Growing forced bars determine non-ideal estuary planform

J.R.F.W. Leuven[1], **L. Braat**[1], **W.M. van Dijk**[1], **T. de Haas**[1], **E.P. van Onselen**[1], **B.G. Ruessink**[1] **and M. G. Kleinhans**[1]

[1] Faculty of Geosciences, Utrecht University, Princetonlaan 8A, 3584 CB, Utrecht, The Netherlands

Key Points:

- Quasi-periodic estuary planforms arise from diversion of flow around forced non-migratory mid-channel bars that causes bank erosion
- Self-formed confinements separate zones in which the estuary is wider and bars are more dynamic
- Confinement spacing scales with bar dimensions and estuary width in experiments and nature

Corresponding author: Jasper R.F.W. Leuven, `j.r.f.w.leuven@uu.nl`

Abstract

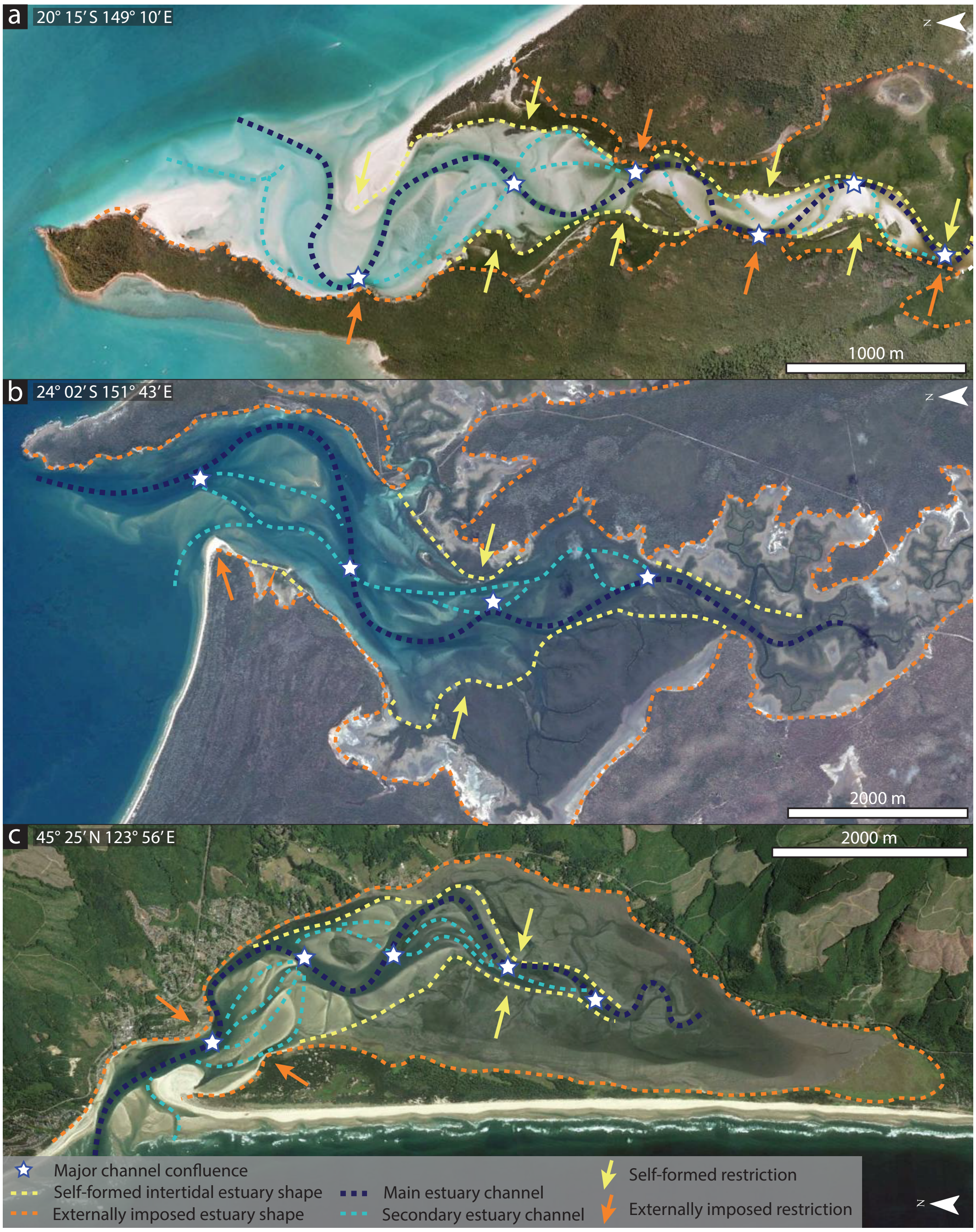
The planform of estuaries is often described with an ideal shape, which exponentially converges in landward direction. We show how growing topographically forced non-migratory bars determine the large-scale estuary planform, which explains the deviations observed in the planform of natural estuaries filled with bars compared to the ideal planform. Experiments were conducted in a 20 m long, 3 m wide tilting flume, the Metronome. From a narrow, converging channel a self-formed estuary developed characterised by multiple channels, braided bars, a meandering ebb channel and an ebb delta. Bars hardly migrated due to the alternating current, but the bar width increased with increasing estuary width. At locations where the estuary width was narrow, major channel confluences were present, while the zones between the confluences were characterised by a higher braiding index, periodically migrating channels and a relatively large estuary width. At the seaward boundary, confluences were forced in place by the presence of the ebb-tidal delta. Between confluences, bars were topographically forced to be non-migratory. Diversion of flow around forced mid-channel bars caused bank erosion. This resulted in a planform shape with a quasi-periodic widening and narrowing at the scale of forced bars. Observations in natural systems show that major confluence locations can also be caused by inherited geology and human engineering, but otherwise the estuary outline is similarly affected by tidal bars. These observations provide a framework for understanding the evolution of tidal bar patterns and the planform shape of the estuary, which has wide implications for navigation, dredging and ecology.

1 Introduction

Estuaries are tidal systems that occur where rivers debouch into the sea. The planform of estuaries is often described by an ideal shape [*Pillsbury*, 1956; *Langbein*, 1963; *Savenije*, 2015], which is defined as an equilibrium state wherein the channel planform converges with a constant along-channel tidal range, average depth and current velocity amplitude. The imposed landward-decrease in tidal prism has a first-order control on the planform shape, resulting in converging ("funnel-shaped") channels for delta branches and tidal creeks. However, previous research showed that in alluvial estuaries a second-order complexity is superimposed on the converging shape, which results in more irregular planforms with locallt widened zones [*Leuven et al.*, 2018a] (Figure 1). Deviations from the ideal shape may occur because the estuary adapted in varying degrees to its equilibrium shape, depending on the time and sediment available to adapt to changing boundary conditions, such as Holocene sea-level rise and antecedent topography [*Townend*, 2012; *de Haas et al.*, 2017]. In addition, the outline may be shaped by external restrictions that impose local confinements, such as inherited geology or human engineering, as well as self-formed restrictions, such as salt marshes and riparian forest [*Townend*, 2012] (Figure 1). Current theoretical and empirical descriptions for estuary planforms neglect the effect that bar formation and bar evolution may have on the planform of the estuary. We propose that the irregular planform of many alluvial estuaries is shaped by a forcing mechanism in which growing mid-channel bars determine bank erosion, leading to quasi-periodic widening and narrowing of the estuary.

In contrast to tidal systems, the forcing mechanism of bars has been thoroughly studied for river systems. Bars can be described as either free or forced, where forced bars are forced to their location by the channel planform shape, while free bars can migrate freely and typically occur in straight or weakly curved channels [e.g. *Tubino et al.*, 1999; *Seminara*, 2010; *Schuurman et al.*, 2013]. For rivers, low-amplitude alternate bars may cause channel curvature, after which the alternate bars evolve into point bars, forcing a meandering planform [*Schuurman et al.*, 2016].

A recently identified mechanism of coupling between meander and bar formation and bank erosion in rivers [e.g. *Parker et al.*, 2011; *Eke*, 2014; *van de Lageweg et al.*, 2014] may also be relevant for their tidal counterparts. In the *bank pull* condition, outer-bend bank erosion causes local flow deceleration resulting in inner bend bar growth, while in *bar push* inner bend



52 **Figure 1.** Aerial photographs of (a) Whitehaven beach (Aus), (b) Rodds Bay (Aus), and (c) Netarts estuary
53 (USA). The outline of these estuaries shows an irregular rather than ideal converging shape. Local
54 confinements occur due to externally imposed restrictions, such as bedrock geology and human engineering,
55 as well as by self-formed restrictions. The major confluences occur at locations of confinement. Google
56 Earth, accessed January-April 2017.

sedimentation causes transfer of flow momentum to the outer-bend, which increases bank erosion. Modelling suggests that well-developed bends fluctuate around a balanced state of bar push and bank pull [*Eke*, 2014], but initially the alternate bars form in a straight channel [*van Dijk et al.*, 2012] suggesting that the process of pattern formation starts with bar push. While this concept has not been applied in estuarine context, the presence of bars and bends suggests that it plays a similar role in estuarine shape and size development. Once variations in width are present, the location and size of forced bars may be induced by channel width variation, for example due to the presence of embayments [*Leopold and Wolman*, 1960; *Yalin*, 1971; *Struiksma et al.*, 1985; *Tubino et al.*, 1999; *Repetto and Tubino*, 2001; *Seminara*, 2010; *Wu et al.*, 2011; *Kleinhans and van den Berg*, 2011; *Schuurman et al.*, 2013]. This suggests an intimate link between bars and river planforms, and we hypothesise a similar dependency between tidal bars and estuary planforms.

Indeed, observations in modern estuaries support the hypothesis that the location where tidal bars occur correlates with by the deviation of the estuary planform from an ideal shape [*Leuven et al.*, 2018a,b,c]. In addition, bar and meander dimensions scale with estuary width [e.g. *Dalrymple and Rhodes*, 1995; *Leuven et al.*, 2016]. From aerial photographs one can observe that the locations where the estuary is relatively narrow correspond to locations with major confluences, defined as the location where two (or more) major channels connect (Figure 1). For braided rivers, the dimensions and spacing of confluences scale with bar dimensions [*Ashmore*, 2001; *Hundey and Ashmore*, 2009]. Confluence locations associated to downstream bifurcations steer the morphodynamics of channels and bars [*Schuurman and Kleinhans*, 2015]. For example, the deposition of a mid-channel bar downstream of a confluence location can create a bifurcation and subsequently erode the channel banks, creating a more irregular planform [*Hundey and Ashmore*, 2009; *Schuurman and Kleinhans*, 2015]. Here, we explore the relation between channel and bars dynamics and estuary planform. In particular, we assess whether channel and bar dynamics can cause the often observed irregular estuary planform and the locations of major channel confluences.

