. Towards the end of the dredging periods this means 7 cm at the river end and almost 40 cm at the seaward end.

Table 3 Dredging events and their characteristics.

Cycle	Dredging Event	Dredging Depth (cm)	Cycles until next dredging event	Abbreviation
3000	Capital Dredge 1	3	100	CD1
3100	Maintenance Dredge 1	3	50	MD1
3150	Maintenance Dredge 2	3	50	MD2
3200	Maintenance Dredge 3	3	50	MD3
3250	Maintenance Dredge 4	3	50	MD4
3300	Maintenance Dredge 5	3	1300	MD5
4600	Capital Dredge 2	3.5	100	CD2
4700	Maintenance Dredge 6	3.5	100	MD6
4800	Maintenance Dredge 7	3.5	100	MD7
4900	Maintenance Dredge 8	3.5	100	MD8
5000	Maintenance Dredge 9	3.5	100	MD9
5100	Maintenance Dredge 10	3.5	-	MD10

Before dredging is started, the locations for dredging are determined from Digital Elevation Models (DEMs) of the Metronome. During the capital dredges the location of the dredged channel is determined by following the deepest natural course in the estuary. This is the path of least resistance, i.e. the path where the least dredging volume is needed for a navigable channel. During the maintenance dredges the method of determining the locations to dredge is similar except that now the location of the channel that was dredged during the previous capital dredge is taken into account. The goal is to deviate as little as possible from the capital dredge course.

The sediment volume that was taken out during dredges was measured with the use of a measuring cylinder. The locations where which amount of sediment was taken out was also noted in metres along the Metronome. Additionally also the feature from which was dredged is noted. The different features are: straight, bend, cross, sill and bar edge (Table 4).

Table 4 Features that are tracked during dredging and their description. Colours are the legend used in later figures.

Feature	**Explanation**
Straight	Straight part of the channel (not necessarily parallel to the long axis).
Bend	Strongly curved part of the channel often found between two crosses.
Cross	Where the channel crosses over from one side of the estuary to the other.
Sill	Ridge formed in the middle of the channel
Bar edge	Where dredging is necessary because the edge of a bar collapsed into the channel.

The dredged sand was dumped back into the system on the nearest suitable location from where it is dredged as this resembles real life dumping strategies. Suitable locations can be on bar edges, scours or side channels. Dumped sediment should have a high mobility compared to undredged sediment. Dry sand is more mobile than wet sand and thus an equal amount of dry sand was used for dumping (Cox, 2018).

2.2 Data processing

2.2.1 Digital Elevation Models

To visualise the development of the estuary morphology, high quality Digital Elevation Models (DEMs) were made. To be able to make DEMs, twenty targets were placed on the flat "floodplains" to the long sides of the Metronome, ten on each side two metres apart with known x, y and z coordinates. A camera was mounted on a pole on the bridge over the Metronome to take photos of the Metronome at an angle. A total of around seventy photos were taken per DEM, half the number with the camera facing towards the seaward end and half with the camera facing towards the river end. These photos were loaded into Agisoft Photoscan software (version 1.4.2) and processed into a DEM and exported as tiff file. (The user guide and target coordinates to produce the DEMs in Agisoft Photoscan is provided in Appendix 1 and 2.)

2.2.2 Water level measurements and tidal range

To measure the water levels during experiments 3 echosounder sensors were used. The sensors are mounted on a bar that can be placed over the Metronome at every location on the long axis between the wave maker and halfway along the Metronome (10 metres). The echosounders measure the distance between the sensor and the water surface. They take a measurement ~10 times per second. This means that the sensors can be used while the Metronome is tilting to find the change in water level height during a tidal cycle. Data was gathered of at least three consecutive cycles (3 x 40 seconds) to get enough data and be able to filter outliers and reduce errors from the data. To find the tidal signal, the rough water level data was smoothed. From the tidal signal, a minimum, maximum and mean water level can be derived for every measurement series for every sensor.

The measured distances from the sensors need to be converted from the distance between the sensor and the water surface to actual water heights relative to the floor of the Metronome to be able to use them. Since the height of the weir is known, the water level elevation is also known when the Metronome is not tilting and set to level. A simple calculation can then be done to determine the height of the sensors above the flume bottom.

$$(h_{weir} + h_{flow} + d_{still}) - d_{moving} = \mathrm{h_{water}} \quad \text{(Eq. 1)}$$

Where h_{weir} is known weir height in mm with still water levels, h_{flow} is the thickness of critical flow over the weir that was estimated to 5 mm in this case, d_{still} is the measured distance in mm between the sensor and the water level during still water, d_{moving} is any measured distance in mm by a sensor at any given point in the flume at any given time and h_{water} is the water level in mm at that location and point in time.

Tidal range can be calculated from the minimum and maximum water levels that were gathered as follows.

$$HW - LW = TR \quad \text{(Eq. 2)}$$

Where HW is high water, LW is low water and TR is tidal range. To plot the tidal range over the length of the estuary a spline interpolation was applied to show a more natural representation of the data. Since there is no data upstream from 10 metres a simple linear fit was applied here.

2.2.3 Tidal zonation mapping

The supratidal, intertidal and subtidal area were mapped to be able to systematically assess the development over time of these areas and their associated morphological features like channels, bars and marshes. To make these maps the maximum and minimum water levels (high and low water) were compared to the DEMs. If the elevation in the DEM is higher than the maximum water level, this area is supratidal. If the elevation in the DEM is lower than the maximum water level, but higher than the minimum water level, this area is intertidal. If the elevation in the DEM is lower than the minimum water level, this area is subtidal.

To be able to compare the DEM to these separate water level data points, two planes with the size of the Metronome were made with the water level data points. One plane with the maximum water levels and one with the minimum water levels. For these planes, the data of the three sensors were averaged over the short axis of the flume and thus only vary in height over the long axis. The water height between the data points was linearly interpolated.

Landward from 10 metres distance from the mouth no water level data was gathered. Assuming that the tides dampen to a tidal range of 0 at the upstream boundary, the data was also linearly interpolated between the last measuring point and the upstream boundary.

The height of the floodplain was known to be 7 cm above the top of the grass and thus 10 cm above the bottom of the Metronome. All DEM data points that are floodplain and not estuary are classified separately. With this classification into four classes (subtidal area, intertidal area, supratidal area and unreworked floodplain) tidal zonation maps are made.

For further calculation the flume was subdivided into the delta region (0 to 18 metres), the middle regions (18 to 10 metres) and upstream regions (10 to 0 metres). For each region the percentage of supra-, inter- and subtidal area was calculated over the area of the estuary and the average elevation of these regions was calculated for every time step.

2.2.4 Channel tool

To find flow patterns and to locate where main and secondary channels were, the channel network tool from Sonke et al. (Conditionally accepted) was used. This tool finds the main channel by connecting the minima in a DEM over the higher saddle points. The persistence method was used, which determines where the channel lies by locally calculation how much sediment volume is between two channels. The tool will add bars together until a set minimal volume of sediment is reached. The higher this sediment threshold, the higher ranked the computed channel is.

The tool was applied to find the course of the main channel for post experiment analysis in experiment 042 and 043. For experiment 043 the channel courses was roughly the same as the dredged course and was thus used to determine channel length. The channel length was used to normalise the amount of dredged material over channel length.

3 Results

3.1 Development of estuary morphology over time

3.1.1 Morhpological features in the Metronome

When experiments are run in the Metronome, several morphological features can be observed. A few examples are given in Figure 3 with a large, high point bar that is attached to the banks in the upstream regions of the dredged estuary (A). Some unattached bars can be seen further downstream in the undredged estuary (B). In the dredged channel the flow creates small mutually evasive ebb and flood channels with sills between them, in image C these sills are visible. Also in the delta mutually evasive ebb and flood channels would form in the undredged experiment. In image D, three ebb and 3 flood channels can be seen that all end on a sill. Lastly in image E a scour very close to the banks is visible that has undermined the bank and caused a bank collapse in the upstream parts of the undredged experiment.

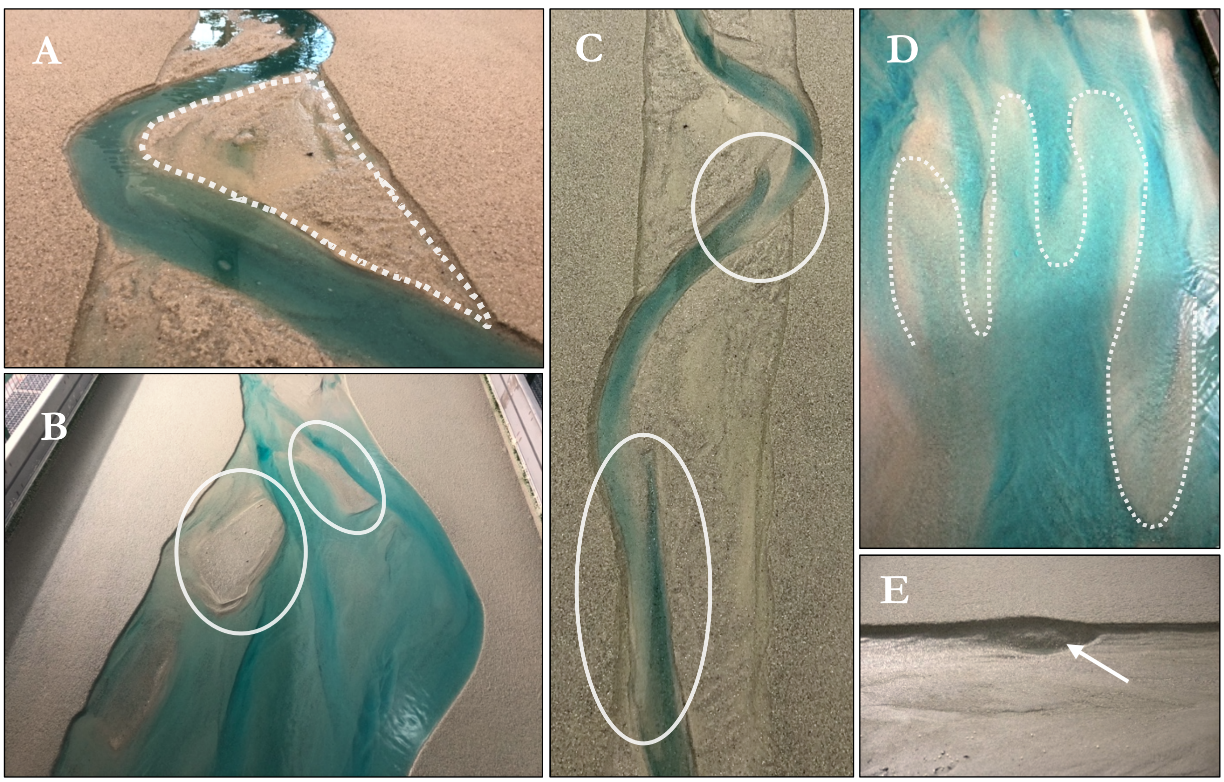


Figure 3 Morphological features in the Metronome. A) Bank attached bar (exp043). B) Unattached bars (exp042). C) Sills in dredged channel (exp043). D) Mutually evasive ebb and flood channels on delta (exp042). E) Scour with bank collapse (exp042).

3.1.2 Estuary formation (0-3000 cycles)

The estuaries developed under identical circumstances for all experiments until 3000 cycles. However, some natural, coincidental variation can be expected in their development. Figure 4 shows the development of the Delta of the estuary around 1000 cycles. Both deltas have similar shape and size, but are not exactly identical. In exp042 the delta seems to have built out a little more in the middle at this point in time, while in exp043 the delta is a bit asymmetrical and has built out more on the left (far end on photo B).

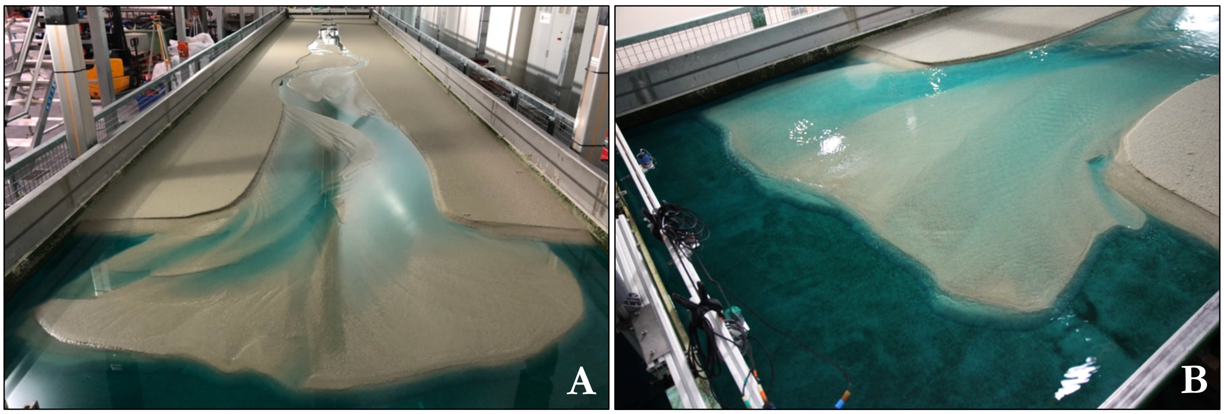


Figure 4 Delta at 1000 cycles into the experiment. A) Exp042. B) Exp043.

Apart from delta, the estuaries also look similar but around 3000 cycles especially the width at the mouth is significantly larger in experiment 042 (Figure 5). This seems to have happened because very early on a very deep channel is undermining the banks between 2 and 4 metres at the mouth. Another difference is the bend that has significantly widened the estuary around 8 metres in exp042, however the general shape is the same.

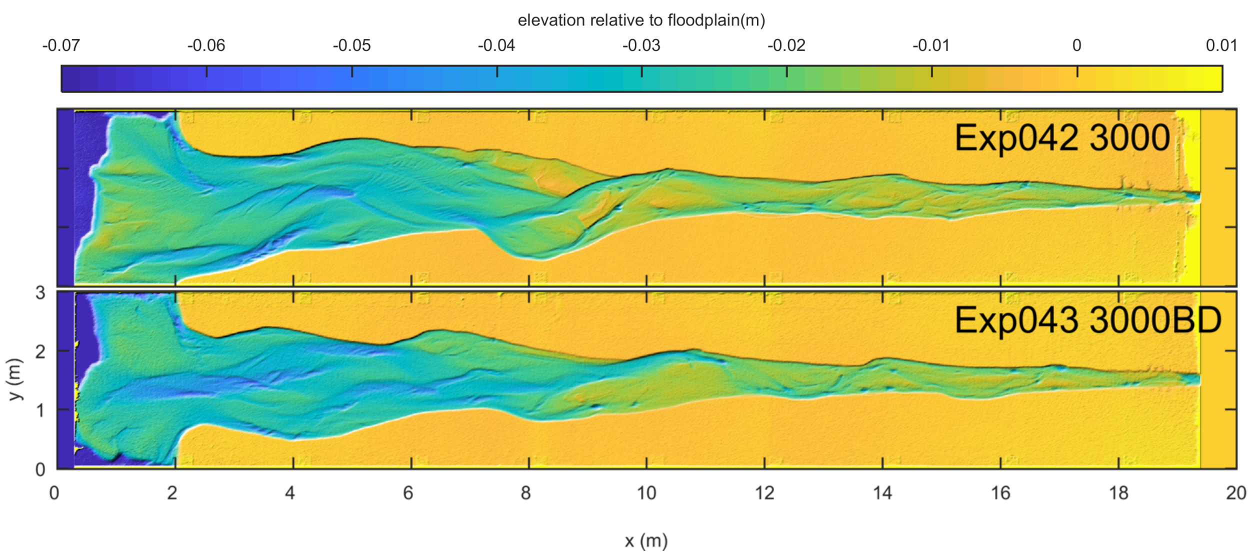


Figure 5 DEMs of experiment 042 (top) and experiment 043 (bottom) at 3000 cycles before SLR and dredging.

