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Analysis of the drainage density of experimental and modelled tidal networks

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Abstract

Based on a controlled laboratory experiment, numerical simulations of micro-tidal and meso-tidal conditions simulate the initiation and long-term evolution of back-barrier tidal networks. The simulated pattern formation is comparable to the morphological growth observed in the laboratory which is characterised by relatively rapid initiation and slower adjustment towards an equilibrium state. The simulated velocity field is in agreement with natural reference systems such as the micro-tidal Venice Lagoon and the meso-tidal Wadden Sea. Special attention is given to the concept of drainage density which is measured on the basis of the exceedance probability distribution of the unchannelled flow lengths. Model results indicate that the exceedance probability distribution is characterised by an approximately exponential trend, similar to the results of laboratory experiments and observations in natural systems. The drainage density increases greatly during the initial phase of tidal network development while it slows down when the system approaches equilibrium. Due to the larger tidal prism, the tidal basin has a larger drainage density for the meso-tidal condition (after the same amount of time) than the micro-tidal case. In both micro-tidal and meso-tidal simulations, it is found that there is an initial rapid increase of the tidal prism which soon reaches a relatively steady value (after approximately 40 yr) while the drainage density adjusts more slowly. In agreement with the laboratory experiments, the initial bottom perturbations play an important role in determining the morphological development and hence the exceedance probability distribution of the unchannelled flow lengths. Overall, our study indicates an agreement between the numerical and experimental tidal networks on the geometric characteristics.

1 Introduction

Branching channel networks are typical landscapes in back-barrier tidal basins such as the Wadden Sea (Wang et al., 2012) and the Venice Lagoon (D'Alpaos et al., 2007a).

These systems consist of various geomorphological elements (Fig. 1) that are shaped by a variety of processes. The ebb delta and the barrier islands act as natural shelters for the flood delta and tidal flats (and associated salt marshes). Tidal flats are often dissected by dendritic channel networks that serve as effective nutrient pathways for

5 flora and fauna, hence providing valuable accommodating space for coastal ecosystems (Allen, 2000; Townend et al., 2011). It is therefore imperative to understand the morphodynamics of these systems, especially in the context of increasingly intensive human intervention and climate change (French, 2006; D'Alpaos, 2011; Coco et al., 2013).

10 Remote sensing, associated with specifically developed techniques to analyse the digital terrain maps (DTM), has enabled a more accurate measure and understanding of the geomorphic characteristics of tidal networks (Fagherazzi et al., 1999; Rinaldo et al., 1999a, b; Mason et al., 2006; Vandenbruwaene et al., 2012). Analyses of these field data indicate that scale-invariance as widely observed in river networks does not

15 necessarily hold for tidal networks (Rinaldo et al., 1999a) because of the more complicated interplay between various competing landscape-forming processes operating in estuarine systems (e.g. bi-directional tidal flow and the presence of locally-generated wind waves).

Drainage density, a measure of channelization in watersheds, has been found of

20 fundamental importance for the understanding of channel network systems since it reflects a balance between climate, geomorphology and hydrology (Moglen et al., 1998). This quantity was firstly defined by Horton (1932, 1945) as the ratio between the total channelized stream length and the watershed area: $D = \sum L_c/A$. Although widely adopted, the "laws of drainage networks" developed by Horton (1945) are still un-

25 der debate. Analysing unbiased samples of networks generated with a Monte Carlo method, Kirchner (1993) found that almost all possible networks follow Horton's laws, indicating the distinctiveness of an individual channel network actually cannot be revealed by Horton's theory (see also Rinaldo et al., 1998). This was also confirmed by Marani et al. (2003) through analysis of both natural networks in the Venice Lagoon

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and highly schematic test settings. In order to overcome the drawback embedded in Horton's laws, Marani et al. (2003) proposed another measure based on the statistical distribution of the unchannelled flow length (l), i.e. the mean distance from a point on the lagoon platform to the nearest channel. This methodology, based on a Poisson-type hydrodynamic model (Rinaldo et al., 1999a), has been used in many studies afterwards (D'Alpaos et al., 2005, 2007a, b; Feola et al., 2005), proving to be a useful geomorphic tool for analysing channel network systems.

Field observations, together with different geometric analyses (e.g. Rinaldo et al., 1999a; Marani et al., 2003; Novakowski et al., 2004; Vandenbruwaene et al., 2012a, b), have confirmed that tidal networks show distinctive landscapes and geometric characteristics, because of the highly complicated interactions between various processes like waves, tides, biological activities and sea level rise. By limiting the number of active processes, controlled laboratory experiments provide an important alternative to gain insight (Stefanon et al., 2010, 2012; Vlaswinkel and Cantelli, 2011; Kleinhans et al., 2012; Iwasaki et al., 2013). Moreover, the data obtained from these experiments (or after proper scaling analyses) can be utilised to benchmark numerical models (Tambroni et al., 2010).

Stefanon et al. (2010, 2012) successfully reproduced the major features of the evolution of tidal networks in the laboratory, which are comparable to natural systems in terms of both the morphological development and the geomorphic characteristics. Zhou et al. (2013) performed a comparative study between these laboratory experiments and numerical simulations at both laboratory and natural scales, exploring the effects of different parameterisations on the long-term morphological evolution of tidal networks. They found that eddy viscosity, sediment transport formulation and bed slope terms played an important role in the resulting morphologies of tidal networks. In this study, emphasis is given to the comparison of the general geomorphic characteristics of tidal network systems using model and laboratory experiments. Specifically, we will explore whether the numerically modelled channel networks are comparable with the experimental (Stefanon et al., 2010, 2012) or natural ones from the perspective of

drainage density. Meanwhile, the variation of drainage density during the morphological development will also be examined, in order to shed light on tidal network ontogeny. The remaining of the paper is organised as follows: Sect. 2 describes the experimental and numerical models, Sects. 3 and 4 present the results and associated discussions, and concluding remarks are made in Sect. 5.

