

Effects of estuarine mudflat formation on tidal prism and large-scale morphology in experiments

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Abstract

Human interference in estuaries has led to increasing problems of mud, such as hyper-turbidity with adverse ecological effects and siltation of navigation channels and harbours. To deal with this mud sustainably, it is important to understand its long-term effects on the morphology and dynamics of estuaries. The aim of this study is to understand how mud affects the morphological evolution of estuaries. We focus on the effects of fluvial mud supply on the spatial distribution of mudflats and on how this influences estuary width, depth, surface area and dynamics over time. Three physical experiments with self-forming channels and shoals were conducted in a new flume type suitable for tidal experiments: the Metronome. In two of the experiments, we added nutshell grains as mud simulant, which is transported in suspension. Time-lapse images of every tidal cycle and DEMs for every 500 cycles were analysed for the three experiments. Mud settles in distinct locations forming mudflats on bars and sides of the estuary, where the bed elevation is higher. Two important effects of mud were observed: the first is the slight cohesiveness of mud that causes stability on bars limiting vertical erosion, although the bank erosion rate by migrating channels is unaffected. Secondly, mud fills inactive areas and deposits at higher elevations up to the high water level and therefore decreases the tidal prism. These combined effects cause a decrease in dynamics in the estuary and lead to near-equilibrium planforms that are smaller in volume and especially narrower upstream with increased bar heights and no channel deepening. This trend is in contrast with channel deepening in rivers by muddier floodplain formation. These results imply large consequences for long-term morphodynamics in estuaries that become muddier due to management practices, which deteriorate ecological quality of intertidal habitats but may create potential area for marshes.

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25 1 Introduction

26 Estuaries are tidally influenced coastal bodies of water that are connected to a river system supplying freshwater and
27 sediments. Estuaries occur in a wide variety of planform shapes and shoal patterns, which are caused by inherited
28 initial conditions and changing boundary conditions. However, it is still unclear how these conditions contribute to
29 the evolution of estuaries and therefore a full understanding of their behaviour is still lacking. Understanding these
30 natural dynamics is relevant for ecology, economy and flood safety, since intertidal areas are important ecological
31 habitats and estuaries often have important shipping fairways to inland harbours that are located in densely populated
32 areas. Many estuaries are heavily managed to balance these values, but there is a need to increase our understanding
33 of the natural dynamics to improve management strategies.

34 Alluvial estuaries are typically flanked by mudflats and salt marshes (Dalrymple et al., 1992; Dalrymple and
35 Choi, 2007). Mud has different erosional and depositional characteristics than sand and can, therefore, affect the
36 morphology of estuaries. Recently, the interest in estuarine mud has increased, because many estuaries have been
37 dealing with increased negative effects of mud (e.g. fluid mud, siltation of channels and harbours, higher turbidity
38 reducing light penetration, the attraction of pollutants; Ridgway and Shimmiel, 2002; Dijkstra et al., 2011; Van Maren
39 et al., 2015, 2016). On the positive side, mudflats are very productive areas for flora and fauna, though vulnerable
40 because of their low biodiversity (Costanza et al., 1993). Only very few studies consider the decadal to centennial
41 effects of mud on the morphology of the estuary. Studying these long-term trends might give better insights in more
42 sustainable or more efficient management strategies and the prediction of the long-term morphological behaviour may
43 improve by accounting for mud. For example, if we can determine how tidal channels migrate over time in relation to
44 the amount of cohesive mud in the system, we can perhaps better manage causes of hyper-turbidity and dredge more
45 sustainably by migrating the shipping route in accordance with the natural trend of the estuary.

46 Previous research on the long-term morphodynamics of estuaries has mostly been conducted by numerical mo-
47 delling (e.g. Lanzoni and Seminara, 2002; Hibma et al., 2003; Van der Wegen and Roelvink, 2008; Van der Wegen
48 et al., 2008; Moore et al., 2009; Van der Wegen and Roelvink, 2012; Van der Wegen, 2013; Dam et al., 2016; Braat
49 et al., 2017), whereas only few studies use physical experiments (Reynolds, 1887, 1889, 1891). Also, long-term field
50 data are scarce and limited to decades rather than centuries. For such long timescales, only numerical modelling
51 studies are available, but these may suffer from weaknesses such as neglected processes, numerical effects, imperfect
52 transport predictors and the need for calibration of physics-based parameters (Baar et al., 2018). Additionally, these

53 studies rarely include mud because this has only become possible very recently (Le Hir et al., 2001; Van Kessel et al.,
54 2011; Dam et al., 2013; Braat et al., 2017). Therefore, complementary to numerical models, additional approaches
55 are necessary, such as physical models that form the entire landscape on scale within one flume.

56 Experiments with self-forming estuaries are rare, especially compared to the large number of delta experiments
57 (e.g. Smith, 1909; Hoyal and Sheets, 2009; Grimaud et al., 2017), meandering river experiments (e.g. Friedkin, 1945;
58 Tal and Paola, 2007; Braudrick et al., 2009; Van Dijk et al., 2013) and braided river experiments (e.g. Ashmore,
59 1991), and even compared to the few tidal channel and inlets experiments (Tambroni et al., 2005; Stefanon et al.,
60 2010; Vlaswinkel and Cantelli, 2011; Kleinhans et al., 2015). Physical experiments with lightweight sediment have
61 been conducted for filling of deltas and river floodplain (e.g. Peakall et al., 2007; Van Dijk et al., 2013; Hoyal and
62 Sheets, 2009). Peakall et al. (2007) describes the necessity of cohesive fines in experiments to maintain a meandering
63 planform. This was later explained by two effects: Braudrick et al. (2009) found that filling of floodplain by suspended
64 sediment reduces the tendency to form chute cut-offs that are the onset of braiding. Van Dijk et al. (2013) found that
65 adding cohesive sediment reduced erosion rates and increases bank strength, while overbank sedimentation and lateral
66 accretion on point bars led to a reduction in chute cut-offs. The resulting reduction of width to depth ratio reduces the
67 tendency to braid and leads to alternate bars associated with the onset of meandering. Hoyal and Sheets (2009) found
68 that cohesive deltas show stronger channelisation, narrow channels, slower channel migration rates and therefore a
69 more complex coastline. With these results in mind, we hypothesise that cohesive sediment deposits in estuaries will
70 also reduce the tendency to form new channels, increase bank strength and limit the migration of channels similar to
71 rivers and deltas.

72 The objective of this study is to identify the effects of cohesive sediment supply on the shape and development of
73 estuaries. We specifically focus on the effect on large-scale parameters that determine landward tidal penetration, bar
74 pattern and large-scale dynamics, such as width, depth and depth distribution, surface area, volume and cumulative
75 erosion and deposition over time.

76 **2 Methods**

77 The results presented in this paper are derived from three experiments. The initial and boundary conditions of these
78 experiments were based on the experience gained from 35 exploratory experiments with varying initial and boundary
79 conditions. In the three experiments that are presented here, we changed the cohesive sediment supply to systemati-

80 cally explore the effects of this changing boundary condition. In this paper we will present an experiment with *only*
81 *sand*, an experiment with a *low mud supply* and an experiment with a *high mud supply*. The experiment with only
82 sand is also presented in Leuven et al. (2018a), where estuaries with growing forced tidal bars are shown to determine
83 a non-ideal estuary planform, which serves as a reference experiment for this study.

84 **2.1 Experimental setup and scaling**

85 The experiments are conducted in the recently built flume, the Metronome, of 20 by 3 m in size, which drives tidal
86 flow by periodic tilting of the entire flume (Fig. 1; Kleinhans et al., 2017b). Until now, it has always been difficult to
87 study estuaries with physical models (Hughes, 1993; Kleinhans et al., 2012), due to scaling problems caused by tidal
88 flow in addition to general scaling issues (Paola et al., 2009; Kleinhans et al., 2014a). Older tidal experiments without
89 the periodic tilting mechanism had a tendency to exclusively form ebb dominated, sediment-exporting systems (as
90 reviewed in Kleinhans et al., 2012). Furthermore, these experiments suffered from low sediment mobility and bar-
91 forming tendencies were often overwhelmed by a significant number of scour holes and small bedforms, probably due
92 to hydraulic smooth conditions (Kleinhans et al., 2017a). The recently developed Metronome flume prevents these
93 scaling issues by obtaining appropriate hydraulic similarity and sediment mobility, and therefore sediment transport
94 similarity, in agreement with proven scaling methods that are required to obtain morphologic similarity (Peakall et al.,
95 1996; Paola et al., 2009; Kleinhans et al., 2014a). In particular, we solved a classic scaling conflict between sediment
96 friction and sediment mobility by using a coarse sediment to prevent hydraulic smooth conditions and associated scour
97 holes (Kleinhans et al., 2017a) and at the same time increasing the Shields mobility number to similar values as found
98 in nature by driving the periodic flow by periodic flume tilting (Kleinhans et al., 2017b) as explained below in detail.
99 Pilot set-ups of this system have already been used in studies on tidal basins and ebb- and flood dominant channels
100 (Kleinhans et al., 2012, 2014b, 2015), and the Metronome has also already been proven to be a more effective method
101 of producing dynamic estuaries compared to solely vertical water fluctuations (Kleinhans et al., 2017b; Leuven et al.,
102 2018a). Previous morphodynamic experiments showed that tidal bars scale similarly as tidal bars in natural systems:
103 the length to width ratio and their correlation with local estuary width is in accordance with natural systems (Leuven
104 et al., 2018a). However, the formation of cohesive tidal flats flanking non-cohesive channels within one experiment is
105 novel in the experiments presented here.

106 The most important scale issue is that of sediment mobility. In scale-experiments where the spatial dimensions of

107 the system are reduced, the sediment often has a similar grain size as in nature, while the water depth is much smaller
108 leading to a lower velocity and therefore lower sediment mobility. If sediment is scaled down similarly to water
109 depth the physiochemical sediment properties would change; sand would become strongly cohesive clay. Therefore,
110 it is common practice in river experiments to increase the slope of the flume to counteract the unscaled grain size
111 to create realistic sediment mobility and as a result realistic transport rates (Peakall et al., 1996; Kleinhans, 2010).
112 The problem in tidal experiments is that water and sediment should be transported in two directions and therefore an
113 increased slope would only favour ebb-related transport. By using the novel tilting method of the Metronome, this is
114 avoided. During ebb flow, the flume is tilted seaward while during flood the flume is tilted landward. With this method
115 we obtain peak Shields numbers of 0.15-0.2 for sand, which is well above the beginning of motion and close to that
116 of small natural estuaries, obtaining sediment transport similarity while maintaining subcritical flow (Kleinhans et al.,
117 2017b). In theory, decreasing the density of the sediment is also a possibility to reduce most of these scaling issues.
118 However, using, for example, plastic sediment is unfavourable for experiments with mud or vegetation and leads to
119 practical problems of cost and waste treatment. The tilting method is based on several pilot studies in smaller flumes
120 (Kleinhans et al., 2012, 2014b, 2015) and a more extensive description, operation and technical information of the
121 flume can be found in Kleinhans et al. (2017b).

