Utrecht University

Department of Physical Geography

MSc Program Earth Life and Climate

Master Thesis

Anticipating Change: Sea-level Rise-Induced Effects on Estuary Morphology

Sandy estuaries with mud and vegetation in scaled laboratory experiments

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August 25, 2021

1 Abstract

During the mid-Holocene, when sea-level rose rapidly, many estuaries formed. When sea-level rise slowed down during the late Holocene, some of these estuaries filled with sediment, where others remained largely unfilled. Vegetation has an important eco-engineering effect and contributes to estuary infilling. It is unclear however, how net importing estuaries will respond to the current and projected sea-level rise. To this end we conducted scaled laboratory experiments in the 20 x 3 m tilting flume the Metronome, which can simulate tidal currents. By asymmetric tilting, a flood dominated, net importing estuary was created, and sediment was supplied to the seaward and landward boundaries. A mud simulant was used and seeds of plant species with eco-engineering behaviour were supplied into the flow periodically. The channel network evolution through time was mapped using a recently developed network extraction tool. This tool can extract fluvial networks from elevation data in an objective way.

It was found that sea-level rise enhances sediment mobility which, in combination with flood dominance, leads to higher sediment fluxes to the upstream part of the experiment than in experiments without sea-level rise. Sea-level rise also allows tidal currents to propagate further upstream which promotes channel formation upstream in the experiment. Most importantly, sea-level rise causes the morphological units in estuaries to shift landward and the upstream part of the system to silt up, given enough sediment is available to fill the created accommodation. In the case of low sediment availability, which is common in systems in which dams and dikes are built, coastal squeeze may prevent transgression and estuarine environment will drown. Two examples, the Scheldt and the Wadden sea, are considered to illustrate what the fate of estuaries could be, considering the current and predicted sea-level rise. It is found that if sea-level rise stays on the low end of the predictions (40 cm/100 yrs), the Scheldt and the Wadden sea area may aggrade to maintain a stable position. In case sea-level rises faster, these systems are likely to transgress but are prone to coastal squeeze because of man-made hard boundaries directly landward of them. It is therefore expected that many of these systems will drown in the centuries to come, unless we change our coastal management strategy and create more space for systems to silt-up and keep up with sea-level. The findings of this study can contribute to managing estuaries sustainably in terms of sediment budgets, navigability and ecology.

Contents

2 Introduction

Estuaries are partly enclosed coastal water bodies, with an open connection to the sea and substantial fluvial input [De Haas et al., 2018]. These systems house important hubs for global transport and contribute to biodiversity by creating a unique environment at the interface of the river and the sea. During the middle Holocene, many coastal regions drowned in response to rapid sea-level rise, giving rise to many estuaries around the world [Shi and Lamb, 1991, Hijma and Cohen, 2010, Vos, 2015, Job et al., 2020]. Many of these estuaries are now filled, which formed new land [De Haas et al., 2018] that is heavily urbanised. To ensure e.g. safety against flooding and navigability, estuaries are managed by the building of dikes and the dredging of channels. However, most such efforts are unsustainable in the long run [van Dijk et al., 2019]. Dredging removes sediment from estuaries which could otherwise aid raising floodplains and bars, and dike-building often prevents the flooding of floodplains and consequently prevents silting up of the entire estuary.

Additionally, little is still known about how the channel and bar patterns of estuaries will respond to future sea-level rise. Under which conditions can bars silt up to keep up with sea-level rise and how is channel and bar mobility affected with predicted greater water depths? These questions are largely unanswered. It is currently also unknown if the effect that sea-level rise has differs locally within an estuary or if estuaries will show a similar response over their entire surface area. It follows that there is an urgent need for accurate conceptual and numerical predictive models of net importing estuaries that can aid policy makers in strategically and sustainably tackling challenges of drowning, flood risk, infrastructure and urban planning in estuaries around the globe.

Conceptual models of estuary infilling exist [Nichol, 1991, Roy et al., 1980, Dalrymple et al., 1992], but are inferred from the depositional record and focus on (multi)-millennial timescales. These models focus on the large-scale spatial and temporal development of infilling estuaries and are therefore too general to determine changes in channel and bar patterns. For decadal to centennial timescales, an experimental approach has two main advantages. Firstly, the causal relationships between the parameters involved may be unravelled. Secondly, low preservation potential deposits are accounted for whilst creating the model. This study will report on experiments conducted in the tilting flume the Metronome, recreating a net importing estuary with sand, mud vegetation and sea-level rise.

3 Review of estuarine morphology and sea level rise effects

A first order classification of estuaries can be made based on their degree of filling. Estuaries range from being nearly completely unfilled, e.g. the Wagonga Estuary (Australia) or nearly filled estuaries, e.g. the Ems-Dollard estuary (Netherlands-Germany) or the Elbe estuary (Germany). Where on the spectrum a particular case lies is determined by the sediment balance: the ratio between accommodation creation and sediment entering (and staying in) the system. Accommodation is naturally created by compaction (short timescales), background subsidence (long timescales) and relative sea-level rise. Accommodation is filled by sediment input and by vegetation. Sediment sources differ per estuary but typically consist of a mix of fluvial sediment input from the hinterland and marine sediment input, brought in by bed erosion, barrier erosion and alongshore currents. The total amount of sediment and water going in and out of the estuary is the tidal prism. The tidal prism determines how much space is available to form intertidal bars and controls channel volumes [Leuven et al., 2018]. The three most important actors in estuarine systems to consider are wave, river and tidal forces. Ternary diagrams are used to classify estuaries based on the relative importance of these components [Dalrymple et al., 1992, Boyd et al., 1992]. This study will focus on systems with limited fluvial power and a mix of wave and tidal energy.

To illustrate what kind of systems were considered when designing the current experiment, an example of the development of the Dutch coastal landscape is included (Figure 1). This figure indicates the most important steps of the last 12,000 years, shaping the Dutch landscape as it is today, as well as estuaries and tidal basins such as the Scheldt, the Rhine and Meuse estuary, the Ems- Dollard and the Wadden sea. Starting with large scale transgression of the coast during the mid-Holocene sea-level rise. When this sea-level rise slowed down the coastline was aggrading or slowly prograding, building out to the coastline we see today. This example is representative for estuaries and tidal basins during the Holocene and is meant to illustrate the temporal and spatial scales that the experiment is simulating.

The following sections will discuss the most important findings from the literature on sea-level rise effects on estuary morphology, eco-engineering effects of mud and vegetation and numerical models of estuaries. Next, field studies of estuaries, dynamical equilibria and laboratory experiments with mud and vegetation are discussed. Lastly, the network extraction method used for the analysis of elevation data is explained.

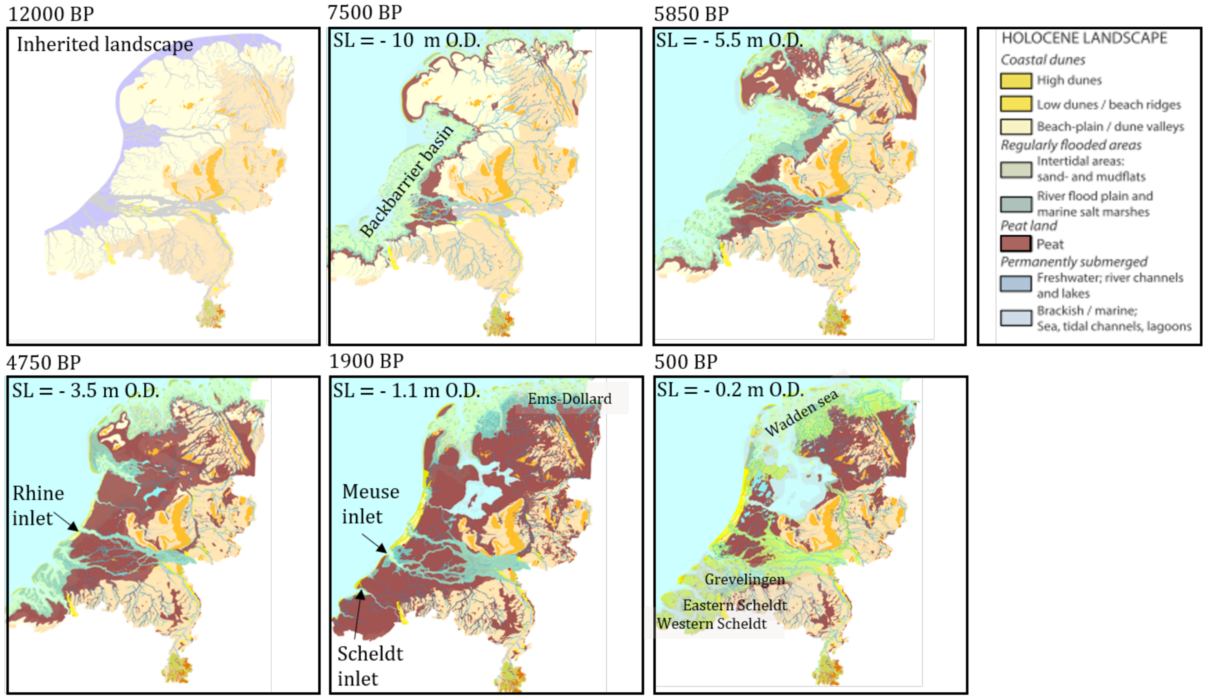


Figure 1: Evolution of the Dutch landscape from 12,000 BP to 500 BP. Modified from [Vos, 2018].

3.1 Effects of sea-level rise on estuary morphology

Estuaries are among the most populated areas world-wide. Sea-level rise is expected to affect estuaries in terms of shipping [Van Dijk et al., 2021], flood risk [Leuven et al., 2019] and change of ecologically important areas (e.g. mangroves and intertidal area) [Xie et al., 2020]. Sea-level rise may also affect the estuarine morphology. Three boundary conditions are expected to control estuary morphology when sea-level rises: sediment supply, tidal amplitude at the estuary mouth and planform shape [Leuven et al., 2019]. Assuming constant accommodation creation, sediment supply determines if a system is prograding, aggrading or retrogradating and if sediment is available for the accumulation of intertidal area by the growth of bars. The tidal amplitude determines the tidal prism, which is important for channel volume and creates space for intertidal bars. Most estuaries are near-equilibrium at present, meaning in this case that on decadal timescales, accommodation creation is balanced by sediment accumulation and the system aggrades to maintain a stable position. This equilibrium is disturbed when sea-level rises and the system will change hydrodynamically, in turn affecting the morphology. Because of sea-level rise the channels deepen, increasing flow velocities, bed-shear stresses, sediment mobility and tidal currents may propagate further upstream. The tidal amplitude at the estuary mouth is determined by the distance between the amphidromic point and the estuary mouth. If the distance increases, so does the tidal amplitude, although this effect is most apparent in semi-enclosed basins such as the North Sea. Amphidromic points are expected to shift as a result of sea-level rise [Idier et al., 2017], changing the tidal amplitude of estuaries. It is unknown how exactly sea-level rise and changing tidal amplitudes will affect tidal wave propagation and bar dynamics in estuaries [Du et al., 2018, Leuven et al., 2019]. Estuary planform determines tidal current propagation by dissipation of energy by internal and bottom friction. Tidal amplification is also a function of estuary planform due to convergence and reflection of the tidal wave at the landward boundary [van Rijn, 2011].

Numerical modelling of sea-level rise in 36 estuaries of varying size and shape suggest the following effects in response to sea-level rise [Leuven et al., 2019]:

1. Deep systems are more prone to sediment starvation, in particular when the tidal amplitude decreases. This is because the changes in tidal prism are the result of changes in tidal amplitude spread over the surface area of the basin, which in these types of estuaries is relatively large. A change in amplitude at the estuary mouth thus needs a relatively large change in sediment input to maintain equilibrium.

2. Small and shallow estuaries are more friction dominated and therefore more prone to tidal amplification. An increase in sea-level reduces the friction in the estuary, which tends to result in tidal amplification.

Besides the cross-sectional dimensions of the estuary, also the estuary length is an important parameter governing the hydro-dynamic response of an estuary to sea-level rise [Du et al., 2018]. What remains unknown, is what the morphological response of bars and channels will be in the estuary when sea-level rise forces a change in tidal amplitude.

