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Hydro-morphological modelling of small, wave-dominated estuaries

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ABSTRACT

Small, intermittently open or closed estuaries are characteristic of the coasts of South Africa, Australia, California, Mexico and many other areas of the world. However, modelling attention has tended to focus on big estuaries that drain large catchments and serve a wide diversity of interests e.g. agriculture, urban settlement, recreation, commercial fishing. In this study, the development of a simple, parametric, system dynamics model to simulate the opening and closure of the mouths of small, wave-dominated estuaries is reported. In the model, the estuary is conceived as a basin with a specific water volume to water level relationship, connected to the sea by a channel of fixed width, but variable sill height. Changes in the form of the basin are not treated in the model, while the dynamics of the mouth channel are central to the model. The magnitude and direction of the flow through the mouth determines whether erosion or deposition of sediment occurs in the mouth channel, influencing the sill height. The model is implemented on the Great Brak Estuary in South Africa and simulations reveal that the raised low water levels in the estuary during spring tide relative to neap tide, are occasioned by the constriction of the tidal flow through the shallow mouth. Freshwater inflows to the estuary are shown to be significant in determining the behaviour of the inlet mouth, a factor often ignored in studies on tidal inlets. Further it is the balance between freshwater inflows and wave events that determines the opening or closure of the mouth of a particular estuary.

1. Introduction

Intermittently open or closed estuaries characterize the coasts of South Africa, Australia, west Africa, California, Mexico and many other areas of the world (Cooper, 2001; Taljaard et al., 2009; Roy et al., 2001; Ranasinghe et al., 1999; Ranasinghe and Pattiaratchi, 2003; Goodman, 1996; Anthony et al., 2002; Jacobs et al., 2011; McLaughlin et al., 2013; Mendoza et al., 2009). These wave-dominated estuaries tend to be small in comparison with river- or tidally-dominated systems (Dalrymple et al., 1992), and the inlet mouths are highly dynamic. Modelling attention has focused on larger estuaries, serving many powerful sectoral interests such as navigation, agriculture, urban settlement, commercial fishing, recreation and tourism. Existing 2-D and 3-D process-based models represent the circulation and sedimentation in large estuaries reliably (e.g. Lesser et al., 2004), but have difficulty in accurately simulating the complex processes involved in the closure and opening of inlet mouths. Recent research has focussed on improving the prediction of sedimentation near the inlet mouths with success (Elias, 2006; Tung et al., 2009; Duonga et al., 2015; Wijnberg et al., 2015). Indeed, an innovative approach using a process-based model in combination with measured data to generate a reliable and complete data set on the morphological development of a tidal inlet was developed in Portugal (Fortunatoa et al., 2014). Unfortunately, these applications require detailed data on sedimentation, are computationally intensive, and were primarily applied to large estuaries.

Two alternative approaches have recently been developed and applied to small Californian estuaries. These include the hydrologic and geomorphic approach of Rich and Keller (2013) in which the outflow over the beach of a bar-built estuary is successfully simulated. Here the emphasis lies on the influence of river inflow and groundwater on the volume flows and the influence of changing channel location and morphometry remains problematic. The data requirements for this approach are considerably reduced from those of process-based models. This is also an advantage of the parametric approach of Behrens et al. (2013, 2015), applied and calibrated on the Russian River. The approach used by Behrens et al.

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(2013) is similar to that adopted in this paper, as originally developed and applied to South African estuaries (Slinger, 1996). The differences lie primarily in the manner in which the (maximal) volumetric flow through the channel is determined, and the sedimentation formulae that are applied.

Another parametric modelling approach focusing on sedimentation in a channel has been followed by Eysink and Vermaas (1983) and van Rijn (2013), who developed an empirically-based prediction tool *Sedpit* often used in conjunction with a harbour siltation model to determine dredging requirements for harbours. Recently, this model was applied to simulate sedimentation at Ijmuiden in the Netherlands with success (van Leeuwen, 2015). However, the application of such a model requires information on wave-current interactions in the nearshore zone, data on longshore sediment transport, and data on different sediment fractions for accurate application. Moreover, both the computationally intensive process-based models such as Delft3D (Lesser et al., 2004) and the empirical model *Sedpit,* have difficulty with accommodating the complexity of the dynamic processes in an inlet mouth, and frequently neglect the effect of freshwater inflows.