122 **2.2 Boundary and initial conditions**

123 The tilting amplitude of the metronome is 75 mm resulting in a maximum slope of 0.0075 mm^{-1} (or 0.75%) and tilts
124 with a period of 40 s for the experiments with only sand and the experiment with a high mud supply. The experiment
125 with a low mud supply was subjected to a slightly lower tilting amplitude of 68 mm, but the same period. Tilting
126 amplitude and period were chosen so that sediment mobility was ensured for correct scaling and the tidal excursion
127 length was shorter than the length of the flume (see Kleinhans et al., 2017b, for description and comparison to natural
128 systems). These values for tilting amplitude and period were chose on the basis of pilot tests with a range of tilting
129 amplitudes and periods (see supplementary Fig. S1 and S2 for the results of these pilots). The mean water level was set
130 0.065 m above the flume floor and -0.005 m elevation relative to the land surface. The resulting water level amplitude
131 of the experiments is 0.5-1 cm which is less than half the typical water depth of 3 cm, a similar ratio as natural systems
132 (Savenije, 2015). Upstream we add a river discharge of 300 Lh^{-1} during ebb, and downstream we generate waves
133 with a paddle during flood with a frequency of 2 Hz and 1 cm amplitude (supplement of Leuven et al., 2018a). The

134 river discharge alone is not strong enough to transport sand in the flume in absence of tilting (supplementary Fig. S3b).
135 However, when tilting is applied without river discharge a closed, short tidal basin develops (supplementary Fig. S3c),
136 showing that a minor river discharge is essential to develop an elongated estuary. The experiment starts with a bed
137 thickness of 7 cm that consists of only sand with an exponential widening shape of 3 cm deep (bottom Fig. 1). The
138 initial shape decreases from 1 m width at the mouth of the estuary to 0.2 m at the river end with a characteristic
139 e-folding convergence length of 3 m. The bottom of the flume is covered with artificial grass. If scours develop that
140 reach the bottom of the flume, the roughness of the grass prevents further erosion in this location. The basin area in
141 which the ebb delta can expand during the experiment is 2 m long. Water levels in the flume are controlled by a weir
142 at the end of the flume while pumps constantly add water to the sea basin. This weir compensates for the tilting of the
143 flume by maintaining a horizontal water level (constant head) in the sea between the end of the flume and the front of
144 the ebb delta at all times. Because the ebb delta grows the compensation of the weir is adjusted during the experiment.
145 Water flowing out of the flume is recirculated. The total duration of each experiment is 15,000 tidal cycles.

146 The experiment with the low nutshell supply had a slightly lower tilting amplitude than the other two experiments.
147 Instead of 75 mm, this experiment used a tilt of 68 mm. This was due to an accidental software update of the
148 Metronome during the period the experiments were carried out, which was only discovered after the experiment was
149 finished. Based on pilot studies focussed on amplitude variations, we do not expect that this error influences the main
150 outcomes of this study. However, we expect that the resulting estuary might be slightly shorter and smaller. The effect
151 of tilting amplitude on estuary length is indicated by pilot experiments shown in supplementary Fig. S1. The length
152 of the estuaries is proximately constant throughout the experiments, in contrast to estuary width.

153 **2.3 Sediment characteristics**

154 To simulate mud in the experiment we used nutshell grains (as used in Baumgardner, 2016; Ganti et al., 2016; Van
155 de Lageweg et al., 2016; Baar et al., 2018). Pre-wetted nutshell was added to the system during ebb with the river
156 discharge. We conducted an experiment with a low concentration of 1 ml nutshell per cycle (0.405 g/L) and an
157 experiment with a high concentration of 5 ml nutshell per cycle (2.025 g/L). In total 12 kg and 60 kg of nutshell
158 was supplied to these experiments over 15,000 cycles. However, not all nutshell deposited in the estuaries, but also a
159 large part was transported out of the estuary and settled in the ebb delta. Throughout the paper, we will refer to these
160 experiments as the experiments with *low* and *high* mud supply concentration.

161 The nutshell was chosen to simulate mud because it is light-weight with a dry density of 1350 kgm^{-3} and therefore
162 travels in suspension, and because it is only slightly cohesive. To test the exact cohesive effect of nutshell over time,
163 we conducted bank erodibility tests with the method of Friedkin (1945) and the exact same setup as Van Dijk et al.
164 (2013); Kleinhans et al. (2014a). Sediment samples created in the lab were subjected to a flow of 400 L/h under an
165 angle of 45 degrees. Pictures were made every 10 seconds to track the volume of the sample over time and to measure
166 the erosion rate. The samples that were tested were 10x37 cm with a triangular corner cut off of 10x10 cm. The
167 samples were made of a combination of 4/5 sand and 1/5 nutshell on top and were kept under similar circumstances
168 as in the Metronome for a variable number of days. To create similar circumstances the samples were almost fully
169 submerged with recirculating water flow with approximately the same amount of anti-algae and chlorine that was
170 used in the Metronome. As other authors suggest, the nutshell is indeed non-cohesive if subjected to experimental
171 condition for only a short time (as mentioned by Ganti et al., 2016). However, mud deposits became more difficult to
172 erode due to slight decomposition over time and perhaps fungal development, as in natural estuaries where the critical
173 shear stress for erosion increases over time due to consolidation and biofilm development (Torfs et al., 1996).

174 Sand in the experiments has a median grain size of 0.55 mm with a D_{10} of 0.32 mm and a D_{90} of 1.2 mm (see for
175 design Kleinhans et al., 2017b). The sand mixture was prepared by wet sieving which completely removed any fines
176 below 0.125 mm. There was no sand supply upstream. The nutshell has a grain size of 0.2 mm. Preliminary test with
177 the nutshell indicated that coarse nutshell (1.3–1.7 mm) not only settles with low velocities but also deposits when the
178 grain size is larger than the water depth on bars. We hypothesise that this effect might be the cause for the different
179 point bar deposits for nutshell and silt in Van de Lageweg et al. (2016), where nutshell deposited dominantly on the
180 downstream half of the point bar, while the silt deposited in the upstream half. A much smaller nutshell grain size was
181 used for the estuary experiments and solved this difference between the silt and nutshell behaviour. This means that
182 we are simulating a finer fraction than in the river experiments by Van de Lageweg et al. (2016).

183 **2.4 Data collection and analysis**

184 Time-lapse images were collected using 7 AVG Mako (G-419C) colour cameras on the ceiling. All images have a
185 resolution of 2048 by 2048 pixels with a footprint of about 3.15 m resulting in a pixel resolution of approximately
186 1.5 mm. The images were taken every tidal cycle when the bed was horizontal. Pre-processing of the images in-
187 cluded: debayering of the original Bayer images, noise removal, lens correction (vignette and distortion), geometric

188 rectification, colour, contrast and brightness correction after which the images were stitched together. The water was
189 dyed blue with food colouring to get an impression of water depth from the top view photographs. Additional images
190 were obtained every 500 to 1000 tidal cycles when we temporarily drained the experiment. This way the nutshell
191 was classified more easily, compared to the images with water. Mud was classified per pixel only based on colour
192 thresholds in the images without water.

193 A digital Canon SLR camera was used to collect oblique photos of the experiment. These photos were used to
194 make digital elevation models (DEMs) by structure from motion software Agisoft PhotoScan (version 1.2.6.2038)
195 and were referenced with 20 ground control points along the sides of the flume at a 2 m interval. In the analysis of the
196 DEMs unaffected areas of the flume were masked and the ebb delta was excluded unless stated differently.

197 Particle image velocimetry (PIV) on floating plastic particles was used to obtain surface water velocities in the
198 entire flume at 16 phases (every 22.5 degrees) of the tidal cycle. Ten images were taken every phase with a sampling
199 frequency of 25 Hz. The MPIV Matlab toolbox was used to calculate the velocities from the floating particles. PIV
200 measurements were performed every 500 to 1000 cycles in the experiment without nutshell up to cycle 8863 and
201 at the end of the experiment with a low input concentration of nutshell. There are no PIV measurements during
202 the experiments with nutshell because the removal of the plastic particles influenced the mud deposits. During pre-
203 processing of the PIV images, lens correction was done before the velocities were calculated from the displacement of
204 the particles, but geometric rectification and stitching of the velocity data from different cameras were done afterwards
205 due to memory issues. Additionally, the tilt of the Metronome was not taken into account, but since discontinuities
206 are barely visible in the stitched images, we assume that the projection errors are negligible.

207 During post-processing, the peak velocity ratio was calculated from the ratio between the maximum ebb and flood
208 velocities. To make the colour-scale more readable we took the negative reciprocal ($-1/x$) of the values between
209 0 and -1 so that ebb dominant would be negative and flood dominant positive. If only flood or only ebb flow was
210 measured, no ratio was calculated and therefore plots as zero. For example, highly elevated shoals sometimes flood
211 and drain in the same direction, because maximum high water does not occur at exactly the same time as slack water.

212 **3 Results**

213 We will first describe the general evolution of the estuary in several phases. This is followed by an analysis of the
214 location of mud deposits and the effects of the mud in the estuary.

215 3.1 General estuary evolution

216 The development of the experimental estuary exists of four phases. In the first phase of the experiments, the expo-
217 nentially converging channel starts to develop a channel-shoal pattern. This pattern develops within approximately
218 100 tidal cycles resulting in an alternate bar pattern (Fig. 2a-c). At the same time, the ebb delta starts to form and
219 continues to grow throughout the experiment. Sand is collected in the middle of the flume, caused by a lack of se-
220 diment input upstream and downstream and an estuary planform that does not exactly fit the imposed hydrodynamic
221 conditions (Fig. 3). At the end of this phase, the estuary contains one big meandering channel with sills between
222 bends (cycle 300, Fig. 2a-c).

223 In the second phase, the estuary widens rapidly by outward and downstream migration of tidal meanders (Fig. 4).
224 In some places, there is little lateral widening over time and in some places, there is a large lateral extension of the
225 tidal meanders. The width generally decreases in the upstream direction even though there local areas that are wider
226 (Leuven et al., 2018a). In addition, the bed profile changes to a more linear profile by reworking of the initial bulge
227 (Fig. 3). Although there is some downstream bend migration, this is limited to the initial phase of the experiment. The
228 widening of the estuary favours the formation of multiple channels and bars across the estuary. Small flood channels
229 that end on bars, named barb channels, increase in size and develop into connected ebb and flood dominated channels
230 (Leuven et al., 2018a, cycle 800, Fig. 2d-f;). After about 1800 tidal cycles these multiple channels become clearly
231 visible as a weakly braided pattern (Fig. 2g-i).

232 In the third phase from cycle 3300, the first effects of the mud are observed on the estuary width (Fig. 4, 2j-l).
233 The first mudflats start forming in the upper part of the estuary and slowly spread further downstream. They, however,
234 settle rarely in the lower estuary due to the large reworking of sediment in the area and constantly migrating channels
235 and bars.

236 In the fourth phase and final state, the morphology after 15,000 tidal cycles for the three experiments is a self-
237 formed, freely-erodible, bar-built estuary with migrating channels and bars (Fig. 2II-IV). The experiments approach
238 dynamic equilibrium from cycle 10,900 (Fig. 2v-x), because we see a levelling of the cumulative sedimentation and
239 erosion (Fig. 5). In the final state, the width of the estuary generally decreases in the upstream direction (Fig. 4) and
240 the bed profile increases linearly (Fig. 3). The typical resulting channel depth at the mouth is 4 cm and average bed
241 levels are 2 to 2.5 cm at the mouth of the estuary (Fig. 3). Typical velocity amplitudes are $0.3\text{--}0.4\text{ ms}^{-1}$ (Fig. 6 and 7),
242 with maximum velocities occurring in the deepest channels downstream (Fig. 6). However, width-averaged velocity

243 amplitudes are lower downstream than upstream.

244 **3.2 Mudflat characteristics**

245 The experiments with mud supply resulted in estuaries with self-formed mudflats. The nutshell particles settle on
246 the highest elevations of intertidal areas and form mudflats (or 'nutflats'). The mudflats occur on bars and flank the
247 estuary (Fig. 8 and Fig. 9). The flats can be recognised by an orange to brown colour which is related to the time the
248 mud has been in the system. We observe mud deposits on all types of bars, for example, mid-channel bars (Fig. 9a,
249 b and e), scroll bars (Fig. 9c) and sidebars (Fig. 9d and e). On the bars, mud first settles at the highest locations after
250 which the flat spreads to lower elevations if it can grow in size.