3.2 Effects of mud and vegetation

landscape scale experiments

Most studies on the effect of mud and vegetation in estuaries use numerical models. Relevant field data for estuaries spanning multiple decades is sparse. Physical experiments have mostly focused on rivers [Dijk et al., 2013] and deltas [Hoyal and Sheets, 2009, Grimaud et al., 2017]. A few experimental cases of estuaries were studied [Leuven et al., 2018, Braat et al., 2019, Weisscher et al., 2021]. These studies highlight the eco-engineering effect of mud and vegetation. The experiments conducted by Weisscher et al. [2021], comprise sand only, sand and mud, sand and vegetation and sand, mud and vegetation experiments, of which the last one is identical to the current experiments except that sea-level rises in the current experiment. These experiments will be a recurring point of reference for this study because in concert with the current experiments, they allow for a discussion on sea-level rise effects on estuary morphology. The most important findings from the mud and vegetation experiments without sea-level rise are: Mud affects estuaries by filling accommodation in the low energy zones such as inter-tidal bar tops and depressions in the inter-tidal and supra-tidal areas. By this filling-mechanism estuaries become shallower and increasingly muddy in the upstream direction. Furthermore, sub-tidal channels in the upstream part of the system are filled with mud, reducing the tidal prism [Weisscher et al., 2021].

Vegetation increases hydraulic resistance of the bed and thereby reduces flow velocities, creating more favourable conditions for mud settling. As a result, supratidal areas form more rapidly compared to experiments without vegetation. Vegetation and mud both have a positive effect on the colonising and settling of the other but also occur in isolation. Mud and vegetation both reduce flow outside of the channels, and thereby reduce the lateral migration of bars, stabilising their position and focusing flow in channels.

numerical modelling

Until recently, numerical models often simulated estuaries with either sand or mud, not both. Modelling sand and mud together is difficult because interaction between them occurs. It is important to include cohesion in models because the ability of a system to re-erode sediment reduces with higher cohesion. This results in longer and deeper channels and bars and levees become more stable [Braat et al., 2017]. Models that do include mixed sediments are e.g. [Van Ledden et al., 2004, van Kessel et al., 2011, Dam et al., 2016, Braat et al., 2017]. Numerical model simulations with sand and varying concentrations of mud, showed that mud reduces channel and bar dynamics and confines an estuary through the development of mudflats that protect the outer bars from erosion [Braat et al., 2017].

Vegetation models are used which asses the role vegetation has on estuary development [Lokhorst et al., 2018, Brückner et al., 2019, Xie et al., 2020] by coupling them to hydrodynamic models. These models show a positive feedback between mud settlement and vegetation colonisation, where mud and vegetation result in channel incision and flow-focusing on a decadal timescale and estuary infilling on a centennial scale. Vegetation and mud do not only co-occur throughout the estuary, but their relative abundance also increases compared to mud-only or vegetation-only runs [Lokhorst et al., 2018]. Numerical models often struggle to simulate net importing estuaries, which makes them unfit for addressing the research aim of this study. An exception is Albernaz et al. [2020], who showed that tidal-influenced environments may be susceptible to an infilling feedback loop. This mechanism works by variations in water discharge, e.g. floods and tides, which when combined with vegetation and sediment supply effectively form levees and crevasses. These morphological units retain sediments in the basin. Accommodation is filled and potential tidal prism growth reduces. This feedback loop is a valuable insight that cannot be obtained from scaled laboratory experiments because variations in tides have so far not been reproduced experimentally. Flooding implies punctuated large volumes of water coming into the basin, which has so far not been done in experiments either.

3.3 Field studies of estuaries and dynamical equilibrium

Many active estuaries today formed during the mid-Holocene sea-level rise when river valleys and glacial valleys drowned. Some of these systems have filled with sediment and became deltas and others are still active today. In the case of a balanced in and outflow of sediment, the system is considered to be in dynamic equilibrium. This means that the systems is dynamic on the scale of channels and bars, but the system as a whole is aggrading to maintain a stable position. Numerical modelling [Dam et al., 2016], and landscape experiments [Braat et al., 2019] suggest that estuaries develop equilibrium, given enough time has passed. A literature review of idealised numerical model data and field data of the Netherlands suggests that river connection is required for estuaries to stay open. On the contrary, tidal embayments which are disconnected from rivers are transient features which will silt up and become closed off [De Haas et al., 2018]. Something that is often lacking in numerical and laboratory studies is the eco-engineering potential of bentic fauna and vegetation and muddy sediment. In fact, field studies suggest that estuarine sediments often show abundant bioturbation [Gingras and MacEachern, 2012], and estuarine vegetation has a significant effect on sedimentation [Li and Yang, 2009]. Including these eco-engineering effects in numerical and laboratory settings are thus a much needed next step in modelling estuarine environment.

3.4 Scaled landscape experiments with sandy, muddy and vegetated estuaries

Scaled laboratory experiments provide insights complementary to numerical modelling and field studies because in the lab all processes are included, acting on the real materials with all their properties, which are often difficult to capture in numerical models and hard to see in the field. Scaled laboratory experiments have mostly focussed on rivers [Dijk et al., 2013] and deltaic systems [Grimaud et al., 2017, Hoyal and Sheets, 2009], but are sparse for estuaries. From such studies in the lab we have learned that cohesive sediment plays an important role in bar stability and the erodibility of the bed [Braat et al., 2017, Dijk et al., 2013]. Experiments which included vegetation and a mud simulant showed that mud and vegetation settle on inter-tidal bars and the bay-head delta, help stabilise the position of bars and confine flow in the estuary [Weisscher et al., 2021]. This suggest that mud and vegetation may contribute to bars keeping up with sea-level rise, though up until now estuaries with mud and vegetation have not been subjected to sea-level rise in an experimental setting. The experiments by Weisscher et al. [2021] further showed a shift from wave dominance to a mix of wave and tidal energy with a minor fluvial component over the course of the experiment.

3.5 Identification of channel networks

Estuaries can be considered as systems of channels and bars, which merge, split, meander and braid to form sometimes intricate patterns. Where two channels join together this is called a confluence. Where channels split it is called diffluence. Channels occur on many different scales, ranging from main channels up to tens of meters water depth to smaller channels connecting larger channels with water depths < 1 m. Especially in braiding estuaries, the fluvial network typically consists of a large number of channels with abundant confluences and diffluences, where the confluences and diffluences are network nodes, and the channels connecting them are links (Figure 2). Networks can be described mathematically which is useful in describing and analysing the evolution of estuarine networks through time.

Formally, a network consists of a number of nodes which are connected by links. The links and link lengths determine the relationship between nodes. The resulting network of nodes and links and their spatial relationships is called a topology. Such a topology can be represented in an adjacency matrix. In adjacency matrices, rows and columns contain nodes. All cells correspond to a link between these nodes and the cell value indicates the link length. For example, the distance between node A and B is 2 (Figure 3). For fluvial and tidal systems, networks can be computed based on a digital elevation model (DEM). Often these methods rely on surface gradients [Pelletier, 2004] and flow accumulation [Tarboton et al., 1991]. These methods successfully extract networks from DEMs in converging systems but are do not work well in systems that have multiple active channels and bifurcations. Flow does not necessarily follow the path of steepest descent at confluences. Negative slopes may occur at bifurcations and channels may flow over bars, which makes them hard to be identified as a channel by local path-seeking algorithms [Hiatt et al., 2020].

For the extraction of channel networks from the Metronome the recently developed Topological Tools for Geomorphological Analysis (TTGA), will be used. This tool provides an objective and mathematically rigorous way to extract fluvial networks from elevation data [Kleinhans et al., 2019, Hiatt et al., 2020]. The utility of the software shows from its ability to quantitatively determine which channels can be considered the same and which are sufficiently different by using a parameter set by the user: *the sand function*. *The sand function* computes how much sediment separates two channels. The user sets a sediment volume threshold above which two channels are considered individual channels, assuming more sediment requires more time to be removed. The sediment volume separating channels is a meaningful way to quantify to which degree channels are the same, because these volumes correspond to an amount of morphological work required to remove the sediment and merge the channels. The threshold parameter helps reduce the network tool output data. The tool allows for easy experimentation with the threshold parameter until a network is extracted which captures the essentials of the fluvial network but is not obscured by details.

The tool was applied on varying scales with different research aims such as shoal margin collapse in the Scheldt [van Dijk et al., 2019], dredging in the Scheldt and in scaled laboratory experiments [Van Dijk et al., 2021], channel network extraction from elevation data from the braiding Waimakariri river (New Zealand) and DEMs from morphodynamic numerical models [Hiatt et al., 2020]. In the Scheldt estuary for example, the network tool was used to study how dredging shipping channels affects channel networks. The network tool was used to extract estuary topologies from numerical model runs simulating different scenarios of dredging. The utility of the tool shows because it allows for objective mapping and quantification of network evolution which is cumbersome if not impossible without such an extraction tool.

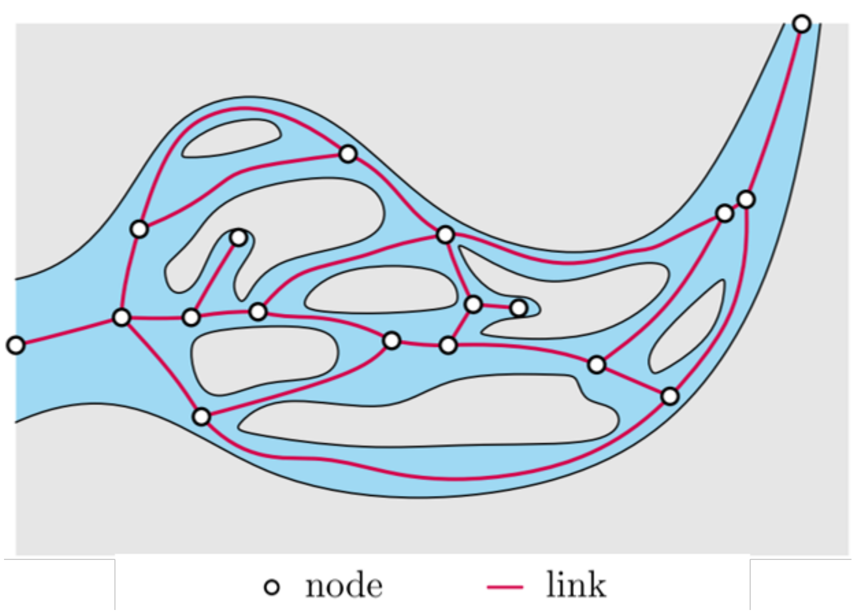
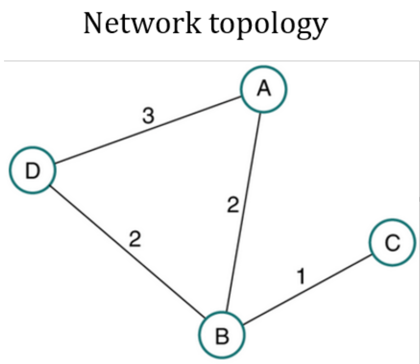


Figure 2: Example of how a braiding system consists of channels, diffluence and confluences. This can be represented as a network of nodes (confluences and diffluences) and links (channels). From Hiatt et al. [2020].



Adjacency matrix

Rows	A	B	C	D
A	0	2	0	3
B	2	0	1	2
C	0	1	0	0
D	3	2	0	0

Figure 3: Example of how a network topology can be translated to an adjacency matrix. The rows and columns represent nodes and the entries in the table indicate the link length. When the length of a link is zero the nodes are unconnected. Modified from [Settle et al., 2018]

3.6 Knowledge gap, research scope and hypotheses

The combined effort of numerical models, scaled landscape experiments and field studies illustrate how vegetation and mud affect estuarine morphology and how sea-level rise is expected to change the hydrodynamics and sedimentation processes in estuaries. There is an urgent need for studies that integrate these parameters and study how sandy estuaries with mud and vegetation respond to sea-level rise.

There are three main hypotheses predicting how net importing estuaries will morphologically respond to sea-level rise. Firstly, the system may drown completely, if accommodation creation overwhelms sediment input. Sub-tidal areas will rapidly increase at the expense of inter-tidal and supra-tidal areas. Secondly, the system may aggrade to maintain a stable position. This scenario requires accommodation creation to be balanced by sediment supply. Locally bars may form and grow but at the expense of drowning of other inter-tidal areas. Thirdly, the system may shift landward. Channel and bar patterns may shift upstream, given enough space is available for morphological units to move in this direction. This hypothesis likely means drowning of the downstream part of the estuary and sediment accumulation in the upstream part.

Furthermore, the total intertidal area is expected to decrease, because many estuaries retain too little sediment to silt-up the bathymetry of the entire surface area of the system. Therefore, some of the intertidal area will be lost as a result of sea-level rise. The intertidal area is expected to decrease more in the downstream half of the estuary than in the upstream part because of the enhanced bar migration into the upper estuary.