Current knowledge on long-term evolution – time-scales larger than decades – of bars and channels in estuaries is limited by a lack of data [*de Haas et al.*, 2017]. This is mainly due to the fact that observations in modern systems are hampered by the time scale for morphological evolution, which is much longer compared to fluvial systems. In our previous work, we studied present-day bar patterns in natural systems [*Leuven et al.*, 2016, 2018a,b]. Here we shift focus to the morphodynamics of channels and bars. Physical scale-experiments and numerical models complement observations in natural systems because they can provide higher temporal resolution, enabling detailed observation of the morphodynamic evolution of bars. In this study we use physical experiments, because the produced channel and bar patterns in numerical models [e.g. *van der Wegen and Roelvink*, 2012; *Braat et al.*, 2017] depend on calibration parameters such as the transverse bed slope effect that strongly affect channel-shoal interaction and bar dynamics [*Baar et al.*, 2018; *Schuurman et al.*, 2018].

2 Methods and materials

2.1 Experimental set-up and procedure

We use a periodically tilting flume of 20 m by 3 m, called the Metronome (Figure 2), that generates dynamic tidal morphology. It produces hydrodynamic conditions capable of transporting sediment during both the ebb and flood phase [*Kleinhans et al.*, 2015a, 2017a], which is uniquely different from earlier physical experiments of tidal systems that relied on periodic sea-level variations [*Reynolds*, 1887, 1889; *Mayor-Mora*, 1977; *Tambroni et al.*, 2005; *Stefanon et al.*, 2010; *Vlaswinkel and Cantelli*, 2011]. The down-scaled magnitude of the water level variations in experiments with periodic sea-level variations, while large relative to water depth, is too low to induce landward sediment transport due to the unscaled grain size. Therefore, previous experiments with periodic sea-level variation resulted in systems with mainly ebb-related transport [*Kleinhans et al.*, 2014]. To obtain similar sediment mobility, scaled estuary experiments with natural sand would require a much steeper bed gradient than natural systems, because of their smaller water depth and bed shear stress, which we obtain by tilting the flume [*Kleinhans et al.*, 2014, 2015a]. The tilting flume allows us to characterize the spatio-temporal patterns of channel and bar evolution. For a more detailed description of the design and hydrodynamics of the Metronome see *Kleinhans et al.* [2017a].

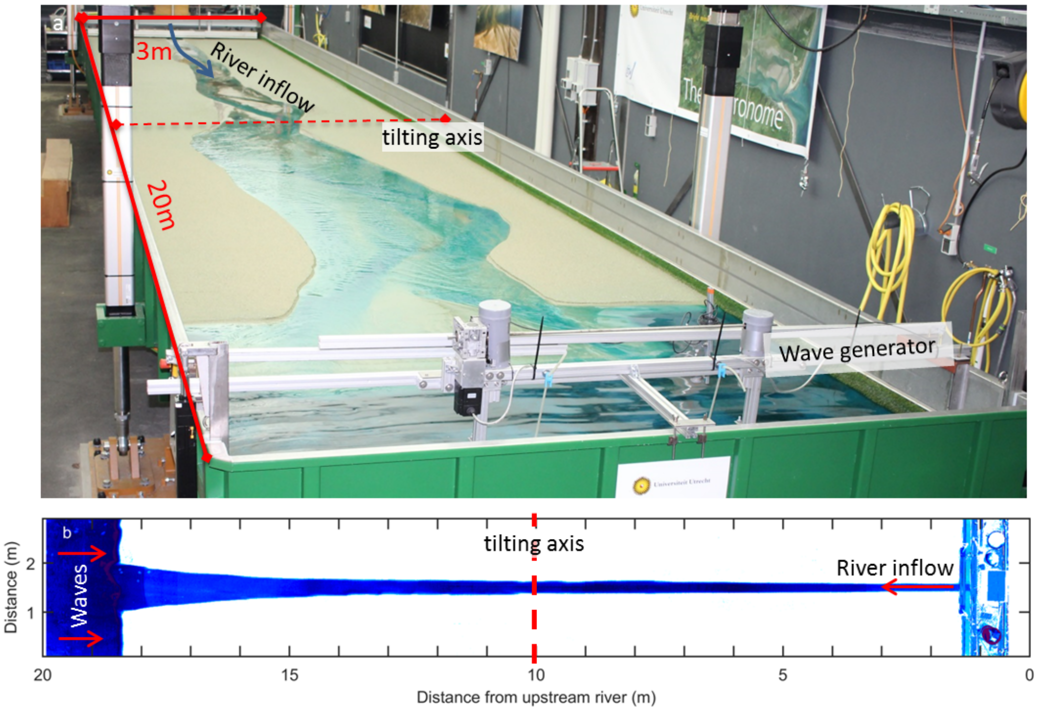
Here, we describe one of the experiments with detailed monitoring of the bed elevation and flow velocities and study the long-term evolution of channels and bars. The experiment was run for 15000 tidal cycles, which corresponds to approximately 20 years of natural tidal cycles assuming a semi-diurnal tide. The experimental settings were selected based on a set of approximately 30 pilot experiments in which boundary conditions have been varied systematically, which are reported in the supplementary material of *Braat et al.* [2018]. It was tested whether the settings were such that sediment was well above threshold for motion and that the tidal excursion length, which is the distance a water particle travels in half a tidal cycle, was shorter than the flume length.

A plane bed of 0.07 m thick sediment was installed on top of a mat with artificial grass in the basin. Sediment consisted of a sand mixture (ρ_s = 2650 kg·m^{-3}) with a median grain size of 0.52 mm and a coarse tail (D_{90}=1.2 mm, D_{10}=0.33 mm) (Supplementary Figure 1). This sediment mixture was selected to prevent the occurrence of scour holes as much as possible [*Kleinhans et al.*, 2017b]. Another set of experiments were conducted with the addition of crushed walnut shell to simulate the effect of cohesive material, which are reported in [*Braat et al.*, 2018]. We will summarise the effect of this as far as relevant for bar growth and estuary widening in the discussion. The bed was approximately 18 m long and 3.0 m wide. An initial channel was carved in the sediment bed to facilitate the initial flow from the upstream boundary to the sea and back. This initial channel was 0.03 m deep and the width increased exponentially from 0.2 m at the river to 1.0 m at the seaward boundary (Figure 2b).

Tidal currents were produced by four actuators that ensured a repeatable tilting with a period of 40 s and a maximum tilting gradient of 0.008 m·m^{-1}. At the upstream boundary water discharge was added to the flume during the ebb phase at a constant rate of 0.1 L· s^{-1}. River discharge was disabled during the flood phase, because otherwise water would pile up at the upstream boundary, resulting in an extreme water pulse when tilted seaward again. The contribution of the river discharge to the tidal prism is 0.002 m^3 (0.1 L·s^{-1}×20 s)), while the total tidal prism is about 0.11 m^3 at the start of the experiment and 0.3 m^3 at the end of the experiment [*Braat et al.*, 2018]. This means that the relative contribution of river discharge to the tidal prism is 1.8% at the start and 0.7% at the end of the experiment. This is within the range that typically occurs in estuaries, e.g. between 0.01% and 20% for estuaries in the UK, with an average of 3% and a median of 0.7% [*Manning*, 2007].

The water level at the boundary between the sea and the land was kept at a fixed elevation by a constant head at the downstream boundary of the flume, allowing free in- and outflow of water. Water depth in the sea was continuously compensated during the tilting by periodic vertical motion of the weir at the seaward boundary, such that the water depth in the sea was always 0.065 ± 0.005 m [*Kleinhans et al.*, 2017a]. The water was dyed blue with Brilliant Blue FCF colourant to enhance the visualisation of morphology.

Paddle-generated waves were introduced at the seaward boundary with a frequency of 2 Hz and an amplitude of approximately 1 cm during the flood phase. Waves were only introduced during the flood phase, because only in that phase the stirring of sand by the waves would cause slight sediment transport in landward direction. Scale-effects of gravity waves in the Metronome tidal facility are described in the Supplementary Material, but our general conclusion is that the wave-induced sediment mobility is much lower than in natural systems even though the relative wave height with respect to shoreface and channel depth is much larger. Nevertheless, waves in combination with the tidal currents were found to subdue the delta height and the tendency to form large, irregular deltas dominated by channel avulsion.



124 **Figure 2.** (a) The Metronome, a tilting flume of 20 m long by 3 m wide. (b) Overhead image of initial converging channel bathymetry. Blueness indicates depth, except in the first meter where the gantry is located. At the landward side, river discharge (0.1 L $\cdot$ s^{-1}) was added during the ebb phase. At the seaward end, paddle-generated waves were applied during the flood phase.

Pilot experiments showed that tilting with a simple sine function result in net exporting systems (Supplementary material *Braat et al.* [2018], which means that the system could be classified as a delta sensu *Dalrymple et al.* [1992]. However, we here refer to the system as an estuary, because the relative contribution of river discharge to the tidal volume is too low (≈1%) while ebb and flood currents are much larger and approximately equal [*Kleinhans et al.*, 2017a]. Furthermore, the observed channels and bars in experiments resemble bars in natural estuaries [*Leuven et al.*, 2016]. Such bars are expected to form much faster than the entire estuary attains equilibrium with its forcing conditions, because bar building only requires lateral sediment displacement over short distances while estuary deformation requires displacement of sediment volumes through the entire system [*Lanzoni and Seminara*, 2006; *Kleinhans et al.*, 2015a]. We therefore argue that the main conclusions in this paper are not sensitive to this simplification.

2.2 Data collection and data processing

Time-lapse imagery from seven overhead cameras was collected each tidal cycle at the horizontal position of the flume when transitioning from ebb to flood flow. The cameras were mounted at equal distances 3.7 m above the centreline of the flume. The CMOS MAKO colour cameras have a resolution of 2048 by 2048 pixels with lenses of a fixed focal length of 12.5 mm. The resulting spatial pixel resolution was 1.5-2 mm. Images were geometrically rectified and a lens correction (vignette and distortion) was applied before they were stitched, and then converted to LAB (CIELAB) colourspace images, in which L represents the colour band with light intensity, A represents red to green and B yellow to blue [also used in *van Dijk et al.*, 2013]. The B-band was extracted from the LAB images, because it enhances the visualisation of morphology by the largest contrast between coloured water and sediment.

The flume was illuminated at about 300 lux with daylight-coloured fluorescent light aimed upward at a white diffusive ceiling at approximately 4.5 m above the flume floor. Light reflection from the water surface on the photographs was minimised by white photography backdrop cloth between the ceiling and flume.

To create Digital Elevation Models (DEMs), photographs were taken with a digital single-lens reflex (DSLR) camera on a dry bed and processed with structure from motion software [*Lane et al.*, 1993; *Chandler et al.*, 2001; *Westoby et al.*, 2012; *Fonstad et al.*, 2013; *Morgan et al.*, 2017; *Agisoft*, 2017]. Drainage of the flume, prior to data collection, was slow enough to prevent modification of the morphology. The first 5 DEMs were made with an interval of 500 tidal cycles, starting at 300 cycles. Subsequently, seven DEMs were made with an interval of 1000 cycles and the final three had an interval of 2000 cycles. The DEMs were referenced with 20 ground control points at equal spacing on the sides of the flume, such that the resulting DEMs could be resampled on the same grid as the stitched images from the overhead cameras.