2 Methods

2.1 Physical model and scaling analysis

Stefanon et al. (2010, 2012) carried out experiments under a range of different settings. One of these experiments (indicated by "Run 4" in Stefanon et al., 2010) was conducted considering a constant mean water level. Run 4 is the focus of this study. The experimental domain included an initially flat lagoon, a gently sloping shelf and a deep sea (Fig. 2a). The lagoon was connected with the shelf and the sea via an inlet which was bounded by non-erodible barriers. Both the lagoon and shelf were filled with coarse low-density non-cohesive grains (medium size $D_{50} = 0.8$ mm and density $\rho_s = 1041$ kg m^{-3}) that were sufficient to prevent the erosion up to the non-erodible bottom. A harmonic tide, with a tidal amplitude $a = 0.005$ m and period $T = 480$ s, was simulated at the sea by a vertically oscillating weir.

The final stable network of Run 4, observed in the laboratory after approximately 8000 tidal cycles, is shown in Fig. 2b. Through scaling analysis (Stefanon et al., 2010), it was possible to "transfer" this experiment to typical natural systems where tidal networks are often observed, i.e. micro-tidal and meso-tidal basins like the Venice Lagoon and the Wadden Sea (see Table 1 for the results of the scaling analysis). The reader is referred to Stefanon et al. (2010) for a detailed description of the experiments and the scaling analysis.

2.2 Numerical model and setup

The numerical model Delft3D is used to simulate the "morphodynamic loop" which in this study consists of the depth-averaged shallow water equations, sediment transport (van Rijn, 1993) and bed level updating equations. At each hydrodynamic time step, the morphological change is calculated feeding back on the hydrodynamics (i.e. "online approach"). In order to reduce the computational cost, the model introduces a so-called "morphological accelerating factor" (*MorFac*) which linearly scales up the bed level change, see Lesser et al. (2004) and van der Wegen and Roelvink (2008) for more details.

Both the scaled-up micro- and meso-tidal cases are simulated in this study according to the scaling laws given in Table 1. A grid mesh of 48 300 rectangular cells is adopted for both cases with different cell sizes (micro-tidal case: 22.5 m × 22.5 m, and meso-tidal case: 31 m × 31 m) and their input bathymetries are deduced by scaling up the bottom perturbations of the initial measured experimental bathymetry with a multiplier factor of 100 and 200, respectively. The bottom perturbation of the initial experimental bathymetry of Run 4 is approximately ±0.004 m; hence the perturbations of the micro-tidal and meso-tidal initial bathymetries are ±0.4 m and ±0.8 m, respectively. As for the meso-tidal case, a second initial bathymetry with different bottom perturbations is considered to investigate the role of different random bed perturbations on the morphological evolution of tidal networks. The magnitude of the bottom perturbations for the second bathymetry is the same as the first one whereas the spatial distributions which were generated randomly are different. Some other key model parameters are chosen through sensitivity tests, including time step ($\Delta t = 30$ s), morphological accelerating factor (*MorFac* = 20), transversal bed slope term ($\alpha_{bn} = 50$) and Chézy friction coefficient ($C = 65$ m$^{1/2}$ s^{-1}).

3 Results

3.1 Pattern formation and velocity field

The morphological formations of micro-tidal (tidal range = 1 m) and meso-tidal (tidal range = 2 m) basins after 5, 65 and 125 yr are shown in Fig. 3. Similarly to the labora-
⁵ tory observations, the initial phase of the channel development proved to be rapid. By scouring the inlet, a central channel was formed within 5 yr. The channel subsequently branched into smaller tributaries which grew wider and deeper and kept on branching, meandering and elongating. After 5 yr, approximately 1/3 area of the micro-tidal basin, while over 1/2 area of the meso-tidal basins (for both the bathymetries), were dissected
¹⁰ by the expanding channel network (Fig. 3a, d and g). As tidal prism kept increasing, the network continued to develop rapidly until a general quasi-stable tidal network took shape after around 50–60 yr (Fig. 3b, e and h). The growth of the channel network slowed down and adjusted to a stable planar configuration after approximately 120 yr (Fig. 3c, f and i). After that, only the inlet area was still subject to small erosion (leading
¹⁵ to further inlet deepening) until the morphological equilibrium state was reached after around 200 yr.

The average depth of the inlet area of the stable tidal network observed in the lab-oratory is around 0.05–0.06 m (Fig. 2b), the corresponding depths of the numerically modelled micro-tidal and meso-tidal systems are 5–6 m and 10–11 m, respectively. This
²⁰ agrees well with the scaling analysis of Stefanon et al. (2010), see Table 1. Overall, the average channel depths of the micro-tidal and meso-tidal simulated networks are ap-proximately 2–3 m and 3–4 m, respectively, with the average tidal flat depths of about 0.3–0.4 m and 0.5–0.6 m, respectively. These morphological features generally resem-ble natural examples such as micro-tidal Venice Lagoon and meso-tidal Dutch Wad-
²⁵ den Sea (Stefanon et al., 2010). Although sharing a similar trend in channel network development, the detailed morphological evolution of the micro-tidal and meso-tidal simulations differs in primarily two aspects. First, these two networks display different final morphologies: the channels formed in the meso-tidal case are more meandering

and occupy a larger portion of the basin area than in the micro-tidal case. Second, the channel network developed more rapidly in the meso-tidal case and the channels were wider and deeper after the same amount of simulation time. This was also found by van Maanen et al. (2013) who showed that tidal networks grow more rapidly for larger tidal range. Finally, our simulations shows that the initial bottom perturbations play an important role on the morphological development of tidal networks (Fig. 3d–i), which was also noticed in the laboratory experiments.