When sea-level rises water depths in the channels increase. This results in higher flow velocities and lower bed friction, creating a larger tidal prism. Because of the asymmetrical tilting this may result in a minor shift of nodes in an upstream direction. The number of main network nodes is expected to remain constant during sea-level rise as the tilting frequency and flume length remain constant throughout the experiment.

Reconstructions of Holocene estuaries and tidal embayments show that the long term evolution of these systems is affected by mud and vegetation. If mud and vegetation are abundantly present, this promotes the continuous import of fine sediment. Consequently, intertidal and supratidal areas grow [De Haas et al., 2018]. It is expected that mud and vegetation will begin to settle in the low-energy areas: shore-connected bars and the bay-head delta. Flow velocities over these bars are reduced by vegetation and bar edges are stabilised by mud, limiting sediment transport from the bars. This may create a positive feedback: bars with mud and vegetation grow faster than bars without mud and vegetation. When sea-level rise starts, the muddy and vegetated areas will keep up with sea-level longer than the non-vegetated bars. This is in accordance with findings from previous Metronome experiments showing that mud and vegetation promote bar longevity and increase elevation [Weisscher et al., 2021]. As well as numerical experiments showing that vegetation increases hydraulic drag, stimulating salt marsh expansion.

Alternatively, higher hydraulic resistance because of vegetation on bars may cause prolonged inundation times of bars. Prolonged inundation may enhance mortality, resulting in a negative eco-engineering effect [Brückner et al., 2019] and a faster drowning of vegetated bars compared to unvegetated bars.

4 Methods

4.1 Experimental setup

To test the hypotheses of sea-level rise effects on estuaries, a scaled landscape laboratory experiment was conducted in the Metronome. All settings were kept the same as the experiment with sand, mud and vegetation in [Weisscher et al., 2021], except the current experiment has forced sea-level rise. The Metronome is a 20 x 3 m flume and was designed to simulate tides by periodic tilting over its short central axis (Figure 4) [Kleinhans et al., 2017]. Two experiments were done, namely a control without mud and vegetation and an experiment with mud and vegetation. The control experiment comprised a sandy estuary with sea-level rise and was run over 10,000 tidal cycles. Sea-level rise started at 4,000 cycles and was increased 2 mm every 1,000 cycles up to 8,000 cycles, which was a total of 8 mm sea-level rise. Based on the response of the control experiment to sea-level rise, as well as creating more opportunity for vegetation to sprout because of shorter inundation times, a different sea-level rise was forced on the main experiment. The main experiment comprised a sandy estuary with mud, vegetation and sea-level rise over 10,000 tidal cycles. Sea-level was increased by 1 mm every 1,000 cycles from 3,000 to 10,000 cycles. In this thesis the first 6,000 cycles of the experiment will be shown and discussed.

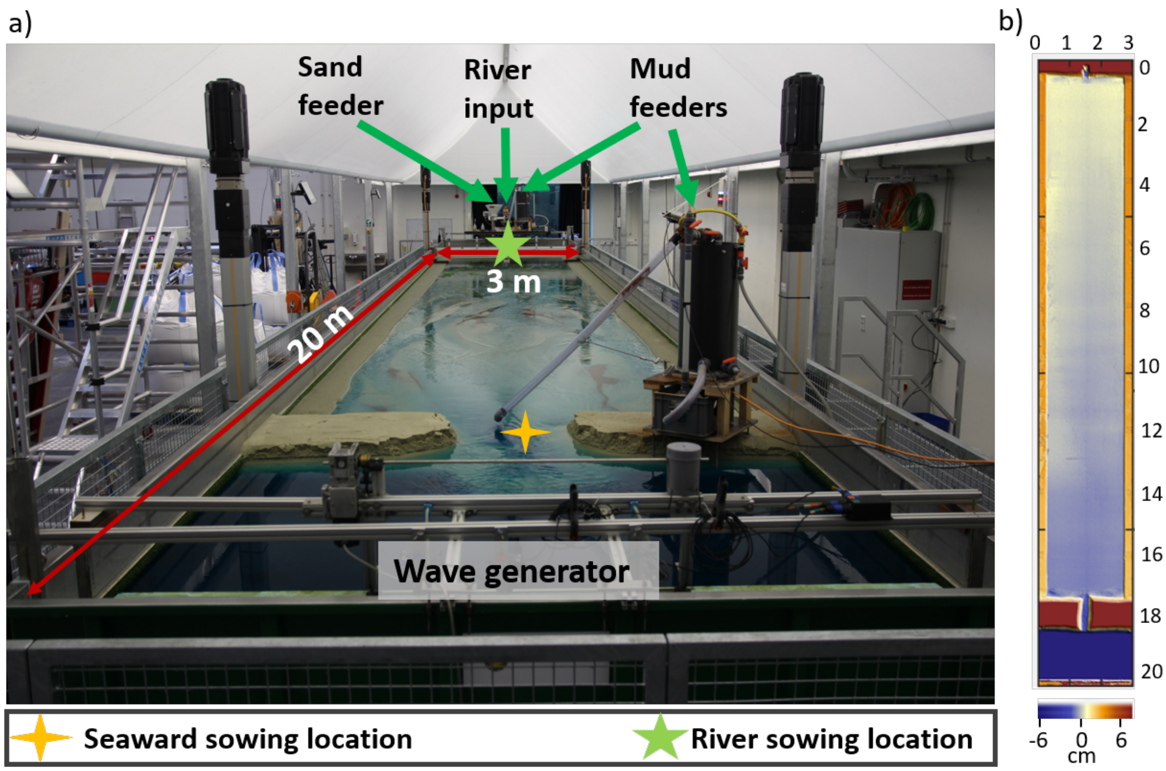


Figure 4: a) Experimental setup of the experiment. The photo was taken around 2,000 cycles into the experiment with mud and vegetation. b) Digital elevation model of the initial bathymetry of the experiment. The increasing slope towards the landward boundary is an artefact of the DEM creation.

The initial setting of the estuary was shaped after Weisscher et al. [2021] and resembled an idealised drowned river valley with an open barrier coast and a large lagoon. The entire bathymetry was flooded at high tide with the exception of the barrier islands, the banks and part of the bay-head delta. A flat valley of 2.4 m wide and 3 cm deep was carved between the river and the barriers in the 11 cm thick sand bed.

Creating tides in experimental settings has been done [Stefanon et al., 2009], but comes with challenges. Simply raising and lowering the sea-level in the flume results in low flow velocities which hardly have the capacity to move the sediment. This results in ebb-dominance and rapidly dissipating marine influence in the upstream direction [Kleinhans et al., 2014]. Many of these mobility related scaling issues have been solved by tilting the flume over its short central axis [Kleinhans et al., 2017]. This creates currents with ample transport capacity in both the ebb and the flood direction and tidal currents penetrate further upstream in the estuary. Morphologically dynamic estuaries with mudflats [Braat et al., 2019] and tidal bars and channels [Leuven et al., 2018] were created in previous Metronome experiments.

A weir controlled the sea-level and maintained a constant water level at the seaward boundary, relative to a reference level outside of the Metronome. This means that when the river side of the Metronome goes up, so does the seaward weir. In this way tidal currents are created whilst maintaining a constant head. During the flood phase, waves were generated at the seaward boundary with a frequency of 2 Hz and a wave amplitude of 3 mm. The waves mobilised sediment from the barriers and ebb tidal delta and thereby contributed to bringing sediment into the estuary. In order to create an importing estuary, tidal asymmetry was forced by tilting the Metronome faster during the flood phase than during the ebb phase. Since sediment transport scales non-linearly with flow velocity, this means that the difference in peak flow velocity between flood and ebb flow determines the net sediment transport direction, more so than the differences in duration of the currents [Dalrymple et al., 2010]. The flood dominance causes flood currents to become stronger than ebb currents, creating a net importing estuary, which is common in nature too, e.g. along the Dutch coast [De Haas et al., 2018]. Simulating alongshore transport of sand and mud was not feasible in this experimental set-up. The barrier islands are therefore made disproportionately large to supply sufficient sediment to the estuary.

Mud was simulated by crushed walnut shell which was shown to behave similar to mud in natural estuaries [Baumgardner, 2016, Braat et al., 2019]. Once per tidal cycle, fluvial mud was added to the river discharge and marine mud was added between the barrier islands. Both feeders added 0.4 L/h of mud (including porosity) to the estuary. Walnut of three different grain sizes was used: 0.45-0.8 mm; 0.8-1.3 mm; 1.3-1.7 mm and was mixed 1:1:1. When the nutshell was not reworked for a day, a film of mold formed. This darkened the colour and created slight cohesion of the nutshell grains [Baumgardner, 2016].

Because of the experimental setup we have great control on how much sediment goes into the basin and how much accommodation is created by rising sea-level. Thus, it is possible to calculate accommodation/sedimentation (A/S) ratios, to sketch the a priori fate of the estuary and formulate hypotheses. Sea-level rise is 1 mm per 1,000 cycles, over an area of about $18 \times 2.5 = 45$ m^2. In terms of volume this equals 45 l of accommodation being created every 1,000 cycles. At the same time 0.4 l of sand and $2 \times 0.4 = 0.8$ l of mud are added to the estuary. The barriers are eroded at a pace of 10 l/1,000 cycles per barrier = 20 l/1,000 cycles, based on estimations from the control experiment. This amounts to an estimate of 33 l of sediment put into the estuary every 1,000 cycles. A/S is thus 45/33. This means the system will probably be slightly transgressive.

scaling

Scaling real-world km scale sedimentary systems down to a laboratory scale comes with challenges. Since certain boundary conditions and system properties such as grain size and bed shear stress cannot be scaled in exact proportion, dynamic similarity cannot be fulfilled [Kleinhans et al., 2014]. A degree of similarity is possible when the most important forces are scaled proportionally and less important ones are not. The length scale of the experiment was roughly 1:1,000. For a 20 x 3 m flume this entails a 20 x 3 km estuary. Although the experiment is designed to allow for comparison with systems on all scales, from natural estuaries such as the Scheldt or the Elbe estuary, but also man made polders or tidal basins like the Wadden sea.

Scaling grainsizes in laboratory-scale experiments is a trade off between sediment mobility and hydraulic roughness which both depend on particle size. This was solved by using a poorly sorted, uni-modal sediment with a grainsize of $d_{5_0} = 0.55$ mm, $d_{1_0} = 0.32$ mm and $d_{9_0} = 1.2$ mm with the aim to avoid hydraulic smoothness and disproportionately large scours. For an extensive discussion of scaling sediment like this see Kleinhans et al. [2014].

vegetation protocol

For vegetation, three species were used that represent different eco-engineering species in a laboratory setting [Lokhorst et al., 2019]: *Medicago sativa*, commonly known as Alfalfa, *Lotus pedunculatus* and *Veronica beccabunga*. Alfalfa has relatively large seeds which are transported as bed load. This vegetation resembles large riparian vegetation such as willows and sedges. *Lotus* and *Veronica* have smaller seeds which are transported as bed and suspended load, depending on the flow conditions. These species represent smaller and more aquatic vegetation such as grasses and reeds [Lokhorst et al., 2019]. Vegetation in estuaries was shown to cause hydraulic resistance [Brückner et al., 2019] and thereby reduce flow velocities on the bars, allowing for salt march expansion and increased inundation periods.

Seeds were supplied to the Metronome after every 500 cycles, starting at 1,000 cycles, through both the river and the tidal inlet. Each sowing event 80,000 seeds of the three species were supplied at the river end of the Metronome. The same amount of *Lotus* and *Veronica* was supplied to the tidal inlet.

Seeds were soaked for 24 hours to increase sprouting potential prior to sowing. Sowing was done after the flume was re-filled, following dry photography of the morphology. The Metronome was wetted for 10 cycles before sowing occurred at the rate of a spoon per cycle over the successive 25 cycles. At the inlet side a spoon per cycle was added for 10 cycles in the main channel just landward of the inlet. The seeds were redistributed in the Metronome for another 25 cycles, adding up to a total of 70 tidal cycles for the whole sowing event.

After sowing, the Metronome was stopped at an offset slope of 0.001 m/m for 4 days to allow for sprouting. A river discharge of 300 L/h was applied to prevent the bed from drying out and sea-level was kept at the current mean sea-level position. So, the sprouting period sea-level increases in the same way as sea-level during the experiment.

4.2 Data collection and analysis

Orthomosaics and digital elevation models (DEMs) were made every 1,000 cycles by means of stereo-photography. Before shooting stereo photos, the Metronome was drained slowly without disturbing the morphology. When dry, 20 targets were placed at the sides of the bed and oblique photos were made every 0.5 m, covering the full flume. A digital single-lens reflex camera was used to take pictures which were processed in Agisoft Metashape (structure-from-motion software).

