Investigating idealized modelling of estuarine sand waves

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ABSTRACT: Here we propose research to investigate the behavior of estuarine sand waves and how this is changed through human interventions in estuaries. To this end, we will develop idealized process-based models that describe the motion of water and sediment processes in estuaries. These models will account for processes that are known to play a role in similar bedforms in seas and rivers. A linear stability analysis of the flat bottom will reveal mechanisms of formation of sand waves; a nonlinear model will explain their equilibrium configuration. Scenarios will show how the bedforms behave under human interventions and climate change.

1 INTRODUCTION

Estuaries are hydrodynamically complex regions where a river meets saline water. In tidally influenced shallow (<100m depth) estuaries, sand waves can be found, which are large rhythmic bedforms. Their height and length are greatly site-dependent – with heights of about 2m in the Weser estuary, Germany (Nasner, 1974) versus 17m in the Long Island Sound (Fenster et al., 1990). Their height relative to the water depth shows more similarity amongst estuaries.

Estuarine sand waves are commonly asymmetric, with the steep slope facing the direction of migration (Bokuniewicz et al., 1977; Ludwick, 1972). In the Long Island Sound (U.S.), their migration rates are of the order of 50m per year (Bokuniewicz et al., 1977), and in the Bahía Blanca estuary (Argentina) they were measured to migrate 33m per year (Aliotta and Perillo, 1987).

Estuaries are the gateway to their hinterland, and therefore they are often used as harbor entrance (which is the case for e.g. the Rhine or Scheldt). To safely navigate in these estuaries, crests of sand waves are often dredged (Figure 1). Because sand waves migrate and regrow, costly surveillance missions need to be performed regularly to ensure navigational safety. Moreover, dredging greatly alters the morphodynamical system and the estuarine ecology (Kennish, 2002). Estuaries function as spawning, feeding and nursery sites for a variety of species (Beck et al., 2001), and are being used as entry to riverine habitats for migratory fish, such as salmon. Therefore, optimizing the efficiency of dredging activities in estuaries is essential to preserve an ecosystem that is vital for the existence of several species.

Figure 1: Animation of a dredging ship (image from B3D Design)

Furthermore, sand waves are a major influencing factor of hydrodynamics (and vice versa). The water’s movement is the leading factor in salt intrusion and flood risks, problems which humans are increasingly encountering (Ghosh Bobba, 2002; Townend and Pethick, 2002). How sand waves influence these problems exactly is not yet known. Moreover, the sand wave-hydrodynamics interaction may be altered by changing hydrodynamical properties. Three ways that this might happen are anticipated: i) the effects of climate change: sea level rise and increased discharge variability (Booij, 2005; Church and White, 2006), ii) changes in the estuaries' planform geometry through land reclamation or widening of the seaway, and iii) changes in sediment input due to sediment trapping in reservoirs.

In summary, it is essential to know more about estuarine sand waves to:

1. Perform dredging more cost-efficiently and with minimal effect to the environment;
2. Foresee potential changes in the sand wave-hydrodynamics interaction due to:
    i. Hydrodynamic effects of climate change;
    ii. Land reclamation or broadening of the seaway;
    iii. Sediment trapping upstream in man-made reservoirs

2 WHAT DO WE WANT TO UNCOVER?

The main aim of the proposed research is to provide universal explanations of estuarine sand wave formation and equilibrium configuration and to evaluate the long-term effect of human interventions on those. This is subdivided into the following questions:

Q1. What are the dominant hydrodynamic behavior and sediment transport processes in estuaries?

Q2. What are the underlying physical mechanisms of formation of sand waves in estuaries?

Q3. What are the underlying physical mechanisms of dynamic equilibrium configuration of sand waves in estuaries?

Q4. What are the effects of anthropogenic influences on estuarine sand waves, such as dredging and climate change effects?

Figure 2 shows an overview of the objectives of the proposed research, and how the methodology (laid out below) relates to these.

3 OUR APPROACH

Central to the methodology will be the development of idealized process-based models. These models will be built on knowledge acquired in the first objective, and will then be applied to execute the other objectives (Figure 2).

The models will describe the motion of water in an estuary that affects the bed by mobilizing and depositing sediment. An idealized model is convenient to reveal physical mechanisms behind sand wave formation and equilibrium configuration. Also, idealized models are computationally relatively cheap to run. This makes it easily