251 The mud supplied upstream is self-distributed throughout the whole estuary, but mostly settles in the upstream
252 regions (Fig. 8). Initially, mud only deposits upstream, which results here in relatively high percentages of mudflats
253 (Fig. 10). For the experiment with high mud supply, the fraction upstream of 10 m after only a few hundred cycles is
254 already approximately 40%. Over time the mudflat area increases upstream and gradually extends more downstream
255 as well, which is especially clear in Fig. 10b, where the front between low and high percentages of mud moves
256 downstream over time. In this experiment, a large volume of mud settles in the lower estuary, but the coverage is still
257 less than 50% of the estuary width (Fig. 10).

258 For the experiment with a higher mud supply, we observe that mudflats are, as expected, larger and more abundant,
259 as high as 12.5 m², compared to 3 m² for the experiment with low mud supply (Fig. 8). Relatively this is a mud
260 coverage of 62% of the surface area for the experiment with high mud supply and 15% for the experiment with low
261 mud supply, which is consistent with the fact that the high mud supply is five times larger than the low mud supply.
262 Additionally, the downstream spreading occurs faster (Fig. 10). After about 8000 cycles the upstream part is so
263 dominated by mud that it also deposits in the channels (Fig. 8). This means that the relative mud cover approaches
264 100% (Fig. 10).

265 Initially, mud only deposits at high elevations between -1.5 and -0.5 cm near the observed high water level, mostly
266 on bars (Fig. 11, dotted lines). Over time this lower knick point in Fig. 11 (dotted lines) becomes weaker and decreases
267 to about -2.2 cm for the highest supply. We hypothesise this is due to different kind of deposits later in the experiments
268 (e.g. filling of abandoned channels). However, the majority of the mud is still located between -1.5 and -0.5 cm.

269 **3.3 Mud preservation**

270 To understand which areas in the estuary are influenced most by mud, we investigated which mud deposits are most
271 stable. The age of mud could be estimated by combining the mud maps to indicate the stability of the mudflats
272 (Fig. 12). We assume that mud was not eroded and redeposited between two images. From this data we can see
273 that some upstream bars show a pattern: first, a small flat develops and then this mudflat expands in the upstream
274 direction and to lower elevations. In the middle of the estuary, the mudflats are very stable in location and size, and
275 some locations have been stable since the beginning of the experiment (for about 15,000 cycles). Downstream, the
276 mudflats are much younger in age (about 2000 cycles) due to larger dynamics of the channels. A small remnant of
277 old mud remained at 9 m (Fig. 12a). This is a remnant of a larger mudflat that has disappeared due to the downstream
278 migration of the biggest channel. Other analysis showed that mud deposits initially at a lower range of elevations as
279 well but is only preserved at high elevations for a long time since older mud deposits occur at higher elevations, which
280 is consistent with our explanation based on velocities and water levels. This is in contrast with rivers, where mud will
281 never deposit at larger depths due to unidirectional flow, except in closed residual channels.

282 **3.4 The effect of mud on morphodynamics**

283 **3.4.1 Bank erosion and erosion rates**

284 The channel banks showed steep cliffs at the edges of bars that were subjected to erosion, which is evidence that the
285 nutshell has some cohesive properties. We observed preferential erosion of sand over the nutshell at the bar margins
286 (Fig. 9f). Sand was eroded from bar margins by undercutting of the mud layer on top of the flat after which the mud
287 eroded by small collapses. This is in contrast with the gentler sloping sandy bar margins.

288 The Friedkin (1945) erosion tests were used to determine the exact effect of the mud on bank erosion. In this case,
289 it behaves as non-cohesive, light-weight sediment as for example plastic sediments that transported and more easily
290 than sand. However, when we added a thin mud layer on top of a sand sample, we observe that after several days the
291 grains stick together and form a mat. This mat becomes stronger over time and changes the erosion mechanism of the
292 samples. Instead of slumping sand, we now observe oversteepening and collapsing (as in Fig. 9f).

293 Despite this difference, there were no significant differences in the erosion rate of the samples with and without
294 mud layer and between different sample times (Fig. 13). Cohesive blocks that end up at the toe of the bank by
295 collapses are immediately removed due to excess basal capacity as observed in similar experiments with cohesive silt

296 (Kleinhans et al., 2014a) and in the field (Rinaldi and Darby, 2007). The transport capacity in the channel is so large
297 that the type of erosion does not affect the erosion rate in this setup. Cohesive blocks are transported as a whole and
298 destroyed rapidly. Even though we do not observe decreased bank erosion with nutshell, we observe that cohesive
299 mats prevent erosion of mud particles with lower velocities under a more gradual slope in the estuary experiments.
300 This suggests that the mild cohesion may reduce channel initiation and incision on bar tops in the experiments, but
301 does not directly confine the estuary laterally.

302 **3.4.2 Bar accretion by mud deposition**

303 Bar accretion is caused by mud deposition on bars. In the experiment without mud supply, the bars are >5 mm below
304 the initial dry estuary margin and are therefore submerged during high tide. In contrast, the bars in the experiment
305 with mud are 3-10 mm higher due to the mud deposits on top of the bars (Fig. 2). The bar accretion can be as high
306 as 5 mm. This is clearly visible in Fig. 11 where the cumulative surface area below 0 to -0.5 cm is constant for
307 the experiment without mud but changes for the experiments with mud. Moreover, the increase in elevation of the
308 bars is visible in Fig. 3, where the 90th percentile of the elevation is higher for the experiments with mud. Visual
309 observations also confirmed that the top of the mudflats on bars changed from intertidal to supratidal (supratidal bar
310 visible in Fig. 9a and b). This is also contributed to the decrease in tidal prism and tidal range which we will discuss
311 later.

312 Because mud only settles at very low velocities and shear stresses (Torfs et al., 1996), the places for deposition
313 are different than for sand (dotted lines in Fig. 7). During ebb flow, mud is supplied to the system and spreads
314 downstream by river discharge. Mud settling occurs mainly during slack tide due to near zero flow velocities (below
315 the critical threshold of mud mobility; Fig. 7), which occurs near maximum high and maximum low water. At mean
316 and low water levels the flow is concentrated in the channels and mud deposits cannot be preserved here due to high
317 peak velocities (Fig. 6b). Fig. 7 also shows that peak velocities below the mud mobility threshold only occur at high
318 elevations. Everything that deposits during low water slack is immediately washed away again during the next flood,
319 while deposits during high water slack are more likely to preserve. During high water, bars are flooded and velocities
320 slow down. Mud settles at these high elevations during slack tide because the water depth is shallow and cannot be
321 re-suspended during mean and low water levels.

322 Peak velocity ratios indicate that mud deposits during high water can be related to flood in the lower and ebb in the

323 upper estuary (Fig. 6d). Upstream, the river has a larger influence and therefore ebb asymmetry is observed for peak
324 velocity over a large area. Around the tidal bars in the lower estuary, peak velocity asymmetry is flood-dominated
325 (Fig. 6d). Duration asymmetry was less pronounced and is therefore not shown. Longer flood durations were observed
326 in small barb channels that terminate on their landward end, however, clear patterns were hard to identify. It is known
327 that duration asymmetry is especially important for fine sediments, so we assume that most mud is deposited during
328 high water slack following the flood, with exception of the most upstream areas. Peak velocity and duration ratios
329 could not be determined in areas where the flow was unidirectional and for supratidal areas.

330 **3.4.3 Mud confines the estuary shape**

331 Deposition of mud on bars and on the sides confines the estuary shape and therefore decreases the width and surface
332 area, especially upstream where there is more mud present (Fig. 4 and 10). The effect on widening downstream is
333 limited because less mud is deposited in this part of the estuary. Not only the width of the estuary is confined by mud,
334 but also the total reworked surface area (maximum values in Fig. 11). Even though the specific tidal meandering leads
335 to a wider estuary mouth of 2.75 m for the experiment with the high mud supply compared to 2.1 m and 1.5 m of the
336 other experiments (Fig. 2), the surface area of that experiment is smaller than the experiment with only sand (Fig. 11a
337 and c). The total estuary area without mud increases up to 25 m², whereas the area of the experiments with mud cover
338 an area of only 20 m² (Fig. 11). Surprisingly, the estuary with the high mud supply is roughly the same size as estuary
339 with low mud supply. This is probably caused by the difference in the geometry of the mouth, which is barely affected
340 by mud and narrower for the experiment with low mud supply. However, we cannot exclude the possibility that this
341 is due to the software error that led to reduced tilting amplitude in the experiment with low mud supply. We expect
342 that under the correct tilting the experiment would have been slightly larger than the experiment with the high mud
343 supply, but still smaller than the experiment with only sand due to the confinement and filling mechanism.

344 **3.4.4 Mud decreases estuary dynamics**

345 Mud decreases the dynamics of channels and bars. Channels initially migrate and shift rapidly within the estuary
346 (Fig. 14), but when mudflats develop the lateral widening of the estuary at the mudflat comes to a halt (Fig. 14e and f).
347 In the cross section of the low mud supply, a mudflat developed on the bottom side and for the high mud supply on the
348 top side of Fig. 14e and f. The migration in the experiment without mud is sometimes so fast that not enough DEMS

349 were made to follow the channel displacement in the time-stack (Fig. 14d). Observations with a higher temporal
350 resolution from the overhead imagery for sand only show that channels remain active and rework bars in specific
351 zones over the entire length of the experiment (Leuven et al., 2018a).

352 The width changes of the estuary in Fig. 4 also shows decreasing dynamics due to mud. For all experiments it
353 holds that initially the estuary largely widens (wider spaced lines) and the widening rate decreases over time (closer
354 spaced lines) as the estuary dimensions get closer to equilibrium conditions (Fig. 4). This decrease in change is more
355 pronounced for the experiments with mud because the mud has confined the estuary, which is then also sooner close
356 to equilibrium with reduced dynamics (Fig. 5).

357 The addition of mud significantly decreases erosion rates within the estuary. Without mud the estuary exported
358 0.25 m^3 of sediment in total and with mud only approximately 0.17 m^3 (Fig. 5). The export is essentially continuous
359 and there are no clear signs of net import. All data so far suggest that the created system is an exclusively exporting
360 system, however visual observations confirmed landward sand movement during flood. This transport was apparently
361 not enough to counteract export. Variations in the general trend of the lines in Fig. 5 are due to inaccuracies of the
362 DEMs. Similar to the analysis of the surface area, the experiments do not show any evidence of decreasing sediment
363 export for higher mud concentration. Both experiments 2 and 3 have similar exported sediment volumes and surface
364 areas (Fig. 5), even though the shape of the mouth is especially different. Due to the tilting amplitude error, the export
365 in the experiment with low mud supply may have been slightly smaller than expected.

366 **4 Discussion**

367 In this section, we will first describe the two effects of mud that impact the morphological evolution of the system.
368 Next, we will discuss the implications of our findings on the understanding of natural systems, followed by a discus-
369 sion of the novelty and contribution of this research to the current state of physical experiments simulating estuaries
370 and experiments with mud.

371 **4.1 Cohesive effect of mud**

372 Two effects of mud were identified to cause morphological differences between estuaries with and without mud. The
373 first effect is the minor apparent cohesion that increases over time because nutshell grains stick together the longer
374 they are in the experiment. The grains form a mat-like structure. These cohesive effects cause small cliffs to form

375 and lead to different bank erosion processes that include oversteepening and mass failures (Rinaldi and Darby, 2007)
376 in contrast to more gentle slopes and gradual erosion for sand. However, auxiliary bank erosion tests did not show a
377 significant effect on erosion rate (Fig. 13). Small effects on the erosion rate are visually observed under low velocities
378 on more gentle slopes.

379 Apparent cohesion can also be created by vegetation (Tal and Paola, 2007). Roots and extracellular polymeric
380 substances (EPS) can stabilise banks similar to cohesive sediment. However, it is still unclear whether vegetation and
381 mud together provide significant cohesion in tidal systems or only reduce the flood storage as discussed below (de
382 Haas et al., 2018). On the one hand, vegetation and mud might settle in the same locations and therefore an additional
383 strengthening effect might be limited. On the other hand, vegetation also reduces flow velocities by creating friction,
384 which might increase significant amounts of mud deposition and more vegetation settling. Further investigation and
385 experimentation of mud in combination with vegetation is part of our future work.

