Morphological characteristics of laboratory generated tidal networks

G. Tesser, A. D'Alpaos & S. Lanzoni
Department IMAGE, University of Padova, Italy

ABSTRACT: In this paper we present the first results of a series of laboratory experiments carried out in a large experimental apparatus, aimed at reproducing a typical lagoonal environment subject to tidal forcings. We observed the growth and development of a tidal network and analyzed its most relevant features, taking into account the role played by the characteristics of the tidal forcings in driving the development of channelized patterns. Such experiments were designed in order to improve our understanding of the main processes responsible for channel network ontogeny and evolution. Mathematical and theoretical analyses of network configurations were also carried out through the use of simplified and complete morphodynamic models. In particular, we analyzed the evolution in time of the morphometric characteristics of the developed networks, and studied the hydrodynamics and sediment transport processes related to different channel configurations. The evolution of channel cross-sectional areas, width-to-depth ratios, and unchanneled flow lengths shows that relevant features of actual tidal networks are reproduced by the tidal patterns developed within our laboratory experiments.

1 INTRODUCTION

Tidal channel networks exert a strong control on hydrodynamics, sediment and nutrient dynamics within tidal environments. Improving our understanding of their origins and evolution is of critical importance when addressing issues of conservation of tidal systems.

A wide literature exists, developed especially in the last three decades, describing the hydrodynamics of tidal systems and their morphodynamic evolution (see e.g. Allen 2000, Friedrichs & Perry 2001, for thorough reviews). In spite of their fundamental role in driving the morphological evolution of tidal basins, only in the last few years mathematical and numerical models analyzing the morphogenesis and long-term morphodynamic evolution of tidal channels have been proposed (Schuttelaars & de Swart 2000, Lanzoni & Seminara 2002, Fagherazzi & Furbish 2001, Fagherazzi & Sun 2004; D'Alpaos et al. 2005, 2007). Moreover, even though the development of tidal channel networks has been analyzed both through field observations and conceptual models (Pestrong 1965, French & Stoddart 1992) the description of the processes leading to the initiation and early development of tidal networks still lacks a proper delineation. In particular, attempts to investigate such processes on the basis of controlled laboratory experiments have not been pursued, except for those recently carried out by Tambroni et al. (2005), who investigated the morphodynamic evolution of the bottom of a single straight tidal channel closed at one end and connected at the other end to a rectangular basin representing the sea. Towards the goal of gaining fundamental knowledge into the description of the main physical processes responsible for tidal network ontogeny, we carried out a series of laboratory experiments in a large experimental apparatus schematizing a typical lagoonal environment, subject to tidal forcings.

We furthermore used simplified and complete hydrodynamic models to carry out numerical and theoretical analyses of the experimental network configurations and to compare the relevant features of experimental and observed morphologies.

The paper is organized as follows. Section 2 describes the experimental apparatus. Section 3 reports on the experiments and related results. In Section 4 we use simplified and complete hydrodynamic models to compare relevant morphometric features of the synthetic and observed networks. Finally, Section 5 draws a set of conclusions and some remarks on forthcoming developments.

2 EXPERIMENTAL APPARATUS

The experimental apparatus, schematically depicted in Figure 1, consists of two adjoining basins reproducing schematically the sea and the lagoon. The lagoon basin is 5.3x4.0m wide, while the much deeper adjacent sea basin is 1.6x4.0m wide. The bed of the lagoon was uniformly covered with a 30cm-thick layer of sediments during the experiments. The sea is separated from the lagoon by a barrier of wooden panels; the lagoon inlet (whose shape and width may be varied) is located in the middle of this barrier while in front of the inlet a shelf enables to reproduce the gentle slope of the sea bed (Fig. 1).

The tide is generated at the sea by a vertical steel sharp-edge weir, oscillating vertically. The water continuously flowing over the weir is collected to a separated tank, where a set of pumps recirculates the flow.