The recently developed Topological Tools for Geomorphological Analysis (TTGA), provides an objective way to extract fluvial networks from elevation data [Kleinhans et al., 2019, Hiatt et al., 2020] (Figure 5). This tool computes multiple lowest paths for different channels which can combine and split at confluences and diffluences respectively. In this way, a network plane is created from multiple channels. The algorithm uses a threshold parameter to consider channels to be the same or different [Kleinhans et al., 2019], which allows the user to tune the program to their question. This threshold parameter is a method to determine whether two channels should be considered the same or not. The parameter is based on the sediment volume separating two channels. This volume corresponds to an amount of morphological work that needs to be done to remove the sediment and merge the channels. With this tool, the network evolution through time can be mapped and quantified in an objective and mathematically rigorous manner. Combining a network extracting algorithm with flume experiments allows for an evaluation of how the TTGA performs within the parameter space (e.g. experiment dimensions, shields parameter, surface slope) of the experiment. Contrary to natural scale systems, in experiments the water can be drained out of the estuary allowing for detailed observations and monitoring. This allows us to develop an intuition for how the network tool works and use it in a meaningful way.

The network tool topologies were processed in the following ways. The main channels that were extracted by the tool were used to calculate sinuosities. After smoothing the lines, the total channel length was divided by the flume length. Two different threshold parameters were used. In one case only the main channel was extracted and in the other case the ten most important channels were extracted.

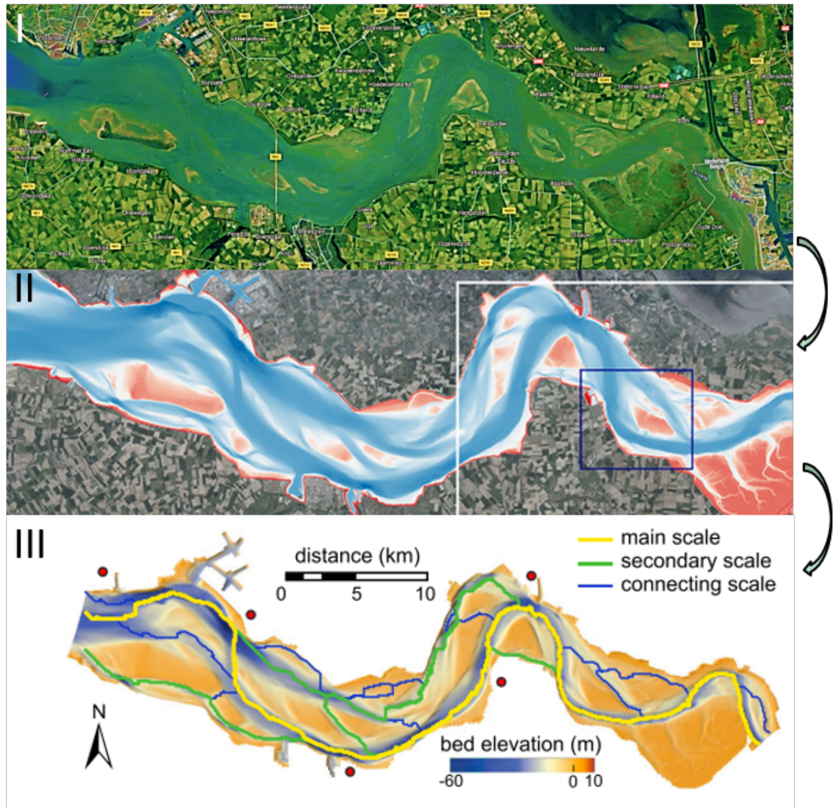


Figure 5: Processing steps to extract estuary networks:from orthophotos or LIDAR (I) a DEM is constructed (II). This DEM serves as input for the network extraction tool which computes the channel network (III) attributing a weight to the various channels. I) from google.maps.com, II) from Brückner et al. [2019], III) from van Dijk et al. [2019].

5 Results

5.1 General estuary development

The general development of the estuary (Figures 6, 7, 8) showed an infilling estuary with a densely vegetated bay-head delta, an increasing extent of mud deposits and salt marshes along the entire estuary, and barrier erosion. When describing various estuary properties in the following sections references will be made to the right and the left side of the flume. The right side of the flume corresponds to y = 0 and the left side to y = 3.

Initially, a low-amplitude rhomboid bar pattern quickly developed in the sea-ward half of the estuary. From this initial bar pattern, a large flood-tidal delta and small ebb-tidal delta formed near the tidal inlet and a bay-head delta formed at the upstream end of the estuary. The bayhead delta built out towards the right side of the flume and avulsed to the left side between 2,000 and 3,000 cycles. Channels are progressively deepening and start to incise further upstream in the Metronome. Until 4,000 cycles the bed between 4 and 10 m hardly shows any morphology. It was observed that sediment mobility in this region is low, close to the threshold of motion for the first 2,000-3,000 cycles. Between 0 and 6,000 cycles channel incision starts to shift upstream until the tidal currents create morphology up until the bay-head delta fringe from 4,000 cycles onward.

Vegetation colonisation patterns were different for the three species. The large *Med-*

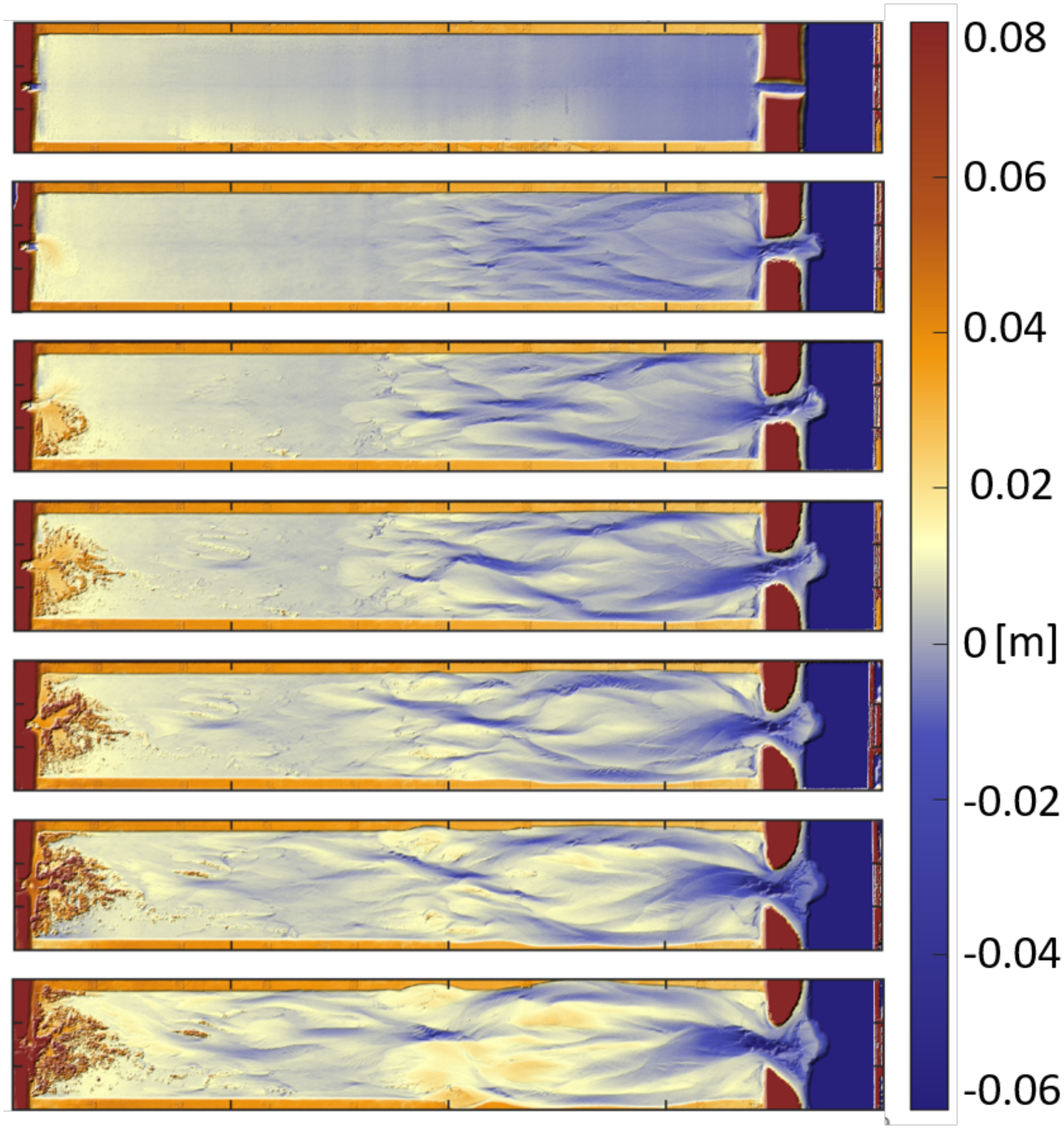


Figure 6: Digital Elevation Models (DEMs) of the first 6,000 cycles. High elevations between 0 and 2 m are the result of vegetation.

icago seeds settled near the bay-head delta and the flood tidal delta. A small portion of the seeds was transported up to about halfway the estuary. The smaller *Lotus* and *Veronica* seeds were distributed through the entire estuary and partially transported out of the tidal inlet during ebb. Initially, *Medicago* was the dominant species on the bay-head delta (Figure 8, II). From 4,000 cycles onward, the other two species also settle here abundantly.

After the first bay-head delta avulsion at 2,000 cycles, the active part of the delta had a main channel with several branches where water flowed into the estuary. Much of the vegetation on the intertidal and supratidal bars had perished and was intermingled with live vegetation. Some of the *alfalfa* seeds reached a stem height of 5 cm. Seeds spread further into the basin and settled on or at the lee side of bars. Some *Veronica* seeds settled and sprouted close to the barrier island on the right-hand side in the coarse mud. Vegetation patches are creating lees for the water flow and sediment settles on a preferred side, depending on the dominant flow direction. Steep bar erosion takes place in the middle of the flume (Figure 8, I).

Vegetation and mud are stabilising the bar and protect it from further erosion. Some vegetation sprouts on the flats next to the tidal inlet, but they are washed away in the subsequent tilting cycles. No vegetation persists in this area. Vegetated bars affect where active channels can form. Channels make their way around vegetated bars and migrate laterally around these areas (Figure 8, V). Much of the vegetation that colonised the bay-had delta died by around 3,000 cycles due to prolonged inundation and mold growing between the vegetation. After this period of lower vegetation density on the bay-head, new vegetation re-settled the previously vegetated areas as well as new areas spreading more laterally and even settling the raised outer banks of the experiment.