3.1.3 Estuary during SLR and dredging (3000-6000 cycles)

From 3000 cycles onwards SLR is initiated in both experiment and in exp043 dredging is also started. After a dredging the estuary responds by trying to return to a more natural morphology, but as dredging continues, the dredged channel becomes more and more stable. Especially crosses tend to fill in fast in the beginning. In Figure 6 such a cross is visible when it has just been dredged in the first maintenance dredging event and 50 cycles after it was dredged. The cross has significantly narrowed and sill formation would make navigation on this channel problematic already after 50 cycles.

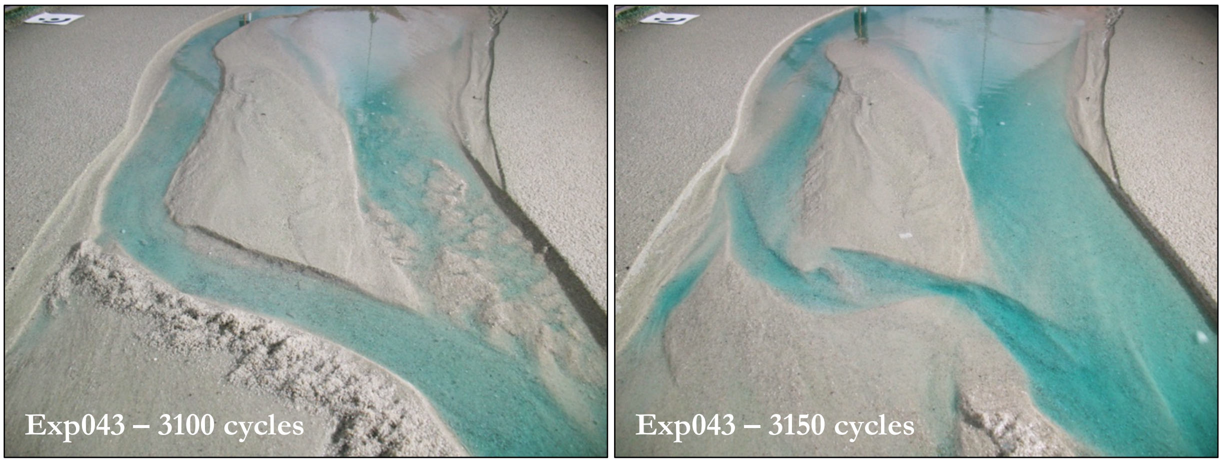


Figure 6 photographs of exp043 of a bar and a cross cutting channel in the middle of the metronome (around 10 metres) at 3100 cycles freshly dredged maintenance dredge 1 (left) and at 3150 cycles 50 cycles after dredging (right).

The effects of dredging are also visible in the bathymetry between the two dredging periods. Figure 7 shows the DEMs of exp042 and exp043 at 4000 cycles, both after 2 millimetres of SLR. In exp043 by 4000 cycles, six dredging events have been undertaken and it is has been 700 cycles since the last dredging event. Especially upstream of 10 metres the difference in morphology is remarkable. In experiment 043 the upstream half of the estuary has a deep single meandering channel, while the estuary in experiment 042 is more braiding, with multiple shallow channels. Even though dredging has already been paused for 700 cycles, the dredged channel has persevered especially in the upstream area.

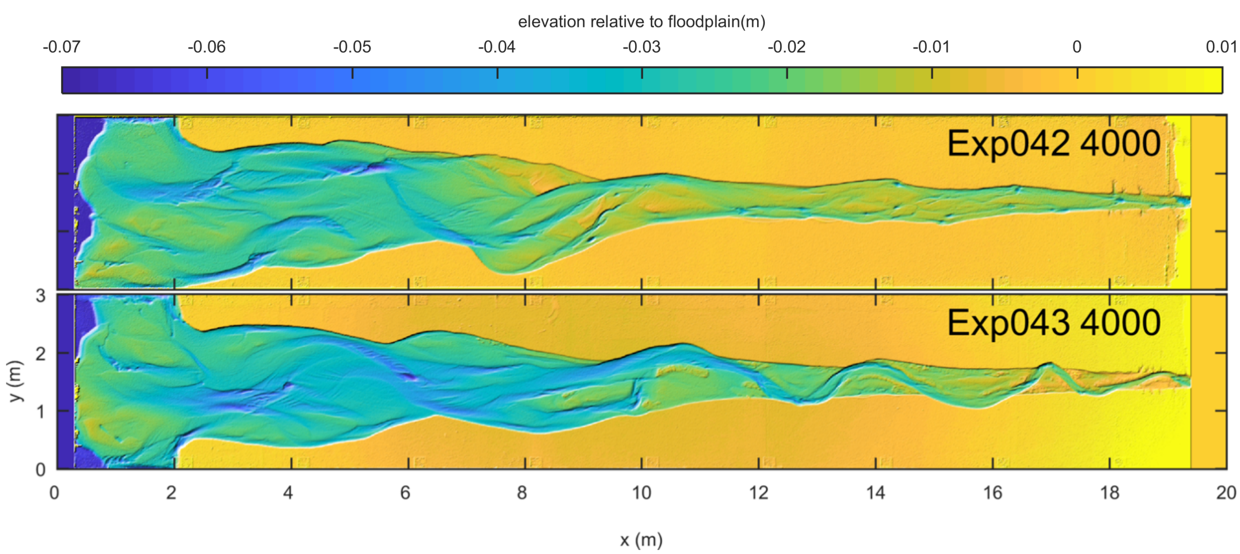


Figure 7 DEMs of experiment 042 after 2 mm of SLR (top) and experiment 043 after 2 mm of SLR and 6 dredging events (bottom) both at 4000 cycles.

The impact of dredging is again apparent around 5000 cycles (Figure 8). In experiment 043, 5000 cycles is during the second dredging period. The dredged channel is now also still visible in the downstream part of the estuary. But upstream of 10 metres in exp043 where a single meandering channel was already visible around 4000 cycles it is now even more pronounced and the meander bends have expanded laterally.

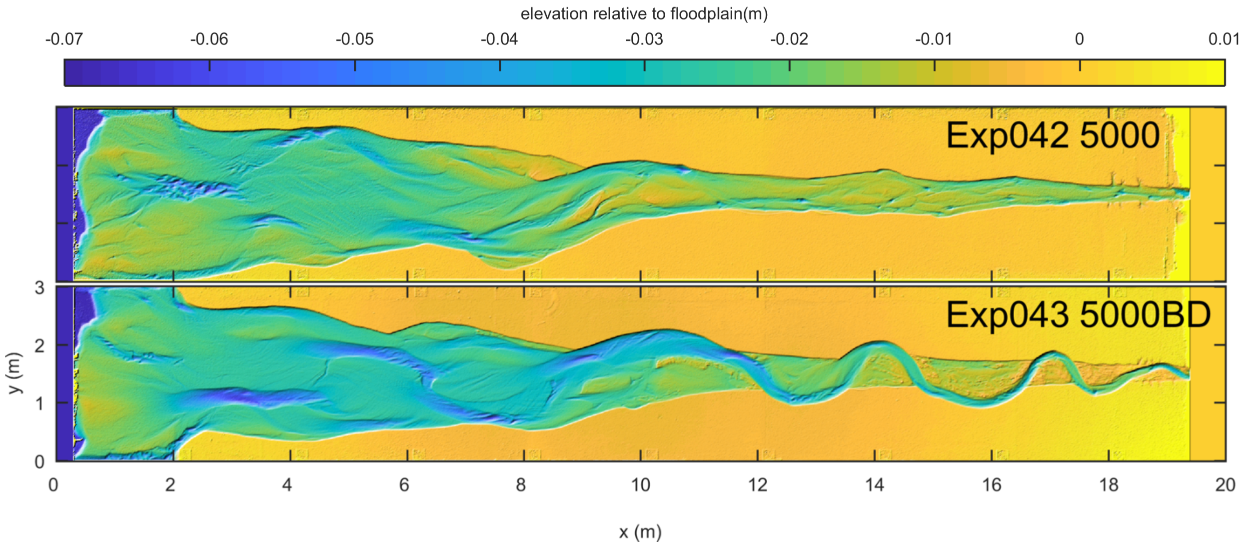


Figure 8 DEMs of experiment 042 after 4 mm of SLR (top) and experiment 043 after 4 mm of SLR and 10 dredging events (bottom) both at 5000 cycles.

3.1.4 Long term development following SLR and dredging (6000-11000 cycles)

The last dredging event in experiment 043 takes place at 5100 cycles, after this the estuary of both experiments is let to develop under the same circumstances again. The last SLR is at 6000 cycles in both experiments. At 11000 cycles, 5900 cycles after the last dredging, the impact of dredging is still clearly visible in experiment 043 (Figure 9). Downstream of 10 metres the estuaries look very similar, but upstream the

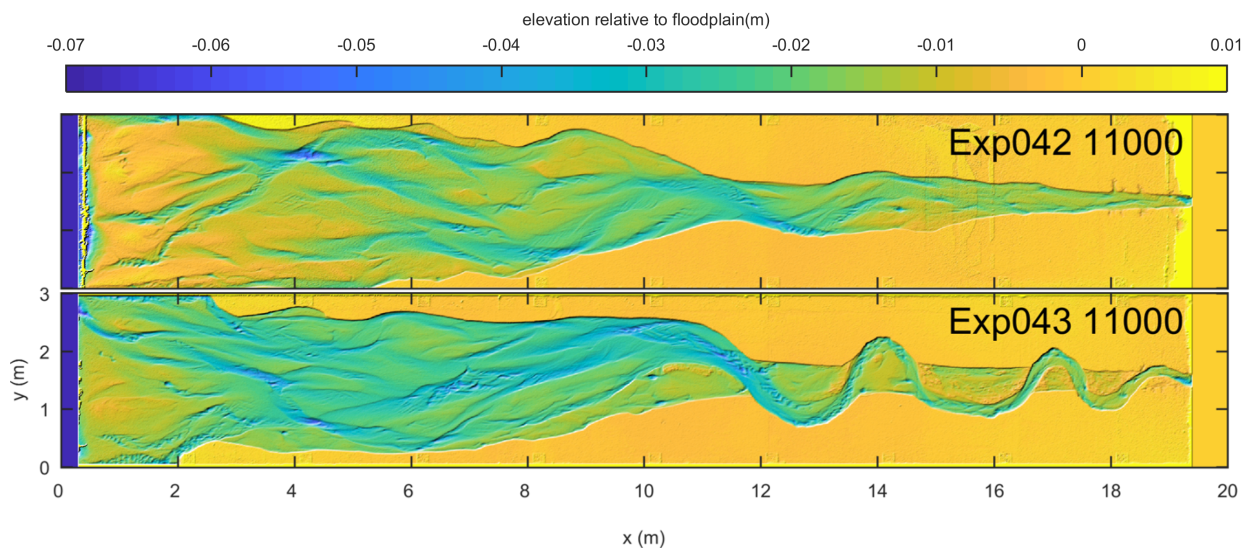


Figure 9 DEMs of experiment 042 after 8 mm of SLR (top) and experiment 043 after 8 mm of SLR and 12 dredging events (bottom) both at 11000 cycles.

single, strongly meandering channel that was created during dredging is still there and has even built out its meanders further.

Even though the channel stays fixed in the same position, its morphology does change. The development of the channel between 14 and 17 metres can be seen in Figure 10. On the left the channel is still dredged, it is deep and without significant bedforms. On the right 1900 cycles have passed since the last dredging event and the channel has widened and has become more shallow with bedforms. Both photos are taken at high water, but the bar is drier around 7000 cycles than it was at 5000 cycles. This indicated that high water became lower after dredging has stopped.

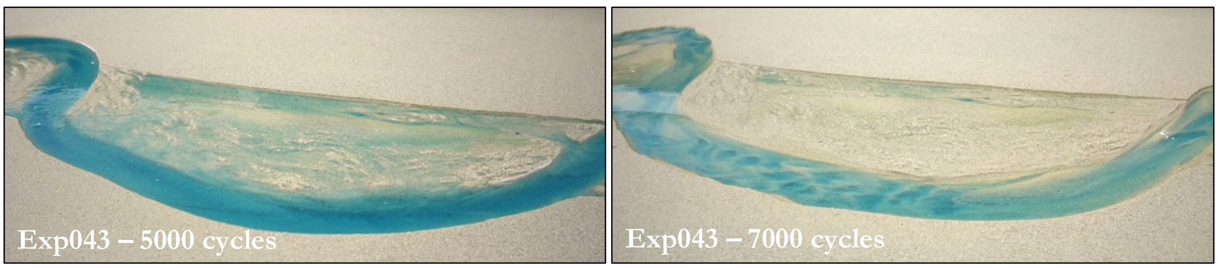


Figure 10 Channel at high water between 14 and 17 metres of exp043 at 5000 cycles (left) and 7000 cycles (right).

3.2 Effects of channel deepening on tidal Range with SLR

During experiment 042 water levels were recorded from 0.3 metres to 10 metres distances along the flume. For most timesteps the tidal range in the Metronome is largest at the seaward end of the estuary where the tidal wave has not yet reached the delta. The initial coastline could be found at 2 metres. The delta therefore lies between 0 and 2 metres along the flume. From Figure 11A it can be seen that while the tidal wave moves over the delta, the tidal range decreases due to increased bottom friction which dampens the tidal wave. From 2 metres onwards the tidal wave enters the estuary and the tidal range starts to increase again due to the funnel

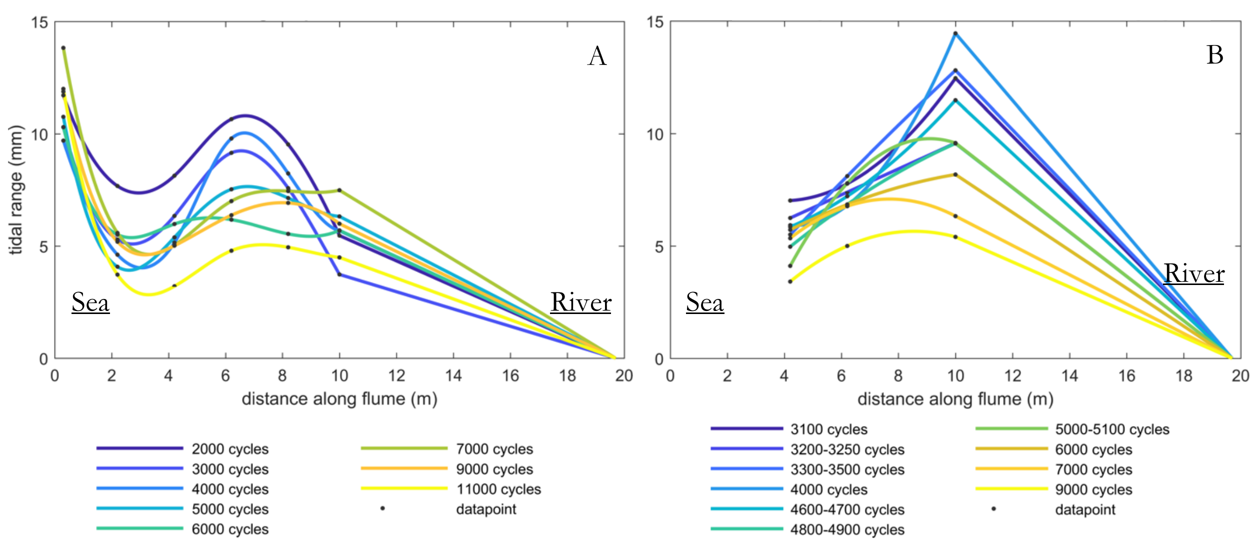


Figure 11 Tidal range over the length of the Metronome through time. Tidal range averaged over widht. A) Experiment 042. B) Experiment 043.

shape of the estuary that amplifies the tidal wave. In exp042 the tidal range reaches another maximum somewhere around 7 metres after which it starts to decrease again for most of the time steps.

