Geomorphology 191 (2013) 23–34

Contents lists available at SciVerse ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Modelling the effects of tidal range and initial bathymetry on the morphological evolution of tidal embayments

B. van Maanen [a,b,*], Giovanni Coco [a,1], K.R. Bryan [b]

[a] National Institute of Water and Atmospheric Research (NIWA), PO Box 11-115, Hamilton, New Zealand
[b] Department of Earth and Ocean Sciences, University of Waikato, Private Bag 3105, Hamilton, New Zealand

ARTICLE INFO

Article history:
Received 16 October 2012
Received in revised form 24 January 2013
Accepted 24 February 2013
Available online 4 March 2013

Keywords:
Tidal embayments
Channel networks
Morphodynamics
Numerical modelling

ABSTRACT

Tidal embayments are characterized by a wide variety of landscape features, often including either complex tidal channel networks or extensive flood-tidal deltas. The origin of these features and the influence of hydrodynamic drivers and initial geological setting on their long-term characteristics are essentially unexplored. A model was applied to simulate the long-term morphological evolution of tidal embayments, with the purpose of providing insight into the environmental conditions that lead to the differences in tidal embayment morphology. Numerical simulations indicated that the interaction between hydrodynamics, sediment transport, and the evolving topography gives rise to the formation of channel networks. The tidal range and the depth of the initially unchannelized tidal basin controlled the way in which the morphology evolved and determined the timescale over which channels and intertidal areas developed. Channel network formation occurred more rapidly when the tidal range increased and/or when the initial basin depth decreased. Tidal basins with a large initial depth showed the development of a flood-tidal delta and for these deep basins channel incision could remain absent over long timescales. Both tidal range and initial bathymetry affected final basin hypsometry and channel network characteristics, including the channel density and the fraction of the basin occupied by the channels. All the simulated morphologies, with different combinations of the tidal range and depth of the basin, evolved towards a state of less morphodynamic activity for which the relative intertidal area was proportional to the ratio of tidal amplitude to basin depth.

1. Introduction

Tidal embayments are amongst the most productive ecosystems in the world (Mitsch and Gosselink, 2007) and understanding their behavior has become increasingly important, especially in the context of climate change. These environments are characterized by a wide variety of landscape features and morphological patterns, with tidal channel networks arguably being the most striking example (Fig. 1a). The channel networks have a strong control on the hydrodynamics and sediment transport (Fagherazzi et al., 1999) and affect therefore both the short- and long-term morphological evolution of tidal environments (Dronkers, 2005). Because of the influential character of channel networks, numerous studies (see de Swart and Zimmerman, 2009) have been performed on their initial formation and subsequent evolution. These advances are largely based on laboratory studies and numerical models, because obtaining detailed measurements of channel network dynamics in reality is a daunting task due to the large spatial and temporal scales involved.

Laboratory experiments have been conducted to explore the dynamics of single tidal channels (Tambroni et al., 2005) as well as the development of complete tidal networks (Stefanon et al., 2010; Iwasaki et al., 2011; Vlaswinkel and Cantelli, 2011). For example, Stefanon et al. (2010) conducted an experiment starting from a plane horizontal tidal flat subject to tidal forcing and showed how the headward growth of the initiated channels and tributary addition drove expansion of the network and shaped the intertidal morphology. In this experiment and in the laboratory study described by Vlaswinkel and Cantelli (2011), the networks which formed displayed geomorphic features, such as the width-to-depth ratios and the seaward widening of channels, which resemble those of natural networks. Such laboratory approaches are meaningful, but up-scaling the results to the time and space scales over which real-world networks develop is not straightforward.

Simplified modelling approaches, in which processes are abstracted, can provide useful insights into the key processes that control the formation of channel patterns and the evolution on larger scales. Schuttelaars and de Swart (1999), for example, used stability analysis to study the initial formation of channels and shoals, and demonstrated that bottom friction plays a crucial role in the growth of bedforms. Later, D'Alpaos et al. (2005) applied a simplified hydrodynamic model and relationships

* Corresponding author at: University of Bordeaux 1, EPOC Laboratory, UMR CNRS 5805, Avenue des Facultés, 33405 Talence, France. Tel.: +33 5 40 00 88 49; fax: +33 5 56 84 08 48.
E-mail address: b.vanmaanen@epoc.u-bordeaux1.fr (B. van Maanen).
[1] Now at Environmental Hydraulics Institute, "IH Cantabria", Universidad de Cantabria, Avda. de los Castros s/n, Santander 39005, Santander, Spain.