The spatial distribution of velocity magnitude at the maximum flood condition based on stable tidal networks is shown in Fig. 4. As expected, velocities in the channels are larger than in the tidal flats (see Fig. 3c and f for morphologies). The maximum velocities are found near the inlet area, with an average value of approximately 0.6–0.7 m s^{-1} for the micro-tidal case (Fig. 4a) while 0.7–0.8 m s^{-1} for the meso-tidal case (Fig. 4b). These values fall within a reasonable range when compared to natural lagoon systems and they are also consistent with the scaling analysis (Table 1) of Stefanon et al. (2010).

3.2 Drainage density

Following the method proposed by Marani et al. (2003) in the framework of tidal systems, the drainage density of tidal networks is evaluated on the basis of the exceedance probability distribution of the unchannelled flow lengths, determined using the Poisson-type hydrodynamic model developed by Rinaldo et al. (1999a). Previous studies on natural tidal networks indicate that the probability distribution of unchannelled flow lengths is exponential (Marani et al., 2003; Feola et al., 2005; D'Alpaos et al., 2007; Vandenbruwaene et al., 2012a). The probability density function shows a linear trend when it is plotted on a semilogarithmic scale and the inverse of the slope represents the mean unchannelled flow length. The drainage density is larger when the slope is steeper, suggesting that the channel networks are more efficient in draining tidal flats and marshes (Marani et al., 2003).

Figure 5 shows the exceedance probability distribution of tidal networks after 5, 35, 65 and 125 yr under the micro-tidal condition. After 5 yr, the slope of the semilogarithmic distribution is relatively gentle when less than 1/3 of the tidal flats is drained. The probability distributions after 35, 65 and 125 yr are close one another since the basic

5   structure of the tidal network has taken shape after 35 yr and only some minor morphological adjustments occur afterwards. The slope of the semilogarithmic distribution increases with time, indicating a decreasing mean unchannelled flow length and an increasing drainage density (Fig. 6). The mean unchannelled flow length decreases sharply in the first 35 yr, indicating a rapid expansion of tidal networks. The decrease

10   of the later phase (when the system is evolving towards equilibrium) is slower (Fig. 6a). Generally, the characteristic of the probability distribution (Fig. 5), as well as the evolution of the mean unchanelled flow length and drainage density (Fig. 6), is in accordance with the trend of the morphological evolution: the initial phase of development is rapid and slows down with time, especially when the morphological equilibrium approaches.

15   Similar results were also presented by Vandenbruwaene et al. (2012a, b) who conducted a 5 yr field study of spontaneous formation and evolution of a tidal network in the Scheldt estuary, Belgium.

The morphological evolution of the micro-tidal and meso-tidal cases differs pronouncedly (Fig. 3), which can also be reflected by the exceedance probability distri-

20   bution. After the same amount of time (i.e. 5 and 125 yr), the unchannelled flow length of the low exceedance probability is larger under the meso-tidal condition (Fig. 7a) than the micro-tidal one (Fig. 5), which occurs because the dimension of the meso-tidal basin is larger. In order to compare the laboratory-scale experiment Run 4 with the micro-tidal and meso-tidal simulations, the unchannelled flow lengths are scaled

25   with the corresponding basin widths (see Fig. 7b). The basin is drained more efficiently under the meso-tidal condition than the micro-tidal condition after the same time (5 and 125 yr, see also Fig. 8b) since the dimensionless exceedance probability curve of the meso-tidal case displays a larger slope. This is consistent with the smaller mean unchannelled flow length shown by Fig. 8a. The drainage densities of both the micro-tidal

and meso-tidal simulated stable networks are larger than those found in the laboratory experiment (represented by the marker "+" in Fig. 7b).

Stefanon et al. (2010) performed two experiments using different initial bottom perturbations under the same tidal forcing and found that the final patterns obtained in the laboratory differed pronouncedly. Their finding was also reflected by the distinctive exceedance probability distributions of the unchannelled flow lengths. Our numerical model results also confirmed this point. The evolved tidal network after 5 yr, obtained using the 1st bathymetry as initial condition, showed less drained area than the one obtained when considering the 2nd bathymetry as an initial condition, which is in agreement with the larger slope of the exceedance probability distribution (in a semilog plot) of the case with the 2nd bathymetry (Fig. 9). However, the 1st bathymetry leads to a larger final drainage density than the 2nd when the morphological equilibrium configuration is reached. This indicates that the lagoon of the 2nd bathymetry can be better drained near the inlet area while the inner lagoon is drained less efficiently when compared to the lagoon of the 1st bathymetry. This is simply the result of different spatially distributed random perturbations of the bottom and the morphodynamic feedbacks they generated. Analogous to the micro-tidal case shown in Fig. 6a, the mean unchannelled flow length decreases rapidly in the beginning phase and tends to be stable when morphological equilibrium is approached (blue lines in Fig. 8a).