Flow velocities were measured over a tidal cycle with Particle Imaging Velocimetry (PIV) [*Mori and Chang*, 2003] at 12 moments during the experiment. These 12 moments correspond with the timing of the first 12 DEMs. White floating particles (diameter ca. 2.5 mm) were seeded on the water surface and resupplied when necessary. At 16 equally spaced phases of the tide, ten images were collected with the overhead cameras at 25 Hz, using a pulse train from a frequency generator. Flow velocities were subsequently calculated from pairs of consecutive images with the MPIV toolbox in Matlab [*Mori and Chang*, 2003]. As in *Kleinhans et al.* [2017a], we used the peak cross-correlation algorithm to determine mean particle displacement in pixels in a 50x50 window with 50% overlap. The resulting vector fields were scaled to metrics with the pixel footprint of the cameras (1.5-2 mm per pixel), correcting for the tilt of the flume. Erroneous vectors were obtained and filtered out where particles were sparse or overly-abundant, as well as when the PIV-window partly covered the flume wall or reflection on the water surface was too large. For processing, the average vector field was calculated for each tidal phase from ten consecutive images and for plotting purposes it was interpolated on a grid with the same size and resolution as used for the overhead cameras and DEMs. Residual currents were calculated as the average flow vector over a full tidal cycle.

2.3 Data reduction

Experimental results are compared with data from natural systems [*Leuven et al.*, 2016] to assess how well the tidal bars in our experiment scale to nature. A detailed comparison is made with the Western Scheldt (NL), for which detailed bathymetries over time and flow velocities are available. In this study, the important scaling properties are the planform dimensions of bars and the elevation distribution of the bathymetry. Therefore, maximum bar length and width were measured in the experiments following *Leuven et al.* [2016]. Hypsometric curves, which are cumulative depth elevation curves, were calculated for four zones in the experiment as well as for the Western Scheldt. These zones were chosen as the part between two successive width confinements in the estuary (Figure 3k, Supplementary Figure 6a).

Estuary width was measured in our experiment as the local width between the non-eroded estuary banks. Channel width was measured as the width of the estuary below an along-channel linear profile that was fitted on the median bed level per cross-section, whereas above the median bed level was classified as bar. Excess width is defined as the estuary width minus the width from an ideal converging estuary shape and summed width of bars was measured as the sum of the width of all bars in a cross-section [*Leuven et al.*, 2018a].

The locations of major channel confluences and the spacing between them over time were determined for the experiment and the Western Scheldt. In addition, these quantities were measured on aerial imagery for a fixed moment in time in 7 other natural systems: Dovey (UK), Bannow (UK), TawTorridge (UK), Teign (UK), Rodds Bay (Australia), Whitehaven beach (Australia) and Netarts (USA). In case of aerial photographs, major confluence locations were visually determined as the deepest point where multiple channels converge, while these points were extracted from bathymetric data for the experiments and Western Scheldt (Figure 4). Deep scours as a result of bank protection, resistant layers that consist of shell fragments (so called 'crags', *Cleveringa* [2013]), or scours associated with outer bends of meanders were excluded. Subsequently, the location and spacing between successive channel confluences were measured with respect to local zones of confinement in the estuary outlines.

The dynamics of channels and bars over time were studied from the blueness images, which is a proxy for the water depth. Blue represents the channel and white the bar. Changes in blueness values were used to study where erosion and sedimentation occurred in the experiment and to determine the youngest time step during which sediment was deposited. The same approach was applied using successive DEMs of the experiment, but the temporal resolution for this was lower. Cumulative bed level change was calculated as a measure of the spatial dynamics within the system and to assess whether the experiment was in dynamic equilibrium during the final stages. Cross-sectional profiles were taken from the LAB images and plotted over time, creating time-stack diagrams that show the migration of channels and bars in cross-section over time.

3 Results

3.1 General morphological evolution

In the initial phase of the experiment, an alternate bar pattern evolved (Figure 5a). As channel widening continued, a main meandering channel formed with riffles between two successive bends. The meandering channel and alternate bars initially migrated seaward (Supplementary Movie). Later, the increased curvature of the meandering channel forced the bars (i.e. they became non-migratory) to their inner bends, while lateral erosion and deposition increased the width of the forced bars. In a later stage, channels stabilised in the landward part of the estuary, while the estuary width kept increasing in the seaward part. This allowed the development of multiple bars and channels in cross-section, which were first observed when flood 'barbs' intersected the forced bars (Figure 5a,b). Barb channels are channels that become shallower in the direction of flow and have a dead end on the bar. Net sediment transport towards the sea formed an ebb-tidal delta, which is a term more commonly used in the context of tidal basins but also applies to estuaries [e.g. *Davis Jr and Hayes*, 1984; *Elias et al.*, 2017]. The ebb-tidal

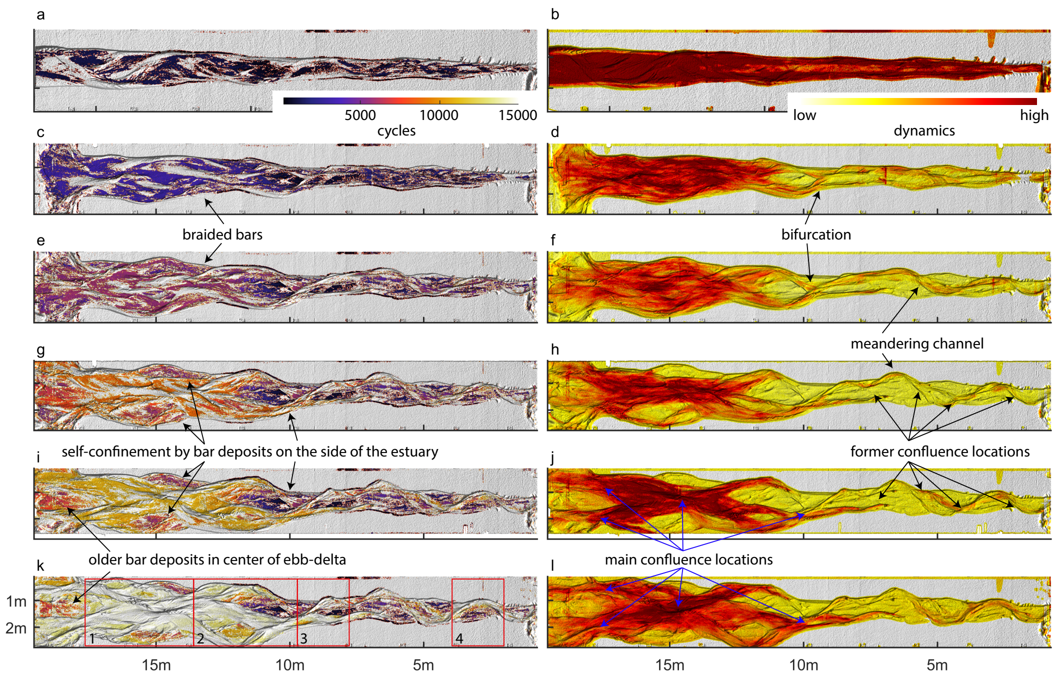


Figure 3. Two representations of spatiotemporal patterns of morphodynamics. [left] Hillshade map of morphology at several time steps, showing increasing age variation as the system develops (top to bottom). The colour scale indicates time of deposition of the top surface, where light colours are the youngest. [right] Hillshade map of morphology at several time steps, in which the colour scale indicates cumulative bed level change between two successive DEMs, which is an indicator of dynamic activity. Maps are given for the following time steps: (a,b) 1250, (c,d) 3300, (e,f) 5900, (g,h) 8900, (i,j) 10900 and (k,l) 15000 cycles. Red numbered boxes in (k) show the zones for which hypsometric curves are calculated (Figure 10c).

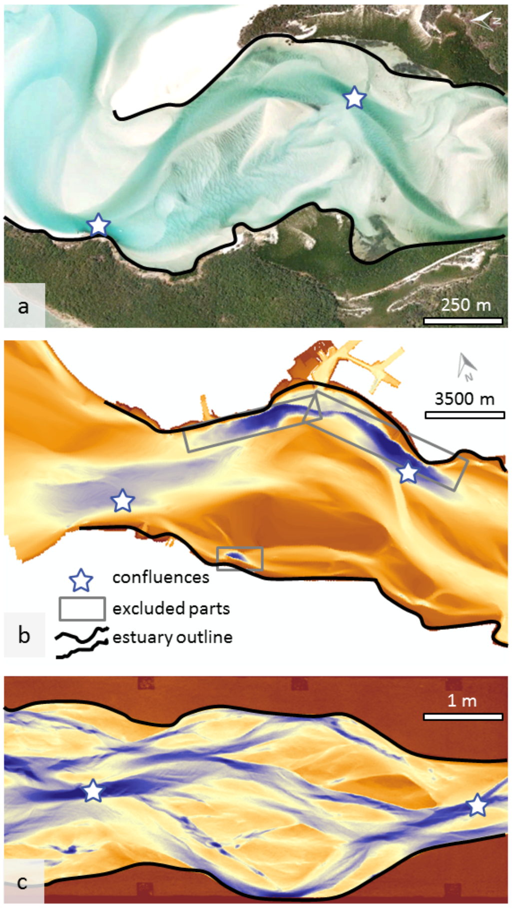


Figure 4. Locations of major confluences were determined in (a) aerial photographs of natural systems, (b) bathymetry of the Western Scheldt and (c) and experiments. Warm colours denote high elevation, cool colours denote low elevation. In case of aerial photographs, major confluence locations were chosen where multiple main channels converge. For the bathymetry of the Western Scheldt and experiment, these points were automatically determined as the maximum depth within a confluence zone. Deep scours as a result of bank protection, presence of hard layers or outer-bend erosion were excluded.

delta limited the inflow of water to the estuary. As widening progressed, forced mid-channel bars diverted the flow and periodically caused bank erosion. These zones were alternated by locations where the estuary width remained narrow or was self-confined by sidebar deposits, resulting in a quasi-periodic planform (Figure 5d,e).

3.2 Channel widening and incipient meandering

The initial phase of the experiment was characterised by the development of the initial converging channel into an incipient meandering ebb-tidal channel (Figure 5a). In the first 200 cycles, the converging straight channel widened (Figure 6) and initially free (seaward migrating) alternate bars formed. The resulting channel pattern consisted of multiple straight channels parallel to the centreline of the estuary, which were separated by sills that connected the alternate bars in along-channel direction. Over time, the straight channels became more oblique to the estuary centreline and curved until they developed a meandering ebb-tidal channel, which forced the bars in place. On top of the alternate bars, circulating flow patterns developed, with residual currents dominantly moving in landward direction onto the bars, then diverting to the channel and flowing back in seaward direction via the meandering channel (Figure 7a). Both the ebb and flood flows caused erosion of the estuary banks by lateral migration of channels in the following tidal cycles (Figure 7b).