An *ad hoc* software has been implemented to drive the weir, allowing us to reproduce a sinusoidal tide of fixed amplitude and period, oscillating around a prescribed average level. The software continuously corrects the motion of the weir on the basis of a feedback instantaneously controlled by water-level measurements at the sea, carried out through ultrasonic probes.

A computer-driven pantograph is used to survey bottom elevations within the lagoon. The apparatus consists of a laser system (300 μm resolution) which measures bottom elevation coupled to a ultrasonic probe which simultaneously gauges the associated water level. The latter measurement is used to determine the local flow depth and to correct laser measurements from refraction effects induced by the presence of water. The bathymetric survey of the lagoonal bottom, in fact, is carried out without stopping the experiment and drying the sediment surface, thus avoiding undesired perturbations of bed topography.

The sediments used in the experiments are cohesionless plastic grains, with density of 1041 kg/m^3 and median grain size, d_{50}, of 0.8 mm.

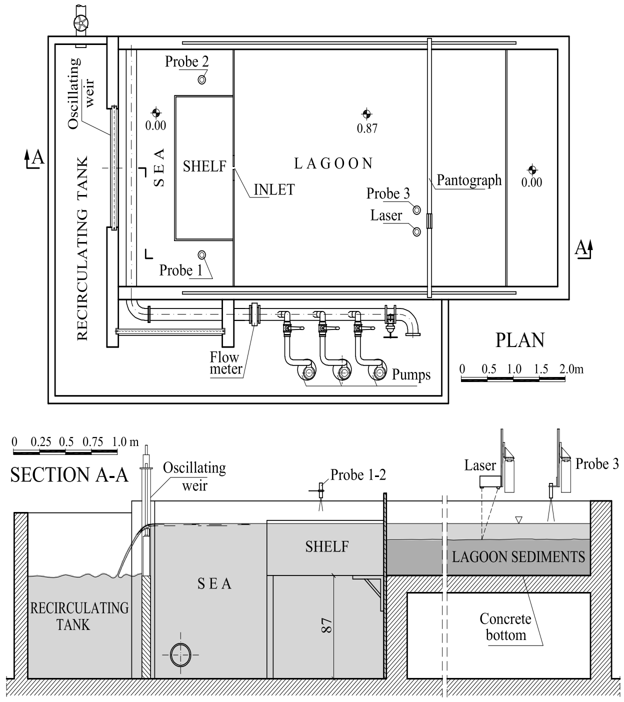

Figure 1: Sketch of the experimental apparatus

3 EXPERIMENTS

The experiments carried out so far mainly aimed at understanding under which conditions a channel network develops. To this end various tides (i.e., characterized by different amplitude, period and mean level) and different shapes and dimensions of the tidal inlet have been considered.

Each experiment started forcing an initially flat bed topography with a given tidal wave. A tidal network was observed to form only for small enough values of the tidal amplitude (1.0-2.0 cm) and of the flow depth (1.0-2.0 cm) and for a mean water level allowing the drying of the sediment surface during the ebb phase. A tidal period of 8-12 minutes was chosen in order to avoid perturbing vortexes and ensure the long-wave character of the tide.

In the presence of a too high tidal amplitude the sediments tended to be transported as suspended load, large dunes formed, and the growth of the channel network was inhibited. In any case, a wide scour, covered by dunes, formed in correspondence of the inlet. The channel network was eventually observed to originate only from the landward border of such a scoured region. It is worthwhile to observe that bed load sediment transport was active during the whole experiment, while ebb and flood peak velocities promoted suspended load along the channels. Finally, in all the experiments the lagoon experienced a progressive net erosion, with the consequent reduction of its mean bottom level.

In the following we focus our attention on two typical experiments, denoted as Run 1 and Run 2.

3.1 *Run 1*

Let us here briefly describe the evolution of the lagoon bed which, starting from the initial flat configuration, was observed in Run 1.