The evolution of the mean unchannelled flow length and drainage density displays asymptotic behaviour (Fig. 8), as also found by Vandenbruwaene et al. (2012a). As a primary landforming force shaping channel networks, the tidal prism of both micro-tidal and meso-tidal simulations also shows a similar evolution (Fig. 10). The tidal prism increases sharply in the first 35 yr when the channel network expands quickly dissecting the tidal flats and slows down afterwards. Although sharing a similar trend, the tidal prism of the meso-tidal case is larger than the micro-tidal one due to the different tidal ranges and basin sizes (Fig. 10). Initially, the tidal prism adapts to the morphological evolutions more rapidly than the drainage density does and then the two quantities vary with similar temporal scales, as also found by Stefanon et al. (2012).

Both the evolution of drainage density and the tidal prism displays asymptotic behaviour (Fig. 10). Therefore, numerical simulations predict that the drainage density of a stable channel network system should correspond to a certain tidal prism. In fact, using varying water levels to simulate different sea level conditions (hence different morphological equilibrium systems), the laboratory experiments conducted by Stefanon et al. (2012) indicate an approximately linear relationship between the landforming tidal prism and drainage density, which is also in qualitative agreement with the results of Marani et al. (2003) for natural salt-marsh basins.

4 Discussion

Exhibiting a variety of morphologies, channel networks (e.g. mountainous, fluvial or tidal) have attracted considerable attention in the academic field (Montgomery et al., 1997; Rinaldo et al., 1998, 1999a; D'Alpaos et al., 2005). A comprehensive understanding of their morphologies as well as their long-term evolutions is fundamental to address their response to environmental variations under increasing climate change and human pressure. Different methodologies (e.g. Montgomery and Dietrich, 1988; Fagherazzi et al., 1999; Passalacqua et al., 2010; Jiménez et al., 2013a) have been developed in order to extract the structure of channel networks and gain insight into their geomorphic characteristics. Due to the high variability in morphologies of channel networks, it is convenient to study these systems from a statistical point of view (Marani et al., 2003; Passalacqua et al., 2013). Recently, Passalacqua et al. (2013) analysed the channel network of Ganges-Brahmaputra-Jamuna delta using a statistical framework based on several descriptors (island area, shape factor, aspect ratio and nearest-edge distance) and their results indicated that the statistical behaviour of these descriptors could distinguish the coastal region and the area along the main rivers, hence geomorphic signatures of processes and vegetation types responsible for delta formation and evolution could be identified.

The current study focuses on tidal networks in which scale-invariance (or self-similarity, i.e. the statistical characteristics of the system do not change over a range of scales) does not hold as found in river networks (Rodriguez-Iturbe et al., 1992) due to the more complex feedback mechanisms between various landscape-forming processes (Rinaldo et al., 1999a). By limiting the number of processes affecting the evolution of tidal networks, controlled laboratory experiments provide a good base to gain insight into these systems. The laboratory observed tidal networks of Stefanon et al. (2010, 2012) are morphologically comparable to natural ones. However, their quantitative analysis almost certainly suffers from inevitable scaling effects which can be difficult to evaluate especially when translated to long term numerical modelling. Based on scaling arguments (Stefanon et al., 2010), we set up numerical simulations in an attempt to understand the evolution of drainage density of tidal networks from a numerical modelling point of view and also examine to which degree numerical model results agree with the scaling laws. Quantitatively, the numerically simulated tidal networks resemble those obtained in the laboratory experiments (Stefanon et al., 2010, 2012; Kleinhans et al., 2012) and some natural back-barrier tide-dominated systems (e.g. the Venice Lagoon and the Dutch Wadden Sea). The flow velocities fall in a reasonable range both in the tidal channels and the flats and are in good agreement with the scaling arguments. Overall, the numerical model appears to be capable of reproducing the major features of tidal network ontogeny.

Consistent to the field observation of the natural systems in the Scheldt estuary, Belgium (Vandenbruwaene et al., 2012a), the drainage density of the numerically simulated tidal networks is asymptotic towards an equilibrium configuration. The exceedance probability distribution of the unchannelled flow lengths of the simulated tidal networks displays an exponential trend, in analogy with the laboratory experiments and natural tidal networks in the Venice Lagoon (Marani et al., 2003; D'Alpaos et al., 2007a). The exceedance probability distributions of the unchannelled flow lengths for the micro-tidal and meso-tidal scale are different after the same amount of simulation time, suggesting, from this perspective, the absence of scale-invariant processes.

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As previously indicated, uncertainties in scaling of laboratory observations could potentially cascade on the scaling adopted in the numerical simulations. Model results indicate that the drainage density of the meso-tidal basin is larger due to the larger tidal prism and associated stronger hydrodynamic-morphological feedbacks. The tidal prism increases rapidly during the beginning phase of tidal network development and soon it reaches a relatively steady value while the drainage density adjusts more slowly, which is consistent with Stefanon et al. (2012).

Model results also show that the random bottom perturbations play a considerable role in determining the long-term morphological development of tidal networks, and hence the overall evolution of the drainage density. Consistent with laboratory observations (Stefanon et al., 2010), the different exceedance probability distributions of the unchannelled flow length (Fig. 9) reflect the pronounced difference of final configurations of tidal networks. This indicates that the channel network in tidal lagoons can be initiated by random perturbations affecting the later evolution though the morphodynamic feedback mechanisms which may ultimately result in pronouncedly different landscapes.