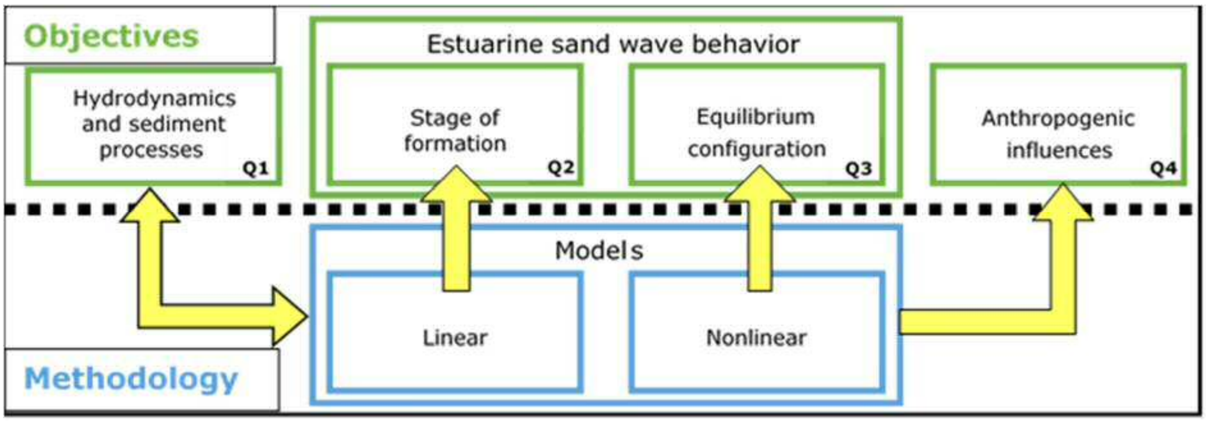

Figure 2. Visualization of the proposed research, linking the objectives to the methodologies. Hydrodynamic behaviour and sediment processes are required to develop the idealized process-based models, model tests will show whether these descriptions contain the right amount of detail. A linear stability analysis of the model will reveal mechanisms of formation; the nonlinear model will explain the equilibrium configuration of estuarine sand waves. The model parameters can then be tuned to mimic human interventions.

feasible to conduct sensitivity analyses with respect to parameters of interest (such as sediment size, river discharge statistics, and geometry) and to look at long-term morphological developments, either natural or after human interventions. Moreover, during the model formulation an appropriate turbulence model can be chosen, which will be important to correctly describe complex flow patterns such as flow separation at steep slopes. Complex process-based models are less suitable to reach the objectives of this research, because those are computationally expensive.

3.1 Hydrodynamic behavior and sediment transport processes

Knowledge of marine sand waves and river dunes will be combined and elaborated to choose descriptions of hydrodynamic behavior and sediment processes with which the following research steps can be executed (Figure 3). This requires finding descriptions which are accurate enough to later explain sand wave behavior, yet do not include processes that are irrelevant in this respect. It is expected that this investigation will be executed iteratively with the research activities lined out in the next two sections.

Central to this subproject will be finding a correct description of flow separation. Flow separation has proven to be highly relevant in river dune formation (Paarlberg et al., 2007). In tidal environments, this phenomenon is much more complex due to reversal of the flow when the tide changes. This can lead to time-varying flow separation (Lefebvre et al., 2013). This research will provide a proper formulation of flow separation either through a suitable turbulence model or in a parametrized way. Also, water motions responsible for marine sand wave growth may need to be accounted for; these too require appropriate turbulence modeling (Borsje et al., 2013; Komarova and Hulscher, 2000).

3.2 Underlying mechanisms of formation

With the descriptions found previously, a coupled model will be developed. This will be employed to perform a linear stability analysis that explains formation of estuarine sand waves. The results will be analyzed to understand how the hydrodynamics interact with the bedforms. The wavelength and orientation of the modeled sand waves will be verified by comparing these with open source data from several U.S. estuaries with different characteristics (NOAA, 1998). This data has a horizontal resolution of 30m, which is high enough to determine the wavelength and orientation of real-world estuarine sand waves.

3.3 Underlying mechanisms of dynamic equilibrium configuration

To investigate the equilibrium configuration (i.e. height and shape) of estuarine sand waves, another idealized model will be developed that includes nonlinear interactions between flow and the bed. These occur when the height of the bedforms becomes significant compared to the water depth. This is also an important factor that determines the equilibrium configuration of marine sand waves and river dunes, and hence nonlinear models have previously been developed and employed to explain these bedforms (e.g. Ji and Mendoza, 1997; van den Berg et al., 2012; Campmans et al., 2018).

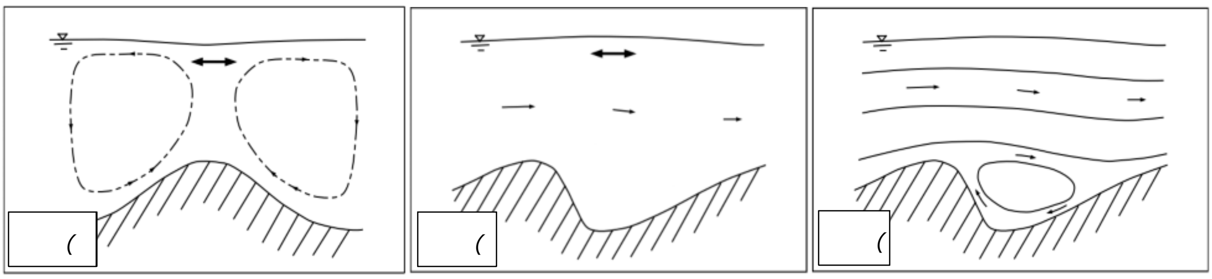

Figure 3: Schematized presentation of the shape and flow profiles (solid arrows) of a) marine sand waves, with dashed circulatory arrows showing residual flows that cause sand wave growth b) estuarine sand waves, with the question mark indicating that the underlying hydrodynamic mechanisms that govern the behavior of these bedforms are not yet understood and c) river dunes including flow separation in the trough (adapted from Hulscher and Dohmen-Janssen, 2005).

These models have the advantage that they can describe equilibrium configurations of bedforms, but at the cost of computation time.

The results of this model will be analyzed to understand how hydrodynamics interact with full-grown estuarine sand waves. The wavelength, orientation, height and shape of the modeled sand waves will be compared with the data on U.S. estuaries mentioned in previous section to establish a reasonable case for the model.

3.4 Effects of anthropogenic influences

The previously proposed models will be used by varying their parameters to describe the effects on the morphological timescale (decades) of the following human interventions: i) land reclamation and seaway widening (geometry changes), ii) reduction of riverine sediment supply (changing sediment size/input quantity), iii) dredging (changes to the bottom profile) and iv) climate change effects (sea level rise and increased discharge variability).

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