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Process-based modelling of morphodynamics and bar architecture in confined basins with fluvial and tidal currents

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ABSTRACT

Tides affect sediment transport dynamics in many coastal environments. Tidal effects may be particularly large in marine-influenced confined settings due to tidal amplification. Yet, it is largely unknown in what ways the width of confined basins and the strength of tidal currents impact sand deposition, and how this would affect reservoir architecture. This study applies the morphodynamic model Delft3D to systematically test models of bar stratigraphy and preservation in confined basins with mixed fluvial and tidal currents. A unique aspect of the methodology is that morphological as well as subsurface data are considered, thus enabling the tidally-influenced bar morphodynamics to be related explicitly to the associated bar deposits. By systematically varying tidal range in idealized confined basins of varying width, it is shown that bar dimensions are primarily affected by basin width, and that tidal range has a secondary effect. An increase in basin width results in a higher bar braiding index, a larger number of bars as well as longer bars, wider bars and thicker bar deposits. Synthetic architectures that can be compared directly with the sedimentary record show a high degree of stratigraphic complexity within tidally-influenced bars. Statistical distributions, summarizing the internal structure of tidally-influenced bars, provide quantification of the preservation of bars and such approaches will improve their three-dimensional characterization in geo-models of tidally-influenced and confined settings.

1. Introduction

Tides combine and interact with fluvial currents at the interface of land and ocean resulting in one of the most dynamic environments on Earth (Dalrymple and Choi, 2007). The combination of fluvial and tidal currents results in continuously changing channels and shoals of sand and mud. These tide-influenced environments, commonly estuaries and deltas, are generally important for navigation, provide recreation areas and host a variety of ecosystems (Conley et al., 2000; Kench, 1999; Roman et al., 2000). And the sedimentary fill of their ancient counterparts may comprise architecturally complex hydrocarbon reservoirs (Zaitlin et al., 1994; Wood, 2004; Dalrymple and Choi, 2007; Feldman and Demko, 2015).

The degree of tidal influence (i.e. from strongly tidal to strongly fluvial) varies spatially along the fluvial-to-marine transition (Carling et al., 2015; Dalrymple and Choi, 2007; Dashtgard and La Croix, 2015; Galloway, 1975) as well as temporally due to fluctuations in fluvial discharge and tidal range (Dalrymple et al., 2015). Tidal dominance occurs when tidal current-driven sediment transport exceeds sediment transport from river currents and is hence responsible for the development of the majority of the geomorphological features (Galloway, 1975; Dalrymple and Choi, 2007). Funnel-shaped confined basins may cause the tide to increase in range because of the progressive decrease in cross-sectional area. Such hypersynchronous conditions characterize tide-dominated environments (Dalrymple and Choi, 2007) where basin resonance may sometimes further increase the tidal range (Garrett, 1972). Well-known modern examples of tide-dominated basins are the Bay of Fundy in Canada (Dalrymple et al., 1992), the South Alligator River in Australia (Woodroffe et al., 1989) and the River Severn estuary in the United Kingdom (Harris and Collins, 1984; Carling et al., 2015).

Observations from natural systems with fluvial and tidal currents indicate that the bar morphology and sedimentology changes systematically from the fluvial environment to the mouth of the funnel-shaped basin (Carling et al., 2015; Dalrymple and Choi, 2007; Dashtgard and La Croix, 2015). Bank-attached point bars in the fluvial realm transition to isolated elongate tidal bars at the mouth of the funnel-shaped as a response to a seaward increase in tidal prism. Similar to fluvial meandering systems, the elongate tidal point bars generate erosionally-based, generally upward fining successions which may depict lateral

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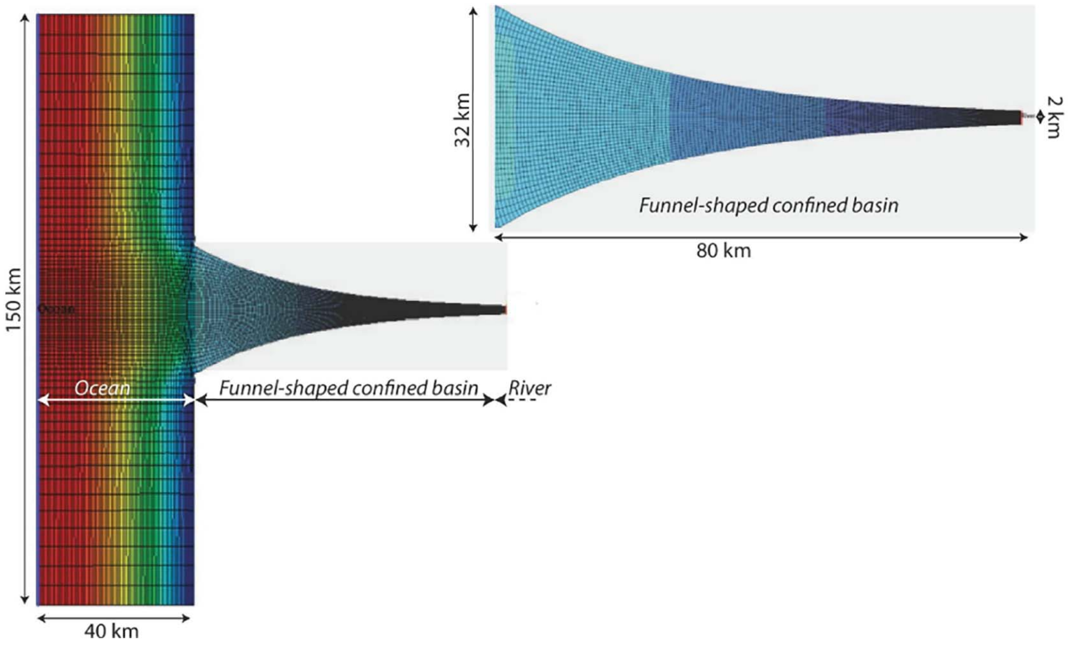