Nevertheless, there are limitations in the current study that needs to be addressed. Firstly, both the experiment and numerical models do not include the effects of waves, biological activities, mud (or sand-mud mixture) sediments and possible river inflow which are commonly present in estuarine environments. Therefore, more processes should be added in both the physical and numerical models so that a more realistic condition can be considered in the future. Secondly, the Poisson-type hydrodynamic model (Rinaldo et al., 1999a), as adopted to calculate the exceedance probability distribution of the unchannelled flow length (and hence the drainage density), assumes friction terms dominate over inertial and advective terms in the momentum equations. This assumption holds well for shallow basins in which the water depth is normally smaller than 5 m (e.g. the Venice Lagoon), while it may not be valid for the deep area in the model domain. As for the current study, the effect of this limitation is minor for the micro-tidal case (water depth is generally below 5 m) whereas the effect is more

significant for the meso-tidal case since channels are more incised with larger tidal prism, especially near the inlet area. This limitation can be overcome by using a more sophisticated hydrodynamic model (e.g. Delft3D); however, this may require more computational costs. The reader is referred to Jiménez et al. (2013b) for some on-going research.

5 Conclusions

We adopt a state-of-the-art numerical model (Delft3D) to investigate the morphological development of tidal networks and compare it to a controlled laboratory experiment. The numerical model is able to reproduce the general behaviour of tidal network ontogeny and the modelled velocity field agrees with the scaling analysis and different natural reference systems.

The comparison primarily focuses on the analysis of the drainage density of tidal networks. Instead of using the classic Horton's method, we analyse the drainage density based on the exceedance probability distribution of the unchannelled flow lengths (the mean of this exponential probability distribution, i.e. the mean unchannelled flow length, is the drainage density). Similar to laboratory experiments and natural systems, analysis of the numerically simulated tidal networks shows that the probability distribution of unchannelled lengths displays an exponential trend. In accordance with the observed morphological evolution, the simulated drainage density increases rapidly during the initial phase of tidal network development and slows down when equilibrium is approached. Because of the larger tidal prism, the meso-tidal basin is more drained than the micro-tidal case when stable channel networks are attained. The initial increase of tidal prism is more rapid than that of the drainage density while later the increase is slower, indicating that the tidal prism adjusts faster to a stable condition. The initial bottom perturbations are found to play an important role in determining the morphological development, which is also captured in the exceedance probability distribution of the unchannelled flow length.

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Using the unchannelled flow length as a descriptor for statistical analysis, we have shown that the numerically modelled tidal networks are comparable to the experimental and natural ones. We have also shown that tidal networks display distinctive morphological features that can be influenced by various factors (e.g. tidal range, initial bottom perturbations). Finally, this study highlights the benefit (and hence need) of complementary studies between physical and numerical modelling in gaining insight into the long-term morphological evolution of complex estuarine systems.

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Table 1. Experimental setting and numerical model parameters after scaling analysis of Stefanon et al. (2010). W, L and D represent width, length and depth scales of the basins; U denotes the typical velocity in tidal channels.

Parameters	a (m)	T (s)	ρ_s (kg m^{-3})	D_{50} (mm)	$W \times L$ (m^2)	D (m)	U (m s^{-1})
Experiment	0.005	480	1041	800	4 × 5.2	0.05	0.05
Micro-tidal case	0.5	43 200	2650	234	3600 × 4700	5.0	0.5
Meso-tidal case	1.0	43 200	2650	234	5000 × 6700	10.0	0.7
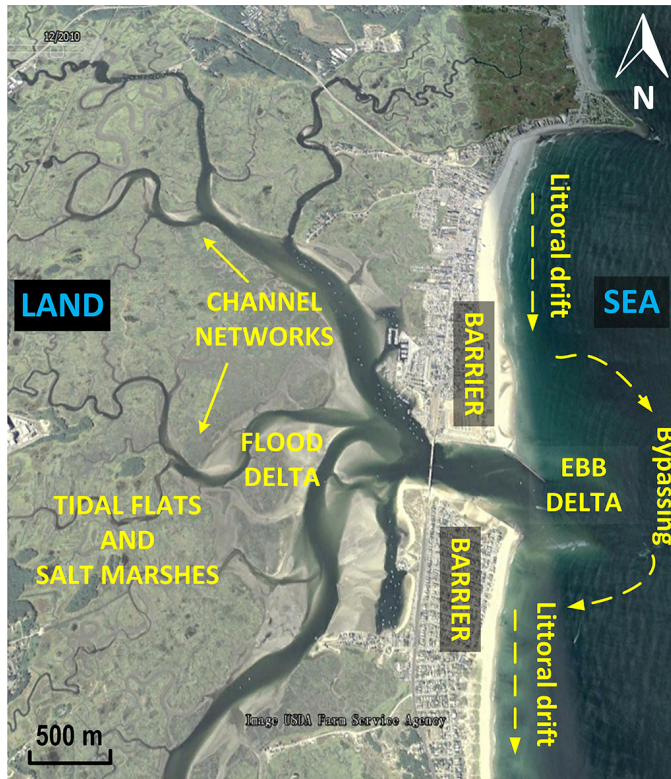
Fig. 1. Demonstration of a typical barrier tidal basin system, showing various geomorphological features including flood and ebb deltas, channel networks, barrier beaches, tidal flats and salt marshes. The system is Hampton harbour inlet, located at 42°53′48″ N and 70°49′06″ W, the East Coast of the US. The image was taken from Google Earth (dated 1 January 2010), accessed on 11 October 2013. © Image USDA, Farm Service Agency, Google Earth 2013.