For exp043 there is no data between 0 and 4 metres, but it is expected that it the tidal range behaves similarly to exp042 in this region because the influence of dredging was small at this location. From 4 metres onwards the tidal range behaves differently compared to experiment 042. It increases up to at least 10 metres for most time steps (Figure 11B). This means amplification of the tidal wave due to funnelling has been stronger during this experiment. This is probably caused by dredging which increased the channel depth and width and thus decreased bottom friction. It is uncertain where along the flume the maximum tidal range is reached in experiment 043 because of the lack of water level data from 10 metres onward.

In exp043, the highest tidal range through time is reached around 10 metres in 4000 cycles during the first set of dredging events between the first and capital dredge the tidal range increases. During the second set of dredging events in exp043 the tidal range decreases. For exp042 the highest measured tidal range maximum is already at 2000 cycles, but the tidal wave is amplified most at 4000 cycles.

The overall trend for both experiments seem to be that tidal range first increases over time and then starts to decrease as the estuary widens and becomes relatively more shallow (Figure 12). This decrease in tidal range through time is especially visible in the middle regions of the estuary around 7 metres in exp 042 and around 10 metres in exp043. In both experiments, especially from 5000 cycles onwards the tidal range is not amplified as much anymore through the estuary and the tidal range starts to behave similar in both experiments. In exp043 the point of maximum tidal range in the estuary does not only become lower, it also seems to move downstream.

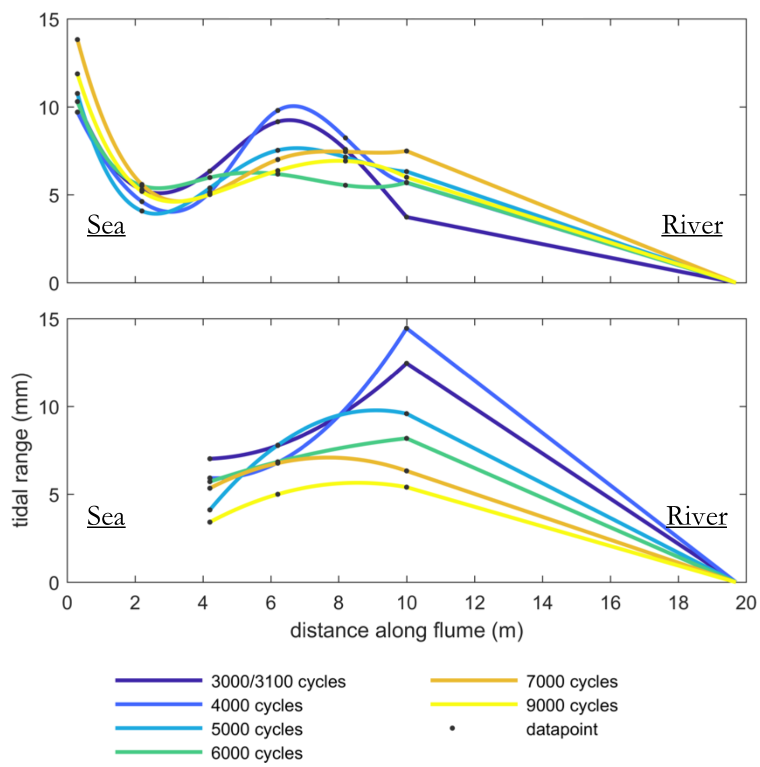


Figure 12 Tidal range in A) Exp042 without dredging, with SLR and B) Exp043 with dredging and SLR. Legend applies to both experiment to make comparison possible.

3.3 Development of supratidal, intertidal and subtidal area

Water level information was used to produce tidal area maps in Figure 13. Due to an unknown error it became apparent that the floodplain was most likely not at 10 cm as this would have resulted in barely any subtidal and intertidal area. The height of the floodplain was set to 8.7 cm above the bottom of the Metronome for the maps in Figure 13. This height was determined by studying photographs that were taken during the experiments that showed what high and low water looked like.

Analysis of the DEMs also showed that the DEMs from experiment 043 all had a curved shape to some extent. The DEMs from experiment 042 did not show this and when compared to the water level data there would be have been a pool of water in the middle of the flume that was not present during the experiment. This means there is probably some sort of distortion happening when processing the data. For most purposes the DEMs were left for what they were, but for the calculations of tidal area, the error would be so large that a small correction was done to filter out the biggest distortion and straighten the DEMs a bit towards the situation during the experiment.

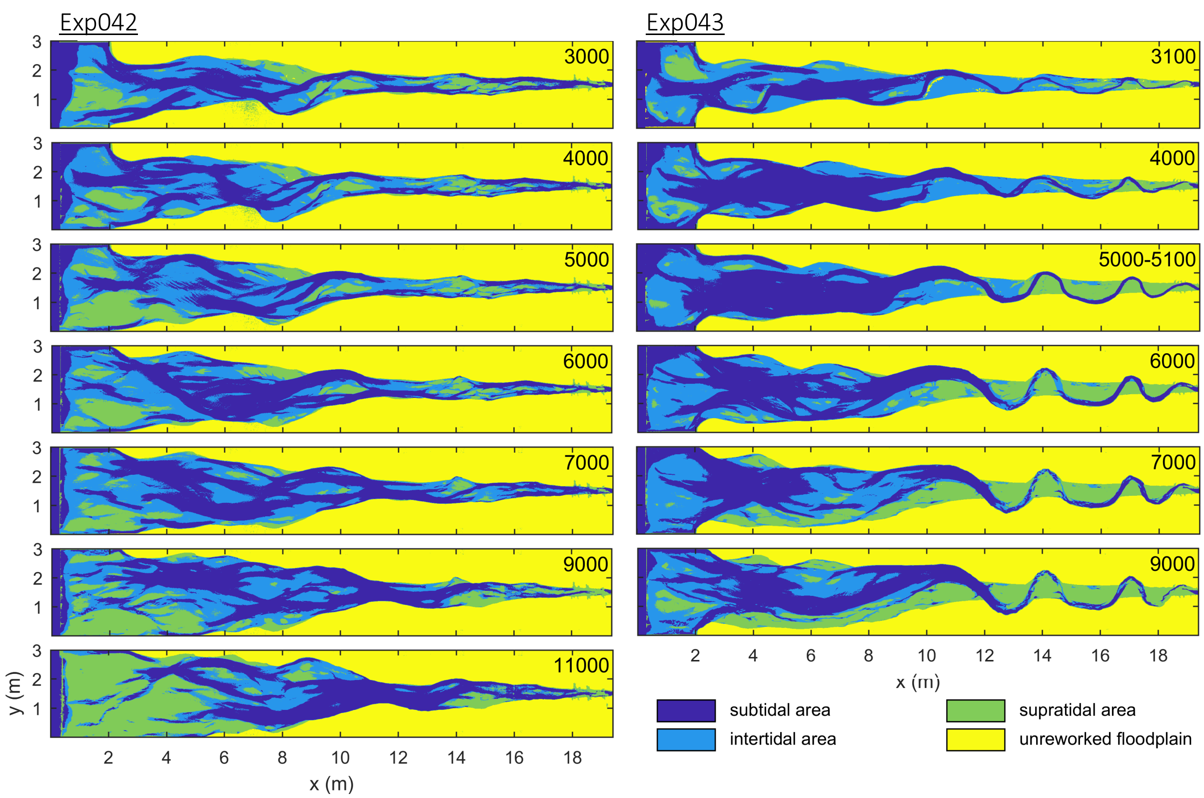


Figure 13 Tidal area maps of experiment 042 (left) and experiment 043 (right). Cycle number in the top right corner of every map. With subtidal area (dark blue), intertidal area (light blue), supratidal area (green) and unreworked floodplain (yellow).

3.3.1 SLR without dredging

In exp042 without dredging the position of subtidal area seems dynamic. From the subtidal areas, it can be derived that for the most part the estuary has multiple channels next to each other that migrate laterally over the width of the estuary. With dynamic subtidal area also comes dynamic intertidal and supratidal area. Especially the downstream half of the estuary is dynamic. In the upstream half of the estuary morphology changes more slowly. Due to these dynamics the sediment is constantly reworked. Higher areas are eroded by channels while lower energy areas gain height by sedimentation. In the dynamic downstream part, not only higher areas within the estuary are reworked, but also the high floodplains. As this process widens the estuary, over time the downstream half of the natural estuary widens most significantly in comparison to the upstream area.

Please note, experiment 042, cycle 11000 shows a very large amount of supratidal area in the downstream regions, which is most likely not accurate and is probably caused by the absence of targets in the downstream area as there was no space to put them (The problem might also already be partly present at 9000 cycles).

3.3.2 SLR with dredging

The most eye-catching change in the maps of exp043 is the highly sinuous single channel especially in the upstream part of the estuary (Figure 13). In the downstream half of the estuary, all tidal areas still seem to be dynamic although the estuary does stay narrower than the undredged estuary. In the upstream half the dredging fixes the channel in place and due to dumping and decreasing tidal range, all intertidal area becomes supratidal. When looking at the distribution of subtidal area, in the downstream half the estuary still seems multi-channelled, but in the upstream half there is a single strongly meandering channel.

3.4 Development of tidal zonation

3.4.1 Subtidal area in natural estuary with SLR (exp042)

Subtidal area development is split into delta area, downstream regions and upstream region (Figure 14). Without dredging (exp042), subtidal area elevation increases with about 8 mm both in the delta (A) and downstream area (B). This is equal to the amount of SLR and thus the response lags a bit. It takes roughly until 9000 cycles to reach 8 mm of subtidal area rise while SLR reaches 8 mm at 6000 cycles.

While subtidal area elevation is keeping up with SLR in the delta region (A), the relative subtidal surface area decreases over time. Part of it can be explained by the delta that is still building out over the subtidal seafloor and part of it is caused by the ongoing widening of the estuary that adds sediment to the system and makes it relatively more shallow. In the downstream region (B) subtidal surface area is smallest during SLR. In this region the tidal range is also largest during SLR, this means that low waters are lower and thus the amount of permanently submerged area is also smaller.

In the upstream region, data is a bit less reliable because it is not based on high resolution water level data. Subtidal area elevation and surface area decrease very slightly. The surface area does show an extra decrease during SLR that cannot be explained in the same way as in the downstream region, because tidal range does not show a clear trend in this region.

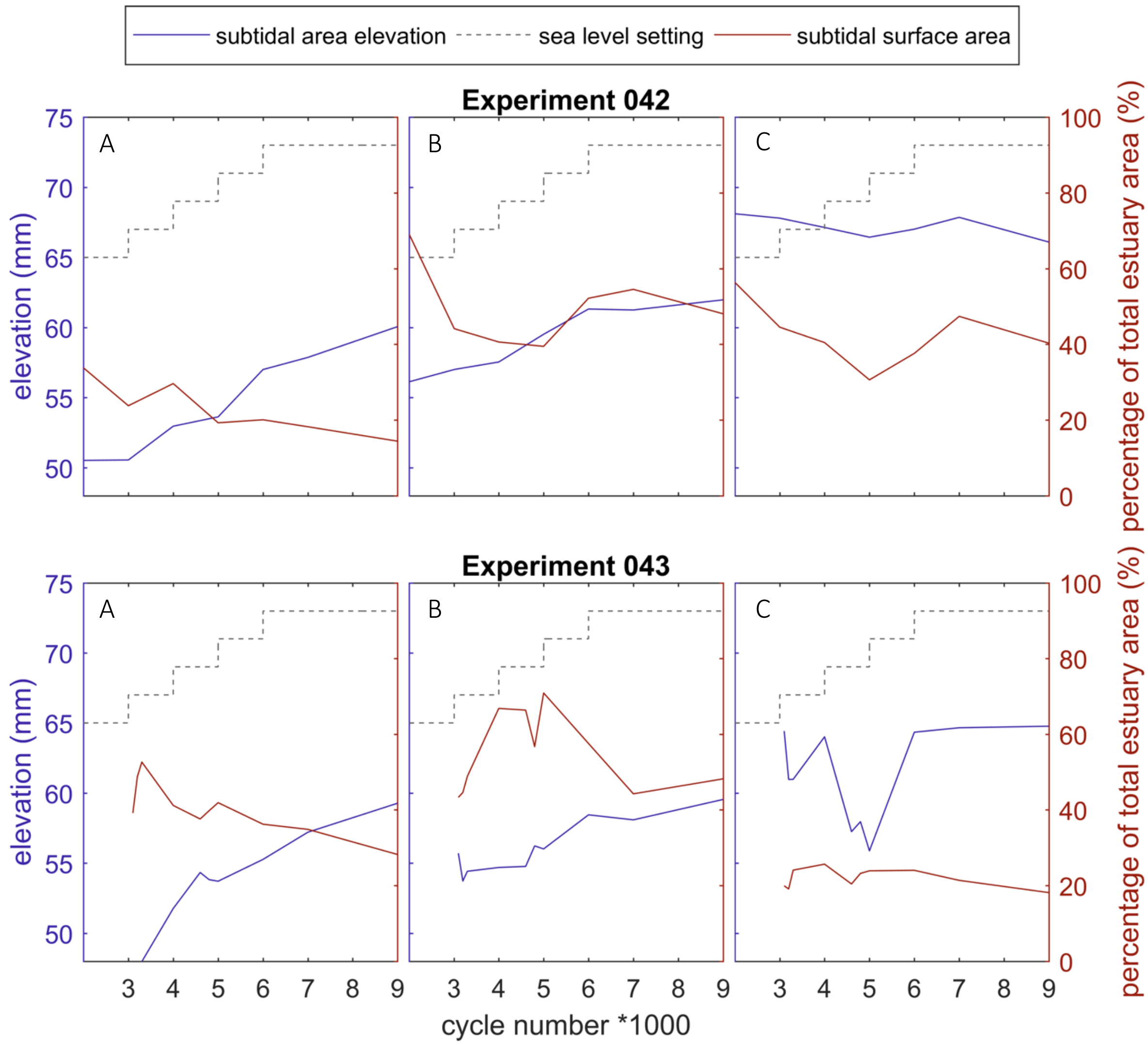


Figure 14 On the left axis in the purple line, the subtidal area elevation and the dashed line with SLR. On the right axis in the red line the percentage of subtidal surface area A) delta region (0.5 to 2.5 metres along flume) B) downstream region (2.5 to 12.5 metres) and C) upstream region (12.5 to 20 metres).