3.3 Alternate bars with initial barb formation

This phase was characterised by the formation of barb channels in the inner bends of the alternate bars. The main meandering ebb channel migrated laterally eroding the estuary banks and alternate bars grew in width. At the landward side shallow sills formed between two successive alternate bars. The sill separated the ebb flow from the flood flow in two separate channels. As the ebb channel migrated further seaward and the flood channel landward, u-shaped bars formed (Figure 5a). The u-shaped bars thereby partly blocked the channel with opposing flow (Figure 5a).

From 1000 tidal cycles onward the braiding index, which is the average number of channels or bars in the cross-section, kept increasing as a result of the increasing channel width, which allowed for multiple braided bars (Figure 5a). Bars were particularly abundant in specific zones (at approximately 8 m, 11 m, 14 m and 15 m) where the summed width of bars was large (Figure 8a,b) and the compound bars were dissected by one or multiple barb channels. Compound bars are more complex bars that probably amalgamated from other bars, in analogy with rivers [e.g. *Bridge*, 2003; *Ashworth et al.*, 2000; *Schuurman et al.*, 2013].

At the seaward side, the export of sediment during the first 2000 cycles formed an ebb-tidal delta. After this period, the delta was large enough to limit the inflow of water into the estuary, while erosion on the delta formed a single major channel at the northern side of the inlet (Supplementary Figure 2h,i).

The location of the main meandering channel shifted from north at 1000 cycles, to south around 2000 cycles and back north at about 3000 cycles at approximately 15 m from the upstream boundary (Supplementary Figure 2e,h,i). Interestingly, the adjacent channel confluence positions (at 13.5 m and at the mouth of the estuary) were relative stable over time, with dynamic bar and channel zones in between. This caused a rather irregular pattern in the outline of the estuary where some parts remained relatively narrow while other parts became relatively wide (Figure 6).

3.4 Mid-channel bars, confluences and evolution of quasi-periodic planform

In the central part of the estuary (8-18 m), widening resulted in the formation of forced mid-channel bars that diverted flow, which caused bank erosion. For example after 4000 cycles, a large estuary width at 15 m allowed the existence of two major channels: one on the northern

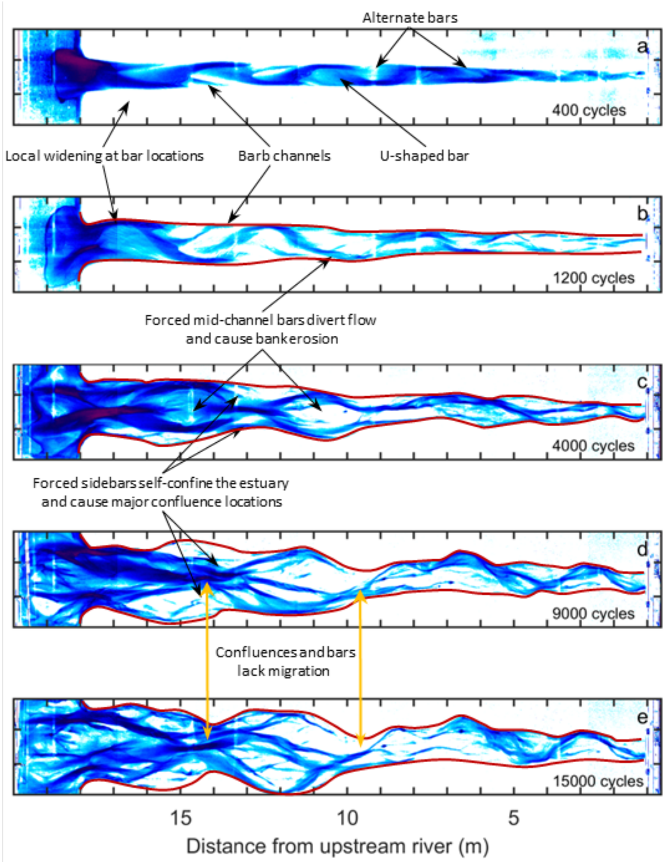


Figure 5. Overhead imagery of the experiment for five moments in time. Blueness was extracted as an indicator for channel depth. For all time-steps, see Supplementary Figure 2 or the Supplementary Movie.

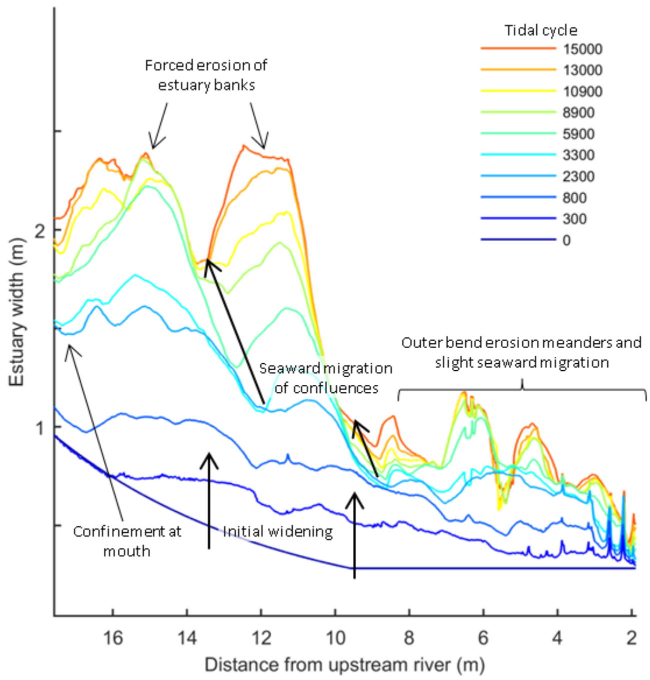


Figure 6. Evolution of the estuary width profile. The planform initially widened and, from 2300 cycles onward, became more irregular. After 3300 cycles, bars and landward meanders rapidly force local widening, while confinements migrate seaward. In the last phase, after 8900 cycles, the bars became static (forced) and bank erosion ceased at the confluence locations, while the amplitude of the quasi-periodic width variation increased where mid-channel bars were present.

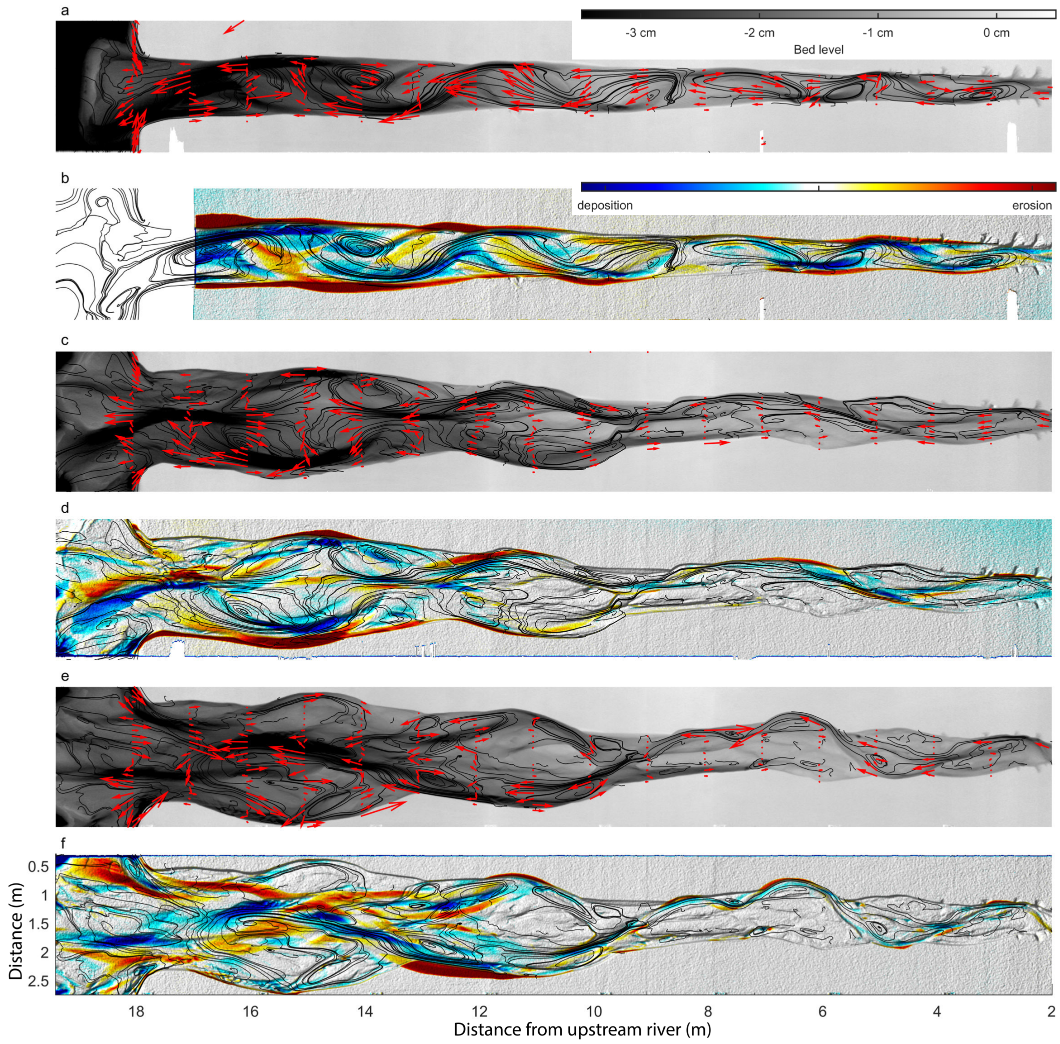
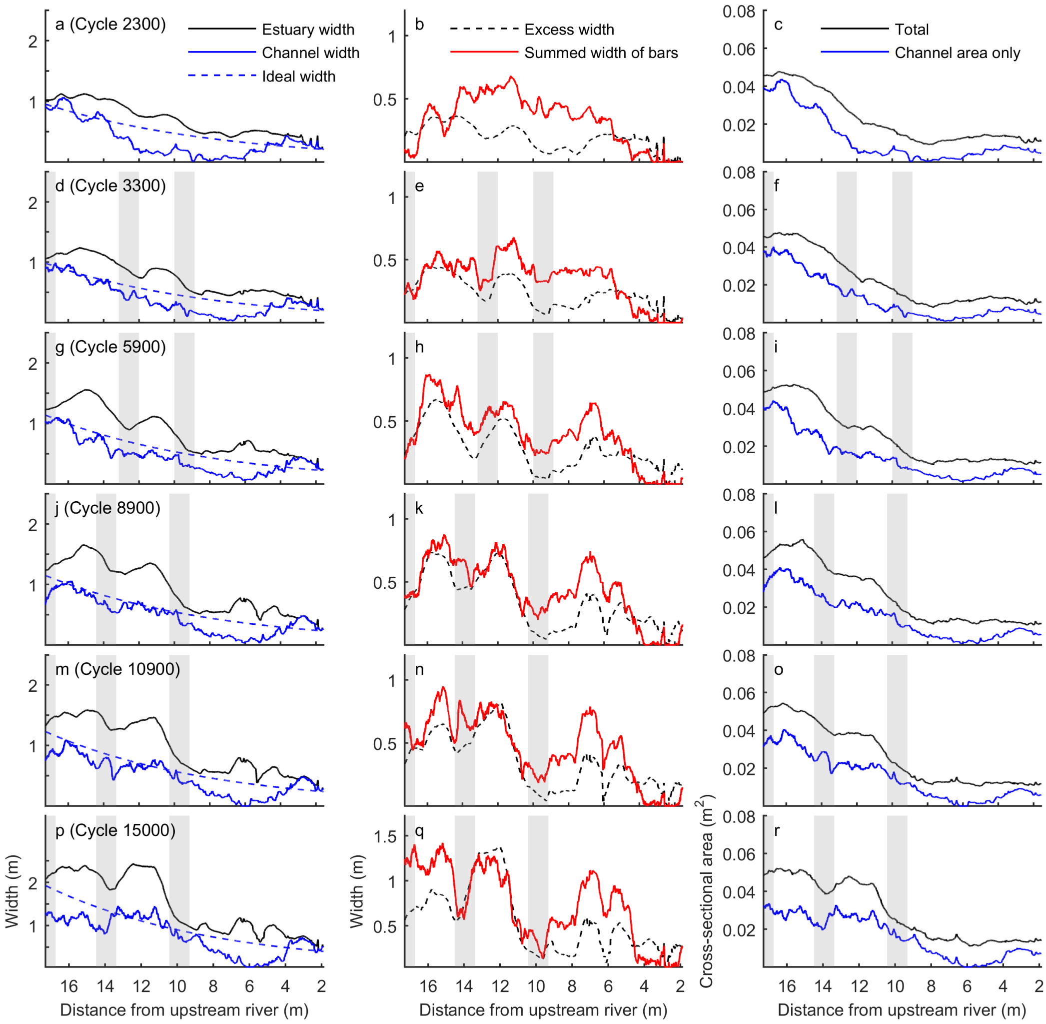