386 **4.2 Filling effect of mud**

387 The second, perhaps more important effect of mud is to fill space and reduce the tidal prism and the possibility for bar
388 splitting. The results showed that mud deposits further increase the elevation of areas that are already relatively high in
389 elevation. For example, sandbars become higher when mud is supplied to the system (Fig. 3). This result agrees with
390 earlier work by numerical modelling of mud in estuaries (Braat et al., 2017). Like the cohesive effects, this deposition
391 contributes to confining the estuary but additionally limits the tidal prism (Fig. 15). The prism is reduced because
392 less water can flow through a cross-section because part of the cross section is now filled with mud. This effect is
393 clearly visible in the upstream part of the estuaries where most mud is deposited. In Fig. 15 the local tidal prism for
394 the experiment with only sand continues to grow up to a local tidal prism of 0.07 m^3 passing the 10 m cross-section.
395 For the experiment with low mud supply, we also observe a growth in tidal prism, but less strong. The prism at 10 m
396 grows up to 0.053 m^3 . For the high mud supply experiment, we even observe a reduction of the tidal prism over
397 time in the upper part of the estuary. The final local tidal prism at 10 m is 0.043 m^3 and only 60% compared to the
398 tidal prism for only sand. Wobbles in these lines can be correlated to individual bends that influence the width of the
399 estuary.

400 A surprising insight from these experiments is therefore the different effect of mud sedimentation in rivers and
401 estuaries. In contrast with rivers where floodplain sedimentation causes the channel to deepen to accommodate the

402 same river discharge through a cross-section (Tal and Paola, 2007), in estuaries the tidal prism adapts to the decrease
403 in cross-sectional area. With a decrease in tidal prism, sediment transport also decreases.

404 In addition to the filling mechanism water level decrease also contributes to tidal prism decrease over time. Be-
405 cause we do not have measurements of water levels, we could only visually observe a decrease in tidal range with
406 time. A fixed high and low water level was assumed along the flume and in time to calculate tidal prism and is,
407 therefore, an overestimation. The prism-reduction effect we describe is therefore probably stronger than visualised in
408 Fig. 15. Tidal prism was calculated along the flume which we define as local tidal prism: the volume between low
409 and high water upstream of this point (Fig. 15). In addition to the decrease in tidal prism by the filling effect of mud,
410 we assume the water level decreases by increased friction in the estuary due to the filling and the development of
411 more complicated bars and channels. According to Dalrymple and Choi (2007), this means that the estuary becomes
412 more hyposynchronous: the friction of the bottom increases and the convergence is less strong leading to a stronger
413 decrease in tidal range towards the tidal limit. This is in accordance with the positive feedback identified by de Haas
414 et al. (2018): the formation of shoals simulates the deposition of more mud leading to a growth of supratidal areas
415 (reduction of intertidal area) further stimulating the growth of new intertidal areas, ultimately increasing friction and
416 reducing tidal prism. This mechanism predicts that, with enough sand and mud available, all estuaries eventually fill
417 up (de Haas et al., 2018).

418 **4.3 Implications for understanding natural systems**

419 The depositional patterns of mud match the classical patterns described by Dalrymple et al. (1992); Dalrymple and
420 Choi (2007). Mudflats are flanking the estuary and are depositing on bars, while the seaward part is largely free of
421 mud citeDalrymple2007. In addition, when the results are compared to data from real-world estuaries we notice that
422 for many real-world estuaries the relative extent of mudflats is larger upstream, similar to our experiments: Western
423 Scheldt (McLaren, 1993, 1994), Ems-Dollard (Van Heuvel, 1991), Dovey (Baas et al., 2008), Severn (Allen, 1987)
424 and the Salmon River estuary (Dalrymple and Choi, 2007). This trend was also observed in numerical models (Braat
425 et al., 2017; Lokhorst et al., 2018). Since the field data supports the experimental results, the experiment can help
426 us understand how the mudflats in the system are formed. Bars in estuaries are mostly built by sand, only when
427 they get more stable, mud starts settling on top of the bars. The preferential settling of mud upstream is not due to
428 supply location, because the mud is transported through the whole estuary and also ends up in the ebb delta. Less

429 mud deposits downstream are due to the larger velocities and larger dynamics in the lower estuary. We expect that a
430 marine supply would lead to a similar spatial distribution between the mouth and the upper tidal limit.

431 When bars increase in elevation because of mudflat accretion, they can change from intertidal to supratidal due to
432 the filling effect and decrease in water level. This has important implications for marsh formation. These areas could
433 potentially be a starting point where pioneer marsh species can find their window of opportunity (Cao et al., 2017;
434 de Haas et al., 2018). This was recently also concluded in a numerical modelling study of estuaries with mud and
435 vegetation (Lokhorst et al., 2018). An important question related to vegetation and mud settling is if the vegetation
436 supports mud settling, or the other way around, or both. Showing that we can create mudflats in these experiments
437 partly solved this chicken-or-egg problem. At least vegetation is not necessary for extensive mudflats and to increase
438 the elevation of tidal bars. In the Western Scheldt, the elevations of bars have been increasing over the past years
439 and are often considered an undesired consequence of dredging and dumping (Cleveringa, 2013; De Vet et al., 2017).
440 However, this study shows that this trend can also partly be attributed to changes in mud supply either by natural or
441 anthropogenic changes.

442 Besides the increase in bar height, the results showed that mud supply also influences the width, size and dynamics
443 of the estuary morphology. Due to the filling mechanism and reduction in tidal prism, the estuary becomes more
444 confined. The reduction in width and size was also observed in numerical models with mud (Braat et al., 2017).
445 Similar to the experiments, the dynamics of channels and bars also decreased in models with mud compared to
446 estuaries with only sand. Observing the same trends with both methods strengthen the certainty of these findings.

447 However, some differences are also observed between the models and the experiments. The models (Braat et al.,
448 2017) show predominantly deposits on the sides, while in the experiments most deposits are on bars instead of on
449 the sides. This probably relates to the balance between the initial and boundary conditions. In the model, there is
450 initial import into the system, while in the experiments the estuary is mostly exporting, despite the filling mechanism
451 discussed earlier. Because the experiments are widening over time, mud is rarely deposited on the sides. An alternative
452 hypothesis is that varying discharge is necessary to form flats on the sides, as seen for floodplain formation in river
453 experiments (Van Dijk et al., 2013). The initial horizontal bed is not flooded during high water for mud to deposit
454 as overbank deposits. We expect that the confining effect of the estuary would be greater if this type of deposit
455 would be formed. This could be achieved, by for example adding spring and neap tides. Other similarities with river
456 experiments were found in strengthening of banks, decrease in meandering and a decrease in chutes (Van Dijk et al.,

457 2013). However, since the prism adapts to the cross sections, we do not observe deeper channels as for rivers where
458 the discharge through the cross-section is forced.

459 The numerical models indicate that confinement of the estuary by mud can lead to a dynamic equilibrium (Braat
460 et al., 2017), but we did not find such equilibrium in the experiments yet. Although, the equilibrium for experiments
461 with mud is probably closer than for only sand (Fig. 5). We hypothesise that the experiments could also reach an
462 equilibrium if filling continues and friction would further increase, decreasing the tidal prism and tidal amplitude. If
463 this is true, this would have important implications for estuary management. Since altering the system by dredging
464 might constantly bring the estuary out of equilibrium. If the equilibrium dimensions of an estuary are known, bringing
465 the estuary closer towards these dimensions will likely decrease the dynamics and will make maintenance of the
466 shipping channel easier, while bringing the estuary out of equilibrium will only increase dynamics and will make
467 maintenance of the shipping fairways more difficult.

468 While high mud concentrations are often seen as negative because of fluid mud, decreasing light penetration and
469 silting up of harbours; some mud is important for ecology. Muddy areas are often the most biologically active areas of
470 the estuary and an important part of the ecosystem (Costanza et al., 1993). These ecosystems can be largely affected
471 by changes in mud supply concentration. The results show that if mud were absent, intertidal flats are lower and might
472 drown species that prefer high intertidal or supratidal regions. Many benthic species also prefer a muddy substrate
473 (Bouma et al., 2005). Results also suggest that if mudflats are absent the estuary will expand faster which might affect
474 surrounding areas if there are no dikes bordering the estuary.

475 **4.4 Novelty of mud in tidal experiments**

476 The results showed an improvement in the methodology of conducting tidal experiments. Continuous dynamics were
477 obtained with dynamic ebb and flood dominated channels that are typical for tidal systems. These channels were
478 already described by van Veen (1950) and are essential for natural estuarine behaviour. It has been somewhat difficult
479 to maintain dynamics in experiments in the past (Kleinhans et al., 2012; Vlaswinkel and Cantelli, 2011), but these
480 experiments show dynamic channels without any extra trigger or irregular forcing. This is because the Metronome
481 was successful in achieving sediment mobility along the whole estuary in both flow directions.

482 Of additional interest is that the shape and patterns are self-formed. Until now, the shape of the estuary was
483 often imposed especially for numerical models (Hibma et al., 2003; Van der Wegen and Roelvink, 2008), but also

484 for experiments (Tambroni et al., 2005). The final shape of the estuary is a self-formed exponential shape with some
485 deviations (Fig. 4). It is widely accepted that an exponential shape is the natural equilibrium planform of most natural
486 estuaries (Lanzoni and Seminara, 2002; Savenije, 2015). However, observations in natural systems show that the
487 width of estuaries can be rather irregular than ideal exponential Leuven et al. (2018b). The locations where the
488 estuary is wider than ideal are locations where bars occur in natural systems, which is consistent with observations
489 in the experiments Leuven et al. (2018a). These bars are intertidal areas and because flow velocity on the bars is
490 low, they are also the places where mud is likely to settle when available. Therefore, the outline of the estuaries is a
491 relevant indicator for the locations of mudflats, which also translates into predictable depth distributions Leuven et al.
492 (2018c).

493 Idealised experimental studies like this are useful to get an understanding of the main processes that are involved
494 in the morphological evolution of estuaries. These processes are hard to isolate from field data, and data is generally
495 sparse. However, detailed results should be interpreted with caution as details in the natural morphology might
496 be hampered by scale effects, such as the occurrence of scour holes (Kleinhans et al., 2017a) or are influenced by
497 processes that were neglected, such as additional tidal components, inherited hard substrates, and salinity. These
498 effects cannot presently be accounted for in large-scale system experiments.

499 A side effect of solving the mobility scaling problem with the tilting flume is that the water level variations are
500 now caused by the flow instead of flow caused by water level variations. This means that the water level is no longer
501 a simple function of the tides but a complex result of local friction and the wave of water going through the system as
502 the flume tilts, while the typical phase relations for estuaries between flow and water level are lost (Kleinhans et al.,
503 2017b).

504 Using nutshell as a proxy for mud also imposes limitations. The cohesive properties could not exactly be simulated
505 at scale, because the degradation of the mud was poorly constrained because it depends on the temperature of the room,
506 water, possibly inundation duration and the total time it has been in the flume. As a consequence, we believe that the
507 cohesiveness of recently deposited nutshell was too low while it was too high for nutshell that had been in the flume
508 for over 10,000 cycles. Since these older deposits were rarely subjected to large velocities, the effect on the final
509 results was minimal, although perhaps the bars in the centre of the estuary might have been over-stabilised.

510 On the other hand, numerical models often also apply similar simplifications, such as ignoring multiple tidal
511 components, multiple grain sizes, salinity and three-dimensional velocity calculations, especially for large time scales.

512 Even though scaling issues are absent, there are uncertainties in the physical representation of processes in models.
513 To quantify these uncertainties and assess their effects, more studies with analogue experiments are desirable. The
514 contribution of the present experiments is to complement the approach of numerical modelling.