3.4.2 *Subtidal area in dredged estuary with SLR (exp043)*

With dredging (exp043) subtidal area development is more erratic compared to a natural system (Figure 14). In the delta region (A), the subtidal area elevation is a lot lower early on in the experiment. this is probably caused by the smaller initial delta, and thus a larger area of subtidal seafloor. Towards the end of the experiment the elevation of the dredged estuary becomes very similar to that of the natural system. In the downstream region (B) the subtidal area elevation behaves similar to the natural system, but it is overall a few millimetres lower because the channel was deepened during dredging. In the upstream region (C), dredging is visible in the deepening of subtidal area during the dredging period. Since the channel is the only subtidal area in the upstream region as can be seen in Figure 13, the subtidal area elevation responds strongly to the deepening of the channel. After dredging stops the elevation becomes the same again as in the natural system.

The subtidal surface area in the delta (A) decreases over time similar to the natural estuary, but overall ends up smaller at the end of the experiment and higher during dredging. In the downstream region (B) subtidal surface are is large during dredging probably due to widening of the channel during dredging, but it decreases again to natural values after dredging stops. In the upstream region (C) during SLR, subtidal surface area percentages is stable, but about 20 percent lower than in the natural system. After SLR the subtidal surface area stays low and does not return to values similar to the natural system. This can be explained by the persistence of the dredged morphology after dredging stopped. The channel stays the only subtidal area in the upstream region.

3.4.3 Intertidal area in natural estuary with SLR (exp042)

In the delta region (Figure 15A) the average intertidal area elevation closely follows the trend of SLR while the amount of intertidal surface area fluctuates up and down but overall stays stable through time. In the downstream region (B) the average intertidal area elevation is again increasing during SLR but does not keep up as well over time. The intertidal surface area initially increases a bit with SLR, but before SLR ends decreases again to pre SLR values and thus stays stable overall. In the upstream region (C) the intertidal area elevation seems relatively stable (keeping in mind that water level data is not of the same quality here). The percentage of intertidal surface area increases a little during SLR but again returns to pre SLR values after SLR.

3.4.4 Intertidal area in dredged estuary with SLR (exp043)

Intertidal area again behaves more erratic during dredging (Figure 15). In the delta region (A) the intertidal area elevation behaves the same as in the natural estuary and keeps up with SLR. The intertidal surface area in the delta overall increases, and is also higher than in the natural system towards the end of the experiment.

In the downstream region (B) the intertidal area elevation is disturbed by dredging, it is higher during dredging than it was without dredging due to dumping of dredged material on the intertidal area. After dredging, no elevation increase is visible and stays the same as it was during dredging. This means that towards the end of the experiment the intertidal area elevation is significantly lower than in the natural system. The intertidal surface area decreases during dredging, stays stable after dredging stops and is lower at the end of the experiment than in the natural system.

In the upstream region (C) intertidal area elevation is similar to the natural estuary at the beginning of SLR and dredging, however as dredging and SLR continues the intertidal area elevation decreases and stays smaller than in the natural situation. The surface area is initially larger during dredging, but strongly decreases as dredging and SLR continues with extra lowering during dredging. Towards the end of the experiment the intertidal surface area is about 10% lower in the dredged system than in the natural system.

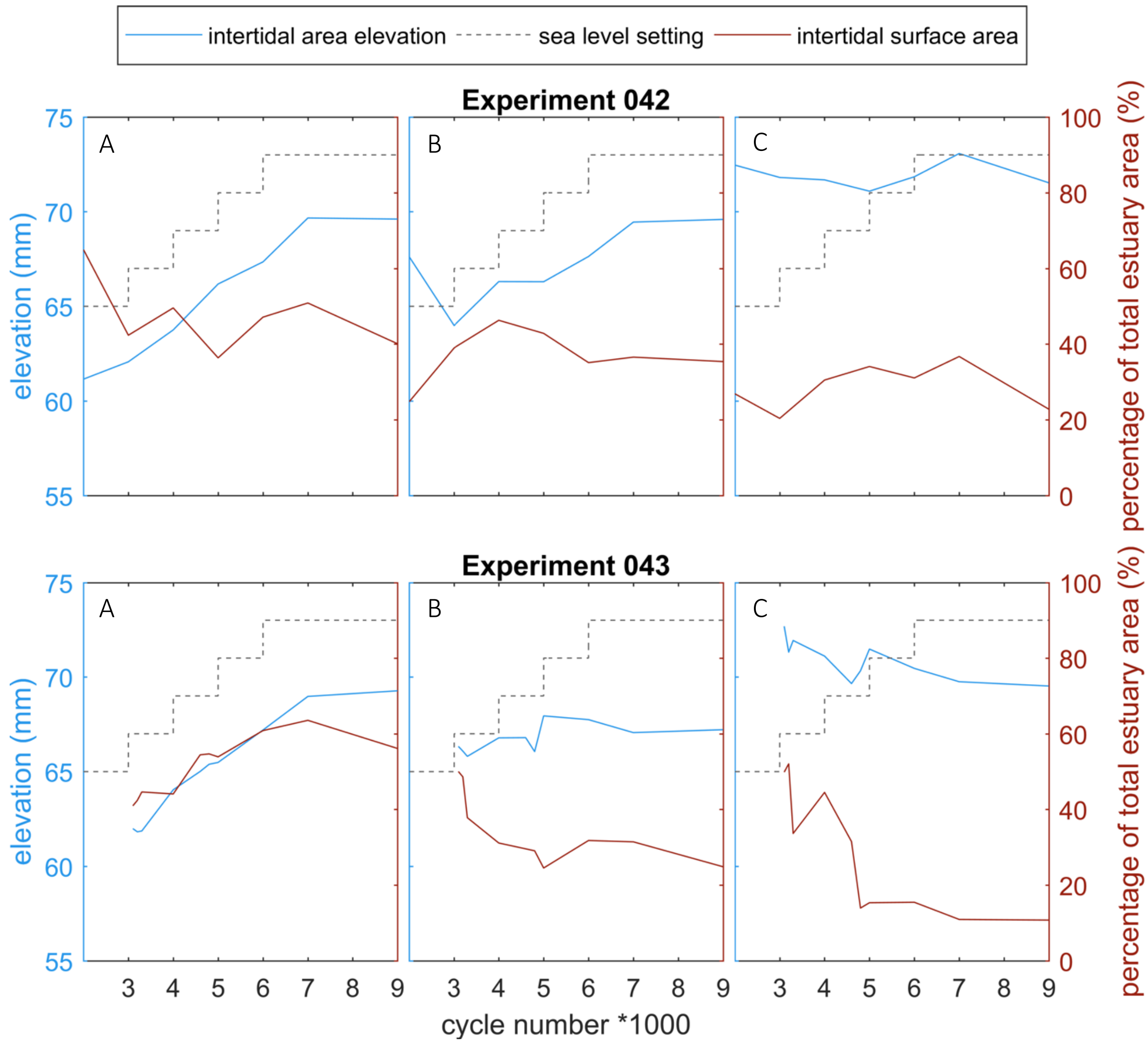


Figure 15 On the left axis in the blue line, the intertidal area elevation and the dashed line with SLR. On the right axis in the red line the percentage of intertidal surface area A) delta region (0.5 to 2.5 metres along flume) B) downstream region (2.5 to 12.5 metres) and C) upstream region (12.5 to 20 metres).

3.4.5 Supratidal area in natural estuary with SLR (exp042)

In the delta region (A) the subtidal area elevation closely follows the SLR trend, similar to the intertidal area, but also with the same values as SLR. The supratidal surface area also overall increases over time. In the downstream region (B) the supratidal area elevation decreases during the first half of SLR and stays stable after that. The supratidal surface area is stable through time in the downstream region. In the upstream regions (C) the supratidal area elevation stays roughly stable. The subtidal surface area is larger during SLR just like intertidal area. After SLR surface area decreases, but recovers towards the end of the experiment again and thus ends up almost 20% higher than before SLR at the end of the experiment.

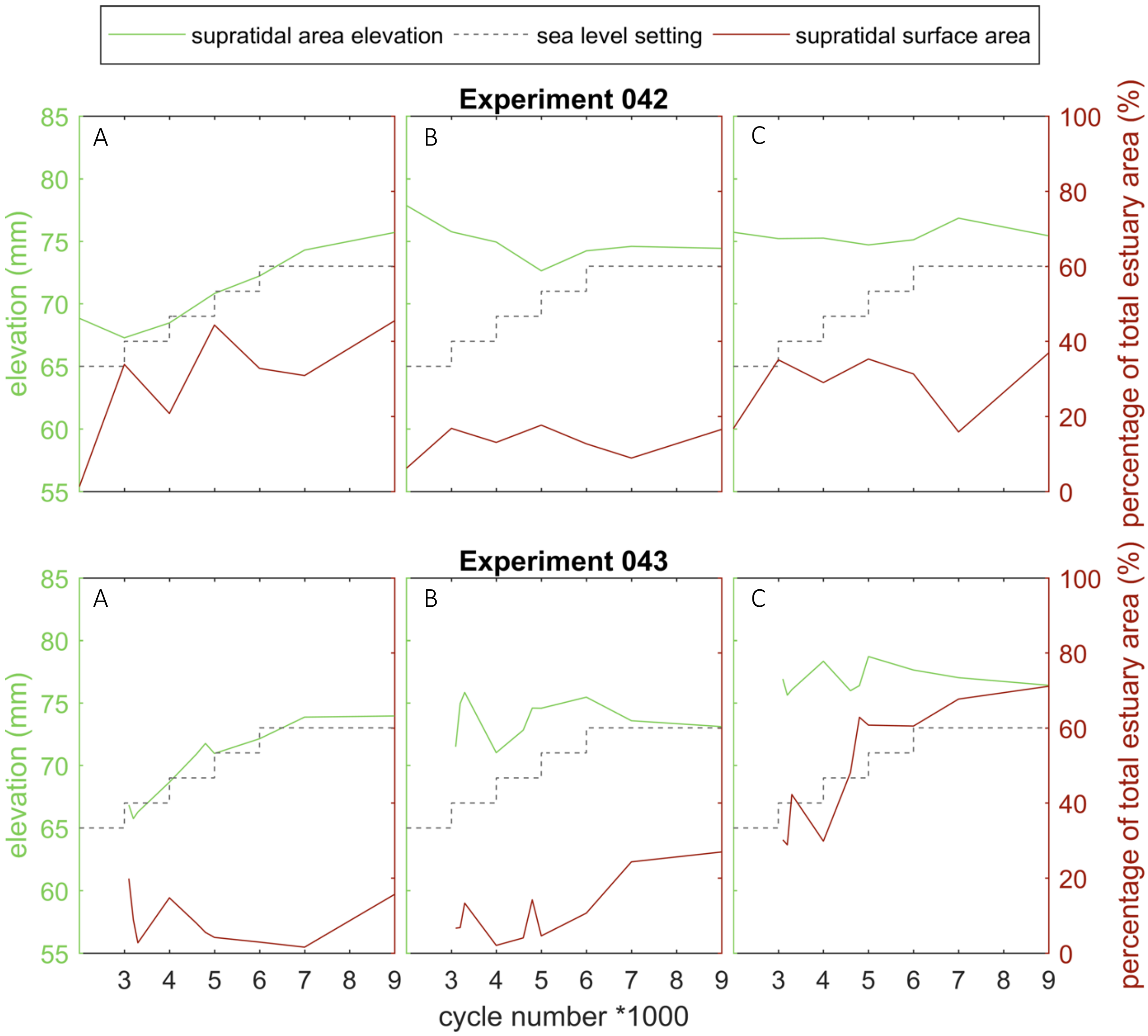


Figure 16 On the left axis in the green line, the supratidal area elevation and the dashed line with SLR. On the right axis in the red line the percentage of supratidal surface area A) delta region (0.5 to 2.5 metres along flume) B) downstream region (2.5 to 12.5 metres) and C) upstream region (12.5 to 20 metres).

3.4.6 Supratidal area in dredged estuary with SLR (exp043)

During dredging the supratidal area elevation in the delta region (A) behaves similar to the natural system, it also closely follows SLR. The surface area is much smaller, towards the end it is about 15% smaller in the dredged experiment than it was in the natural experiment. In the downstream region (B) supratidal area elevation is overall stable. Elevation does increase during dredging due to dumping of dredged materials in these areas and decreases right after dredging. At the end of the experiment the elevation is similar to the elevation in the natural system. The supratidal surface area is low during dredging but increases after dredging to values higher than the natural system. In the upstream region (C) supratidal area elevation stays stable like in the natural system, but with a bit more fluctuation during dredging. Early on in the experiment, the Supratidal surface is the same as the natural system, but increases strongly over time with extra fast increases during dredging. At het end of the dredged experiment the supratidal surface area is about 30% larger than it was in the natural system.

3.5 Estuary width and SLR

In experiment 043 the data density through time is a lot higher for the dredging periods. In Figure 17-top all these data points are plotted while in Figure 17-bottom the widening speed was only calculated over time steps of a 1000 cycles. This is done because this way a clear trend can be analysed while on the small time scale the widening speed fluctuates largely.

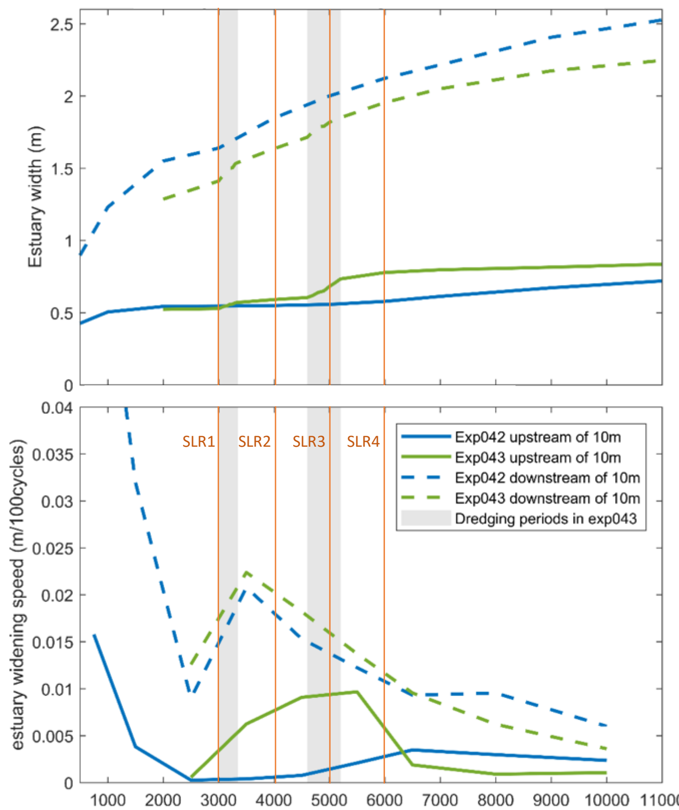


Figure 17 Average estuary width (top) and widening speed (bottom) through time for upstream and downstream half of the estuary.