The forcing tide with amplitude of 2 cm and period of 8 minutes, was oscillating around a mean level equal to the initial bed elevation. A 0.50 m wide rectangular-shaped inlet was located at the center of the sea-lagoon boundary.

As pointed out before, a wide scour region rapidly formed in front of the inlet. After 220 tidal cycles a few isolated channel started to form at the landward edges of this scour region, beginning to cut the portions of the lagoon subject to draining. These channels progressively experienced a head cut-growth during the ebb phase and, after 500 cycles, some little ramifications begun to form. After 1200 cycles, four main, nearly straight channels were present (Fig. 2a). The ramifications of these channels in some cases were unstable: some smaller creeks were observed to abandon a main channel to join another one. In some cases these smaller creeks migrated laterally, forming little bends. After 2300 cycles, the main channels lengthened significantly and at 2800 cycles three pronounced bends were observed to develop along one of these channels. However, the small scale bed forms (mainly dunes), initially covering the deep scour facing the inlet, progressively extended throughout the lagoon, tending to destroy the channel network. In order to smooth out these undesired bed forms and enhance the growth of a well defined channel network, we slightly decreased the mean sea level (about 0.5 cm). Figure 2b shows the bed configuration obtained after 6000 cycles, when the experiment was stopped.

3.2 *Run 2*

This experiment was characterized by a forcing tide with amplitude of 2 cm, period of 10 minutes, oscillating around a mean level 1.5 cm higher than the bed elevation. The width of the trapezoidal-shaped inlet varied from 0.05 m at the lagoon concrete bottom to 0.20 m at the sediment surface.

At the beginning of the experiment the mean sea level submerged the sediments during the whole tidal cycle. A wide scour region, covered by dunes, rapidly formed near the inlet. The scour was deeper than in Run 1 because of the larger values attained by the velocity (and hence by the bed shear stress) as a consequence of the narrower inlet. After 800 cycles, some isolated and unstable channel started to form at the landward boundary of the inlet scour. At 1300 cycles we reduced the mean sea level to allow draining of the sediment surface during the ebb phase and, soon after, a more defined tidal network began to form, characterized by three main channels that lengthened significantly during the following tide cycles. Some bends were also observed to form. The well developed small scale bed forms, previously observed to form in the main channels, tended to reduce sensibly their dimensions. Moreover, pronounced localized scours formed at the main junctions (Fig. 2d). The evolution was anyhow very slow and only in the last 1000 cycles the channels deepened appreciably, forming a more complex network, with some bends forming also along the main channels (Fig. 2c). The run was stopped after 7710 cycles.

Figure 2: Lagoon topography observed in Run 1 after: a) 1200 cycles b) 6000 cycles and in Run 2 after: c) 6000 cycles; d) 7710 cycles.

4 ANALYSIS OF EXPERIMENTAL DATA

Bed elevations acquired through the laser system and suitably corrected to account for refraction effects were used to produce topographic maps of the lagoon bed at various instants. Figure 3 shows the distribution of bed elevations at four different instants of Run 1 and Run 2: the temporal evolution of channel networks clearly emerges.

In order to classify small scale bed forms, which were observed to form during both the experiments, we used the bottom topographies measured at the end of Run 1 and Run 2 to carry out some fixed bed numerical simulations. The 2D shallow water equations were solved numerically by using a semi-implicit staggered finite element model, based on Galerkin's approach. The equations were modified to deal with wetting and drying processes in irregular domains. We refer the reader to D'Alpaos & Defina (1995), Defina (2000), D'Alpaos & Defina (2006) for a detailed description of the modified shallow water equations, the numerical techniques adopted, and for model validation.

The numerical results, obtained setting to 30 $m^{1/3}s^{-1}$ the Gauckler-Strickler friction coefficient, K_s, indicate that in Run 1 the higher values of both flow velocity U (~3.7 cm/s), and bed shear stress τ (~0.091 Pa), were attained during the ebb phase, in correspondence of the deep scour which formed in front of the inlet and in the first reaches of the channels departing from it. Secondary channel ramifications exhibited lower values of U (~2 cm/s) and τ (~0.0002 Pa).