515 **5 Conclusions**

516 The aim of the present research was to examine the effects of mud on the shape and dynamics of estuaries. Expe-
517 riments in a novel tilting tidal flume, the Metronome, show that mudflat formation confines the morphology of the
518 estuary. The main effect of mud is that it deposits in areas that would not be filled with sand otherwise and therefore
519 decreases the local tidal prism, which, in turn, reduces the migration of channels and the large-scale widening of the
520 estuary. As a result, the estuary becomes more confined as the width remains smaller, especially upstream, and total
521 surface area of the estuary remains smaller with mud compared to only sand. Cohesive effects are surprisingly minor
522 compared to the important role of cohesive floodplains on river patterns.

523 The second major finding was that mud increases the elevation of the bars and can transform bar surfaces from
524 intertidal to supratidal. Bars and channels migrate slower and the estuary exports less sediment when mud is added to
525 the system. Mud has a non-uniform spatial distribution along the estuary: more mud deposits upstream and therefore
526 more morphological effects of the mud are observed upstream than downstream. In more detail, we found that mud
527 is mostly deposited at intertidal bed elevations but preservation over time increases for higher elevations.

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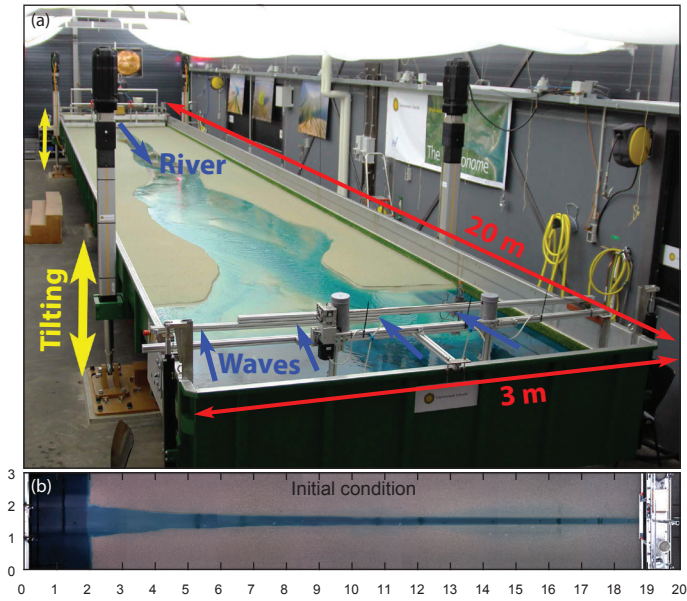


Figure 1: The Metronome: (a) the flume drives the flow by periodic tilting of the entire 20 by 3 m flume. Upstream input is river discharge and mud and downstream waves are generated. (b) Overhead imagery of the initial conditions with estuary mouth on the left and river on the right.

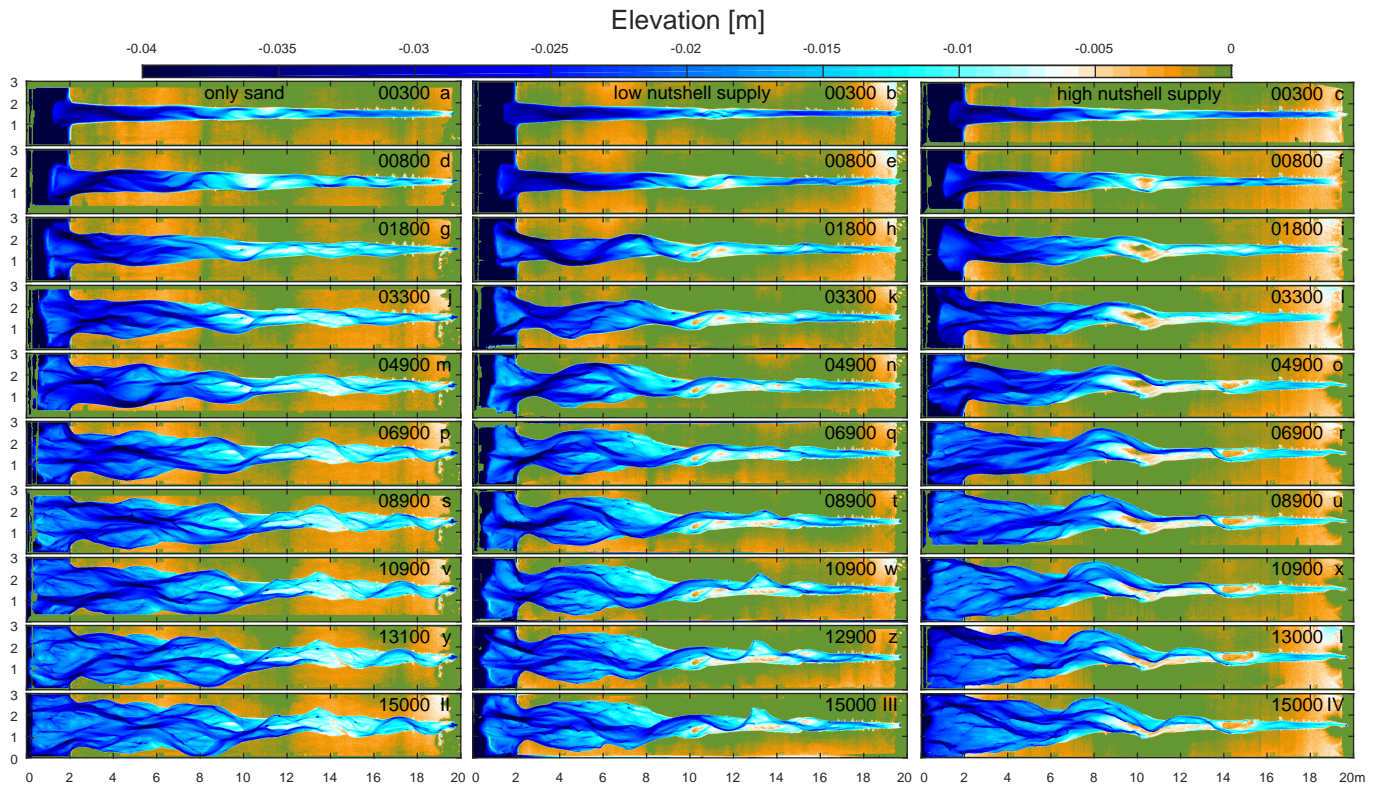


Figure 2: Time series of digital elevation models of the experiments without mud (left column), with a low mud supply (middle column) and a high mud supply (right column).

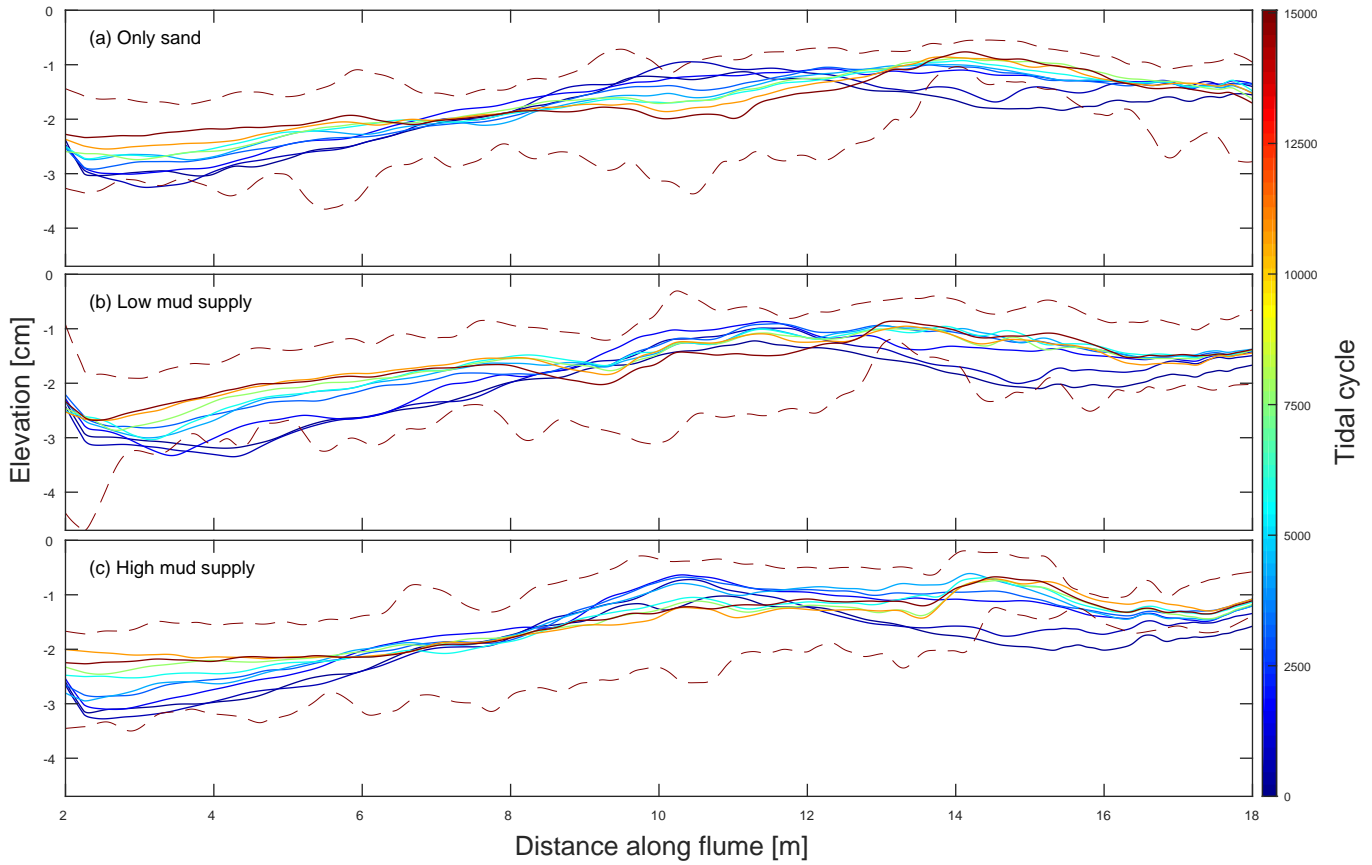


Figure 3: Mean (solid), 5 and 95 percentile (dashed) elevation along the estuary for the experiment with (a) only sand, (b) a low mud supply, and (c) a high mud supply indicating the evolution over time. Colours indicate different moments in time. The along bed elevation was median filtered over a length of 500 pixels, which equals 0.5 m.