Figure 7. (a,c,e) Vectors indicating the residual currents after (a) 800, (c) 4400 and (e) 6900 cycles for transects with a spacing of a meter on top of a map with the streamlines based on a vector field with residual currents and the bathymetry. (b,d,f) Streamlines based on a vector field with residual currents, plotted on top of a map that indicates the erosion (in increasing magnitude from yellow to red) and sedimentation (from cyan to blue) in the subsequent phase of the experiment.

side and one on the southern side of the estuary, separated by a relatively wide bar in the centre of the estuary (Figure 5c). The confluences of these two channels occurred at the mouth of the estuary and at 13.5 m in a channel located in the middle of the estuary. While the two major channels at 15 m continued to migrate towards the outer banks of the estuary (Figure 9d), the bar between these channels obtained an oval shape as a result of an almost symmetrical ebb and flood barb on both its landward and seaward side. The residual current showed two major circulation cells at this compound bar (Figure 7c). The flood barb facilitated flow onto the bar, which diverged over the bar to the channels north and south of the bar. The ebb flow predominantly used the northern and southern channel around the bar and any flow entering the ebb barb also diverged into these channels. This caused bank erosion on both the north and south side of the estuary and sedimentation that increased the width of the mid-channel bar (Figure 7d). A similar process occurred in a more landward part slightly later in the experiment.



332 **Figure 8.** [left] Evolution of estuary width, channel width and ideal width. [middle] Evolution of excess width and summed width of bars. [right] Evolution of cross-sectional area. Estuary width is the sum of channel and bar width. Ideal width is the largest fitting exponential shape in the estuary outline. Excess width is the estuary width minus the ideal width. The channel width approaches an ideal converging shape over time. Summed width of bars approaches the excess width. Total cross-sectional area is the area below the estuary banks. Channel cross-sectional area excludes the area above bars. Shading indicates the locations where the estuary remained confined. At these locations, the summed channel width and summed bar width remain relatively low.

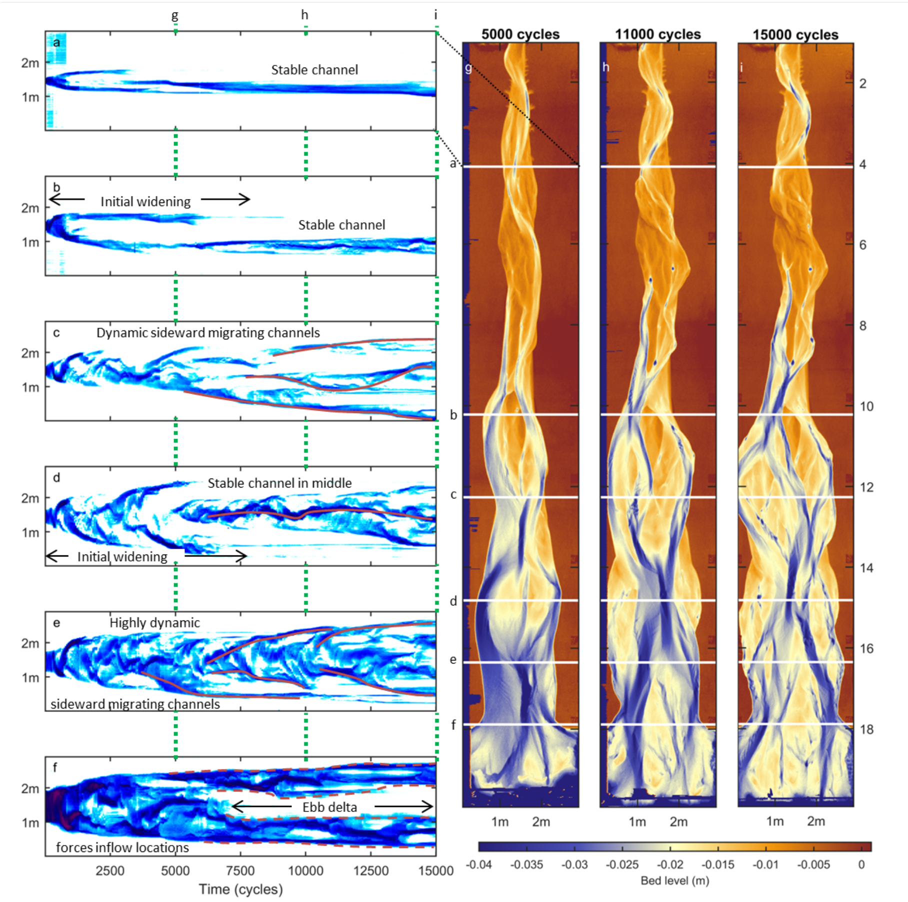


Figure 9. (a-f) Time-space diagrams of cross-sections at 4, 10, 12, 14.5, 16 and 17.5 m, which are indicated in (g,h,i) bathymetry after 5000, 11000 and 15000 tidal cycles. (a,b) A single landward channel stabilises from 7500 tidal cycles onwards. (c) In the centre, dynamic, sideward migrating channels occur. (d) Outward migrating channels erode the estuary banks. From about 6000 cycles the mid-channel bar is cross-cut and a single main channel forms in the middle of the estuary. (e) In the seaward part, multiple very dynamic, migrating channels occur. The channels migrate from the estuary centreline towards the estuary banks. (f) An ebb-tidal delta forms and stabilises after 7500 tidal cycles. This forces the inflow locations to be on the sides of the ebb-tidal delta.

In the landward part of the estuary (0-8 m) the individual channels became more curved and connected, so that a main meandering channel formed from 5000 cycles onward (Figure 5c,d). The channel orientation of the upstream channel affected diversion of flow and sediment at the former bifurcation at 9 m, so that now the landward river system fed the southern branch instead of the northern branch (Figure 5c,d). This channel subsequently migrated (Figure 9c) by eroding the southern bank of the estuary at 10 m (Figure 7f), whereas the northern channel was only connected during flood flow. Seaward, the southern channel merged with the major channel that formed in the middle of the estuary at approximately 13 m. At this point multiple smaller barb channels formed onto the bar at 11 m that evaded each other and migrated over the bar.

At the mouth, the estuary was slightly narrower than the part of the estuary directly landward of the mouth at 16 m. Specific zones occurred where estuary width was relatively narrow with a major confluence and approached its ideal width. The zones were alternated by zones in which the estuary was much wider (Figure 8). Over time, the confluences migrated slightly seaward and the planform became progressively less ideal (Figure 6). The landward channel (0-8 m) eroded the estuary banks in the outer bends of the meanders until approximately 8000 tidal cycles. From that moment on the configuration of channels and bars in the landward part (0-8 m) remained relatively stable over time (Figure 5d,e, Figure 9a,b). The later phases of the experiment (6000-15000 cycles) were characterised by specific zones that were active (Figure 3h,j,l). These zones connected the major channel confluences at 10 m, 14 m and 18 m. The active zones were relatively narrow at locations where the confluences occurred (e.g. at 14 m and 18 m in Figure 3j) and relatively wide in the zones in between (e.g. at 16m).

3.5 Cross-cutting of mid-channel bars

In the seaward part, the phase with mid-channel bars and bank erosion continued until 5000 cycles, when a channel was able to progressively cut through the middle of the bar, connecting the barb channels around 5000-5500 cycles (Figure 5c,d). This caused a main channel along the centreline of the estuary. During this phase, the major in- and outflow was focused in the middle of the ebb-tidal delta. This reduced bank erosion in the most downstream part of the estuary from that moment onward (Figure 6, 14-18 m), preventing the estuary shape from becoming more irregular.

In the central part of the estuary, the cross-cutting event also caused the direction of the residual circulation cells to reverse, with flood flows now predominantly occurring along the sides of the estuary, while the channel in the middle of the estuary was ebb dominant (Figure 7e). This reduced erosion of the estuary banks at this location and triggered the formation of new channels that connected the main ebb channel with the newly formed outflow locations on the ebb-tidal delta (Figure 7f). Because the main channels in the middle of the seaward part of the estuary (14-18 m) gradually exported sediment to the central parts of the ebb-tidal delta, this process eventually blocked the in- and outflow of water (6000-8000 cycles) (Supplementary Figure 2n-p). The ebb delta thus stabilised in place after 7500 tidal cycles (Figure 9f,h), after which the in- and outflow of water became diverted to the northern and southern sides of the ebb-tidal delta (Figure 9f).

Similarly to the previous bar cross-cutting event around 5000 cycles, a similar process occurred at the compound bar more landward (9.5-13 m), where after 9000 cycles the cross-cutting of the middle parts of the bar occurred (Figure 5d). This isolated a southern part of the compound bar at 9.5 m. In short, the estuary evolved from an initially converging channel into an estuary filled with bars that inherited its quasi-periodic planform from phases in which mid-channel bars diverted flow laterally, causing bank erosion.