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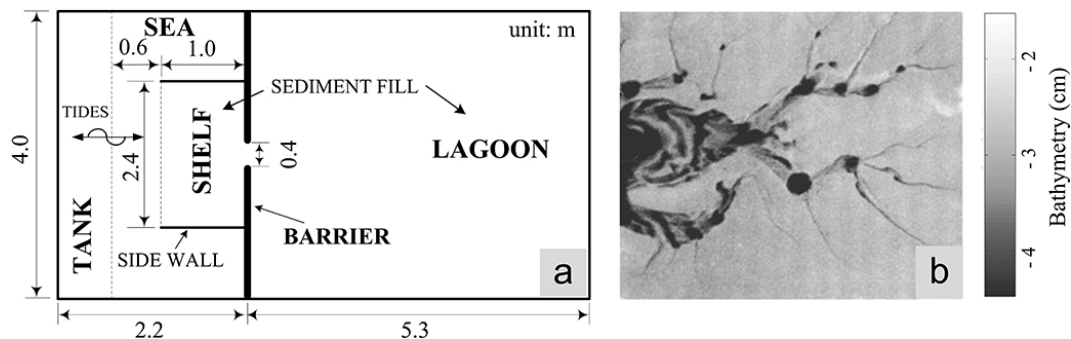
Fig. 2. Laboratory experimental setting and results of Stefanon et al. (2010). **(a)** Schematic overview of the experimental apparatus; **(b)** Final stable channel network obtained in the lagoon of the experiment Run 4.
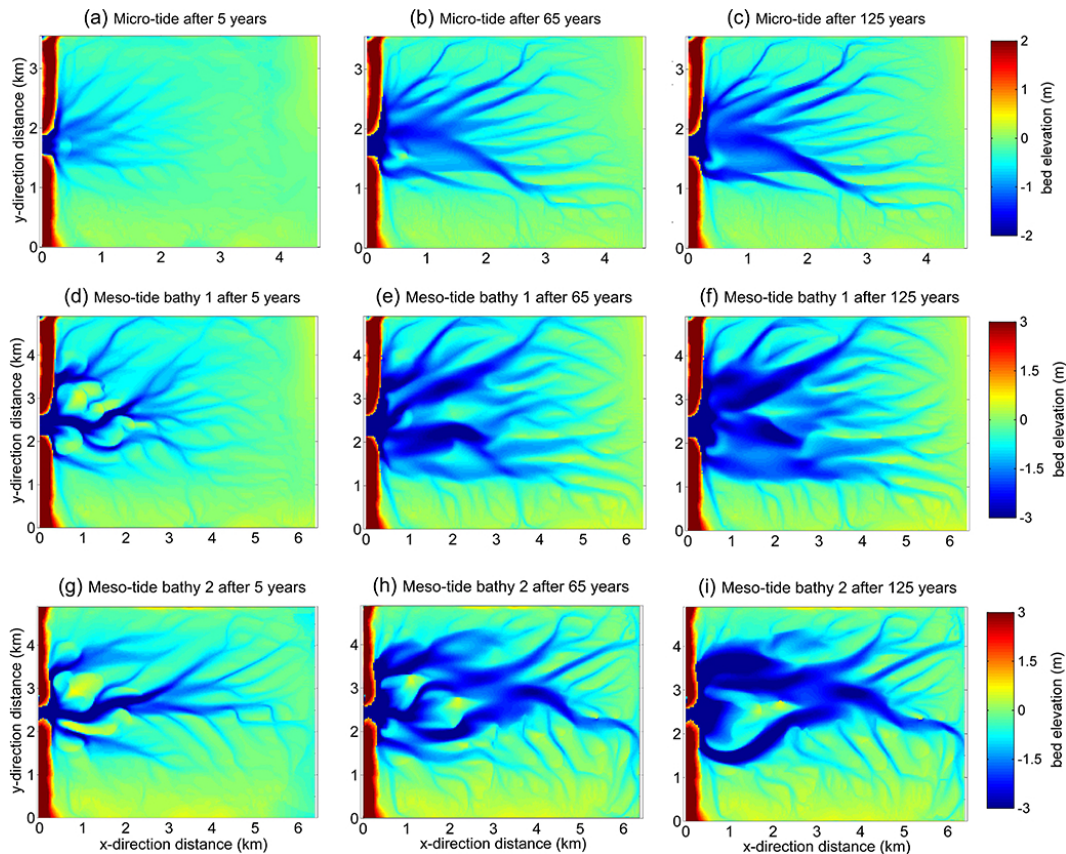
Fig. 3. Morphological pattern formations after 5, 65 and 125 yr simulated by the numerical model. **(a–c)** Micro-tidal condition, **(d–f)** Meso-tidal condition with the first bathymetry, and **(g–i)** Meso-tidal condition with the second bathymetry.
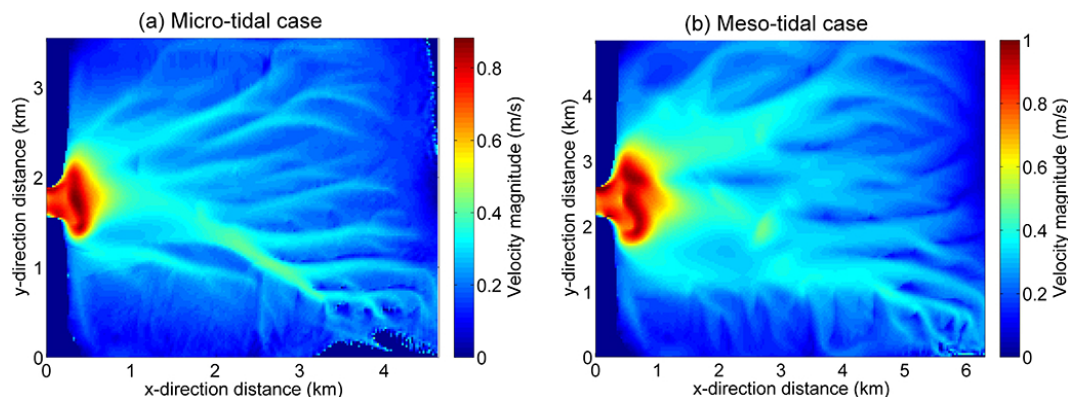
Fig. 4. Spatial distribution of velocity magnitude at the maximum flood condition based on stable tidal network: **(a)** Micro-tidal case and **(b)** Meso-tidal case with the first bathymetry.
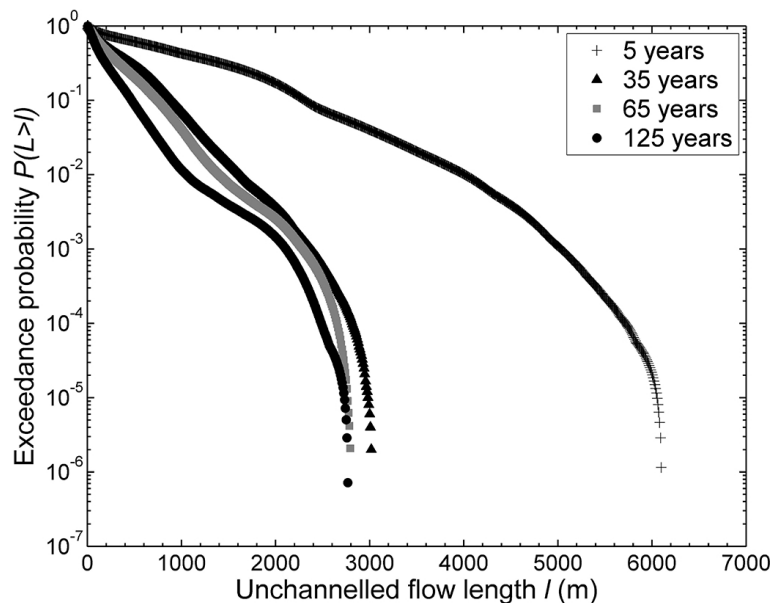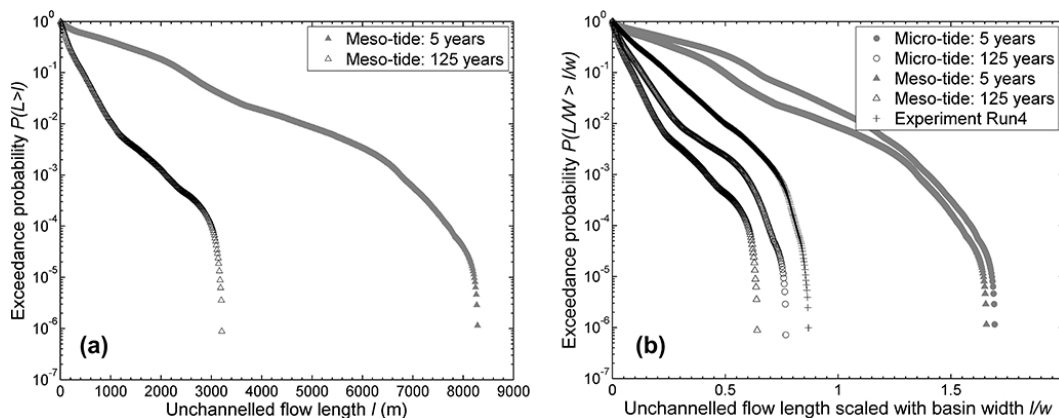
Fig. 5. Semilog plot of the exceedance probability $P(L>l)$ of the unchannelled flow length l, computed for the configurations of channel networks under the micro-tidal condition after 5, 35, 65 and 125 yr, see also Fig. 3a–c for the morphologies of corresponding networks.
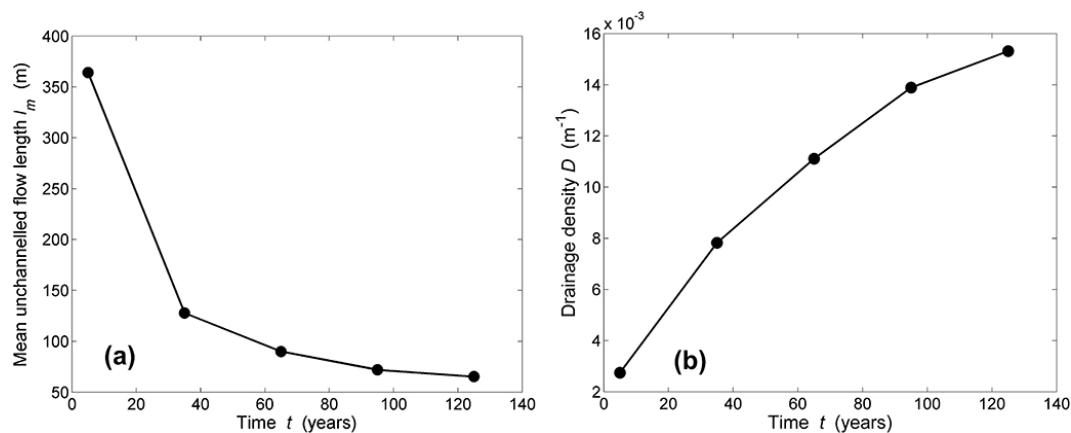
Fig. 6. (a) Evolution of the mean unchannelled flow length l_m with time, and **(b)** evolution of the drainage density D of the developing tidal networks under micro-tidal condition.