In the downstream half of the Metronome, the average width of the natural estuary is larger than that of the dredged experiment (Figure 17 top). This was noted before in section 3.1.2. Here it is confirmed that this larger estuary width is not caused by the absence of dredging because the difference in width already exists before 3000 cycles. The bottom plot also supports this, because widening speed in the downstream half of the Metronome is very similar from 2000 cycles until the end of the experiment. The bottom plot also shows that during the first two SLR events, the widening speed of the estuary was significantly increased in the downstream part of the estuary.

The average width in the upstream half of the natural estuary and the dredged estuary are initially the same (Figure 17 top). During SLR the upstream width of the natural estuary barely changes and the widening speed is very low. In Figure 18 it is confirmed that during SLR the upstream part of the estuary is very stable and does not widen significantly.

During the first dredging period, the width increases strongly and during the second dredging period the width increases even more. These increases are also visible in the high widening speed during the two dredging periods. This extreme upstream widening in the second dredging period also becomes apparent in Figure 19 where the erosion of the bends into the floodplain are visible in red.

Since the experiment is set up without any external sediment input, sediment to form morphology has to come from the banks and bed of the estuary itself. More estuary widening therefore also means that more sediment is added to the system that might need to be dredged out.

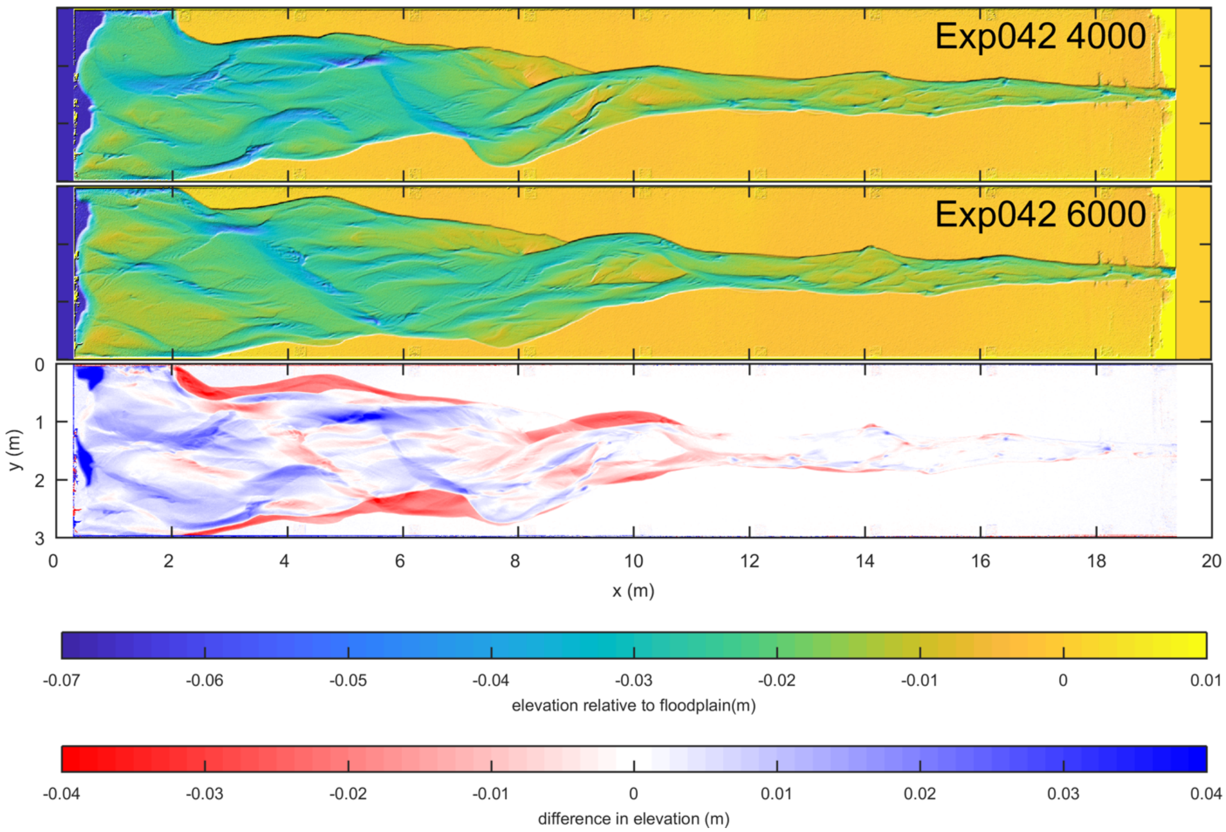


Figure 18 Two DEMs from exp042 after 2 mm of SLR and after 6 mm of SLR (top two) and the difference between the two DEMs (bottom) with erosion in red and accretion in blue.

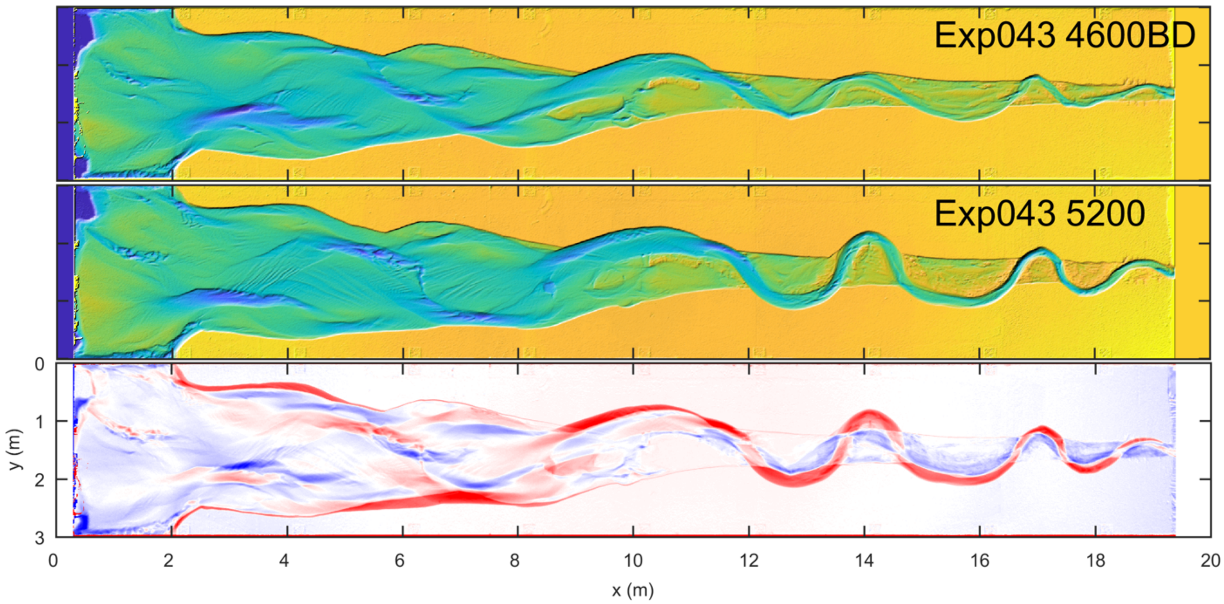


Figure 19 Two DEMs from exp043 right before the second dredging period and at the end of the second dredging period (top two) and the difference between the two DEMs (bottom) with erosion in red and accretion in blue. (for colorbars see figure 18)

3.6 Dredging analysis

3.6.1 Total dredged volumes per dredging event with and without SLR

The increased widening and thus sediment addition to the system is also visible in the volumes that are dredged form the system during capital dredged (CD) and maintenance dredges (MD) (Figure 20). Without SLR (exp023: Cox (2018); Van Dijk et al. (2021)) the dredged volume in the second capital dredge is less than half of the first capital dredge. With SLR (exp043) the capital dredging volumes are roughly the same for both capital dredges.

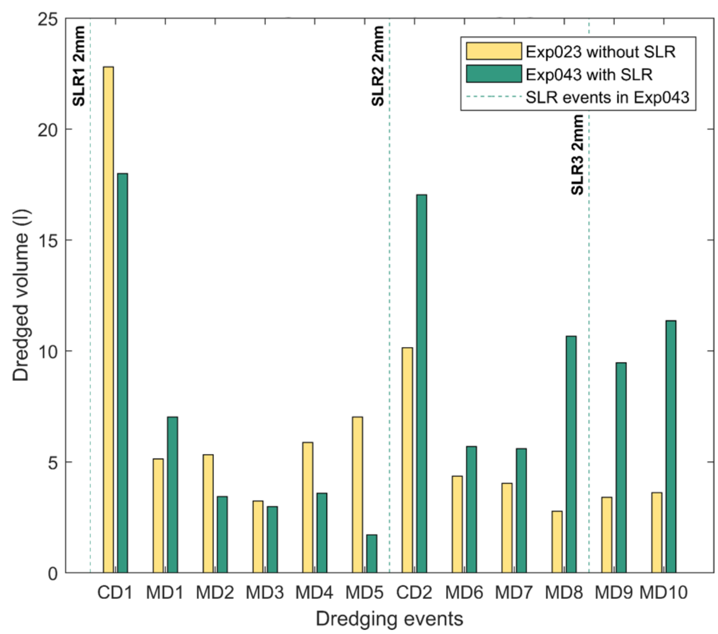


Figure 20 Total dredged volumes in litres per dredging event for experiment 023 without SLR (Cox, 2018; Van Dijk et al., 2021) and experiment 043 with SLR. (Where CD is Capital Dredging event and MD is Maintenance Dredging event.)

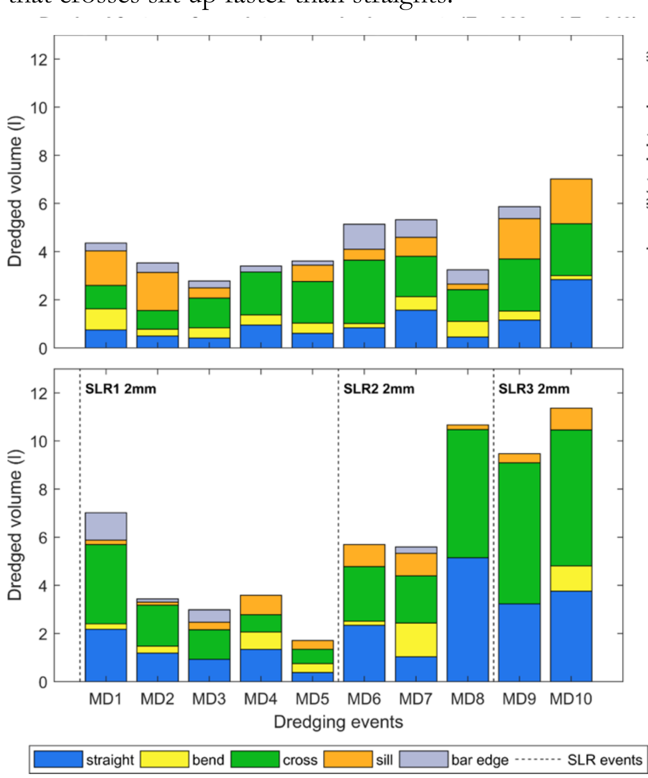
When looking at the maintenance dredges after capital dredge 1 the dredged volumes are somewhat stable through time without SLR, only a very slight increase can be observed. With SLR the dredged volumes decrease after the first capital dredge.

After capital dredge 2 in exp023 the maintenance dredge volumes are a bit lower than after capital dredge 1 but again roughly stable with now a very slight decrease through time. In exp043 with SLR, the behaviour changes drastically after the second capital dredge. The dredged volumes are higher and increase strongly over time especially from MD7 to MD8. Dredging took place every 50 cycles after the first capital dredge, and every 100 cycles after the second. Since dredging decreases in the second dredging period in exp023 it can be assumed that the estuary stabilizes to the new situation and less dredging is necessary to keep the shipping channel open. Since the volumes that need to be dredged in exp043 increase strongly in the second dredging period it can be assumed that this stabilising effect from dredging in exp023 is counteracted by SLR. From the DEMs in section 0 it is known that the dredged channel persists. This means that dredging volumes do not increase because the estuary morphology becomes more natural again. The increase in dredged volume is most likely linked to the widening of the estuary and thus increased sediment input from the banks.

3.6.2 Dredging volumes per feature

For both dredging experiments data was gathered on the features that needed to be dredged during maintenance dredges (MD) and are now compared (Figure 22). The absolute volumes of dredged material are higher for most features when total dredged volume is higher.

For both experiments there is almost always more material dredged from crosses than from straights (Figure 22). In exp023 there is relatively more dredged from crosses than from straights compared to exp043. Only in MD1, MD7 and MD10 this is not the case. The fact that more dredging is needed in crosses overall means that crosses silt up faster than straights.



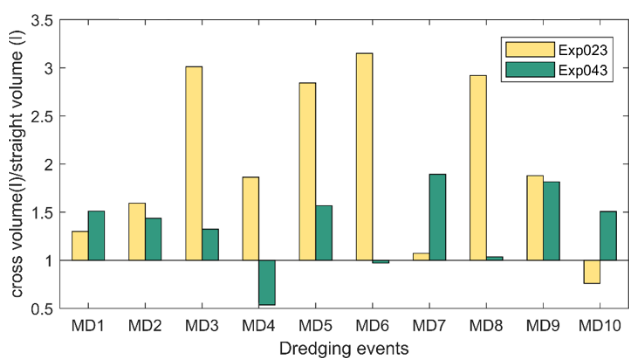


Figure 22 Dredged volumes from crosses relative to straights (axis should be changed).

Figure 22 Volumes dredged from all features for experiment 023 (Cox, 2018)) and experiment 043 (with SLR). (definitions of features in Table 4*)*

3.6.3 Dredging volumes over flume length

In Figure 23 the dredged volumes of every dredging event are plotted cumulative over the length of the flume for every 0.5 centimetre. This means that a value of MD10 on the y axis is the total amount of litres that was dredged at that specific 0.5 centimetres length in the flume. This also means that the area under the graph is the total amount of litres dredged in the entire flume. Narrow high peaks of dredged material occur where crosses have a large angle with the x axis.

When comparing the dredged locations during the first dredging period to the second dredging period, the most striking is the increase in dredged material upstream of 12 metres in the second dredging period (Figure 23). It does need to be taken into account that during this dredging period dredging took place every 100 cycles instead of every 50 cycles like in the first period. Additionally, the estuary has also been growing wider. Since the width of the dredged channel is calculated from the estuary width, the dredged channel was also wider in the second dredging period. Lastly the dredged channel has also become more meandering, meaning that the length of the channel that needed to be dredged has increased.