Fig. 1. Geometry and dimensions of idealized standard funnel-shaped and confined basin. Colors represent bathymetry with an initial depth of 8 m at the fluvial head. Depth increased linearly to 28 m at the mouth of the confined basin. Towards the ocean boundary, the depth increased linearly but at a higher rate than in the confined basin and reached 100 m at the ocean boundary.

accretion bedding and inclined heterolithic stratification (Fustic et al., 2012; Hubbard et al., 2011; Martinius and den Berg, 2011; Musial et al., 2012; Olariu et al., 2012). However, some tidal bars show an upward coarsening and thickening sequence with a gradational base over a silty mudstone (Mutti et al., 1985; Clark and Reinson, 1990; Feldman and Demko, 2015; Feldman et al., 2008; Shanmugam et al., 2000; Zhang and Zhang, 2008).

The controls on the formation of tidal bars, their dimensions, their distribution and their orientation remain poorly understood. For tidal environments, a limited number of physics-based predictors of bar dimensions exist. These theories predict bar length to increase with flow velocity as well as with tidal excursion length (Schramkowski et al., 2002) and with basin width (Seminara and Tubino, 2001; Toffolon and Crosato, 2007). Furthermore, empirical relations obtained by Leuven et al. (2016) from natural systems, physical models and numerical models indicate that bar length and bar width in tidal environments increase as a function of basin width.

This study addresses the effects of tidal range and the width of funnel-shaped basins on bar formation in systems with mixed fluvial and tidal currents based on idealized Delft3D process-based modelling. Tidal range is used as a proxy for tidal excursion length because the former can be specified as a boundary condition while the latter is self-formed in the numerical model. All other factors being equal, a larger tidal range results in stronger tidal currents and larger tidal excursion lengths. Waves, either wind generated or ocean swell waves, are not incorporated although research has shown that wave-dominated sedimentary features are commonly preserved within bar sequences interpreted to be of fluvial-tidal origin (Tessier, 2012). A better understanding of the formation of tidally-influenced bars will allow for better predictions of future bar behavior, which is vital to make informed decisions for future management of tidally-influenced environments (e.g. navigation and dredging, recreation, ecosystems and flood safety). In addition, process-based numerical models allow bar morphodynamics and bar deposits to be examined at the same time. This ability to explicitly tie the bar morphology to the resultant deposits is crucial to quantitatively describe and predict sand distribution and preservation of bars in tidal environments and provides quantitative information for reservoir engineering purposes.

2. Methods

This study reports on idealized Delft3D numerical model simulations of confined basins with mixed fluvial and tidal currents. The open-source code (version 5.00.10.1983) of Delft3D was used to generate hydrodynamics and morphodynamics. A detailed description of the of the hydrodynamics and numerical scheme of Delft3D can be found in Lesser et al. (2004) and van der Wegen and Roelvink (2008).

An idealized funnel-shaped basin was designed to systematically evaluate the impact of tidal range and basin width on sand distribution and bar formation in the absence of natural complexities and local features. Below, the modelling and analysis is described in three steps involving, first, the model design and chosen boundary conditions, second the quantification of tidally-influenced bar morphology and third, sensitivity analyses.

2.1. Model design of confined basin

The bar morphodynamics in Delft3D result from sediment transport, bank erosion and mass conservation in the bed. The Engelund-Hansen (1967) total load formulation was selected to calculate sediment transport rate and resultant bar deposition and bar erosion. At the upstream boundary, the amount of upstream sediment inflow was equal to the local sediment transport capacity, which kept the bed level constant. There was no sediment exchange with the initial bottom layer and also no marine sediment source was included, disqualifying these model simulations as estuaries according to the definition provided in Dalrymple et al. (1992). A uniform sediment size of 200 μm was used. Bank erosion of a dry grid cell occurred when a neighboring grid cell was eroded, where 50% of the incision of the wet cells was applied to the dry cells (van der Wegen and Roelvink, 2008). After each time step, the bed level was updated using the Exner equation (Exner, 1925) for mass conservation of sediment:

$$\frac{\delta z_b}{\delta t} = MorFac\bullet\left(\frac{\delta q_x}{\delta x} + \frac{\delta q_y}{\delta y}\right) \tag{1}$$

in which *MorFac* is an acceleration factor for bed-level change which reduces computational time. The applied morphological acceleration