3.6 Progressive infill from the sea and dynamic equilibrium with stable confluences

The zones where the estuary was confined reflect the locations where bars were relatively less abundant. For natural systems, a correlation was found between the occurrence of tidal bars and locations where the excess width is large [*Leuven et al.*, 2018a], which is defined as the local estuary width minus the ideal estuary width. This is in agreement with the experimental results (Figure 8h,k,n), where summed width of bars indeed approaches the excess width in the later stages of the experiment. While the zones between 4-8 m and 14-18 m deviated from this rule in magnitude, the along-channel pattern is the same, i.e. low excess width corresponds to low summed width of bars and vice versa.

In the last phase, the estuary reached a dynamic equilibrium with stable confluences, while active channel migration remained in the parts between the confluences. Mean changes in bed level and sediment export illustrate that the experiment was close to dynamic equilibrium (Supplementary Figure 3). Generally, the increase in estuary width that was observed in previous stages decreased and only in the part 10-13 m and at the mouth of the estuary a slight increase in width occurred during the last 2000 cycles of the experiment (Figure 6).

In the final stages of the experiment, flow from the landward side bifurcated around the newly isolated bar at 11 m (10000-12000 cycles, Figure 5d,e), after which the northern branch began to erode the southern side of the former bar between 9.5 m and 12 m. At the same time the southern branch continued to erode the southern bank of the estuary until reaching the flume wall, which was the reason to end the experiment after 15000 cycles.

4 Discussion

This study presents the first physical scale-experiment of an estuary with dynamic channels and bars, stable confluences, and a self-formed planform. Below, we first describe a conceptual model on how forced bars determine the estuary outline. Second, we discuss the spatial and temporal scaling of bars. Then, the effect of bar patterns on the flow patterns is compared with the evolution of natural estuaries. Last, the observed experimental cyclicity in channel and bar migration is compared to natural systems.

4.1 Conceptual model for estuary planform forcing

We summarise the evolution of a self-formed estuary in a conceptual model containing three phases. In the first phase (Figure 13a) an alternate bar pattern develops, while the estuary widens. The initially straight channels connect to form a meandering channel with alternate bars [comparable to alternate bars in rivers *Struiksma et al.*, 1985; *Ikeda and Parker*, 1989; *van de Lageweg et al.*, 2014]. As soon as the bars exceed a width-to-length ratio of approximately 1/7, the flood flow is capable of forming barb channels onto the alternate bars (Figure 13a). The barb channels progressively cut through the alternate bars. Both the outer bends of the meandering channels and the flood barbs erode the estuary banks, which creates an irregular estuary planform.

In the second phase, the first mid-channel bars have formed that are large enough to divert the flow such that the outer-bend erosion is accelerated and major confluences are formed seaward and landward of the mid-channel bars forming a quasi-periodic estuary planform (Figure 13b). At the confluence locations, estuary width generally remains narrow and dynamic channels and bars only occur within a small stretch of the estuary width. As outer-bend erosion continues, the gradient over the mid-channel bar becomes favourable for both the ebb and the flood flows. These flows create new barb channels onto the mid-channel bar, which over time are capable of cross-cutting the bar, forming a new main channel in the middle of the estuary (Phase III, Figure 13c). The timing of this event may vary along the estuary and confluences typically migrate seaward over the course of these phases.

After this phase, a dynamic equilibrium at the bar-confluence scale is reached, in which sediment from bars and banks is reworked into new bars within the estuary. The confluences remain stable and bank erosion is reduced. Dynamic zones of channels and bars typically occur in stretches between the major confluences. In both experiments and natural systems we observed the development of irregular estuary planforms and the forcing of channel confluences and zones with dynamic channels and bars. The conceptual model implies that quasi-periodic deviations from the ideal estuary shape can be formed autogenically. This means that the planform shape of natural estuaries is not necessarily externally forced, i.e. allogenic, for example by the presence of bedrock or resistant layers.

Our observations show that the mechanisms of bar push and bank pull identified in rivers [e.g. *Parker et al.*, 2011; *Eke*, 2014; *van de Lageweg et al.*, 2014] may apply in estuaries as well. Initially, the alternate bars form in a straight channel, which was also the case in river experiments [*van Dijk et al.*, 2012], suggesting that the process of pattern formation starts with bar push. However, in later phases, as soon as the increased curvature and local widening [e.g. *Repetto and Tubino*, 2001; *Seminara*, 2010; *Zolezzi et al.*, 2012] forces the bars to be non-migratory, the usual meander bend migration mechanism of curvature-driven momentum displacement towards the outer bank kicks in, causing bank retreat. This is followed by inner bend accretion, meaning that this phase is dominated by bank pull. Upon further widening, the bar regime shifts to mid-channel bars that are non-migratory because of curvature and local widening as well as the tidal reversing flow, and the process continues on both sides of the bar. We hypothesise that this stage is dominated by a balance between bank pull and bar push as in *Eke* [2014].

4.2 Spatial and temporal scales of channels and bars

The dimensions of tidal bars in the experiments scale well with bars observed in natural systems, as reported in *Leuven et al.* [2016] (Figure 10a). All experimental bars are within the uncertainty margins given for natural bars. However, most experimental bars plot above the trend line, indicating that their shape is slightly more elongated compared to the bars in natural systems (length-to-width ratio of approximately 8 in experiments, compared to 7 in nature). Moreover, the bar length is well within the range as expected based on local estuary width (Figure 10b). The experimental bars have similar dimensions as the alternate bar pattern reported in *Tambroni et al.* [2005] where the average bar wavelength is 3-6 times channel width, thus bar length is 1.5-3 times channel width. However, in contrast with experiments with fixed channel planimetry [*Tambroni et al.*, 2005, 2017] that result in a system with a braiding index of 1, we observed rapid widening of the estuary, which allows braiding index, bar width and bar length to increase. Most experimental bars fall exactly on the trend expected from natural systems. The largest outliers occur at the lower uncertainty band. These bars are an order of magnitude smaller than the other bars and formed in later phases of the experiment in one of the larger channel branches in the estuary. In this case, the width of the single branch is responsible for the bar dimensions. Therefore, scaling with the full estuary width may result in large deviations from the expected trend.

Hypsometric curves for four zones within the estuary (indicated in Figure 3k and Supplementary Figure 6a) show a large similarity between the experiment and the Western Scheldt (Figure 10e), where zones were defined as the estuary area between two successive confinements. Only zone 4 in the Western Scheldt deviates significantly from the hypsometry in the experiment (Figure 10e). At this location the estuary width is smaller and thus a larger part of the width is influenced by dredging to maintain shipping fairways. When channels are excluded and thus hypsometric curves are drawn for compound bars only, bars in the Western Scheldt show a more linear elevation profile, while bars in the experiment have a more s-shaped curve (Figure 10f). The s-shaped curves for the experiment are caused by a small portion of the compound bars being highly elevated and a small portion being very low elevated. High elevated parts developed on the oldest parts of bars that accreted over time and lack flooding and morphodynamic activity in later phases. The relative scarcity of high elevated areas is caused by the lack of cohesive material and vegetation, which would otherwise accrete tidal bars and estuary banks [*Braat et al.*, 2017, 2018; *Lokhorst et al.*, 2018]. Low elevated parts are previous channels or scours on bars for which time was too short to fill in.

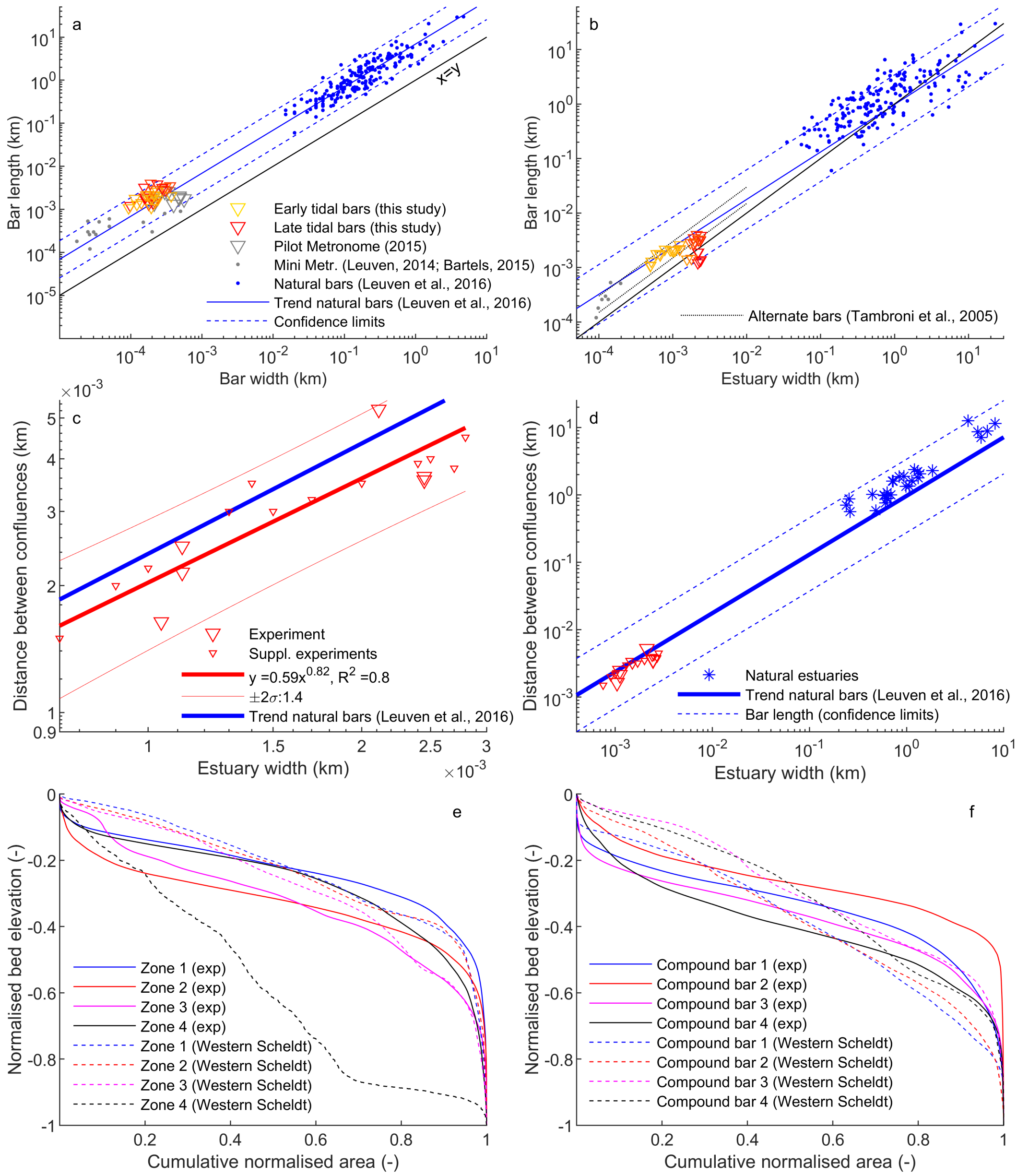


Figure 10. (a) Comparison of planform bar dimensions (length versus width) in the experiments and in natural systems. Triangles represent bars in the experiment, with colour indicating the tidal cycle during which the bars were measured: yellow was early in the experiment, red was at the end. (b) The scaling relation between estuary width and bar length that was found for natural systems holds for the experiments [*Tambroni et al.*, 2005; *Leuven*, 2014; *Bartels*, 2015]. (c) Confluence spacing as a function of local estuary width for experiments. Each triangle is the spacing between two successive confluence locations. (d) Comparison of confluence spacing in experiments with natural systems. A line with predicted bar length (×1.5) is drawn for comparison and shows that confluence spacing scales with bar dimensions and estuary width. (e) Hypsometric curves of zones between two successive confinements in the estuary outline, with numbering increasing in landward direction. The corresponding zones are given for the experiment in Figure 3k and for the Western Scheldt in Supplementary Figure 6a. Parts above the high water level were excluded. (f) Hypsometric curves of compound bars in the same zones.