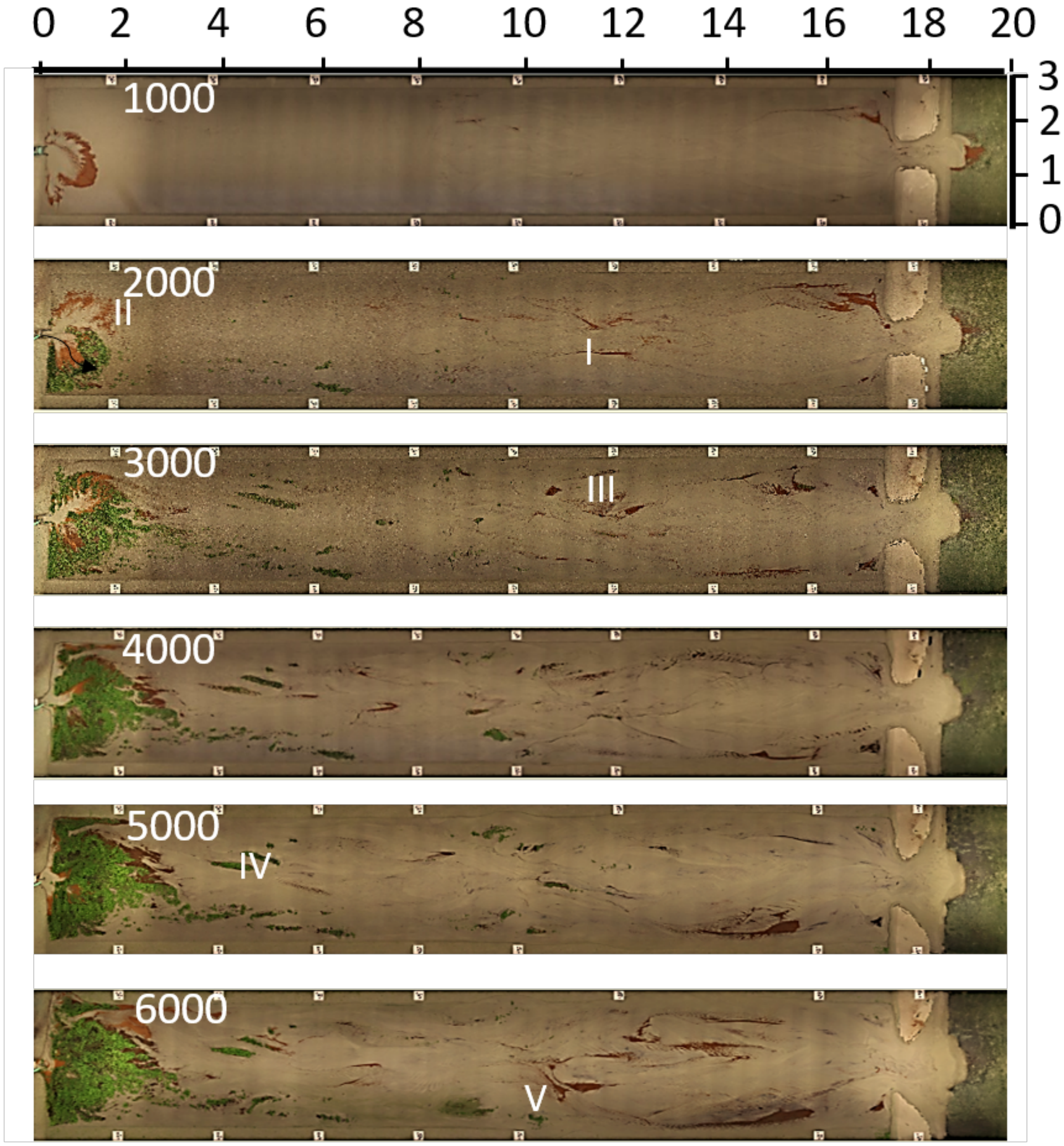


Figure 7: Orthophotos of the experiment showing the morphological evolution of the experiment in time. After the delta avulsion between 2,000 and 3,000 cycles, the bay-head delta changes from a single thread to a multi-thread delta. Numerals I-V correspond to the photos in Figure 8.

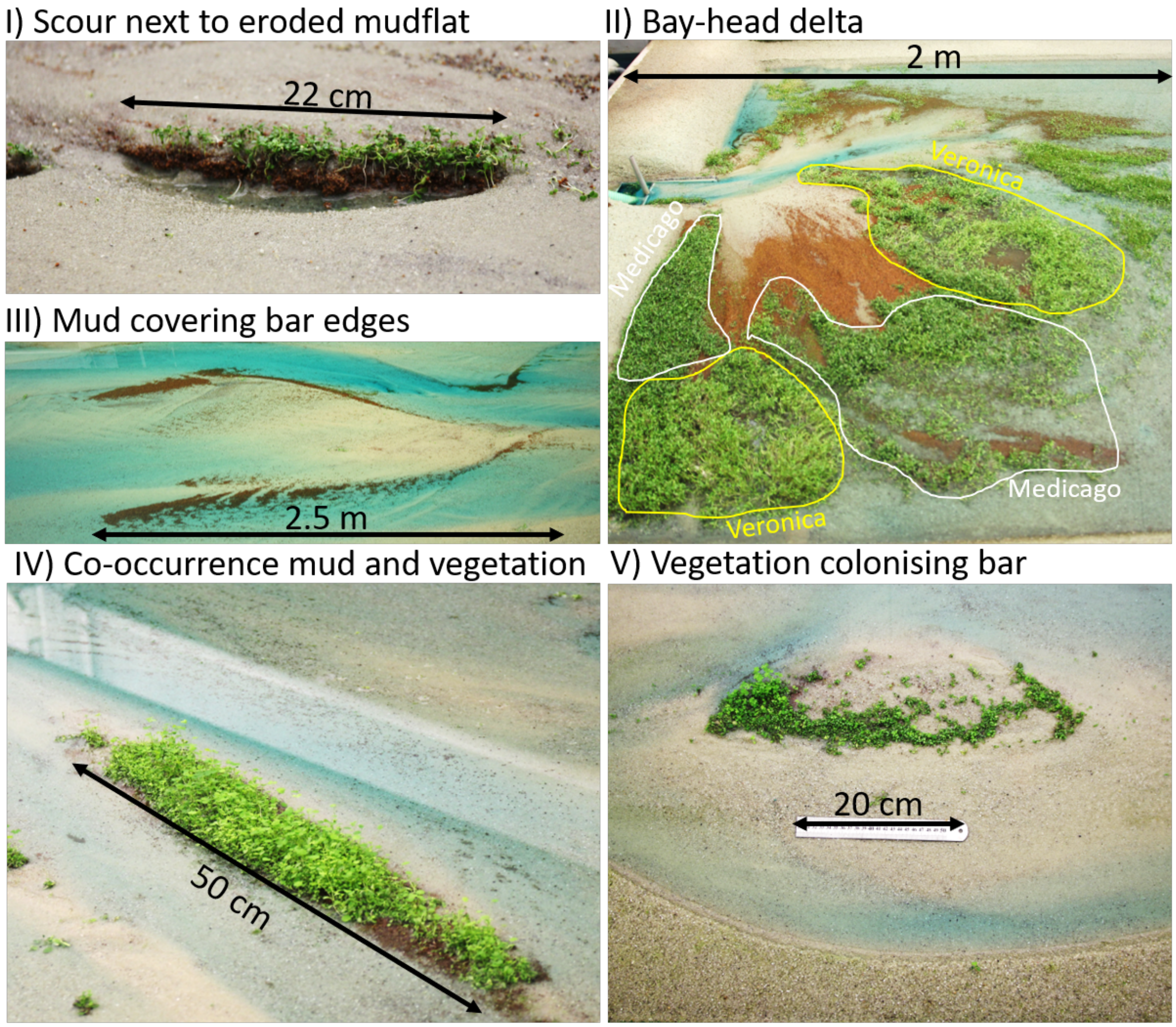


Figure 8: Effects of mud and vegetation on morphology. I) A scour cuts a mudflat overgrown with vegetation. II) the bay-head delta just after 2,000 cycles following a recent delta avulsion. Different colours of vegetation correspond to *Medicago* (darker) and *Veronica* (lighter). III) Nutshell settling along subtidal bar fringes, IV) Co-occurence of mud and vegetation, V) Vegetation on intertidal bar with bank erosion where flow goes around the vegetated bar.

As for the effect of mud, the large mud fraction concentrated in two locations: the toe of the bay-head delta and the newly formed fringes flanking the flood tidal delta. Finer mud fractions spread throughout the estuary but are more difficult to observe. The smaller fractions mix with the sand and are often buried. From 3,000 cycles onward, mud concentrated at the channel-bar interfaces, more so than on the bar tops (Figure 8, III). Vegetation and mud are often co-occurring on bars where vegetation reduces flow velocities which allows mud to settle (Figure 8, IV).

During the experiment, accommodation in the estuary progressively fills with sediment. Simultaneously, sea-level rise creates accommodation. Whether sedimentation keeps up with sea-level rise or not varies locally. Some bars, especially the vegetated ones, manage to remain on the inter-tidal, supra-tidal boundary. Others are inundated longer as sea-level rises. This increased inundation time of bars with vegetation sometimes means the vegetation dies. The increased inundation also affects sprouting of seeds during sprouting periods. Bars close to the tidal inlet receive abundant seeds during the sowing periods. Between 1,000 and 3,000 cycles, some vegetation settled here, which was mostly washed away in the subsequent tidal cycles, except for some small patches close to the left barrier (Figure 7, 3,000 cycles). But from 4,000 cycles (3 mm sea-level rise) onward these areas are flooded for too long for new vegetation to sprout at all. Bars further upstream (Figure 7, IV and V)

5.2 Network extractions

The main channels extracted by the network tool (Figure 9) mostly fall on top of the lowest parts of the DEMs. It happens that the main channel connects two low sections in the network (Figure 9, 3,000 cycles, 12-14 m) by crossing bars with higher elevations. This can be observed in the Metronome too but it is likely that in these instances a single channel is not sufficient to describe the network at this location. The network tool connects the main channel to a deeper part of a sub-channel, and considers it the same because of the sediment volume separating them, whereas in reality the channel would split at a diffluence, often partially flooding the bar between the two branches. The main channels have depths ranging from 7.5 cm at the shallowest parts to about 2.5 cm in the tidal inlet. Most of the main channel depths are about 6 cm, which means they incised 2 cm relative to the initial bed elevation. Since the bed elevations also increased 0.5 to 4 cm during the experiment, total channel incision is ranges between 2.5 and 6 cm. The relatively straight channels in the first 6 meters of the DEM up to 4,000 cycles highlight that channels are more shallow and less abundant than in the downstream part of the experiment. There are no substantial channels in this part of the Metronome yet until 4,000 cycles. These channels started to develop between 4,000 and 5,000 cycles.

The multi-channel plots (Figure 10) show the ten most important extracted channels predominantly formed in the seaward half of the metronome in the first 4,000 cycles and thereafter spread out through the estuary over the course of the experiment. Channel depths range from 5.5 to 7.5 cm with the deeper channels being located mostly in the downstream part of the estuary.

5.3 Hypsometry

Cumulative percentage surface areas are calculated for each time step (Figure 11). The areas correspond to a,b,c,d in the Metronome layout below the plots. Elevation increases are small in section c and d compared to section a and b, meaning more sediment is stored in the upstream part of the Metronome during the experiment. Secondly, elevation increases are accelerating with increasing tidal cycle numbers in a and b.

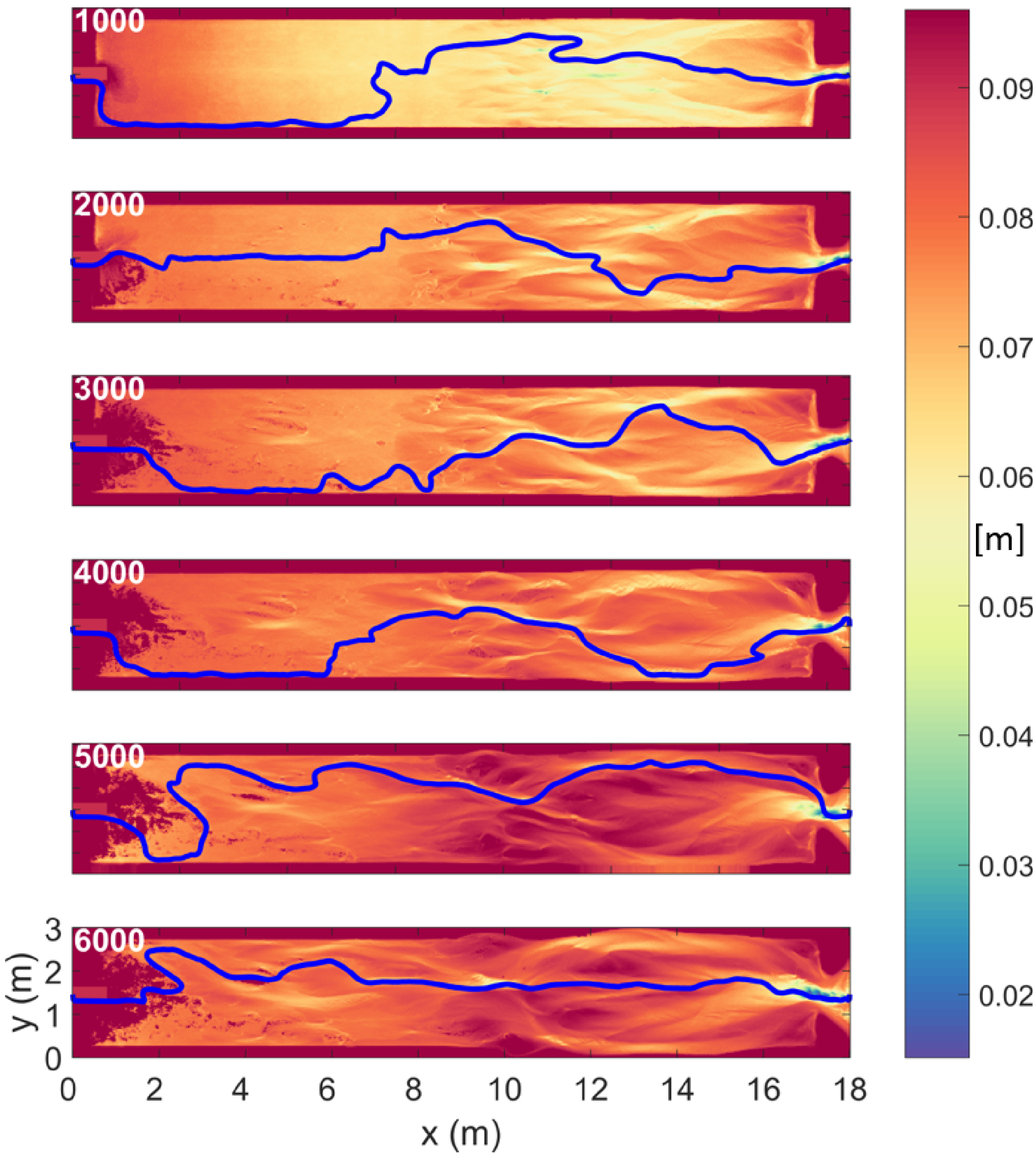


Figure 9: DEMs with the extracted main channels from the network tool. Note that the sea was disregarded in the network analysis and is not represented in this figure. Lines are smoothed using a 0.025 m ∗ 18 m window.