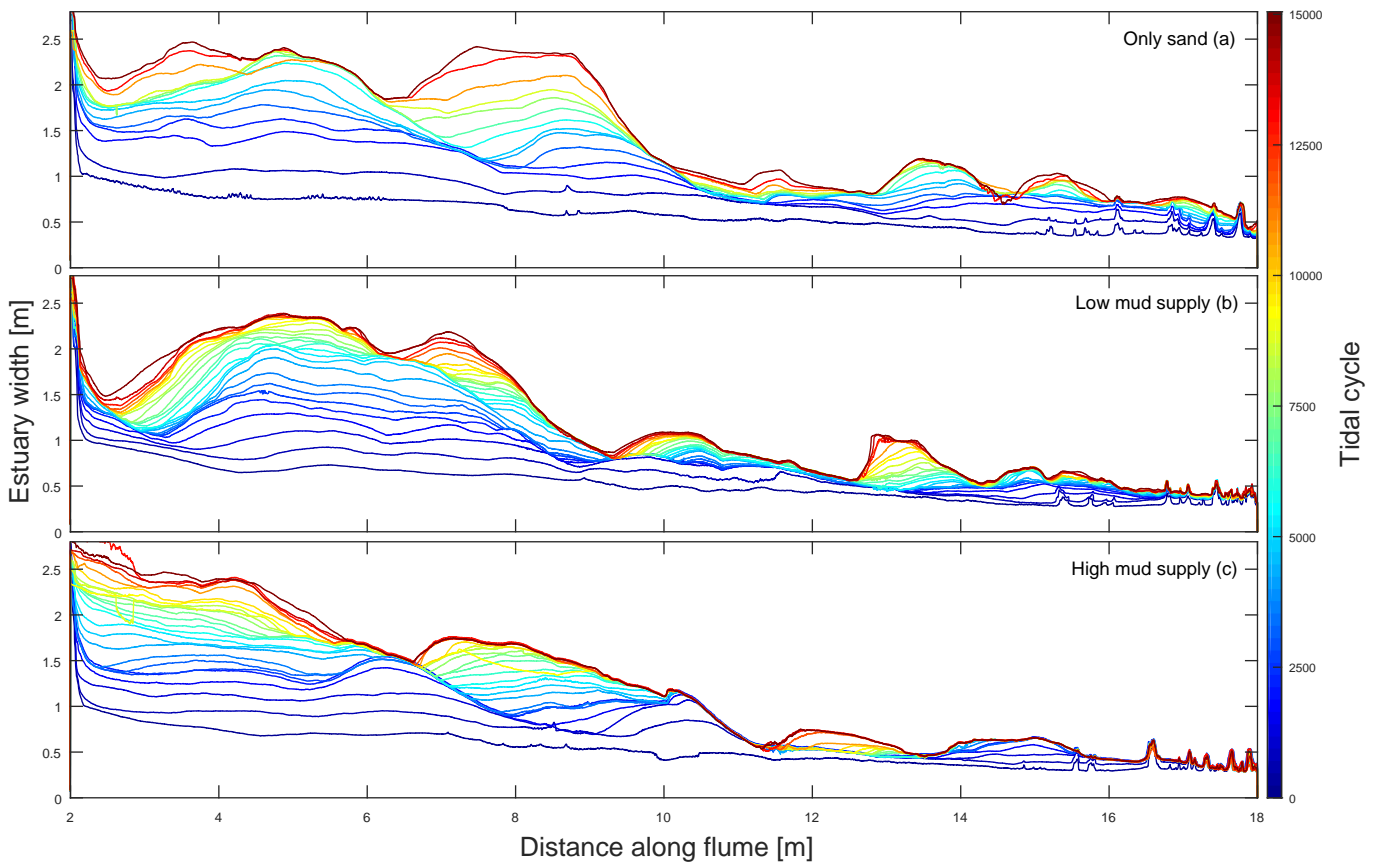


Figure 4: Width along the estuary for: (a) the experiment with only sand, (b) the experiment with a low mud supply, and (c) the experiment with a high mud supply. Colours indicate different moments in time.

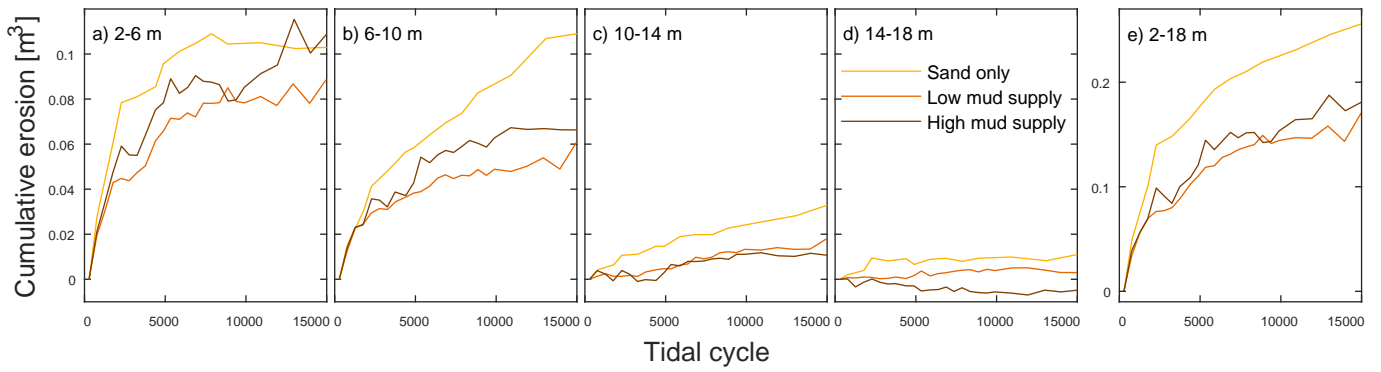


Figure 5: Cumulative sediment removed from the estuary over time for the three experiments, between (a) 2-6 m, (b) 6-10 m, (c) 10-14 m, (d) 14-18 m and (e) 2-18 m. Larger export occurred for the experiment with only sand. Experiments approach dynamic equilibrium.

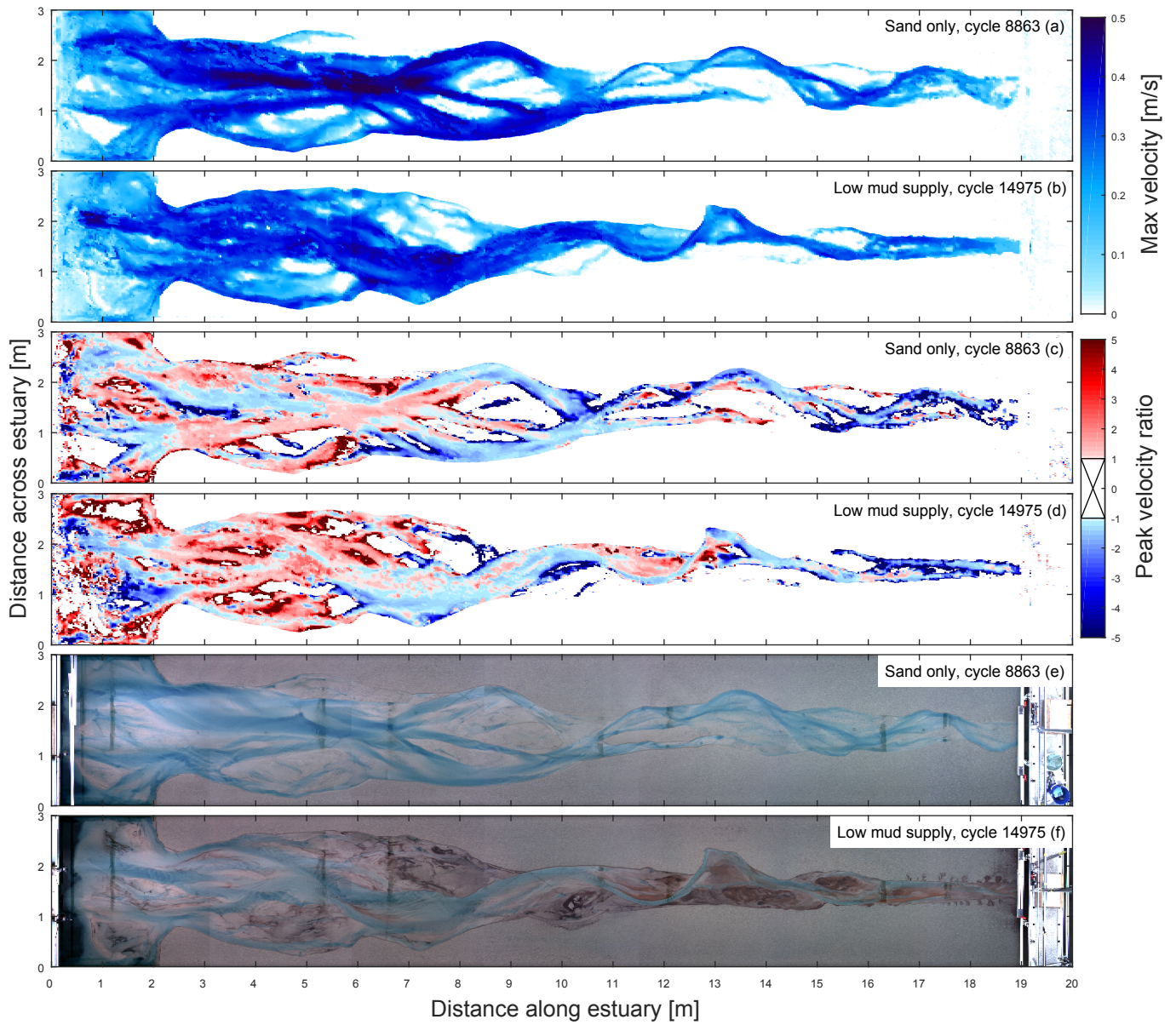


Figure 6: Maximum surface velocity over a tidal cycle for (a) sand only at cycle 8863 and (b) low mud supply at cycle 14975. Peak velocity ratio for (c) sand only at cycle 8863 and (d) low mud supply (b) at cycle 14975. Positive numbers indicate flood dominated and negative is ebb dominated. The number indicates the times the peak flood or ebb flow is larger than the flow in the other direction. No data if the flow was unidirectional or if the area was not flooded during the measurement. Related time-lapse images are shown in (e) for sand and (f) for low mud supply.

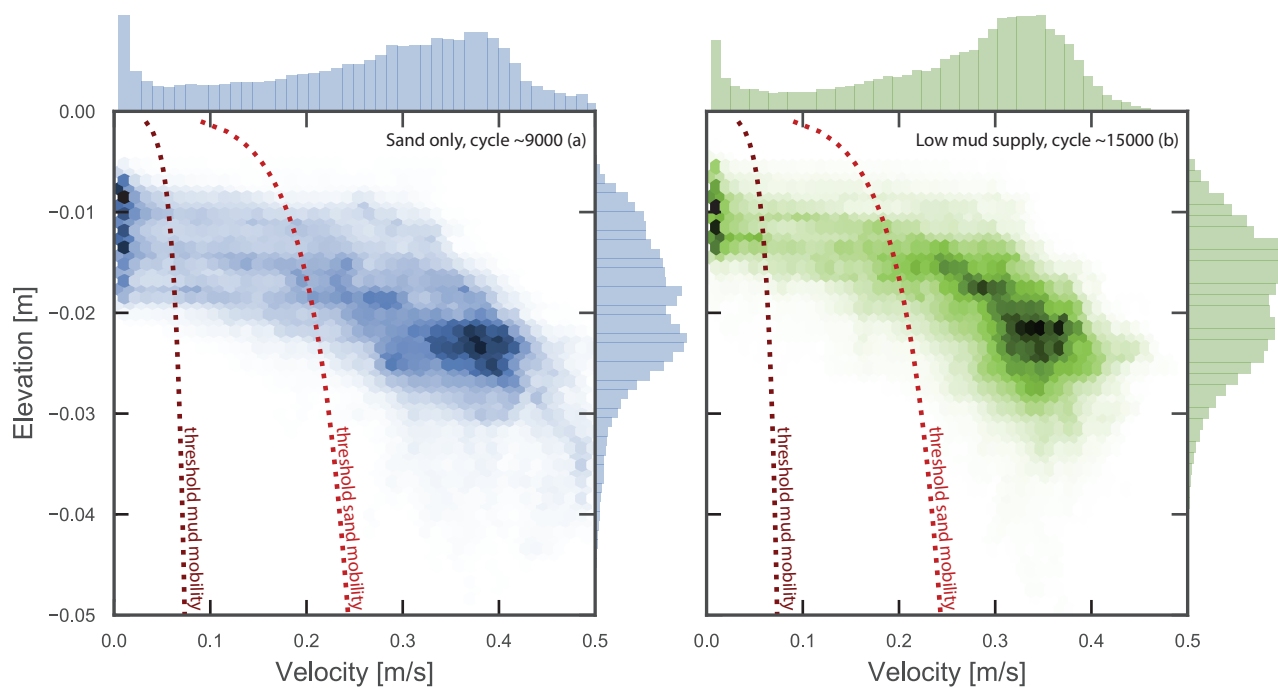


Figure 7: Scatter plot of elevation plotted against maximum surface velocity. Colour intensity and histograms on the sides indicate the velocity and elevation distribution. Still water level is at -0.005 m. Dotted lines indicate the critical threshold of motion for sand and mud. (a) Experiments with only sand at cycle 8863, (b) experiment with low mud supply at cycle 14975.