As bars separate the major confluences, it was expected that confluence spacing scales with bar dimensions, which scale with estuary width (bar length $\propto$ channel width$^{0.87}$, *Leuven et al.* [2016]). Indeed, this was found to be the case (Figure 10c,d), which means that the spacing of confluences scales well with bar dimensions and estuary width. In general, this also implies a decreasing confluence spacing along-channel from the sea in landward direction, because estuary width and bar dimensions decrease. To quantify the location where confluences occur, we measured the distance from the location of the major confluences to the local minima in the outline of the estuary. The measured distance was normalised by the average spacing with the successive landward and seaward confluence locations. Results show that the major confluences in all cases occur within 16% of local confinements for the experiments and Western Scheldt over time, as well as for the aerial photographs of 8 natural systems (Supplementary Figure 4).

The timescale over which the channels and bars in the experiment evolve is 15000 tidal cycles, which corresponds to approximately 20 years of natural tidal cycles. All the sediment eroded in the experiment is either used for bar formation or exported to the ebb delta, which is a long-term sink for the eroded sediment for lack of intense littoral processes. Most modern estuaries typically evolved over centuries to millennia during the middle to late Holocene under rising sea level [*van der Spek and Beets*, 1992; *Hijma and Cohen*, 2011; *de Haas et al.*, 2017]. As such, their evolution comprised many more tidal cycles than our experimental estuary. Typically, modern estuaries initially enlarged as former river valleys that drowned, because of the rapid sea-level rise around the start of the middle Holocene. Part of the slower evolution may thus be explained by the time required for aggrading after sea-level rise decreased, in contrast to the erosional behaviour in the experiment. The relatively rapid evolution of bar patterns and bank erosion was also observed in river experiments and may partly be explained by a lack of bank strength in experiments without vegetation and cohesive material [*van Dijk et al.*, 2012].

Additional experiments with added cohesive material [*Braat et al.*, 2018] revealed two major effects compared to the experiment reported in this study. First, the mud fills up inactive areas and predominantly accretes on the tidal bars and estuary banks, which reduced the tidal prism. This counteracts the positive feedback mechanism between estuary widening, increased tidal prism and therefore increased cross-sectional area at the mouth. The second effect is that the cohesiveness of mud has a slight stabilising effect on gentle slopes. However, the cohesion has no effect on the bank erosion rate as bespoke experiments demonstrate. The combined effects result in a narrower, confined estuary planform, but with similar bar patterns and dynamics, although higher in elevation, compared to the experiment without cohesive material reported here [*Braat et al.*, 2018].

Nevertheless, the general evolution of the experiment can be compared to the Western Scheldt, which evolved in the past 2700 years from a narrow creek in a peat bog to an alluvial estuary with a quasi-periodic planform (Figure 11). The timescale over which estuaries widen from a narrow creek after ingressions is typically in the order of hundreds of years, which may still be an estimate on the higher end for organic peat, which decays rapidly after erosion [*Pierik et al.*, 2017; *de Haas et al.*, 2017] and thus does not contribute to sediment available for bar formation. Despite their contrasting early evolution, the later stages of the experiment and natural systems were more similar.

Bar dynamics typically occurs in tidal inlets, embayments and estuaries on timescales from 15-40 years [*Israel and Dunsbergen*, 1999; *Levoy et al.*, 2017]. A comparison of the experiment with this timescale may be more appropriate, because these processes are not limited in sediment supply. Nevertheless, scaling relations for bar patterns in experiments [*Kleinhans et al.*, 2015a] and the natural processes that form bars [*Leuven et al.*, 2016] and confine estuaries are not well understood. Recent numerical models show that mud deposits may be required to confine estuary planform and that self-formed estuaries with mud can reach an equilibrium within 500-1000 years [*Braat et al.*, 2017].

4.3 Role of circulation cells and confluences on the evolution of estuaries

The historic evolution of channel and bar patterns in the Western Scheldt (1800-1900) was characterised by an initial phase of migration and meandering of the main ebb channels, after which the meander bends reached the embankments on the sides [*Jeuken*, 2000]. In the inner bends, the compound bars extended laterally and flood barbs formed. This evolution is very similar to the initial phases of the experiment (Figures 6,11). However, after 1900, the morphological evolution was largely influenced by human interference: dikes were constructed, side branches that slowly filled-in were embanked and the first dredging activities started in 1922 [*Kleinjan*, 1938; *Jeuken*, 2000].

In 1944, *van Veen*, described the occurrence of circulation patterns in the Western Scheldt, where flow circulates through an ebb and a flood channel enclosing an intertidal bar. These circulation cells are similar to the circulation cells observed in the experiment, where the main meandering channel is ebb dominated and circulation cells covered the flood barb and adjacent ebb channel. These circulation cells divide the Western Scheldt into six main zones, which were later described as macrocells [*Winterwerp et al.*, 2001; *Toffolon and Crosato*, 2007; *Jeuken and Wang*, 2010; *Monge-Ganuzas et al.*, 2013] (Supplementary Figure 6). These cells were determined from the observed morphology of the main ebb and flood tidal channels and numerically modelled residual flow, which resulted in cells that covered the enclosed area of an intertidal compound bar with its surrounding meandering channel. The boundaries of these cells in along-channel direction were chosen at the location of major channel confluences and correspond to the locations where the estuary width is relatively narrow. The concept of macrocells [e.g. *Winterwerp et al.*, 2001; *Toffolon and Crosato*, 2007; *Jeuken and Wang*, 2010; *Monge-Ganuzas et al.*, 2013] is similar to concept of mutually evasive transport paths [e.g. *Ludwick*, 1975; *Harris*, 1988; *Dalrymple et al.*, 1990; *Wells*, 1995; *Harris et al.*, 2004; *Dalrymple and Choi*, 2007]. The latter, for example, occurs around elongated tidal bars, where the opposite sides of the bar crest have opposing directions of residual sand transport and residual water flow, forming a circulation pattern. The difference between the latter and former group of authors is that the macrocells describe only the largest scale of bars, whereas the mutually evasive transport paths occur at a range of scales, including that of the smallest shoals as also observed in experiments [*Kleinhans et al.*, 2014, 2015b].

The experimental results in this study show that already after 800 tidal cycles serial circulation cells have evolved and that these circulation patterns can be used to explain how forced mid-channel bars cause bank erosion (Figure 7a,b). After the experimental estuary became wide enough, a pattern with parallel circulation cells or cells with a mixed coupling [*Winterwerp et al.*, 2001] evolved (Figure 7c,e). Later phases of the experiment illustrated that the boundary of two successive circulation cells typically occurred at a major confluence and at locations where the estuary width is relatively narrow. The length of circulation cells scales with bar length, and both bar length and circulation cell length correlate with estuary width (Figure 10b,c,d). These patterns resemble the patterns observed in the Western Scheldt (Figure 12, Supplementary Figure 6).

4.4 Cyclicity of channels and bars in tidal systems

Cyclicity is the periodic migration of channels and bars, in which the original configuration after a given period reoccurs. This has previously been reported for natural tidal systems as well as experiments. For example, experiments of short tidal basins show periodic migration of channels and shoals, which is coupled to reorganisation of the channels in the tidal basin [*Kleinhans et al.*, 2015b]. Most of the studies so far focussed on cyclicity on the ebb-tidal delta [e.g. *Oost*, 1995; *Israel and Dunsbergen*, 1999; *Elias and van der Spek*, 2006], on which channels migrate from one side to the other, after which they disappear and reappear at their initial position. However, besides ebb deltas and the quasi-cyclic morphologic behaviour of the smaller-scale connecting channels that link the large ebb and flood channels in macro-cells [*van Veen*, 1950; *van den Berg et al.*, 1996; *Jeuken*, 2000; *Toffolon and Crosato*, 2007; *Swinkels et al.*, 2009; *de Vriend et al.*, 2011], little is known about the cyclicity of bars and channels within tidal basins or estuaries.

Levoy et al. [2017] observed an 18.6-year cycle in the migration of channels and tidal flats in the bay of Mont-Saint-Michel (France). They state that the periodic increase and decrease in flood-dominance corresponds with the periodic shift in the location of the channel, which is either located in the north or the south of the embayment. In this case, the bayward migration of tidal sand ridges forced a change in the in- and outflow direction of the tidal channels. It is hypothesised that a progressively northward swing of the northern channel configuration is caused by sand choking, i.e. a large sediment supply partly blocking the main channel. This latter mechanism could be similar to the observations in the final stage of the scale-experiments, in which the ebb-tidal delta progressively expands in landward direction, followed by a southward migration of the channel at 11-12 m (Supplementary Figure 2s-u).

While not explicitly stated in the original paper [*Levoy et al.*, 2017], the presence of a monastery and some local bedrock in the middle of the entrance of the embayment may have had a forcing effect on the inflow location and direction of the tidal channels. Similarly, the local confinement present eastward in the embayment could force the main confluence location there. The observation in our experiments, where major confluences and narrow zones in the outline are self-formed thus fits with observations in this natural system. In addition, *Levoy et al.* [2017] recorded that infill of channels by reworking of bar sediments can cause sudden shifts of channels, which was also observed in the experiments when an ebb channel progressively blocks the evading flood channel by forming a u-shaped bar into that channel.

Our experimental results suggest that without any human interference (e.g. dredging or bank protection) the morphodynamics of macrocells remain active: the roles and locations of ebb and flood tidal channels may reverse within approximately 1000 tidal cycles and intertidal bars between these channels are continuously reworked. This is in contrast with natural systems under human interferences, in which dredging may cause degeneration of the affected cell and subsequently evolve into a single-channel system [*Wang and Winterwerp*, 2001; *Jeuken and Wang*, 2010; *Wang et al.*, 2015] and for which smaller connecting channels are disappearing by marsh formation on top of the shoals [*Swinkels et al.*, 2009]. Open questions include what the effect of dredging and dumping will be on the morphodynamics of estuaries and how an engineered estuary compares to a reference case with exactly the same initial and boundary conditions but without any human interference.