0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.02.023

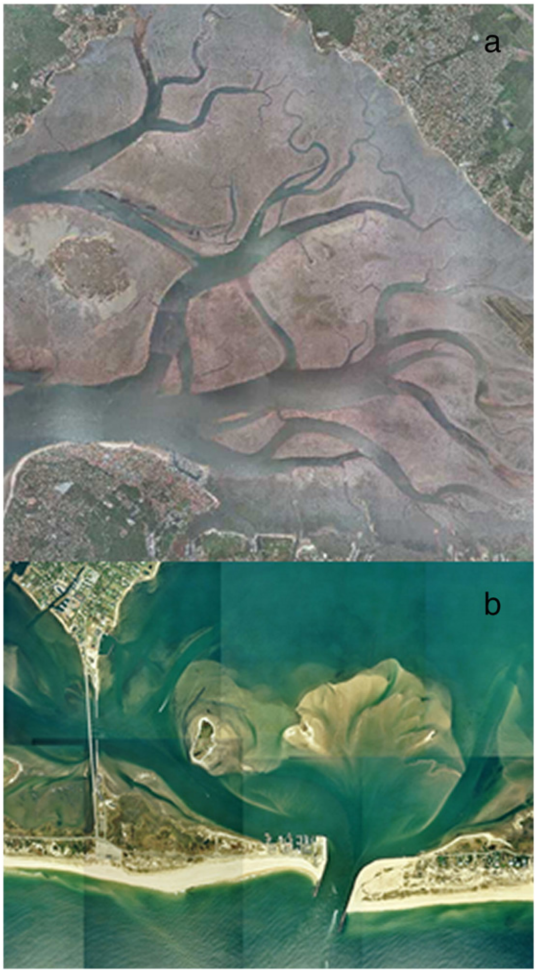

Fig. 1. Aerial view of a (a) well developed (Bassin d'Arcachon, France) and (b) underdeveloped (Shinnecock Inlet, USA) tidal channel network. Photo courtesy of Aquitaine Coast Observatory/SIBA and "Inlets Online", Coastal Inlet Research Program (CIRP), U.S. Army Corps of Engineers.

describing channel characteristics to simulate tidal network initiation and its progressive headward extension within tidal flats. This model was capable of reproducing statistical properties of an observed network in the Venice Lagoon (D'Alpaos et al., 2007). Di Silvio et al. (2010) proposed a modelling approach in which deposition and erosion rates depend on the difference between the local transport concentration and the local equilibrium concentration. The model was used to simulate the formation of a channel network in a tidal lagoon and results indicated that morphodynamic changes are rapid when the system is far from equilibrium but slow down once a network has developed.

A different type of modelling approach involves the coupling of comprehensive hydrodynamic models and commonly used sediment transport formulations. Marciano et al. (2005), for example, simulated morphological evolution by coupling the solution of the unsteady depth-averaged shallow water equations with a sediment transport module based on the formulation of Engelund and Hansen (1967). To facilitate the execution of long-term simulations and to overcome the issue related to the difference in time scale over which hydrodynamic and morphodynamic processes occur, Marciano et al. (2005) accelerated morphological change by extrapolating the bathymetric changes as the result of residual sediment transports over a single tide. The model simulated the evolution of branching channel patterns in a short idealized basin. The resulting channel network displayed a branching behavior similar to patterns observed in natural basins. Dastgheib et al. (2008) used a similar type of model to explore channel network formation and the interaction between adjacent tidal basins in a multi-inlet tidal system. Simulations were carried out with different initial bathymetries (a sloping bed inside the basin as well as a flat bed at different depths) and the model results followed empirical equilibrium relations suggested in the literature.

These laboratory and modelling experiments have provided useful insight into the processes governing channel network formation and have highlighted the importance of the feedbacks between hydrodynamics, sediment transport, and the evolving morphology. However, there are many landscape features that characterize natural tidal basins which are not reproduced by these network-forming experiments. In some tidal basins, the flood-tidal delta may be the dominant feature (de Swart and Zimmerman (2009) and see also Fig. 1b), with the network being a minor or even an absent characteristic. Such tidal basins often lack not only the channel network, but also the extensive adjacent intertidal areas and it is especially these intertidal areas that can provide valuable ecological habitats (Mitsch and Gosselink, 2007). If models are ultimately to be of theoretical as well as of practical use, then reproducing the different landscape characteristics is critical. This study therefore aims to provide insight into the environmental conditions that lead to the observed differences in tidal embayment morphology. Tidal basins evolve in sedimentary environments, and their landscapes may range widely because of the large variety in tidal conditions and in the underlying shape of the basin. We hypothesize that the balance between the initial depth of the basin and the strength of the tidal currents that redistribute the sediment ultimately control the type of basin that eventuates. Here we apply a numerical model based on the morphodynamic interactions to perform controlled experiments on tidal embayment evolution by varying both tidal range and initial depth to test this hypothesis.

2. Numerical modelling

2.1. Model description

The numerical model developed and used throughout this study simulates morphological change as a result of the interactions between hydrodynamics, sediment transport, and the evolving morphology. Fluid flow was simulated using ELCOM (Estuary and Lake Computer Model; Hodges et al., 2000) which is a 3D hydrodynamic model based on the unsteady Reynolds-averaged Navier–Stokes equations. Although a 3D-model was applied we only used the horizontal velocity components for the computation of sediment transport. Influences of Coriolis force, density differences, wind and waves were neglected. The continuity and the horizontal momentum equations in this case read:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0, \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-g\frac{\partial \eta}{\partial x}+\nu_x\frac{\partial^2 u}{\partial x^2}+\nu_y\frac{\partial^2 u}{\partial y^2}+\nu_z\frac{\partial^2 u}{\partial z^2}, \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-g\frac{\partial \eta}{\partial y}+\nu_x\frac{\partial^2 v}{\partial x^2}+\nu_y\frac{\partial^2 v}{\partial y^2}+\nu_z\frac{\partial^2 v}{\partial z^2}, \tag{3}$$

where u, v, and w are the velocity components in the horizontal x-, y- and in the vertical z-direction, respectively. t is time, g is the gravitational acceleration, υ_x, υ_y, and υ_z are eddy viscosity coefficients, and η is the water level which can be described as:

$$\frac{\partial \eta}{\partial t}+\frac{\partial}{\partial x}\left(\int_{-h}^{\eta} u dz\right)+\frac{\partial}{\partial y}\left(\int_{-h}^{\eta} v dz\right)=0, \tag{4}$$

where h is the water depth. The solution grid uses rectangular Cartesian cells, enabling the application of a simple, efficient finite-difference/finite-volume scheme on a staggered grid. ELCOM applies a z-coordinate system in the vertical direction. The numerical scheme for computing the