Fig. 7. (a) Semilog plot of the exceedance probability $P(L > l)$ distribution of the unchannelled flow length l, computed for the configurations of numerical tidal networks under meso-tidal condition after 5 and 125 yr, and **(b)** semilog plot of the exceedance probability $P(L/W > l/w)$ of dimensionless unchannelled flow length l/w (scaled with basin width w), computed for the configurations of stable experimental tidal networks (Run 4) and numerical tidal networks under both micro-tidal, meso-tidal condition after 5 and 125 yr, see also Fig. 3 for the morphologies of corresponding networks.
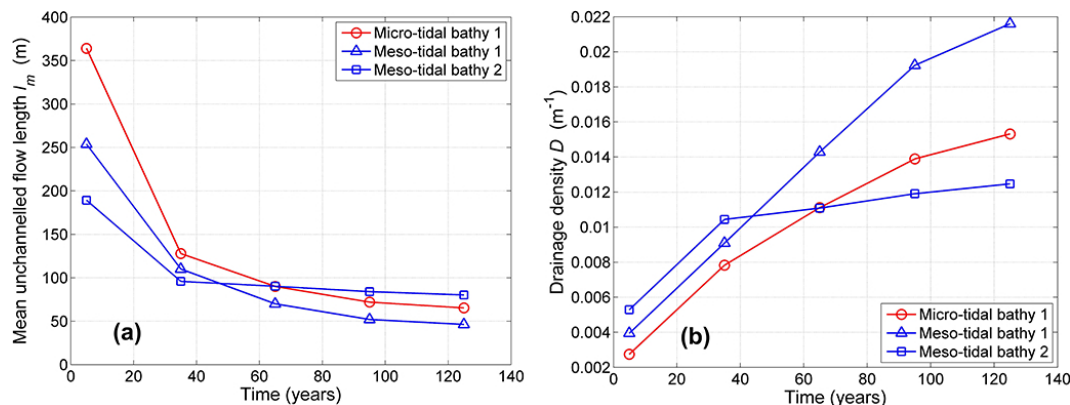
Fig. 8. Comparison of the evolution of **(a)** the mean unchannelled flow length, and **(b)** the drainage density between micro-tidal, meso-tidal 1st and meso-tidal 2nd bathymetry, see also Fig. 3.
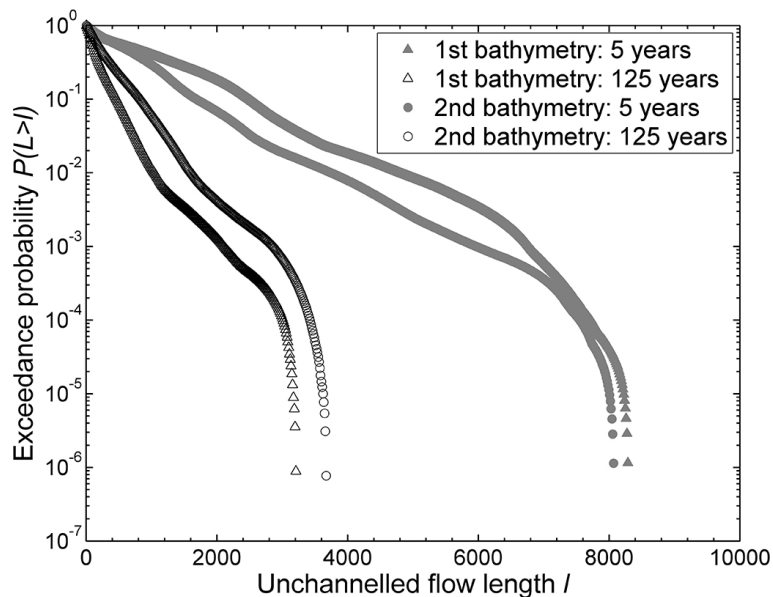
Fig. 9. Semilog plot of the exceedance probability distribution of the unchannelled flow length, computed for the configurations of channel networks with different initial bottom perturbations under the meso-tidal condition after 5 and 125 yr.