5 Conclusions

An experiment in a periodic tilting flume revealed the long-term evolution of channel and bar patterns in self-formed estuaries. Typically, in the landward part a stable meandering channel forms, whereas in the seaward part dynamic channels and bars form that periodically shift laterally. The estuary banks are eroded in phases when forced mid-channel bars are present, which results in an estuary planform that is locally wider than the ideal converging shape. Zones with abundant and dynamic bars are separated by locations of channel confluences. We conclude that stable confluence locations in self-formed estuaries are controlled by the spacing of tidal bars, which both are a function of estuary width. The channels between the stable confluences are highly dynamic, which results in a quasi-periodic estuary planform.

The self-formed experimental estuary specifically shows that major confluences occur at relatively narrow parts in the outline and that these confinements are self-formed by sidebar formation. This corresponds to observations in natural systems in which major confluences also occur at self-formed confinements, for example by salt marsh formation, as well as at forced confinements, for example by inherited geology or human engineering. However, natural channels and bars are limited in their dynamics, because channels are largely fixed or maintained in place. While the ideal estuary shape may be applicable to tidal creeks and branches of deltas in equilibrium, the experimental results and observations in natural systems suggest that in self-formed alluvial estuaries in absence of any external forcing (geology, human influence) an autogenically-formed quasi-periodic estuary planform evolves.

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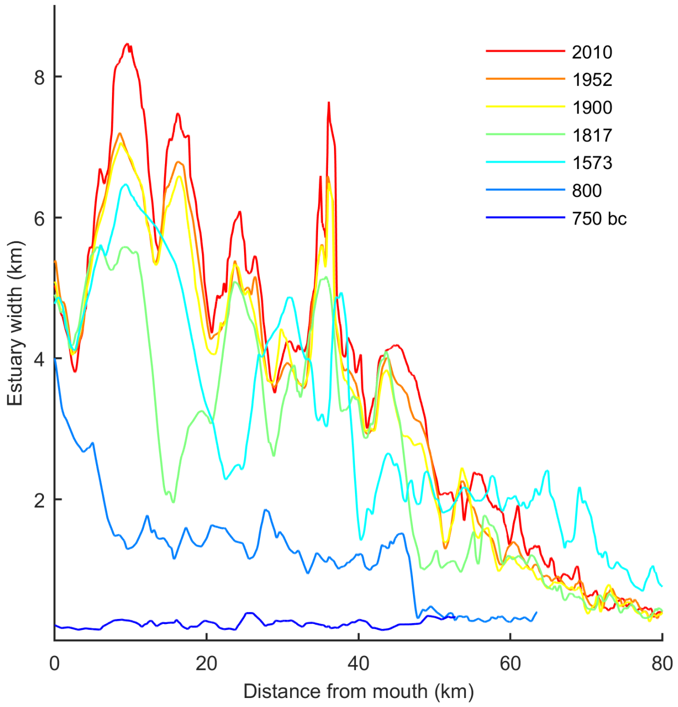

578 **Figure 11.** The estuary width profile of the Western Scheldt (The Netherlands) over time, which shows a
579 similar evolution as the experiment.

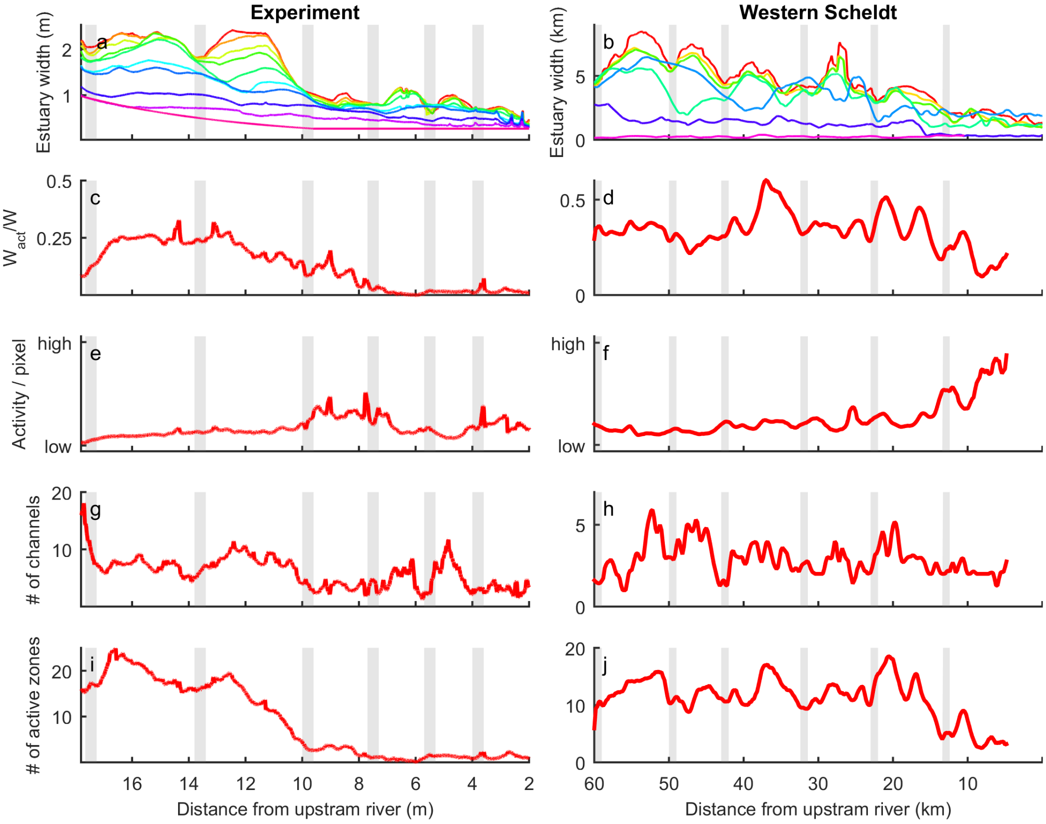

Figure 12. Along-channel profiles of (a,b) local estuary width over time, (c,d) time-averaged active channel width normalised with local estuary width, (e,f) sum of absolute bed level change per pixel, (g,h) number of channels in cross-section and (i,j) number of active areas in cross-section. Shading indicates locations of confinement in the estuary outline. These locations correspond with locations where the active width, activity per pixel and number of channels are generally low. The along-channel profiles (c-j) were averaged over the period 7500-15000 cycles for the experiment and the years 2000-2015 for the western Scheldt.

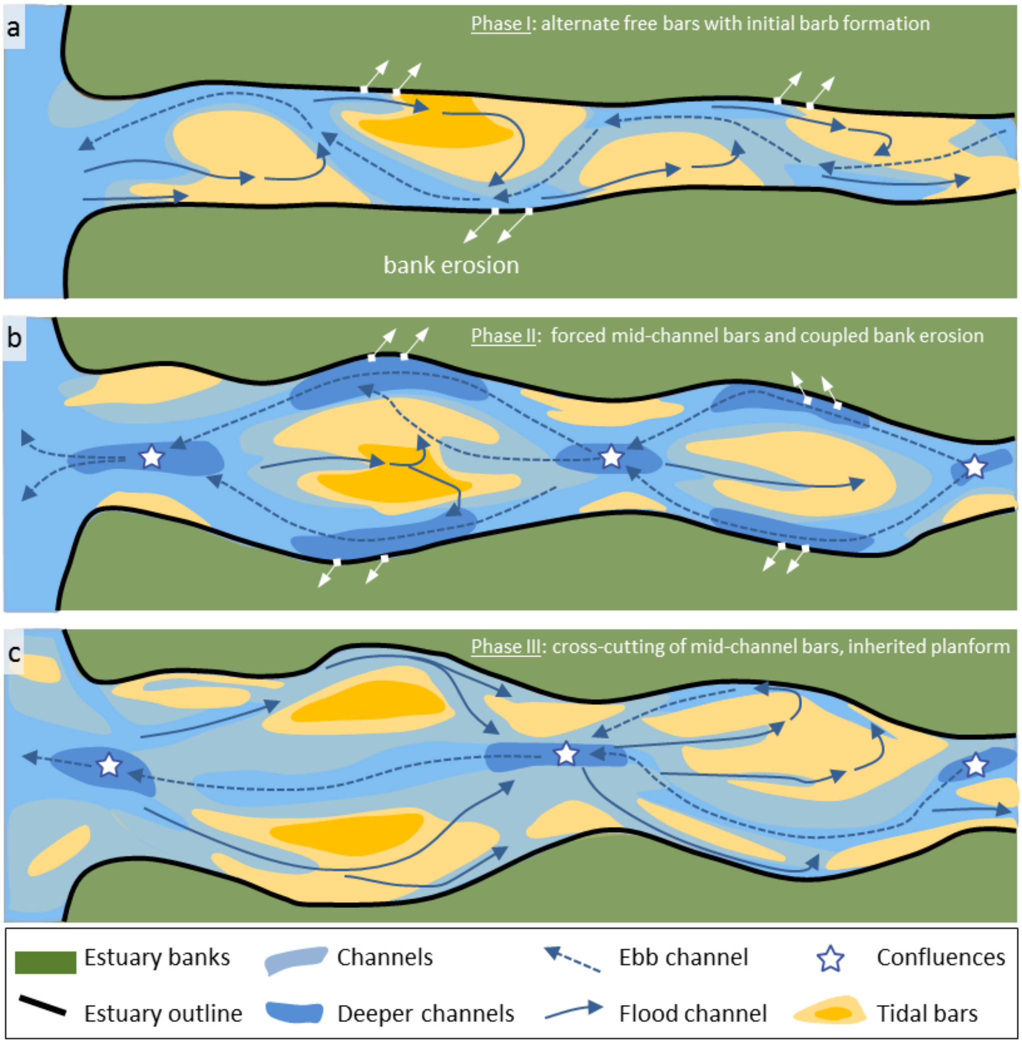

Figure 13. Conceptual model for the development of self-formed estuaries. (a) Phase I: the initial converging channel widens and (free) migrating alternate bars form. The meandering channel around the alternate bars is predominantly used as ebb channel, eroding the outer bends. While the alternate bars widen, initial flood barbs form onto the alternate bars. The main meandering channel migrates slightly seaward in Phase I, causing a longitudinal displacement in the next phase. (b) Phase II: the flood barb channels progressively cut through the alternate bars, isolating forced mid-channel bars in the middle of the estuary. This creates two major confluences: one at the mouth and one upstream of the mid channel bar. The flow is diverted around the mid-channel bar, which causes bank erosion, resulting in an even more irregular planform. (c) Phase III: the barb channels on the mid-channel bar enlarge and subsequently connect, cross-cutting the bar. This forms a new channel in the middle of the estuary and limits the erosion of the estuary banks. The resulting quasi-periodic planform is inherited from phase II. Major confluences separate zones in which channels periodically rework tidal bars.