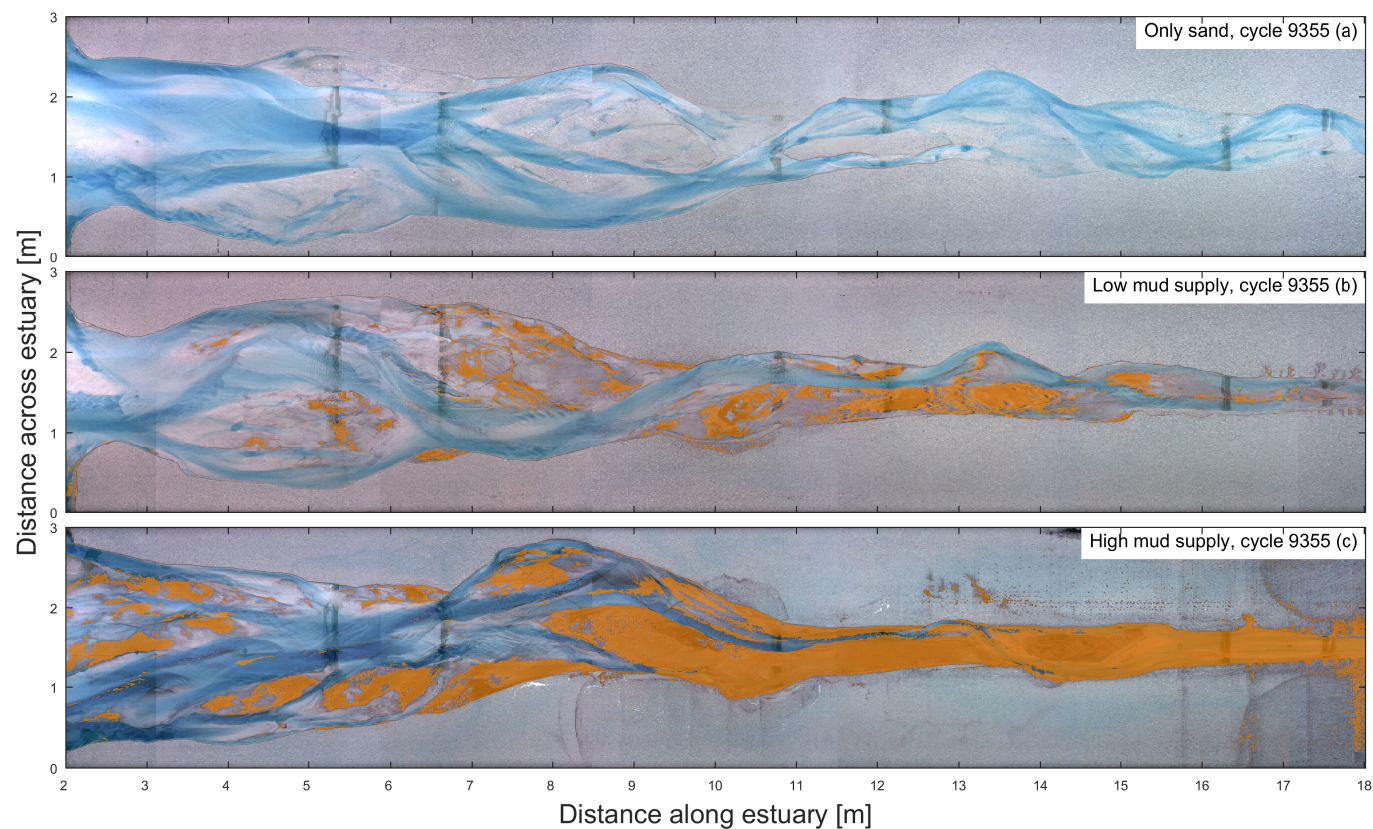


Figure 8: Spatial distribution of mud (classified in orange) in the estuary with: (a) only sand, (b) a low mud supply and (c) a high mud supply at cycle 9355.

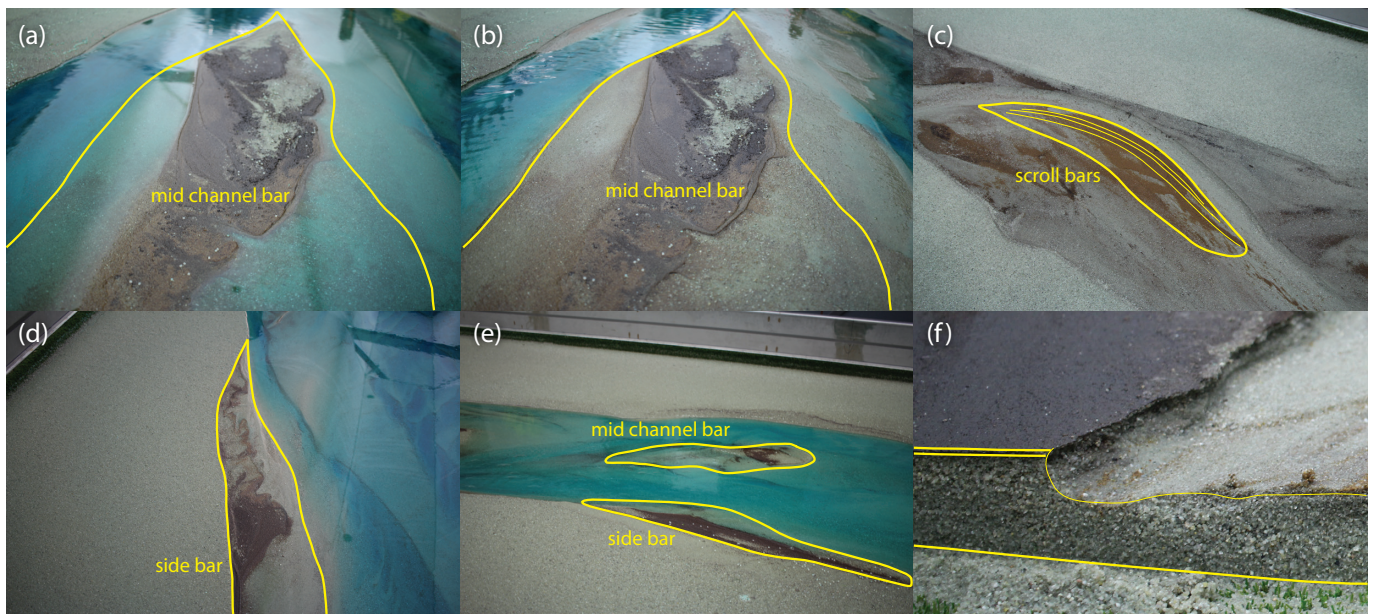


Figure 9: Detailed photographs of mud deposits in the experiments. a) Mudflat with high water, b) mudflat with low water, c) scrollbars, d) mudflat on the side, e) mudflat on a bar and on the side and f) cross-section of a channel with steep banks, indicating cohesive nature of the nutshell deposits.

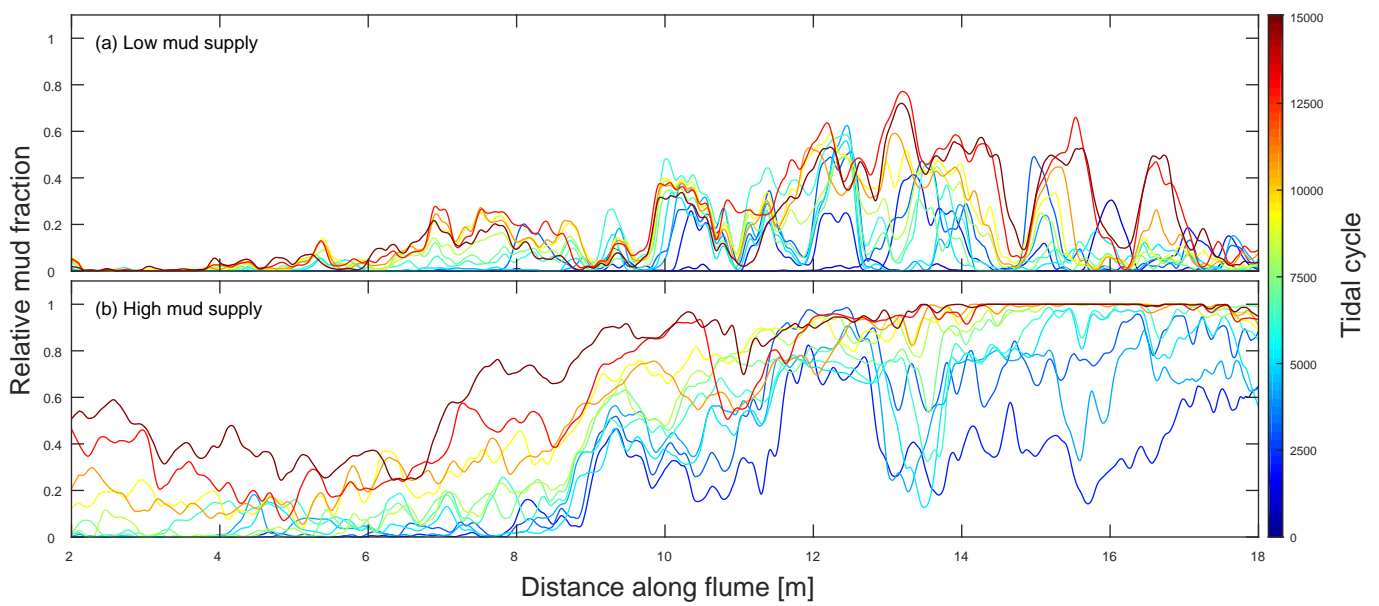


Figure 10: Mud cover relative to the estuary width along the estuary for (a) the experiment with a low mud supply and (b) the experiment with a high mud supply. Colours indicate different moments in time. The relative mud fraction was median filtered over a length of 200 pixels, which equals 0.2 m.

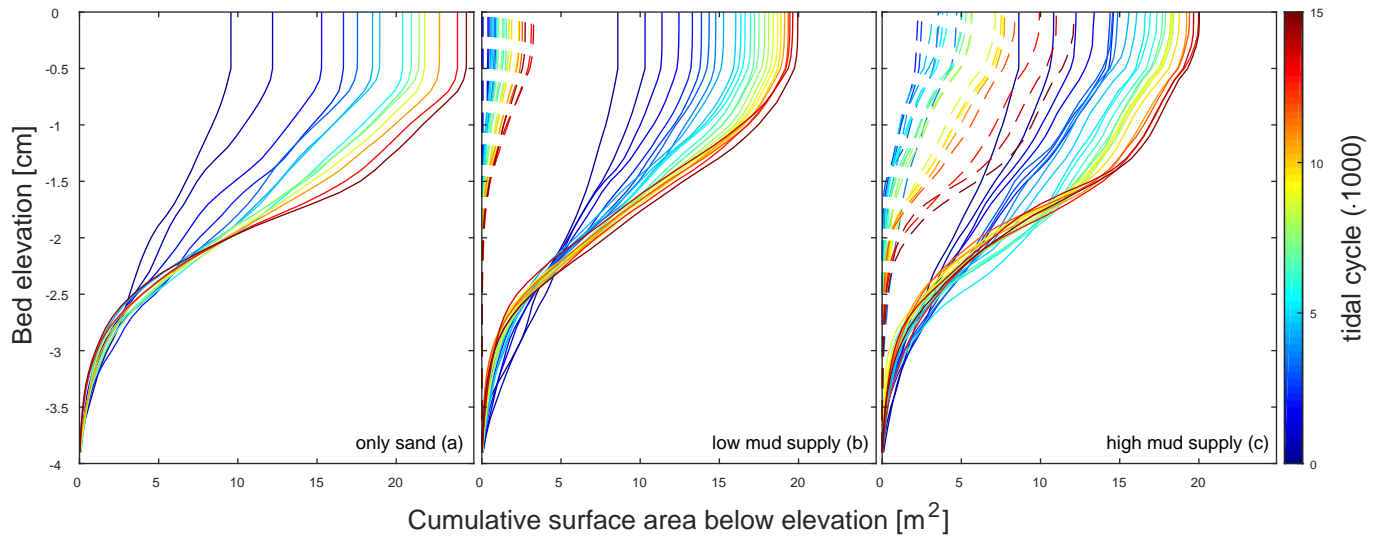


Figure 11: Cumulative total estuary area (solid) and mud covered area (dashed) below a certain elevation for the experiment with (a) only sand, (b) a low mud supply and (c) with a high mud supply. Colours indicate different moments in time.