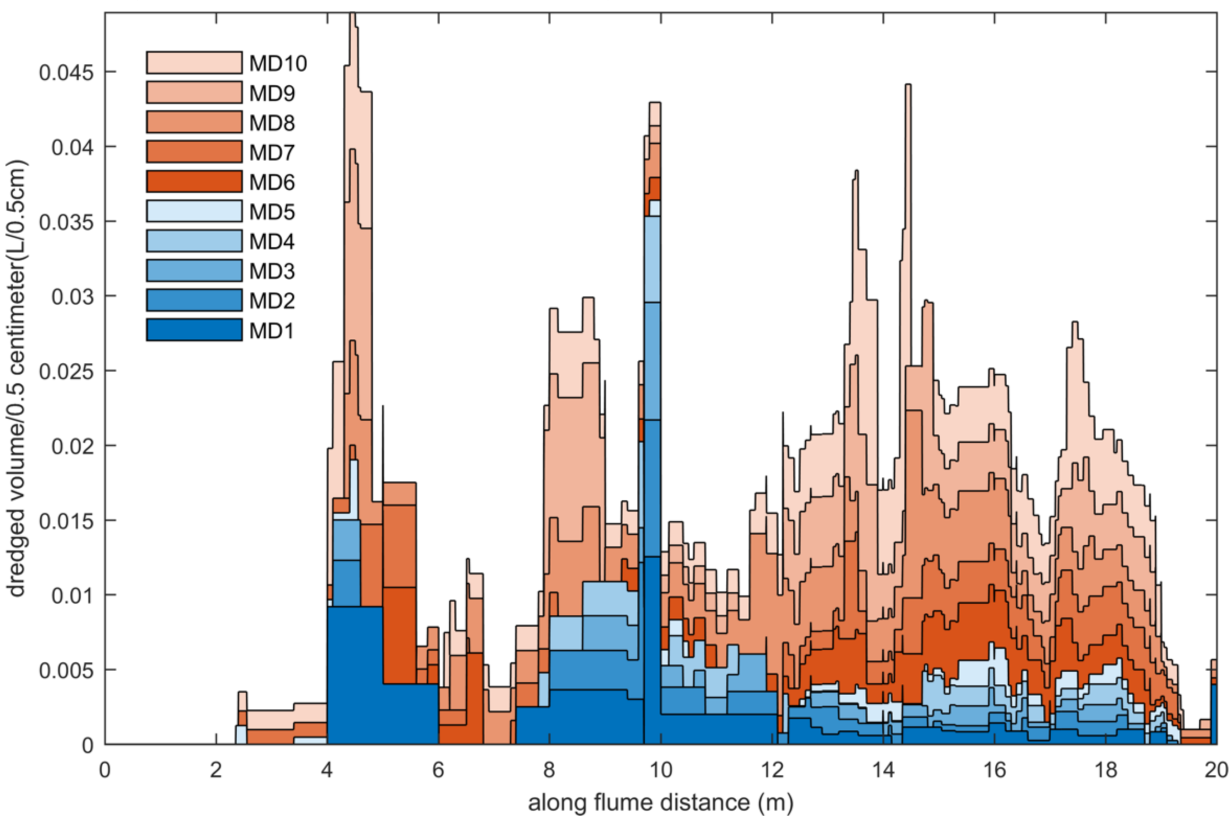


Figure 23 Cumulative dredging volumes of all maintenance dredges for every 0.5 cm of Metronome length. Dredged volumes were recorded for the entire length and location of every feature. The volumes were therefore divided over the length of the corresponding feature. All volumes now represent the dredged volume over 0.5 cm (the same resolution as Metronome DEMs). With the first dredging period in blue shades and the second dredging period in red shades.

To be able to check if the differences between dredging could also be related to continuing SLR, the graphs need to be normalised over the before mentioned factors (Figure 24). The overall visible trend is that up to 9 metres the first and second dredging series do not differ significantly. Between 9 and 20 metres the volumes in the first series are higher than in the second series. The high peak at 10 metres is partly caused by the fact that the channel tool found that the main channel is in a different location from the dredged channel. Therefore the volumes were divided over a shorter channel length than they were actually dredged. From 12 metres up to the river end, the difference is most significant. Here the dredged volumes are structurally much higher for the second series than the first series. When looking back at Figure 17 this is also the moment where the estuary widens fastest. The sediment that is eroded from the banks probably ends up in the channels and needs to be dredged out in the following dredging event.

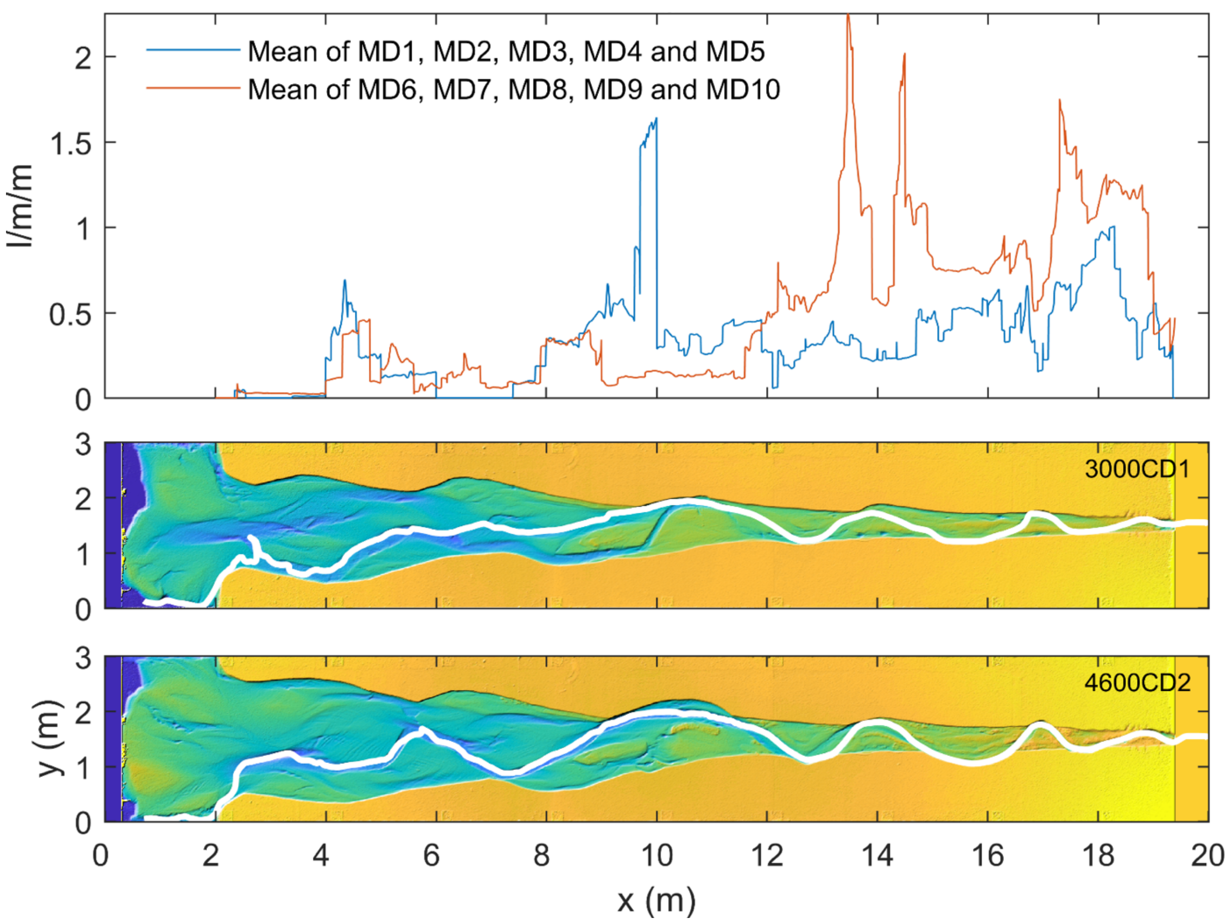


Figure 24 Normalised dredging volumes from the first dredging period in blue and the second dredging period in orange (top). (Dredged volume(l) / channel length(m) / estuary width(m)/cycle between dredges = normalised dredged volume(l/m/m).) And the main channel course in white of the first capital dredge (middle) and second capital dredge (bottom) generated by the channel tool (Sonke et al., Conditionally accepted).

4 Discussion

4.1 Hydrodynamics of estuaries with SLR

The effect of SLR on hydrodynamics in the system can studied by analysing water level data of the Metronome experiments with and without SLR. Detailed water level data was produced for the natural experiment without SLR (exp006, Leuven et al., 2018a), but not for the dredged experiment without SLR (exp023, Cox, 2018). However, since Leuven et al. (2018a) did not publish any analysis of the water level data of exp006, it is hard to analyse the effect of SLR on tidal range in the Metronome.

What does become apparent from the tidal range development over time is that the tidal wave is amplified most during the first half of SLR in both the dredged and the natural experiment (Figure 12). This could be an indication that SLR only causes amplification of the tidal wave in the first two SLR events and causes dampening during the two subsequent SLR events. Du et al. (2018) and Leuven et al. (2019), showed that amplification of the tidal wave is dependent on the length, depth and bathymetry of the estuary. Based on their finding it could be concluded that during the first two SLR events, the estuary in the Metronome could still be characterised as a long, shallow estuary in which tidal amplification due to SLR was expected. During the last two SLR events the tidal wave was dampened more, because the estuary had become relatively short, with large shallow areas next to the channels due to ongoing widening. It is hard to confirm this theory without detailed analysis of the tidal range development in the natural estuary without SLR (exp006).

Dredging in combination with land reclamation and embankment has increased tidal range and moved the maximum tidal range upstream over the past century in real life estuaries (Winterwerp et al., 2013). In the Metronome, even though only dredging was applied, the dredged estuary also shows increasing tidal range and an upstream shift of the maximum tidal range relative to the natural estuary. This indicates that dredging and dumping play a big role in the deformation in the tidal wave in these life size estuaries, as was also suggested by Temmerman et al., 2013.

The results show that dredging causes an increase in tidal range, this means that flood dominance increases in a dredged estuary (Friedrichs, 2010; Winterwerp et al., 2013). The risk of such increased flood dominance is that a life size estuary can cross into a hyper turbid state. Hyper turbidity is a state where the estuary does not have a turbidity maximum around the salinity head, but has high near surface suspended sediment concentrations over the entire length of the system. The increased flood dominance causes more sediment import in the form of mud and causes trapping of these sediments. The mud deposits decrease the hydraulic drag in the system and thus cause even more flood dominance. This results in a positive feedback loop that keeps the system stable in hyper turbid state. The Ems-Dollard is an example of such a life size estuary that has become hyper turbid due to ongoing deepening of the navigation channel (Winterwerp, 2010). The Western Scheldt is an example of an estuary that has not yet become hyper turbid, but might be at risk of doing so although this remains uncertain (Wang et al., 2019). If SLR indeed increases tidal range and therefore more flood dominance, it can be another contribution on top of dredging to pushing not yet hyper turbid systems into hyper turbidity.

4.2 Tidal zonation development with SLR

SLR impacts the development and distribution of subtidal, intertidal and supratidal area. Intertidal areas of estuaries promote a large species diversity due to existing gradients (Baeyens et al., 1997; Nicolas et al., 2010; Raffaelli & Hawkins, 1996). In many dredged estuaries, intertidal areas are under pressure due to a decrease of intertidal area caused by dredging (Van Dijk et al., 2021). The experiments with SLR from this thesis, show that SLR does not pose a threat to these biodiverse intertidal areas in natural estuaries and these areas might even become larger.

In this study, based on modelling by Van Dijk et al. (2021), it was hypothesised that intertidal area elevation would increase with SLR and that its surface area would decrease. In the experiments with a natural estuary, the intertidal area elevation indeed increases with SLR in the downstream regions of the estuary (Figure 15-top A & B), and it is also able to keep up in terms of surface area. Especially during the beginning of SLR where the intertidal area even briefly increased, due to the increased tidal range (Figure 15-top B).

In contrast, in the dredged estuary, the intertidal area was only able to keep up with SLR in the delta (Figure 15-bottom C), while in the rest of the dredged estuary the intertidal area rapidly decreases during dredging. This is in line with the expectation that dredged systems might be more starved for sediment and therefore less able to keep up with SLR. The intertidal surface area in the dredged system was not even able to recover again after dredging had stopped (Figure 15-bottom), which is linked to the fact that the dredged morphology is persistent, even after dredging. This means that dredged systems might suffer from an additional loss of biodiverse intertidal area due to SLR.

The subtidal area was expected to either increase in surface area or decrease in elevation for both natural and dredged systems. The latter seems to be true for the natural system, because although subtidal elevation is increasing in big parts of the estuary, it is not keeping pace with SLR (Figure 14-top), resulting in an on average deeper subtidal area. On top of the deepening, against expectations, the surface area also decreases during SLR. This decrease in surface are is most likely also caused by the high tidal range during SLR that was responsible for the increase of intertidal area during SLR. This indicates that the subtidal area, in contrast to the intertidal is not able to keep up with SLR, but is able to recover its surface area when SLR stops.

In the dredged system, the influence of dredging on the subtidal area is much larger than that of SLR (Figure 14-bottom) and therefore dredging makes the influence of SLR on the subtidal areas of a dredged system marginal. What does become clear is that especially in the upstream regions the effect of dredging on the subtidal area remains large after dredging stops, and the estuary is not able to recover towards a more natural situation. In the more downstream area, the subtidal area is better able to recover. In the previous experiment without SLR, this ability to recover after dredging in the downstream area was not observed (Van Dijk et al., 2021).

The supratidal area is able to keep up with SLR in terms to surface area in natural system, however, the supratidal area elevation is stable which means that it is decreasing relative to SLR (Figure 16-top). This means that although surface area is keeping up, the supratidal area might become more prone to flooding during extreme high waters in real life estuaries. In the dredged estuary, the supratidal area shows similar behaviour, but under the influence of dredging, the supratidal surface area ends up much higher after dredging is stopped (Figure 16-bottom). This is at the cost of the previously described intertidal areas, which decrease due to dredging.

In summary, the Metronome experiments confirm the hypothesis that natural estuaries would be less starved of sediment than dredged estuaries and thus better able to keep up with SLR. Although natural systems are also affected by SLR, they are able to recover after SLR stops. Dredged estuaries do not show this capability to recover, because dredged morphology is persistent. In life size dredged estuaries this sediment starvation is also observed (Cox et al., 2021), and it is therefore likely that they will respond similar to the experimental estuaries.

4.3 The effect of SLR on channel mobility and sinuosity in dredged systems

The natural experiment without SLR (Leuven et al., 2018a) shows more erosional and accretional surfaces in the upstream half than the natural experiment with SLR in Figure 26. This indicates a more dynamic system with a higher channel mobility. It was hypothesised that channel mobility would decreases with SLR due to increased influence of the tide on the system. In the upstream half of the natural system with SLR the channel mobility has indeed decreased compared to the natural system without SLR, as was predicted by Lentsch et al. (2018). It is not entirely clear if the channel mobility also decreases in downstream half of the estuary. More analysis would be needed to be able to draw conclusions about this.

The dredged systems tell a very different story. Against expectations, the channel mobility was high in the upstream regions when dredging and SLR occurred together, and the single meandering channel started to migrate (Figure 7 and Figure 8). Unlike river meanders, the bends are kept in place and not cut of due to the alternating flow direction of ebb and flood (Figure 9). Bars are known to also stay in place in estuaries due to alternating ebb and flood flow (Leuven et al., 2018a), these experiments show that meander bends show the same behaviour in dredged estuaries as these bars in a natural systems.