A similar picture emerges from the simulation of Run 2 but with higher values of both the velocity (~5.8 cm/s) and the bed shear stress (~0.24 Pa) in the scour facing the inlet and in the reaches of the two main channels developing from it. Con-

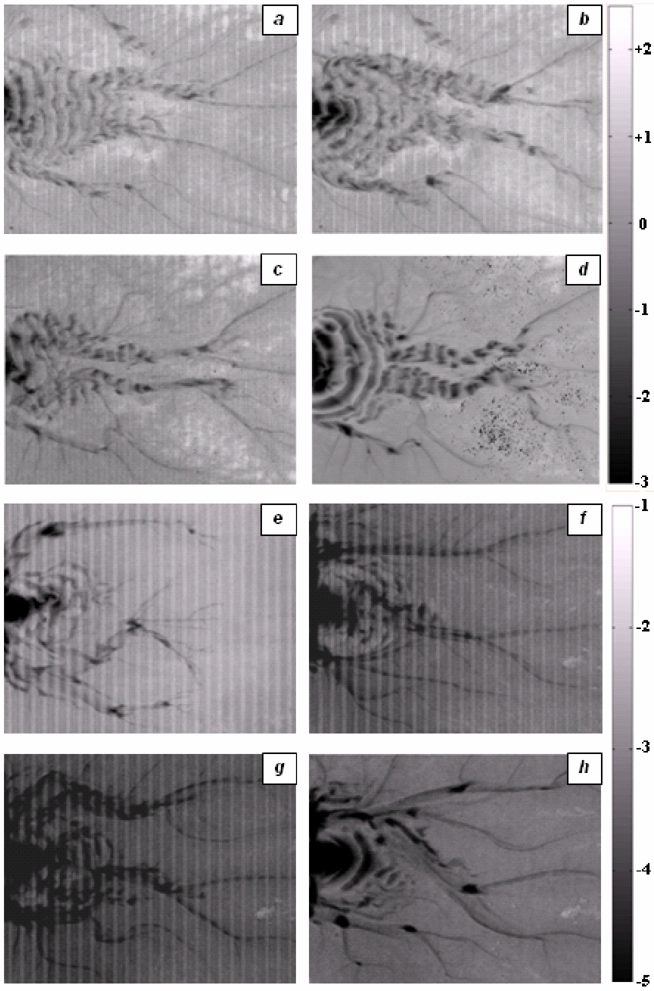

Figure 3: Distribution of bottom elevations measured within the lagoon in Run 1 after: a) 1650 cycles; b) 2900 cycles; c) 3910 cycles; d) 5950 cycles; in Run 2 after: e) 2200 cycles; f) 6270 cycles; g) 6845 cycles; h) 7700 cycles. Vertical bands are the consequences of changing tidal levels during the acquisition of the bathymetry. Elevations are referred to the initial uniform bottom elevation.

versely, secondary channel ramifications exhibited lower values of U (~ 1.5 cm/s) and τ (~ 0.0015 Pa).

The bed shear stress resulting from numerical calculation was used to determine the dimensionless Shields stress, τ^*:

$$\tau^* = \frac{\tau_0}{g \cdot (\rho_s - \rho) \cdot d} = \frac{u^{*2}}{\Delta \cdot g \cdot d} \qquad (1)$$

where: d is the representative sediment grain size, g is the gravity constant, ρ and ρ_s are water and sediment specific weight, respectively, $u^*=(\tau^*/\rho)^{1/2}$ is the friction velocity, ν is the kinematic water viscosity, and $\Delta=(\rho_s-\rho)/\rho$ is the relative density of submerged sediment.