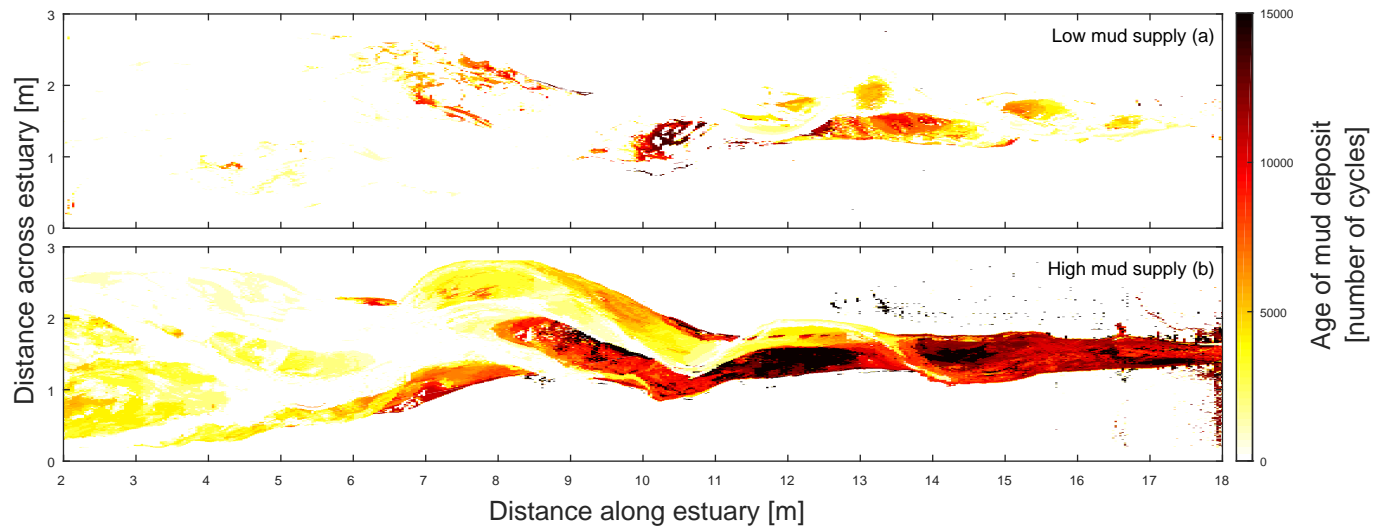


Figure 12: Spatial maps of the age of the mud deposits for the experiments with (a) a low mud supply and (b) a high mud supply. Darker colours indicate older deposits. (c,d) Histograms of maps (a,b) of mud age for the final situation.

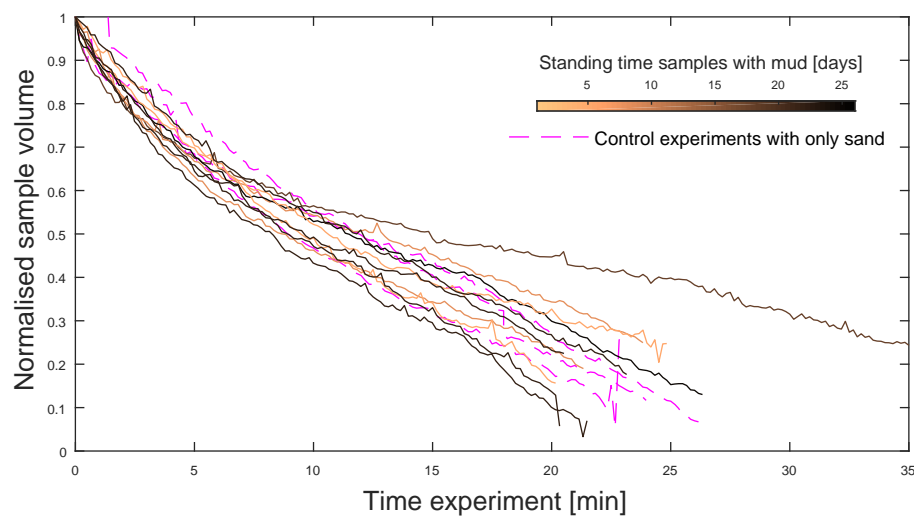


Figure 13: Volume of samples during bank erosion tests over time. Pink colours are control experiments with only sand. Orange-brown colours indicate the standing time of the samples with a mud layer before between making the sample and conducting the experiment. There are no differences in observed erosion rates for sediment type or standing time, which implies that bank erosion is not affected by mud.

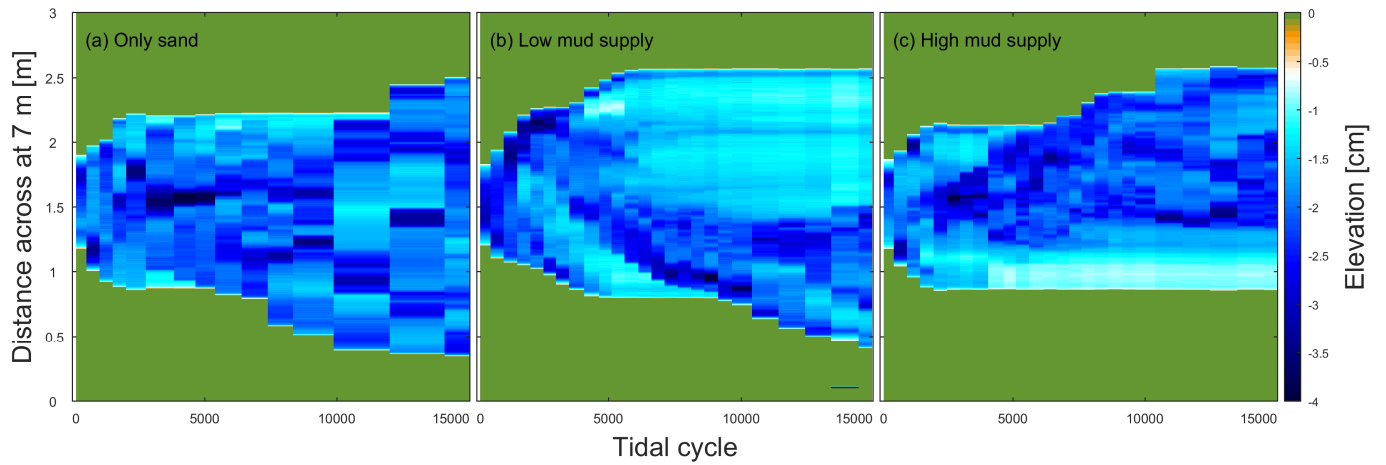


Figure 14: Timestacks: Bathymetric evolution of a cross section at 7 m over time for the experiment with (a) only sand, (b) a low mud supply, and (c) a high mud supply. Cross sections increase over time. Shallow areas in (b) and (c) are mudflats that prevent the channel migrating in that direction. The temporal resolution of the DEMs in (a) is too low to track the fast channel migration.

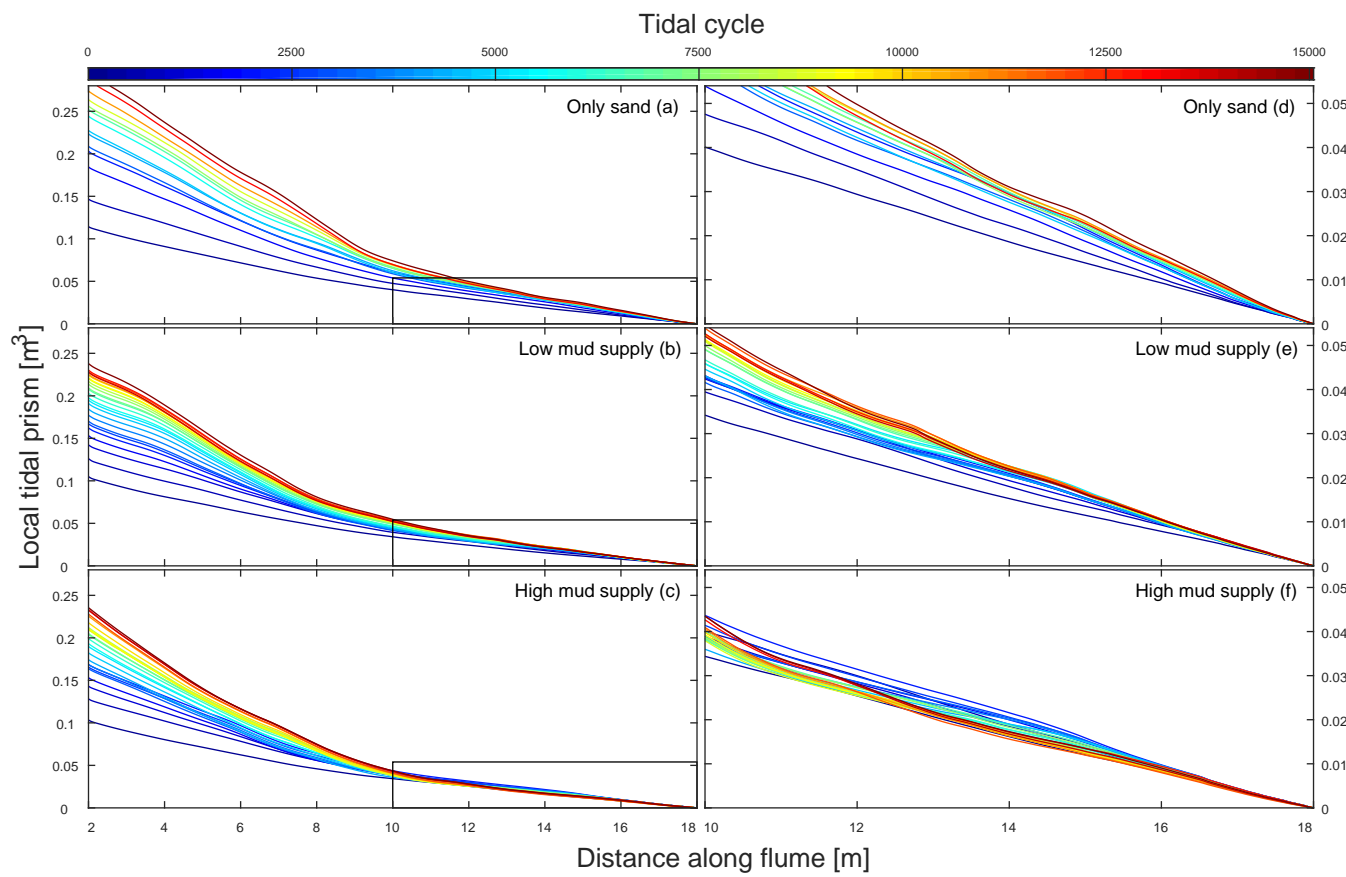


Figure 15: Locally defined tidal prism along the estuary at different moments in time for: (a) the experiment with only sand, (b) the experiment with a low mud supply, and (c) the experiment with a high mud supply. (d-f) Zoomed in on the upstream region of the estuaries. Tidal prism increases in the upstream region with high mud supply.