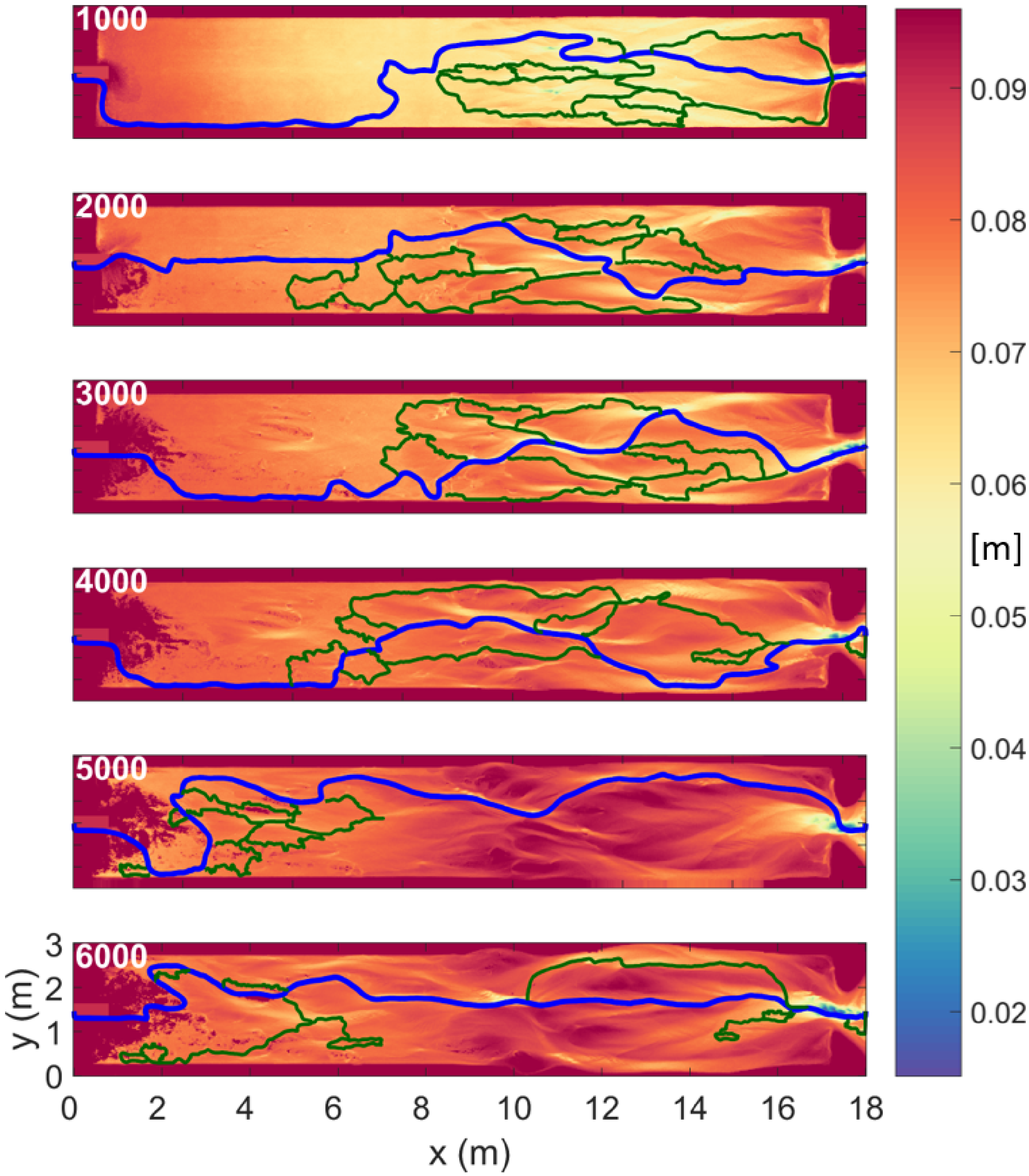


Figure 10: DEMs with the extracted main channels and secondary channels. Lines are smoothed using a 0.025 m ∗ 18 m window.

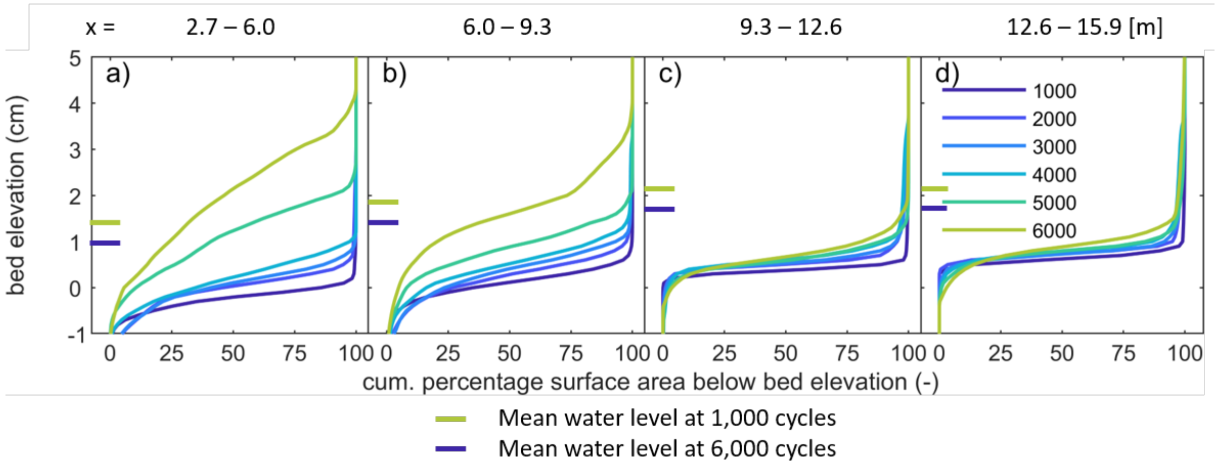


Figure 11: Cumulative percentage surface area plots from 1,000 to 6,000 cycles. Percentages are calculated over the Metronome x-intervals indicated above the panels. Sea-level was increased by 1 mm every 1,000 cycles starting at 3,000 cycles. Water levels are indicative. Note that water level increase towards the sea because of the offset slope of the Metronome.

6 Discussion

The experimental estuary and its development can be characterised as an underfilled, largely sub-tidal estuary, which is importing sediment from the sea and the river. Initially, sand, mud and vegetation fill accommodation in the basin and inter-tidal area increasingly. With sea-level rise more accommodation is created and the infilling, relative to accommodation creation, slows down in the downstream part of the estuary. In the upstream part of the estuary infilling increases relative to accommodation creation. Morphological units such as channels, bars and the flood tidal delta shift towards the landward side of the basin compared to the experiments without sea-level rise [Weisscher et al., 2021] (Figure 12).

6.1 The effect of sea-level rise on morphological development

Sea-level rise results in a transgression of morphological units and higher sediment mobility in the upstream part because tidal currents penetrate further into the Metronome. The extracted networks (Figure 9 and 10) both show a shift from significant channels being active almost exclusively between 7 and 18 meters to increased channel formation in the upstream part of the Metronome. It is striking that for cycles 5,000 and 6,000 (Figure 10) the dominant channels concentrate just downstream of the bay-head delta. This is a surprising result because based on observations in the Metronome during the experiment, the larger channels converging to the confluence between 10 and 11 m seem more important. Accordingly, the sediment volumes separating individual channels near the bay-head are larger at this point in time. This result can probably be explained by greater sediment import in the upstream part of the Metronome than in the downstream part, resulting in larger sediment volumes between the channels.

The estuary hypsometries (Figure 13) show an overall trend of increasing surface elevations, as expected for a net importing estuary. The largest increase of bed elevation is about 4 cm in 6,000 cycles between 3 and 6 m, relative to about 10 mm water depth

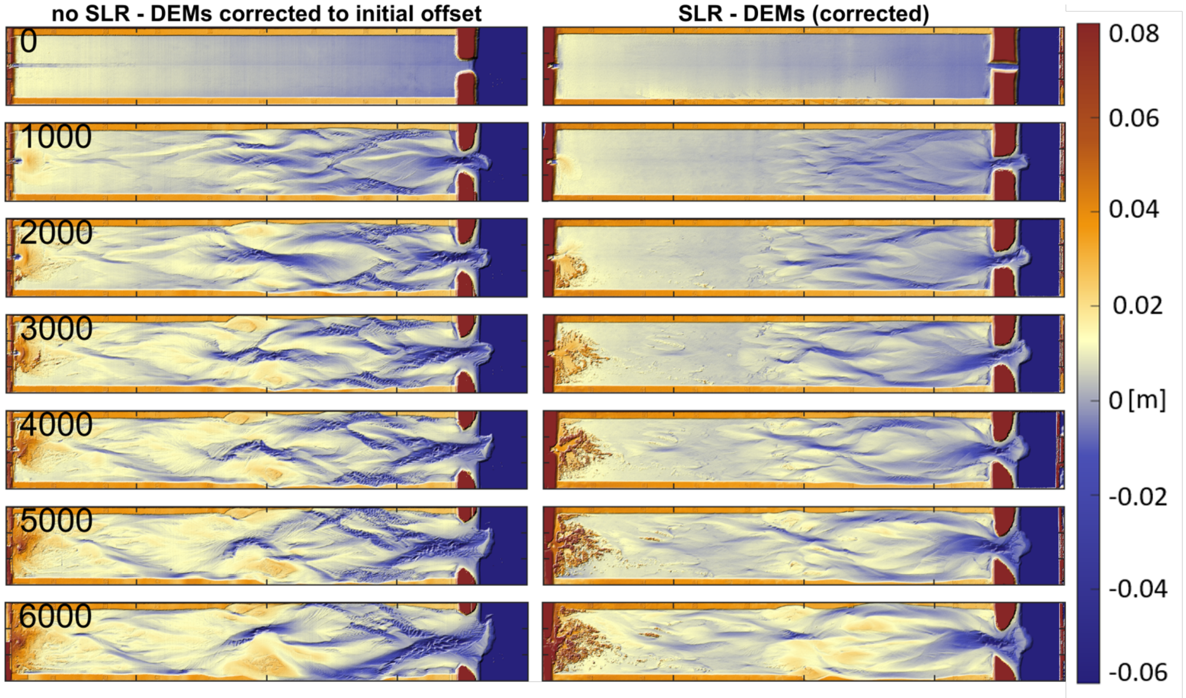


Figure 12: Comparison of 6,000 tidal cycles without sea-level rise (left; Weisscher et al. [2021]) and with sea-level rise (right) but otherwise the same boundary conditions.

+4 mm sea-level rise is about 14 mm water depth by 6,000 cycles. It is impressive that after 4,000 cycles the accumulation rate increases considerably in the upstream half of the system, up to a sixfold increase in section a at its maximum. There are three explanations for this which are not mutually exclusive.

1. Sea-level rise increases water depth in the channels over the entire flume length. Because of the flood dominance this results in increased sediment transport in the landward direction, causing an accelerating increase of surface areas.

2. The added acceleration of accumulation rates may come form sediment from the bay-head delta which is transported into section a and, to a lesser extend, into section b. Based on the DEMs (Figure 6) and the orthophotos (Figure 7), this explanation is likely for section a, because the bay-head delta fringe intersects the 3 m. Given these dimension of the bay-head delta no sediment transport from the bay-head to section b is expected.