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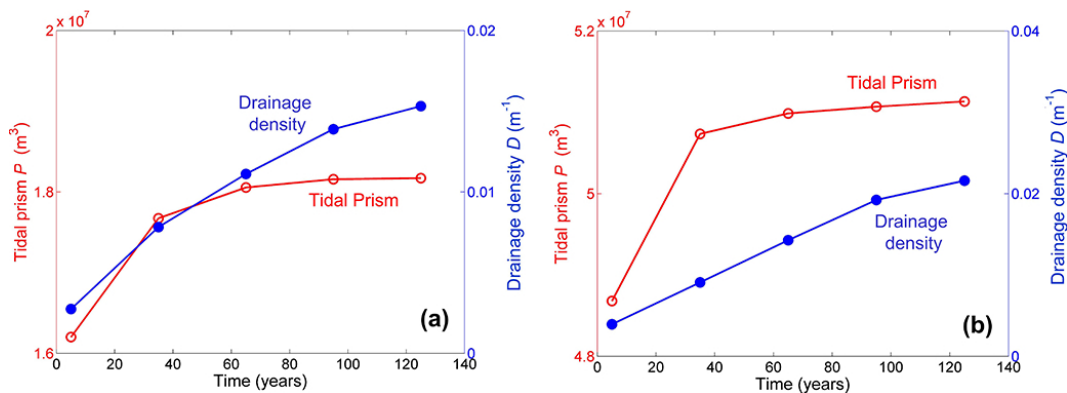
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Fig. 10. Evolution of tidal prism and drainage density for **(a)** the micro-tidal case, and **(b)** the meso-tidal case.