Figures 4a,b show the spatial distribution of the excess Shield stress, $\tau^*-\tau^*_c$, during the ebb phases of Run 1 and Run 2, i.e., when bottom shear stress attains its maximum. The critical value τ^*_c for incipient sediment motion has been

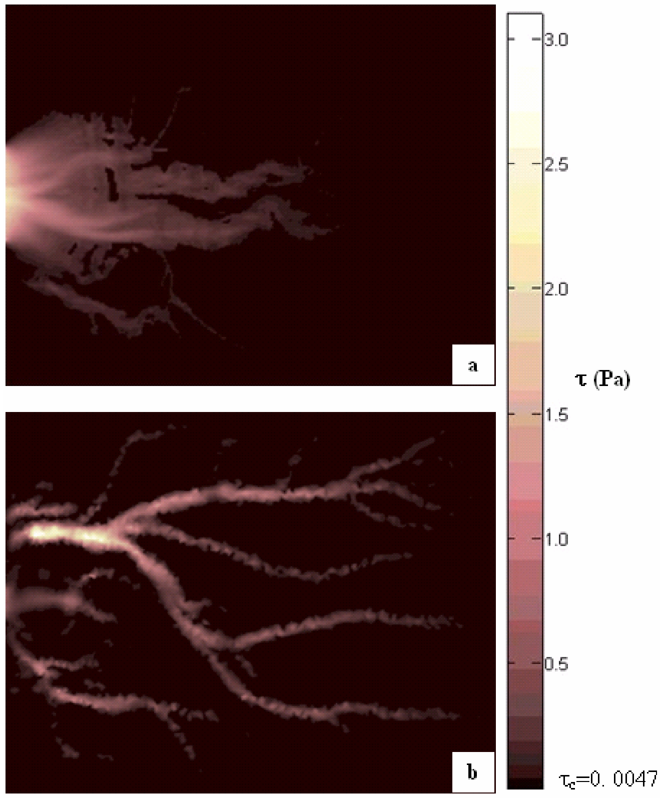

Figure 4: Spatial distribution of the excess Shield stress, $\tau^*-\tau^*_{cr}$, computed: (a) or the final configuration of Run 1 and (b) of Run 2. Both τ^* and τ^*_{cr} have been calculated using d_{50}=0.8mm, as representative grain size of the adopted sediments.

evaluated using the analytical relationship proposed by Brownlie (1981):

$$\tau^*_c=0.22\, R_p^{-0.6} + 0.06 \exp(-17.77\, R_p^{-0.6}) \text{.......}(2)$$

where R_p is particle Reynolds number:

$$R_p = \frac{\sqrt{\Delta \cdot g \cdot d^3}}{\nu} \qquad (3)$$

It clearly emerges that in both runs a large portion of the lagoon is interested by sediment transport. Additional analyses showed that choosing a different value of the representative grain diameter (e.g., d_{90}) does not significantly modify the percentage of lagoonal surface interested by sediment transport.

The computed values of the Shields stress, τ^*, and of the particle Reynolds number, R_p, have been used to determine the portions of the lagoon in which, according to the criterion proposed by Simon & Richardson (1966), small scale bed forms are likely to develop. Figure 5 reports a comparison between the computed and experimental spatial distribution of bed forms for Run 1 and Run 2. The agreement between computed and observed results is pretty satisfactory.