In this study, we address these limiting conditions, by developing a simple, parametric, system dynamics model to simulate the opening and closure of the mouths of small, wave-dominated estuaries. In the model, the estuary is conceived as a basin with a specific water volume to water level relationship, connected to the sea by a channel of fixed width, but variable sill height. Changes in the form of the basin are not treated in the model, while the dynamics of the mouth channel are central to the model. As in the approaches of Eysink and Vermaas (1983), van Rijn (2013) and Behrens et al. (2013, 2015), the magnitude and direction of the flow through the mouth determines whether erosion or deposition of sediment occurs in the mouth channel. Erosion reduces the sill height, while deposition increases the sill height. We then illustrate the application of the model with a detailed case: the Great Brak Estuary in South Africa, a small, intermittently closed system typical of many estuaries along the South African coast. Data on both the opening and closure of the estuary mouth and the associated circulation in the estuary are available from a number of measurement campaigns. Whereas an Escoffier analysis (cf. Goodman, 1996) simply places the case study estuary into the unstable, or even the normally closed, category, we are able to establish that the estuary suffers an increase in the frequency and persistence of mouth closure owing to reductions in freshwater inflows.

The model further sheds light on the primary determinant of the higher low water levels during spring tide than during neap tide in small, wave-dominated estuaries, and confirms that the balance between freshwater inflows and wave events plays a significant role in mouth opening or closure.

First, the formulation of the model is described with reference to the relevant literature in section 2. Then, the choice for simulation method and a description of the case study are provided in the first part of section 3. Next, the application to the case is explained in the rest of section 3. This is followed by a discussion and conclusion in sections 4 and 5, respectively.

2. Model formulation

The estuary is conceived as a basin with a specific hypsometry, connected to the sea by a channel of fixed width, but variable sill

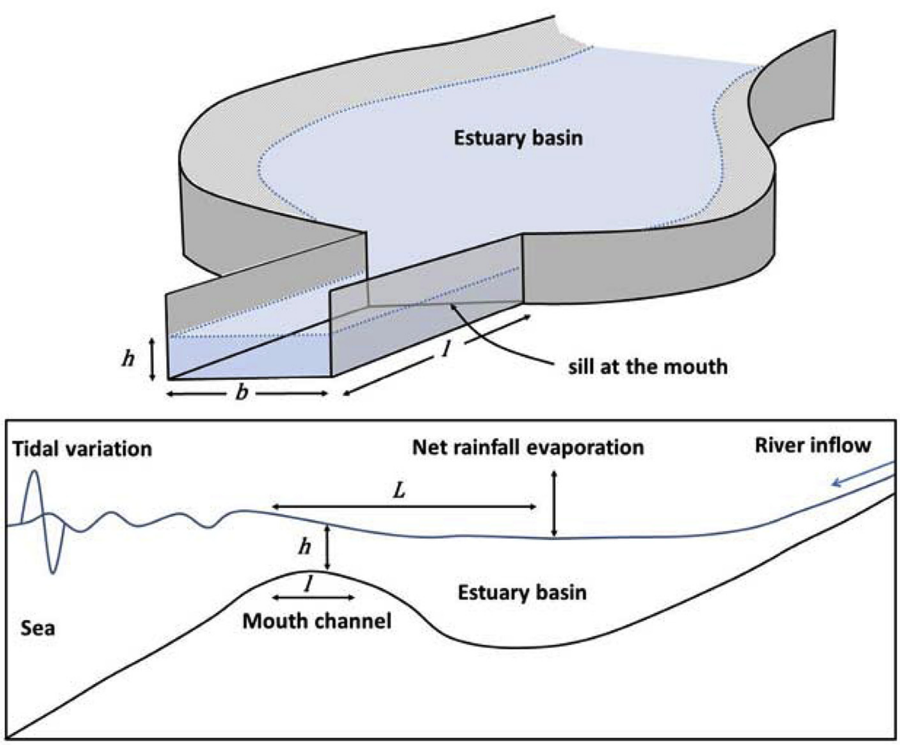

Fig. 1. The mouth is modelled as a rectangular channel connected to an estuary basin at the sill height. The dimensions of the mouth are depicted frontally above (adapted from Slinger 1996), and in side view below. The effective depth of flow (h), the width of the mouth (b), the length of the mouth (l) and the characteristic length scale (L), are indicated.