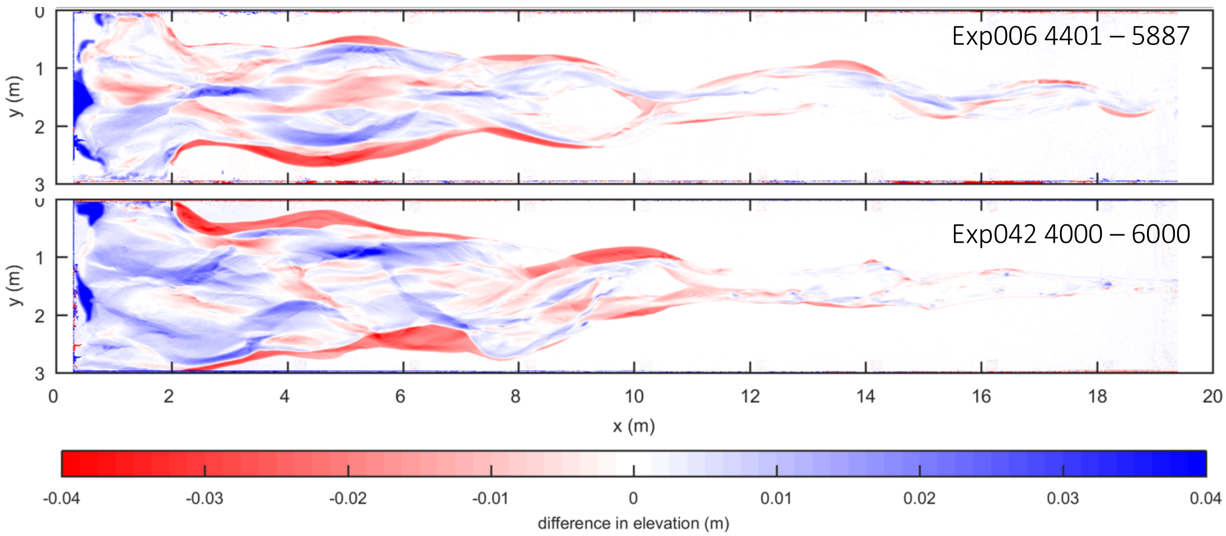


Figure 26 Difference maps of the natural experiment without SLR (Leuven et al., 2018a)(top) and of the natural experiment with SLR (bottom). With erosional surfaces in red and accretional surfaces in blue.

The channel mobility is caused by lateral migration of these bends towards the floodplains, attacking the banks and becoming increasingly sinuous (Figure 8). Dredging alone had a stabilising effect on morphology (Figure 25-top, Cox, 2018; Van Dijk et al., 2021). In combination with SLR, the increased tidal energy did not stabilise the channel more by eroding downward, but instead destabilised the channel by eroding laterally (Figure 25-bottom).

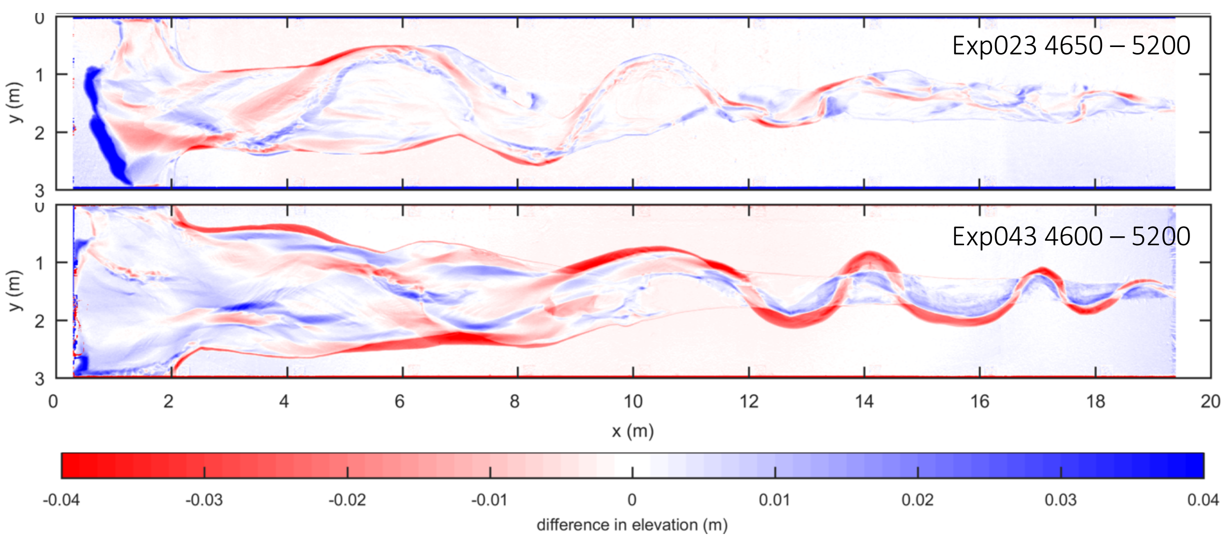


Figure 25 Difference maps of dredged experiment without SLR (Cox, 2018; Van Dijk et al., 2021) (top) and of the natural experiment with SLR (bottom). With erosional surfaces in red and accretional surfaces in blue.

4.4 Bank stability with SLR

In the natural experimental setup without SLR (Leuven et al., 2018a) the widening speed of the estuary generally decreases over time along the entire estuary (Figure 27). This means that the estuary banks become increasingly stable over time. In the natural estuary, SLR causes increased widening speed and thus decreased bank stability in the downstream part, while in the upstream part the widening speed is lower with SLR than without SLR. This implies that SLR has a bank stabilising effect in the upstream part of the estuary, which is in line with the hypothesis stated in the introduction. This effect can be linked to the decreased channel mobility in the upstream part of the natural estuary with SLR. However, it is uncertain to what extent the effect can be related to SLR and to what extent to natural variation, since widening speed is already lower before SLR in the two SLR experiments compared to the natural experiment without SLR (Figure 27).

As observed before, in the dredged estuary with SLR the widening speed behaves the same as the natural estuary with SLR (Figure 17-bottom), which indicates that SLR also here decreases bank stability in the downstream part of the estuary. The upstream half of the dredged estuary with SLR does not only behave very different from the natural estuary with SLR, but also from the natural estuary without SLR (Figure 27). Widening speed and thus bank instability is significantly increased during the combination of SLR and dredging. The width increases most in the second dredging period with 6 millimetres of SLR. Without SLR, the upstream part of the dredged systems widens most during the first dredging period, although not as much as in the second dredging period with SLR. Without SLR, the upstream part of the dredged estuary does not widen at all anymore in the second dredging period (Cox, 2018).

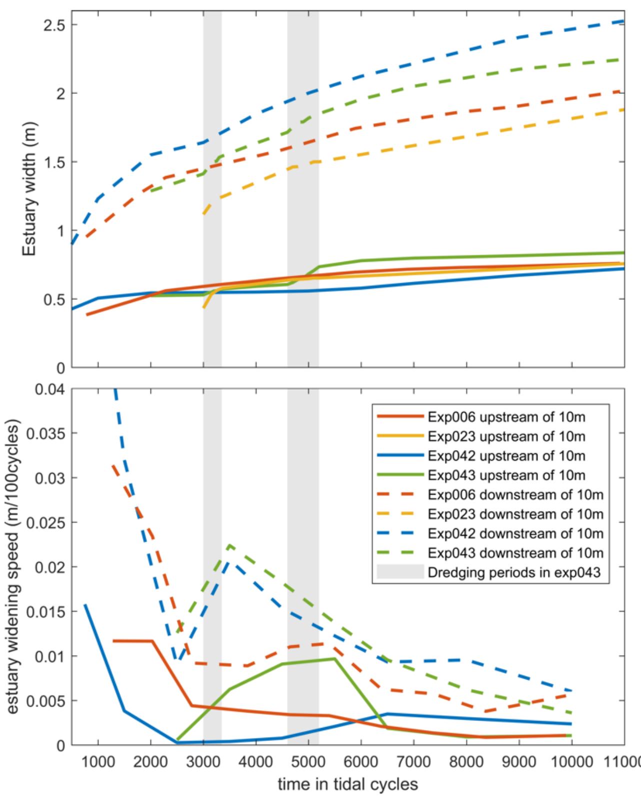


Figure 27 Average estuary width (top) and widening speed (bottom) through time for upstream and downstream half of the estuary.

This indicates that dredging makes the banks less stable in the upstream part at first, but as dredging proceeds, it indeed stabilises the banks as was concluded by Cox, 2018; Van Dijk et al., 2021). With SLR this is not the case, instead of stabilising the banks over time in the upstream part of the estuary the widening speed increases as dredging continues and bank stability decreases significantly.

The erosion caused by the previously observed lateral migration of the meander bends has implications for the bank stability in the upstream part of the estuary. As the channels are migrating and eroding mainly in the outer bends, the banks are undermined and collapse into the channel. In many life size estuaries among which the Western Scheldt, there is no room for the channels to migrate laterally because of the presence of hard engineering structures, such as dikes along the banks of the estuary (Cooper, 2009; Jeuken, 2000). These dikes will increasingly be attacked and possibly undermined when SLR continues, especially in the upstream regions of dredged estuaries.

4.5 Sustainability of current dredging strategy with SLR

Total dredging volumes with SLR remain similar with the first small amount of SLR, but as SLR and dredging proceed, total dredging volumes increase significantly (Figure 20). As the estuary becomes more dynamic, and channel mobility increases, dredging will have to be undertaken more frequently and with higher volumes to keep the channel navigable. However, increased dredging intensity might exacerbate the problem due to the positive feedback loop that this would create. Dredging and SLR caused the necessity to intensify dredging, while more dredging will possibly cause the system to become even more dynamic, which in turn increases the required dredging volume.

In the Metronome experiments, relatively large volumes are dredged from crosses (Figure 22) that do not match the dredging patterns found in the Western Scheldt (Cox, 2018). High dredging volumes in crosses are therefore not directly representative of dredging in life size estuaries. But with SLR the increase in sediment volume dredged from crosses plays a relatively small role in the increase of total dredged volumes as can be derived from the cross/straight ratio (Figure 22). This means that the results from the Metronome area likely to also be applicable to life size estuaries like the Western Scheldt.

In the Western Scheldt the depth of the dredged channel is dependent on the draught of the ships that want to navigate to the harbour of Antwerp. A minimum depth during low water is guaranteed so that a large amount of the ships can navigate upstream regardless of the tide (Claus et al., 2009). The tidal range development under SLR in the experimental setup shows that as tidal range increases, low waters become lower. This means that the maximum draught of ships that can pass independent of tide will become smaller and thus less ships can pass during low water. This could give the incentive to dredge the channel deeper than before SLR and thus increase dredging volumes even more.

In the Westerns Scheldt, locations where dredging is needed are always the same (Claus et al., 2009). However, with ongoing SLR, it was shown that not only total dredged volumes increased, but also that the most heavily dredged area will also move upstream (Figure 23 and Figure 24). This transgressional trend will move the most heavily dredged areas further landward and into the areas where harbours are typically found, like the harbour of Antwerp in the Western Scheldt.

5 Conclusion

Two experiments were done in the Metronome tidal flume and were compared to investigate the influence of SLR on the morphology of natural and dredged estuaries. Afterwards the results were discussed in relation to previously done experiments with the same setup, but without SLR.

The morphology of natural estuaries responds differently to SLR than morphology of dredged estuaries. The natural system was in most respects better capable to keep up with SLR:

- Subtidal and intertidal area are able to rise with SLR although it must be noted that in natural systems the elevation of supratidal area is not able to keep up and possibly makes them more prone to flooding during extremely high waters.
- In the upstream areas of natural estuaries channel mobility decreased and bank stability increased. In this respect the estuary is very able to adapt and becomes even more stable with SLR
- In the downstream areas of the natural estuary, the opposite was true and bank stability of the natural estuary decreased. In this respect the estuary is not as able to keep up with SLR.

The morphology of dredged estuaries are overall less able to keep up with SLR than the natural system:

- In the upstream part of the dredged estuary, bank stability decreased significantly relative to the dredged system without SLR and the natural system with SLR.
- The decreased bank stability was caused by the high increase in channel mobility. The channel became highly sinuous and destabilises the banks by eroding the outer bends.
- In the downstream part of dredged estuaries bank stability was similar to natural estuaries during SLR and increased relative to dredged estuaries without SLR.

The dredging strategy applied to the system, that was based on the dredging strategy of the Western Scheldt, was also analysed and it can be concluded that:

- Current dredging strategy is not sustainable, because with SLR total dredging volumes will increase and dredging events will need to be more frequent to keep pace with this.
- The most heavily dredged locations will move upstream due to transgression.
- SLR might put dredged estuaries at higher risk of becoming hyper turbid due to a further increased tidal range and flood dominance.

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Appendices

Appendix 1

Metronome Agisoft DEM guide

1. Import all photos (e.g. by dragging)
2. Make sure:
   - There is as least one target visible in every photo
   - There are no blurry photos
   - There are no two identical photos
3. Workflow → align photos
4. Optimize cameras (references tab – the wand or star button depending on version)
5. Reference tab (bottom left) → import → import .txt file with marker locations (find on RDL drive, and see appendix…)
6. Photos tab (bottom right) → click on each photo to add the markers
7. Right click on correct location (target) → place marker (select correct number) and drag to centre of the target
8. Repeat for all photos and all markers
9. Workflow → build dense cloud (high quality, this may take a while)
10. Remove extraneous points (select by rectangle – toolbar across the top of screen) – delete anything outside Metronome extent
11. Workflow → build mesh (ensure not arbitrary 3D but height field 2.5D)
12. Workflow → build orthomosaic (if needed)
13. Reference tab → refresh/update
14. Workflow → build DEM
15. File → export DEM (as .tiff) (Make sure you only export the extent of the Metronome; x = 0 to 20, y = 0 to 3)
16. File → export orthophoto (as .tiff) (if needed).