3. The DEMs which serve as input for the hypsometry function contain vegetation, which create an artificial added elevation in the hypsometry plots. However, the difference between the lines in the hypsometry plots represent change of bed elevation relative to the previous time step. Vegetation coverage did not change significantly for section a and b after 4,000 cycles, as the densely vegetated part of the bay-head delta falls outside of the hypsometry area boundaries.

Further support for the hypothesis that sea-level rise results in more sediment transport to the upstream areas of the Metronome follows from a comparison with no sea-level rise experiment hypsometries (Figure 13) [Weisscher et al., 2021]. Here the sediment accumulation rate between initial and 5,000 cycles is smaller than the experiment with sea-level rise by a factor 1.5–2 and the overall bed elevation change is more uniform in

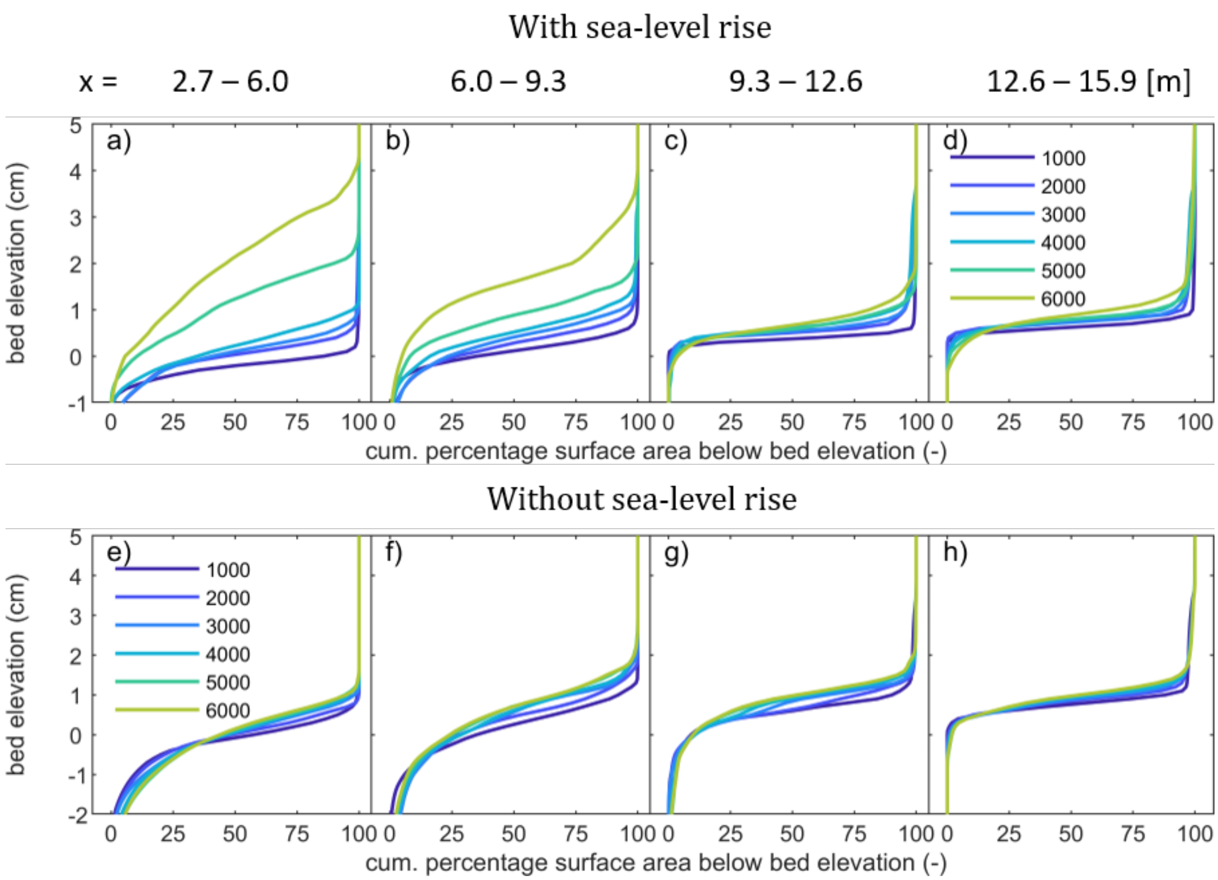


Figure 13: Hypsometry of the experiment with sea-level rise a), b), c), d) of an infilling estuary with no sea-level rise e), f), g), h). Modified from [Weisscher et al., 2021]. Sea-level was increased by 1 mm every 1,000 cycles starting at 3,000 cycles.

the experiment without sea-level rise. It thus shows that sediment accumulation in the upstream part of the estuary is affected stronger by sea-level rise than the downstream part.

The experiments with and without sea-level rise are also morphologically similar in the sense that a fluvial network develops comprised of roughly three nodes and two anti-nodes with smaller super-imposed nodes and anti-nodes. Nodal positions are very similar with and without sea-level rise. The first nodes forms between the barriers, the second is located just landward of the flood tidal delta and the last is roughly located at the bay-head delta toe. This is in accordance with studies that showed that the location of stable confluences (nodes) in self-formed estuaries are determined by tidal bar spacing. Both these nodal positions and tidal bar spacing are a function of estuary width [Leuven et al., 2018]. As there is no difference is estuary width in the Metronome nodal positions are expected to be the same, with or without sea-level rise. However, lateral estuary expansion by bank erosion is limited to the hard boundaries of the Metronome. In natural systems sea-level rise may eventually widen the estuary, which may in turn affect tidal bar length and nodal positions. In the sea-level rise experiment the flood tidal delta was more prominent, whereas in the experiment without sea-level rise a side-bar configuration established, which captured much of the marine sediment.

The most apparent difference is that in channel depth and in channel development in the upstream part of the flume. Channels are deeper and more pronounced in the no sea-level rise experiment. Furthermore, channel development in the upstream part of the Metronome starts to be visible already at 1,000 cycles and is well established by 3,000 tidal cycles. This goes considerably slower in the sea-level rise experiment. If sea-level rises and water depth increases, this is expected to result in higher flow velocities in channels upstream and deeper and more pronounced channels than without sea-level rise. However, these results show the opposite development. Comparison of the DEMs shows that already here a strong difference in channel formation is present around 1,000 cycles. As sea-level did not rise yet at this time, this suggests sea-level rise may not be the cause of this difference in channel formation. It is unclear what causes this reduced channel formation in the sea-level rise experiment. It is possible that relocation of the Metronome to a new laboratory between the two experiments caused minimal differences in the experimental set-up. There is a chance of very slight bending of the metronome to a convex up or a concave up shape. This will cause an increase of incision of the centre of the bed and increased incision of the sides respectively. Over the full length of the Metronome this can cause elevation differences of about 2 mm. Alternatively, algae growth in the sediment may account for these differences, which initially concentrated downstream of the bayhead delta. Algae make the sediment more cohesive and therefore reduce mobility. This could explain why the channel development varies between the two experiments. However, algae abundance was limited for the first 3,000 cycles of the experiment, so it is unlikely that they are responsible for the differences in channel depth between the sea-level rise and no sea-level rise experiments.

Sinuosity (Figure 14) ranged from 1.11 to 1.28 and had a mean value of 1.19. These values fall within ranges reported for rivers in literature (e.g. [Kleinhans and Berg, 2011]) and calculated for estuaries from Google Earth (Figure 15). Up until 6,000 cycles, no trend in main channel sinuosities is observed. It is also questionable if main channel sinuosities are a meaningful metric in a system which is predominantly braiding. It is possible that some of the apparent meanders in the main channels extracted by the Network tool are in fact diffluences or confluences, so more than one channel. In that case, calculating a sinuosity may not be relevant.

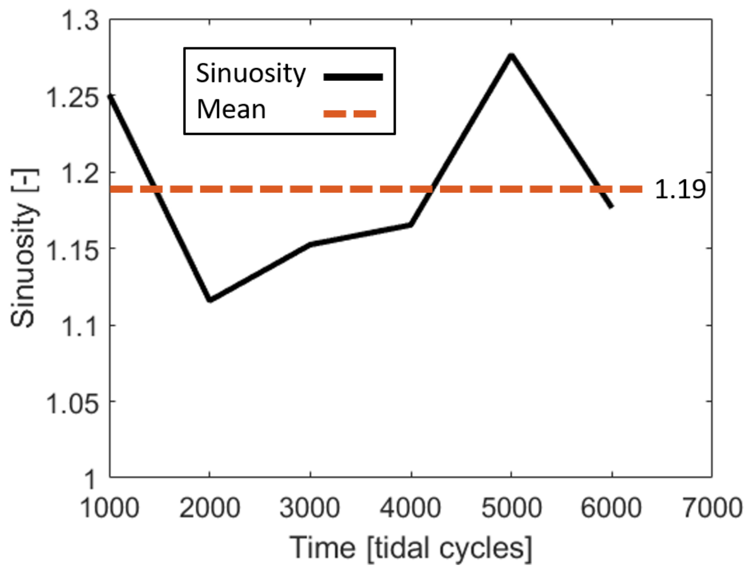


Figure 14: Development of the main channel sinuosity through time.

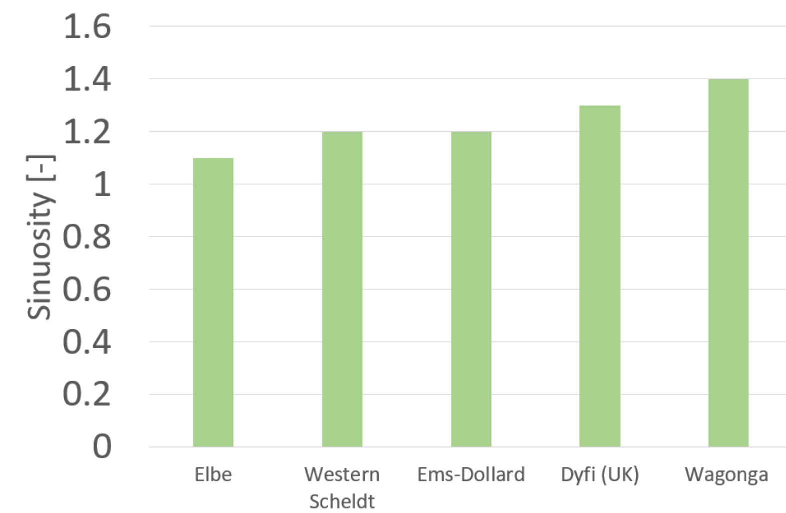


Figure 15: Main channel estuary sinuosities calculated from Google Earth images.

6.2 Implications for estuaries worldwide

The findings of this experiment allow for a discussion of the fate of estuaries worldwide in light of the current and predicted sea-level rise. Many estuaries active today, formed during the mid-Holocene rapid sea-level rise and have either filled in or maintained dynamical equilibrium and remained open since. A key boundary condition determining whether an estuary can remain open at its tidal inlet, is its river discharge [De Haas et al., 2018]. Along the Dutch coast tidal asymmetry causes flood dominance which brings sediment into the estuaries. A substantial fluvial input is needed to counteract this marine sediment influx. This experiment suggest that sea-level rise allows tidal currents to penetrate further upstream and sediment accumulation will increase more in the upstream parts of the estuary (Figure 13). Furthermore, if mud and vegetation are present abundantly, this often results in continuous fine sediment import and growth of supra- and intertidal areas [De Haas et al., 2018]. Compared to the experiments without sea-level rise by Weisscher et al. [2021], the spatial extent of vegetated bars is reduced in the sea-level rise experiment. Sea-level rise is likely the cause for this but it remains unclear why exactly. There are two hypotheses: Firstly, sea-level rise increases inundation stresses on vegetation, reducing their rooting potential and in some cases even uprooting vegetation that has already rooted. Secondly, bars may be eroded more easily with greater water depths. Tidal currents are faster, increasing their erosive power and their ability to cut through bars. Although vegetation and mud do partially counteract bar-cutting (Figure 8, I), where mud and vegetation stabilise the bar. There is definitely evidence for the inundation stress hypothesis in the sea-level rise experiment. Pictures were taken of the Metronome after every sprouting period and it shows that some areas where seeds were deposited abundantly showed a change from sprouting and rooting, to only sprouting to no sprouting at all, especially close to the tidal inlet, where relative sea-level rise was the greatest.