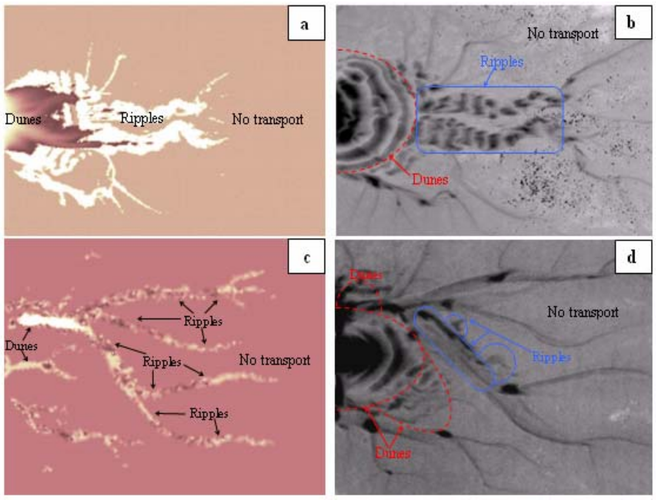

Figure 5: Spatial distribution of bed forms: (a, c) predicted through the criterion of Simons & Richardson (1966) applied to the computed values of R_p and τ^* for Run 1 (a) and for Run 2 (c); (b, d) arising from experimental observations for Run 1 (b) and for Run 2 (d).

Indeed, dunes are observed to form in the scoured zone facing the inlet and in the first reaches of the main channels. Dune wavelength (λ_d≈20cm) appears to be in accordance with predictions given by the empirical relationships proposed by Van Rjin (λ_d≈ 6 D) and Yalin (λ_d≈ 7.3 D) (Van Rjin 1984c, Yalin 1977, Yalin & Ferreira 2001). In fact, the mean flow depth, D, in the portions of the lagoon covered by dunes was of about 3 cm.

The final configuration of Run 2 was characterized by less developed bed forms, except for the dunes (λ_d≈7-8cm) covering the 0.8-1cm deep scour close to the inlet. Very small ripples affected the larger reaches of main channels.

We also carried out morphometric analyses of the experimental networks by using a simplified hydrodynamic model (Rinaldo et al. 1999a, b), successfully applied to the study of various tidal environments (Marani et al. 2003). The hydrodynamic flow field obtained through this simplified model makes it possible to determine the unchanneled hydrodynamic flow path connecting any unchanneled site to the nearest tidal channel and to compute its length. The probability distributions of unchanneled flow lengths, ℓ, exhibits a linear trend in a semi-log plot (Fig. 6), suggesting the same type of exponential decay determined by Marani et al. (2003) in different areas of the Venice lagoon.

Finally, in Figure 7 we report the two digitalized final network configurations of Run 1 and Run 2, whereas in Figures 8 and 9 we report some relevant features of channel network cross-sectional geometry, namely channel width, B, channel depth, D (measured along channel axis), width-to-depth ratio, β=B/D, and cross-sectional area, Ω.

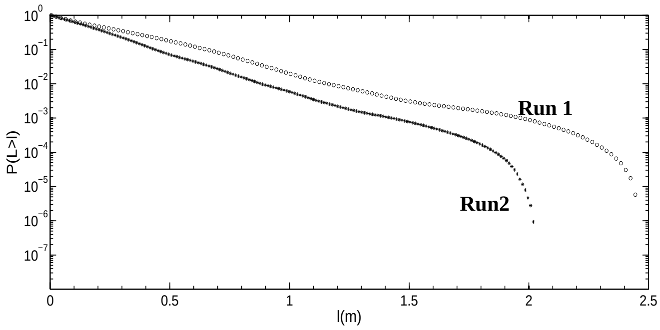

Figure 6: Probability distribution of unchanneled lengths for the channel network observed at the end of Run 1 and Run 2.

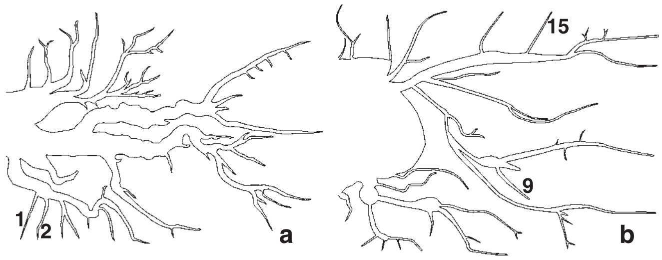

Figure 7: Border of final network configurations obtained in Run 1 (a) and Run 2 (b). Channels denoted by numbers 1, 2, 9 and 15 are those considered in the plots of Figs. 8, 9, 10.