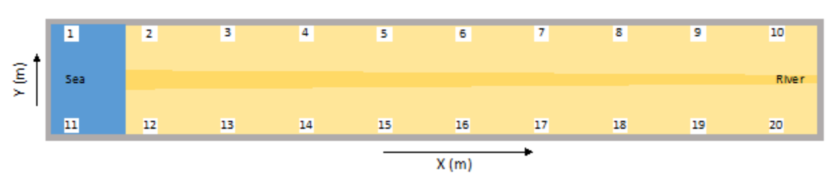


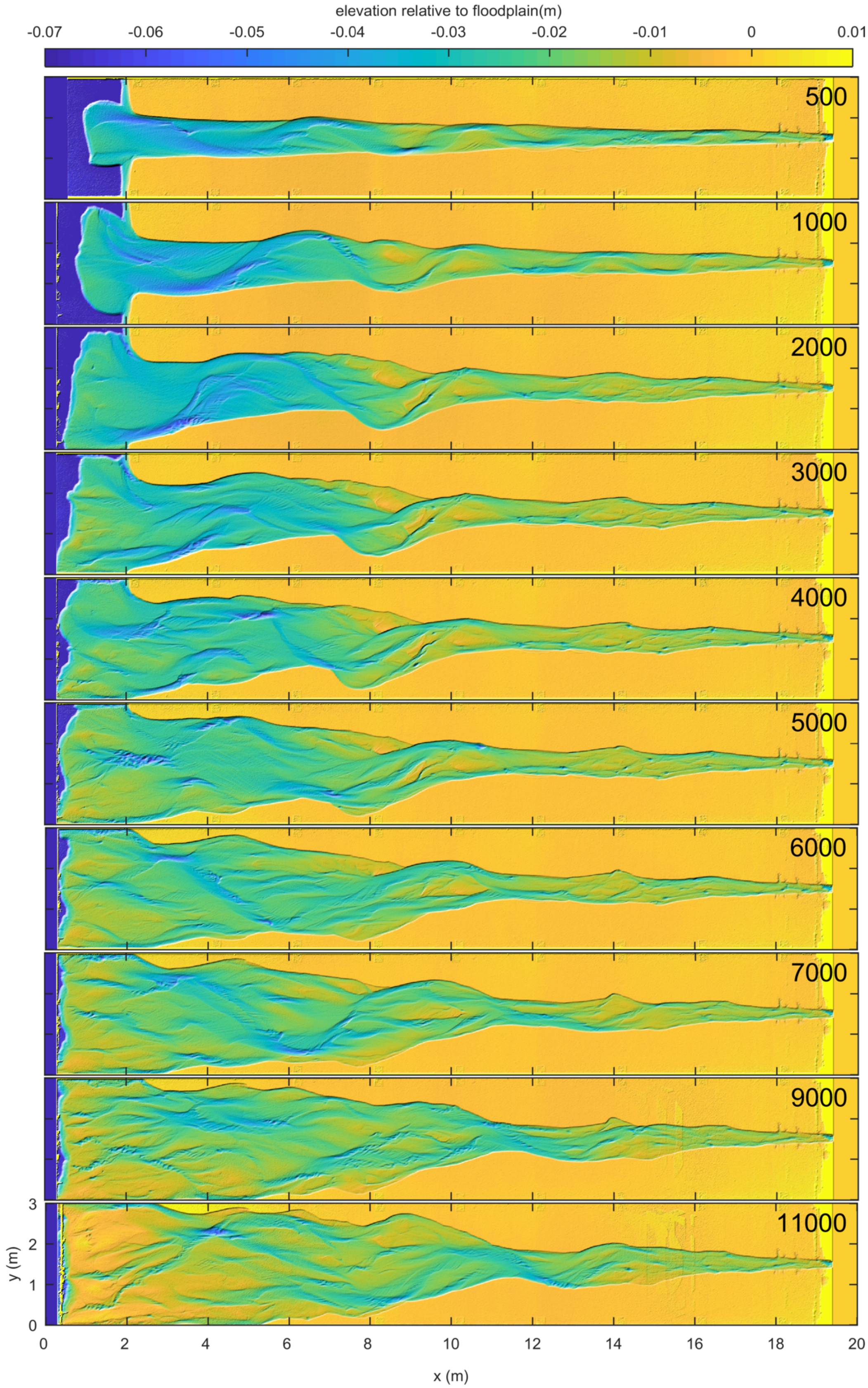
Figure: Metronome plan with target locations.

Appendix 2

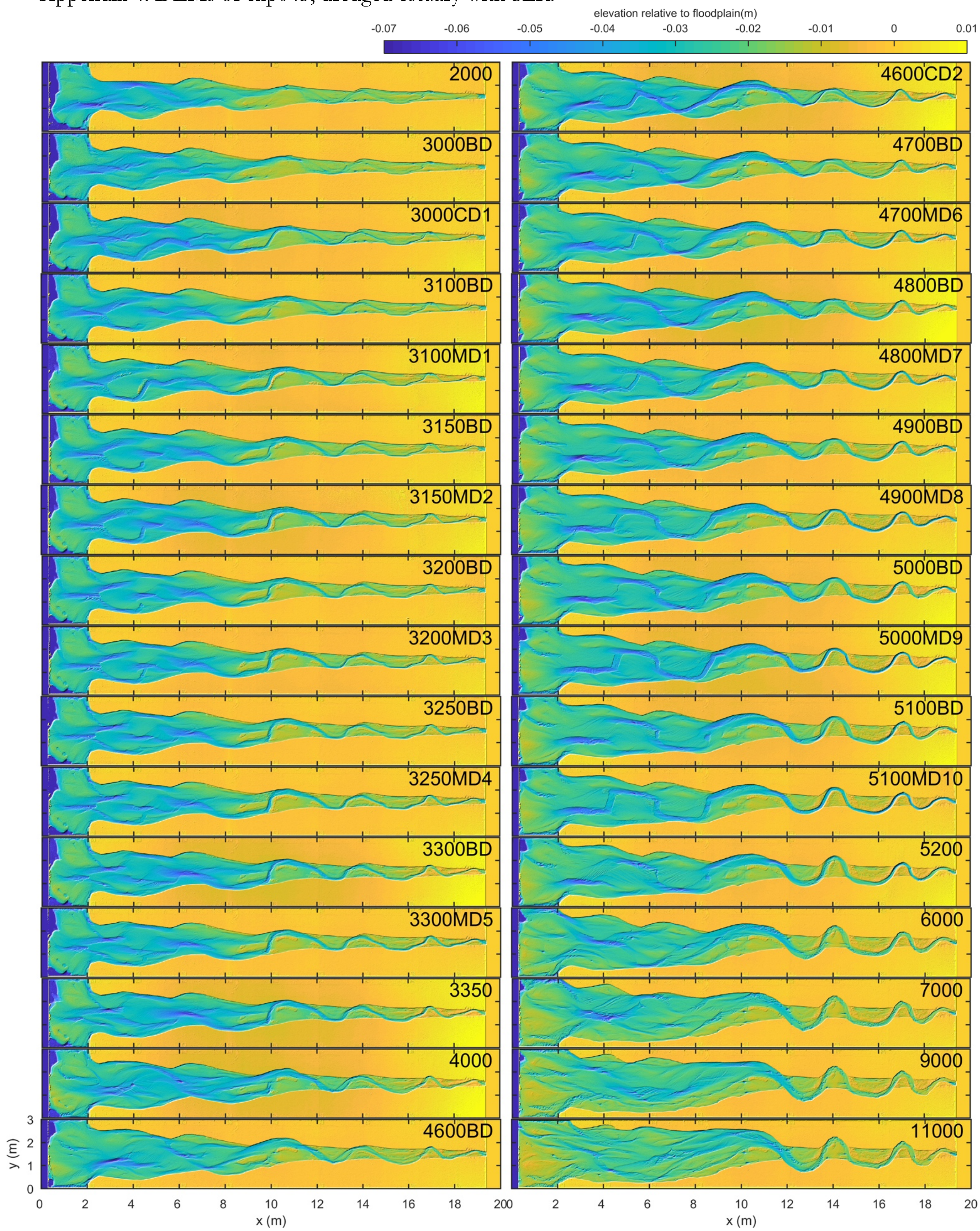
Target coordinates to make DEMs (marker.txt can be found on RDL drive):

nr	x	y	z
target 1	2.85	19.80	-0.067
target 2	2.85	17.80	0.00000001
target 3	2.85	15.80	0.00000001
target 4	2.85	13.80	0.00000001
target 5	2.85	11.80	0.00000001
target 6	2.85	9.80	0.00000001
target 7	2.85	7.80	0.00000001
target 8	2.85	5.80	0.00000001
target 9	2.85	3.80	0.00000001
target 10	2.85	1.80	0.00000001
target 11	0.16	19.80	-0.067
target 12	0.16	17.80	0.00000001
target 13	0.16	15.80	0.00000001
target 14	0.16	13.80	0.00000001
target 15	0.16	11.80	0.00000001
target 16	0.16	9.80	0.00000001
target 17	0.16	7.80	0.00000001
target 18	0.16	5.80	0.00000001
target 19	0.16	3.80	0.00000001
target 20	0.16	1.80	0.00000001

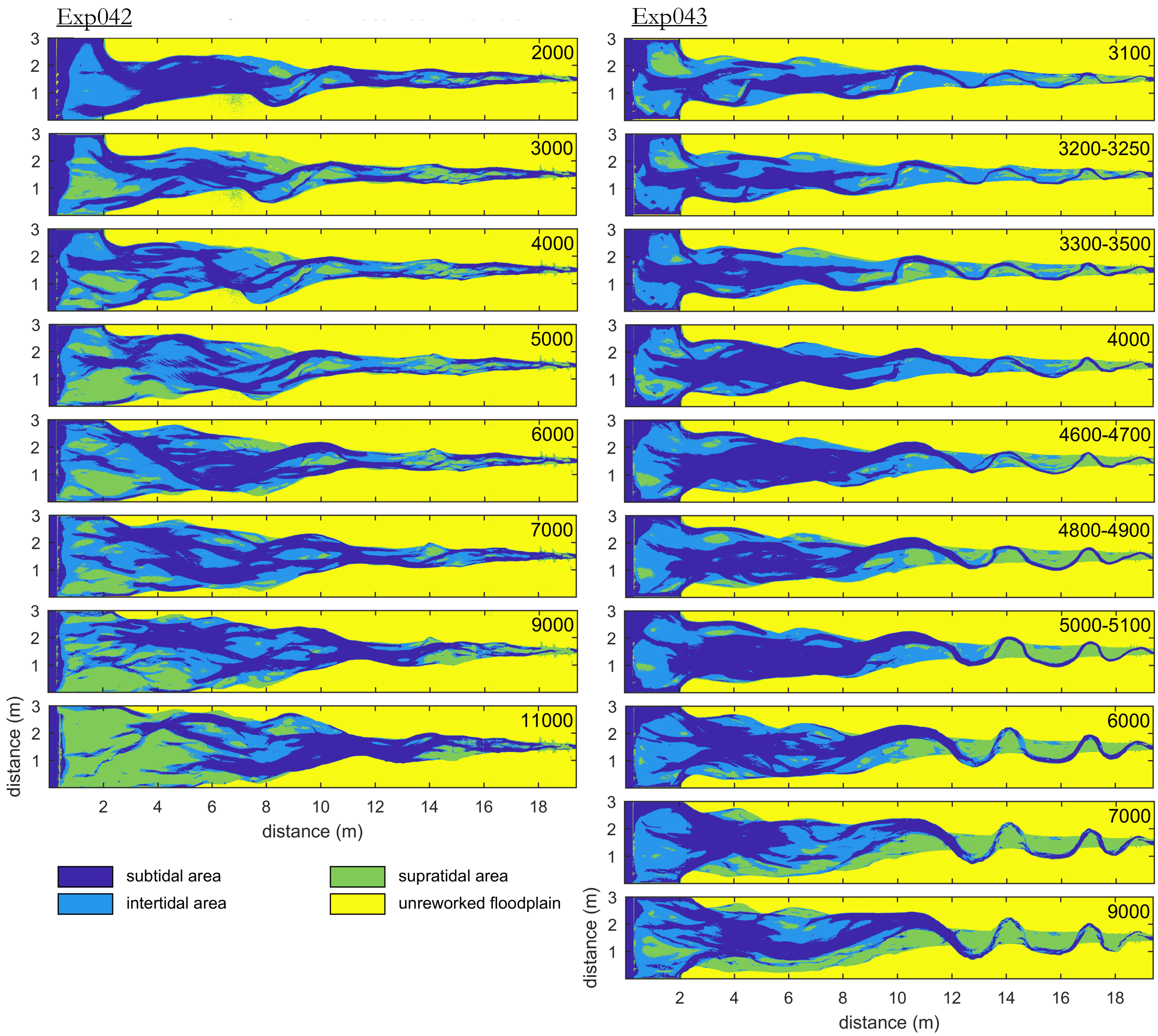
Appendix 3: DEMs of exp042, natural estuary with SLR.



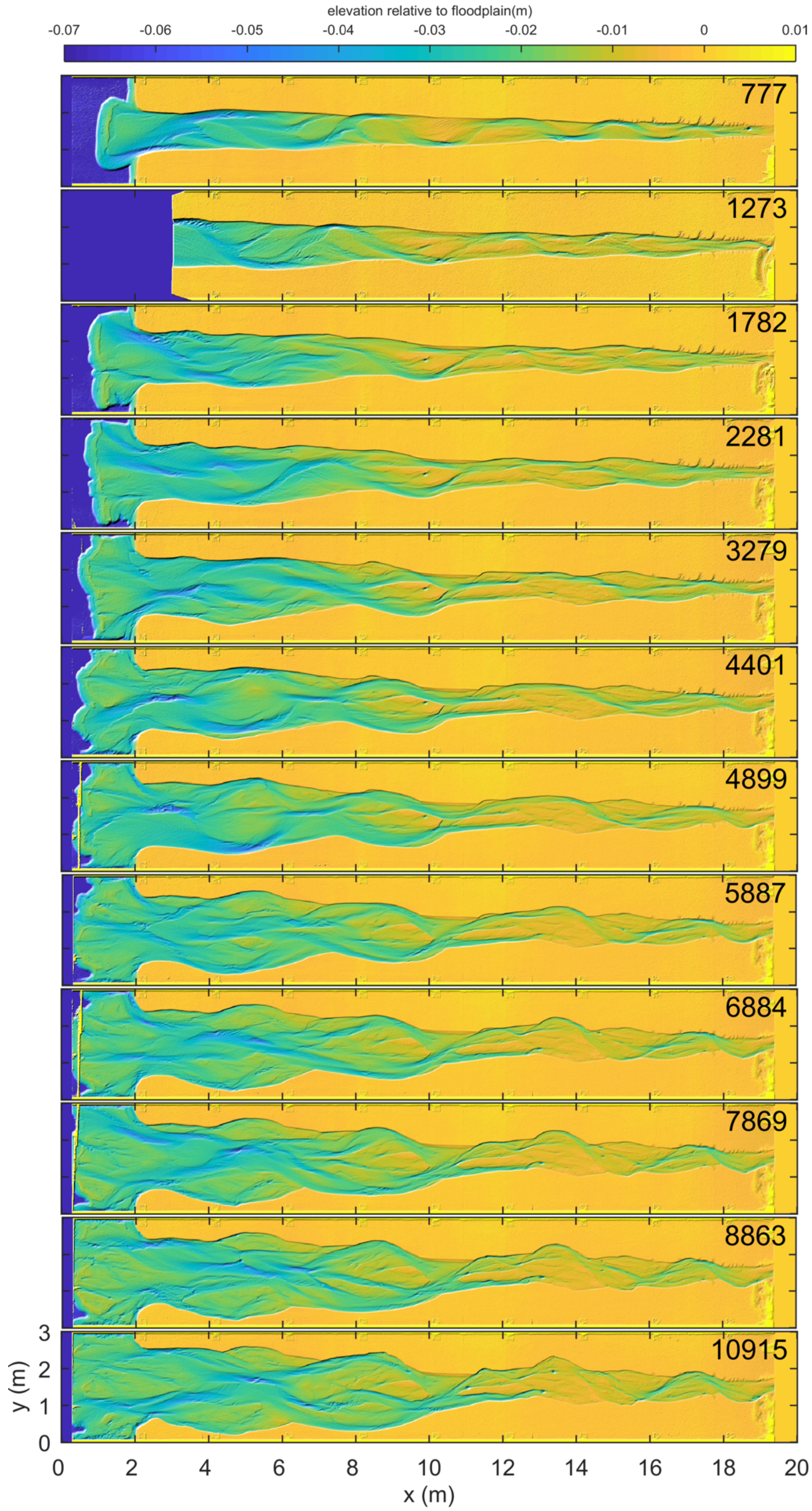
Appendix 4: DEMs of exp043, dredged estuary with SLR.



Appendix 5: All intertidal area maps for exp042 and exp 043.



Appendix 6: DEMs of experiment 006, natural estuary (Leuven et al., 2018)



Appendix 7: DEMs of exp023, dredged estuary (Cox, 2018; Van Dijk et al., 2021).