There are two feedbacks in place in estuaries which counteract each others effect. A conceptual model for this was proposed [Van Den Berg and Jeuken, 1996] and extended with eco-engineering species [De Haas et al., 2018] (Figure 16). The model shows that an increase in tidal wave asymmetry leads to sand import into an estuary, this leads to shoal formation which reduces the tidal prism and reduces tidal asymmetry: this is the small, negative feedback. When shoals form, an other effects occurs: lag effects between slack water and maximum current velocities during ebb increase due to water storage on shoals during flood. Decrease of shoal water levels lags behind the channel water levels [Dronkers, 1986], shifting the peak ebb current velocities further back in the tidal cycles, giving, especially fine grained sediment mud and fine silt, more time to settle. This causes supra-tidal areas to grow [Van Den Berg and Jeuken, 1996], which is further enhanced by eco-engineering species [De Haas et al., 2018]. When coupled, the feedbacks can predict an equilibrium state of the estuary, given the correct boundary conditions are met. The self-regulating effect of the feedbacks does not entail that an equilibrium state will establish necessarily, given enough sediment availability mud and vegetation abundance and limited fluvial power to counteract the flood dominance, estuaries will fill in. The small, sand driven feedback clearly shows from the hypsometries of the current experiment. The lag effect is less apparent. Probably also because the small walnut fractions in the Metronome are expected to settle relatively fast still compared to mud in natural systems, decreasing the sensitivity to the lag effect in the Metronome. The walnut fractions in the Metronome are chosen to scale well with mud in natural systems [Braat et al., 2019] but flow is supposed to be turbulent for this to work. It could be that flow over bars in the Metronome is laminar for part of the tidal cycle, contrary to natural systems. To determine to which extent this is the case, a quantitative comparison of water depths and mud sedimentation between the Metronome and natural systems is required, but this has not been done so far.

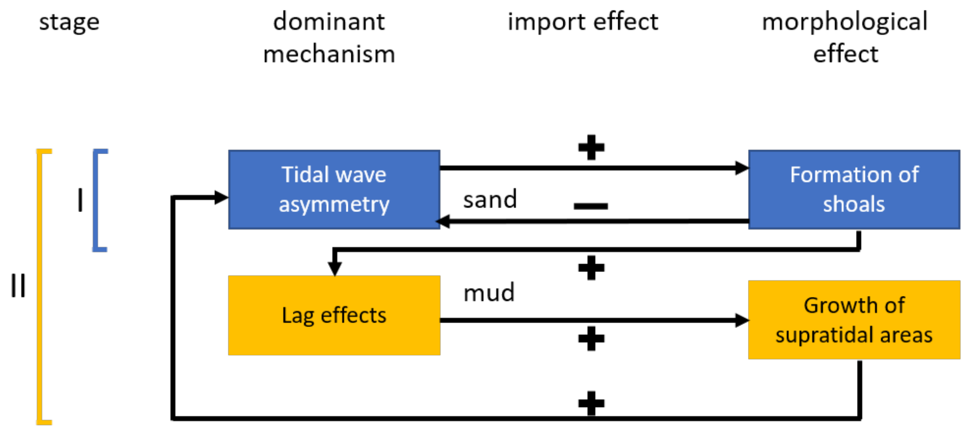


Figure 16: Two coupled geo-morphological feedbacks. Plus and negative signs indicate if the relationship between the two boxes is positive or negative. I) is the negative shoal feedback, II) is the positive lag effect feedback. Modified from Van den Berg et al, 1996.

In order to create a conceptual predictive model determining the faith of estuaries globally it is important to map the dominant boundary conditions, quantify them and compare them to data from the geological record which serve as test cases for such a prediction. Mud and eco-engineering species, sand availability and the rate of accommodation creation are the dominant boundary conditions needed to discuss the future of estuaries under sea-level rise conditions. During the Subboreal 5560 - 3710 B.P. estuaries and tidal embayments filled up, despite the sea-level rise of about 15 cm/100 yr. Sediment accumulation rates are estimated to be 30 cm/100 yr [Van Den Berg and Jeuken, 1996]. How does this compare to current and predicted sea-level rise, and is the available sediment enough for estuaries to keep up or will they drown? Studies predicting sea-level rise into the future work with representative concentration pathways (RCPs). Depending on which RCP is used for the prediction, sea-level rise is expected to rise between 1 and 5.5 m by 2300 [Jevrejeva et al., 2014]. This is a 40 cm/100 yr or a 200 cm/100 yr respectively. About 8,000 year BP sea-level in the Netherlands rose 80-100 cm/100 yr [Vos, 2015], and the coastline transgressed. Around 6,000 yrs BP sea-level rise had slowed down to about 30 cm/100 yrs and was balanced or exceeded by sedimentation, resulting in silting up of the back-barrier areas [De Haas et al., 2018].

At present average sediment accumulation rates for the Scheldt estuary are reported to be about 130 cm/100 year [Van Den Berg and Jeuken, 1996] and ranging from 84 to 170 cm/100 yr [Zwolsman et al., 1993], assuming flooding frequencies between 25 and 175 times per year. Extrapolating values of this order of magnitude to the future suggests that if sea-level rise stays on the lower end of the predictions, sedimentation may be able to keep up with sea-level rise. If the higher RCP scenario comes true, estuaries will drown rapidly. As an other example we can consider the Dutch coastal back-barrier system the Wadden sea. Sediment accumulation rates for this system, averaged over the various tidal inlets, are reported to be about 40 cm/100 yr, calculated between 1935 and 2005

[Elias et al., 2012]. This means that for the Wadden sea system, only in the lowest RCP scenario of 40 cm/100yr sea-level rise the system will be able to aggrade to maintain a stable position. Therefore, it seems likely that the system will transgress slightly towards the mainland. In doing so, however, it will quite soon reach the man-made dikes serving as a barrier against the sea. Without any drastic measures in managing this coast, e.g. opening dikes up periodically to let polders be flooded by the sea, it is likely the Wadden sea area will drown in the centuries to come.

The aforementioned flooding frequency is an important parameter to discuss in more detail. Since antropogenic interference in estuaries started, flooding frequencies decreased, mostly due to the building of dykes. Furthermore, the building of dams reduced sediment availability in many systems. At the same time, considerable quantities of sediment are dredged from estuary channels and disposed of outside of the estuaries [van Dijk et al., 2019]. This reduces sediment availability in estuaries and concentrates flow in the deepest channels, further reducing the flooding frequency of surrounding bars and floodplains. However, many of the estuaries in van Dijk et al. [2019] are narrow, converging estuaries, contrary to the wide estuary in the current experiment. Dredging in wide estuaries possibly even has a stronger effect on the sediment balance than in narrow estuaries, because sediment is spread out over a larger area, meaning that more sediment is needed for a wide estuary to keep up with sea-level rise. When too little sediment is available for systems to silt-up with sea-level rise, morphological units may not transgress but instead drown completely, as there is no space for them to transgress to. This process is called coastal squeeze and this is a serious risk for many estuaries world-wide. Besides the importance of the internal estuary dynamics and feedbacks, changes in boundary conditions, e.g. offshore wave height, river sediment load, will also affect the response of estuaries to sea-level rise.

6.3 Recommendations for future work

Something that is likely to be important but has not been studied successfully experimentally is the lag effect. It remains uncertain what the relationship between sea-level rise and mud sedimentation on the bars is exactly. Because on the one hand, sea-level rise increases flow velocities over bars, possibly increasing transport of mud away from bars. On the other hand, sea-level rise may cause mud to reach the most elevated parts of bars, which otherwise would not receive sediment at all. If a scaling similarity between the fine walnut fractions and the slack water duration can be achieved it is possible to study the interaction of intertidal area accumulation and lag effect changes. This will also allow the double feedback (Figure 16) to be studied in an experimental setting.

metronome specific recommendations

Working with the Metronome intensively for the last four months resulted in the following suggestions for working with the set-up:

Technical:

- It would be good to install a floater switch on the seaward mud-feeder too, like on the river one. It occurred that mud/water mixtures in the mixing tank got to low levels when the experiment ran, so some air got sucked in with the mixture. A float switch will switch off the pump in case of a too low level and prevent dry running, overheating and potential fire hazards inside the pump. Currently the pump housing and the water it circulates get quite warm at times.

- I have doubts if the mixing of walnut and water in the mixing tanks works well enough. I did some measurements on walnut volumes before and after running 430 cycles with the Metronome. It looks like the mixing ratio water/walnut in the discharge from the feeders is not exactly equal to the mixing ratio in the tanks. I think what happens is that a layer of walnut forms at the bottom of the tank which is stationary and does not get mobilised by the flow re-entering the tank from the top. Perhaps placing the suction point of the pump lower in the tank would improve this. It would be good to do some careful measurements on this to make sure this is done correctly in future experiments.

- Filling and cleaning the walnut feeders is now a somewhat risky operation. One needs to stand on the edge of the Metronome and lean into the mixing tank to suck up the left-over walnut with the vacuum cleaner. This is alright for most people, but there may be people for who this is physically challenging or impossible.

- The filter behind the weir which is supposed to prevent vegetation flowing over the weir does not work well. Vegetation falls into the filter and is thrown over the filter edge, into the water reservoir by the water falling down on the filter. The filter needs a longer edge pointing more vertically to prevent this.

- The power cables at the riverside of the set-up for the pumps and bio-filter are on the short side. They form a tripping hazard for people walking there.

- The river-pump needs something to prevent it from sucking up vegetation from the water reservoir. A net or a fine mesh cage would work. Preferably something that is removable so it can be cleaned regularly.

- The biofilter needs to be cleaned regularly. To make this easier it is best to connect a discharge hose to the waste outlet of the filter. Mounting the filter in the reservoir more securely is also advisable because with high water levels the filter floats, because there is some air inside.

- Draining the Metronome to make a DEM takes a quite long when walnut and/or algae are present. It can take up to 2 hours to fully drain the water out. This process could be sped up by having a small, manual pump which has two nozzles on it. One to put in the scour holes containing the last water, and one discharge hose. Siphon pumps with long nozzles, like the ones used for siphoning fuel in tanks, would be ideal for this purpose. The draining process should be about 45 minutes faster in this way.

Protocols:

- Mold control: I used higher concentrations of tea-tree oil and pimafix to spray the bed against mold. Mold seemed to be less of an issue in the current experiment than in the previous one with mud and vegetation. Perhaps this is partially related to this concentration difference. I used 5 ml 1:1 pimafix/tea-tree oil on 5 l of water. Which is a 10 times higher concentration than goes into the walnut mixing tanks. Make sure not to spray this on the vegetation and only on the bare walnut and the sand bed.

7 Conclusion

1. How does sea-level rise affect estuarine morphology?

   (a) As the experiment progresses, the upstream part of the Metronome shows increasing sediment accumulation rates, sometimes greater than accommodation creation, allowing for the formation of inter-tidal and supra-tidal area. This sediment came from barrier and bank erosion in the downstream area of the system. Most of the fluvial sediment input was captured by the bay-head delta, which is elevated considerably compared to its surroundings. Whereas the downstream part shows much smaller sediment accumulation rates, which are not accelerating with time. Downstream sediment accumulation is often equal to or smaller than sea-level rise, so much of this part of the system drowns over time.

   (b) The increased sediment mobility in the upstream part of the estuary relative to no sea-level rise experiments is interpreted as an increase of tidal current velocities as a result of greater water depths, allowing tidal currents to penetrate further upstream into the estuary.

   (c) Sea-level rise causes channels in the upstream part of the estuary to incise more and as sea-level continues to rise the most important channels shifts from the downstream part of the experiment to the upstream part between the bay-head delta and the central part of the estuary.

   (d) The amount of nodes and anti-nodes in the system did not change in response to sea-level rise. Morphologically the experiment with sea-level rise and without sea-level rise were similar with some notable differences. In the sea-level rise experiment the flood tidal delta was more prominent, whereas in the experiment without sea-level rise a side-bar configuration established, which captured much of the marine sediment.

2. What are the implications for the fate of estuaries worldwide?

   For low RCP scenarios (40 cm sea-level rise in 100 years), estuaries may be able to keep up with sea-level rise, given enough sediment is available. Antropogenic interference with coastal systems such as dredging, dam and dike building tend to reduce sediment availability in estuaries, resulting in coastal squeeze. This means that coastal systems are not able to transgress in response to sea-level rise but will drown without migrating landward. Eco-engineering effects of vegetation and mud may be important in contributing to sediment accumulation rates. For high RCP scenarios, (200 cm sea-level rise in 100 years), unrealistically high accumulation rates are required for estuaries to keep up with sea-level rise and most, if not all, estuaries will drown. For low RCP scenarios (40 cm/100 yr) systems like the Dutch Wadden sea and the Scheldt may be able to aggrade to maintain a stable position based on their reported accumulation rates. However, for higher RCP scenarios these systems are prone to coastal squeeze and may drown.

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