We also reported in a semi-log plot channel width, B, versus the along channel intrinsic coordinate, s (Fig. 10).
In both runs, B and D attained relatively small values, falling in the range 1-2 cm and 8-10 cm, respectively. The results shown in Figure 8 suggest that, for a given channel, a nearly linear relationship exists between D and B.

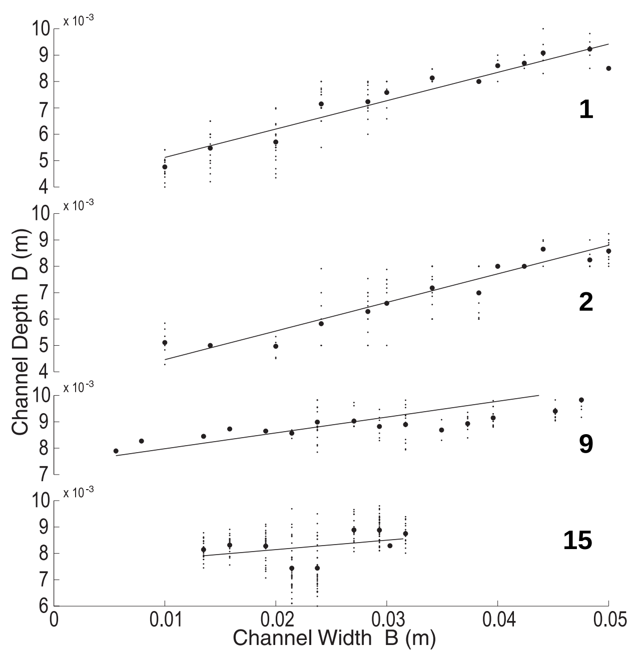

Figure 8:Channel depth versus width for the cross sections of channels indicated in Fig. 7.

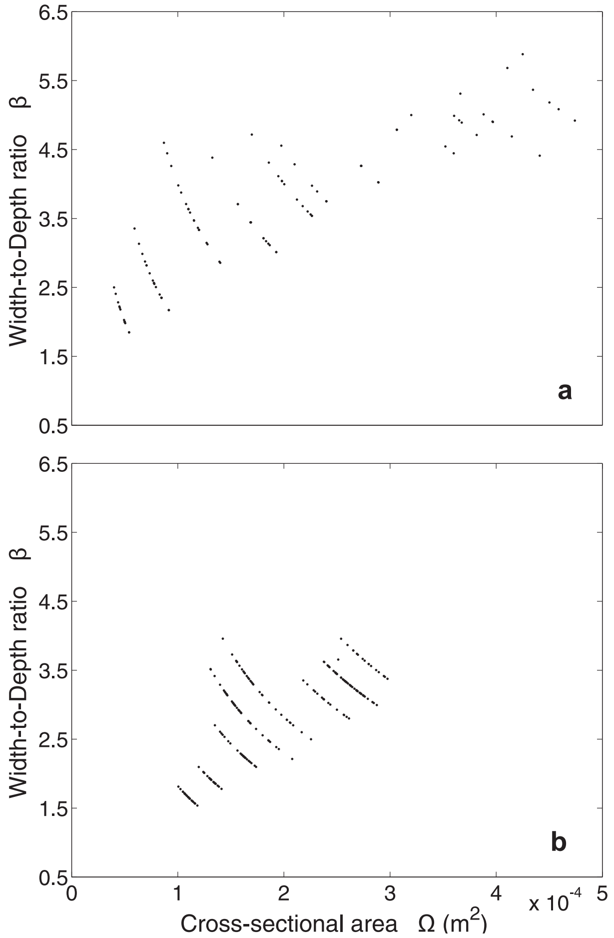

Figure 9: Comparison between the curve of width-to-depth ratio β–cross sectional area Ω of two straight channels: a) channel 1 of Run 1; b) channel 15 of Run 2.

The aspect ratio, β, displayed in Fig. 9, was found to vary between 2, for smaller channels, and 20, for the main channels, with an upper limit of 50. These values are in accordance with field surveys carried out in the Venice Lagoon (Marani et al. 2002). Finally, Figure 10 emphasizes the progressive exponential widening experienced seaward by channels, which is typical of tidal environments (Lanzoni & Seminara 1998, Marani et al. 2002).

5 CONCLUSIONS

The morphometric analyses of the laboratory generated tidal channels described in the present contribution suggest a close analogy with real networks. The similarity between field and laboratory probability distributions of unchanneled flow lengths, as well as the range of variation of the aspect ratio, suggest that present experiments can be used to get a better understanding of the morphodynamic processes responsible for the initial growth and subsequent development of channel networks within tidal basins.

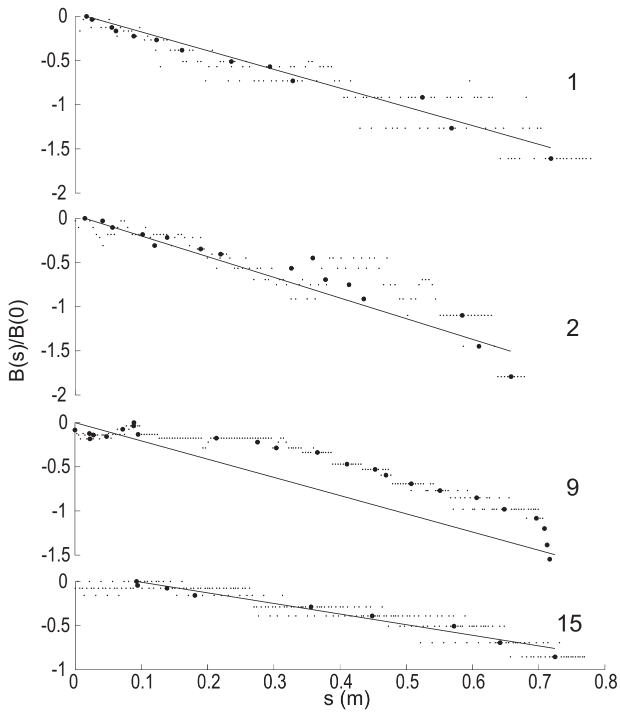

Figure 10: Logarithm of the ratio B(s)/B(0), with versus the intrinsic coordinate, s, for the channels indicated in Figure 7. B(s) is channel width at s, B(0) is width at channel inlet.

Laboratory channel networks were observed to form, starting from an initially flat and horizontal bed, only for: i) low enough values of the flow depth; ii) a mean sea level allowing the drying of the bottom during the ebb phase; iii) a tidal period of about 8-12 minutes. Higher flow depths enhance the formation of bed forms (ripples and dunes) and prevent the formation of well defined channels.

Channel networks were observed to form mainly through headward growth.

The rate of network growth was very slow at the beginning of the experiment whereas as soon as a well developed network began to form, the mean rate of channel elongation was approximately of 1.5-2 cm every 150 tidal cycles. After a quite rapid growth phase the tidal network appears to be subject only to small adjustments, thus supporting the usually adopted hypothesis that a time in the life of a tidal network exists during which it quickly cuts down the intertidal areas giving them a permanent imprinting. Such a process is later followed by slower elaborations including meandering and network contractions/expansions.

Clearly, a more systematic series of experiments is needed to further support the above findings.

Other points also need to be addressed in future developments of the research. In particular, the effects of the initial configuration (plane in the present experiments) on channel network structure has to be analysed, possibly accounting for the random irregularities that likely characterize the bottom of real tidal flats. The analysis of sediment cohesion, typical of lagoonal environments is deemed of importance, as well. Finally, the study of the influence exerted by different boundary conditions (e.g., the role of different lagoon inlet locations, and of external inputs of sediments) deserves further attention.

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