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Two-dimensional reduced-physics model to describe historic morphodynamic behaviour of an estuary inlet

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ABSTRACT

Understanding medium to long term morphodynamic change is important for sustainable coastal and estuary management. This paper analyses morphodynamic change of a complex estuary inlet which is subjected to multiple environmental drivers and proposes a reduced physics model to explain the historic medium term morphodynamic change of the inlet. The analysis shows that even though the estuary inlet undergoes multiscale morphological change, the changes that take place over a timescale of several years are more significant and important. The reduced physics model suggests that this simplified modelling approach is able to recognise principal historic morphodynamic trends in the estuary. However, the length and quality of the inlet bathymetry data set limits the applicability of the models and the quality of model outputs.

1. Introduction

Estuaries are arguably one of the most delicate morphodynamic systems in the world and many contain ports, power generation plants, valuable real estate and rich biodiversity. They constantly evolve under the pressures of natural environmental forcings and human intervention (Prumm and Iglesias, 2016). Projected climate change impacts on estuarine morphodynamic drivers such as mean sea level, river flow and waves may exacerbate these changes in future (Duong et al., 2016).

Morphological changes of coasts and estuaries take place at a range of time and space scales. Timescales of estuary morphodynamic change may vary from hours to days (short term), months to few years (medium term), decades to few hundred years (long-term) and several millennia (geological scale). In the spatial dimension, the smallest morphodynamic phenomena are the development and evolution of ripples and dunes on the sediment bed, which are categorised as microscale features. Changes to morphological features such as intertidal channels and shoals are categorised as meso-scale evolution. Evolution of large features such as tidal deltas, tidal flats and inlet channels belong to the macro-scale change. The changes to the entire estuary and the surrounding coastal areas are classified as mega-scale (De Vriend, 1996; Hibma et al., 2004).

Modelling the morphodynamic change of estuaries is a challenging task because of its complexity, encompassing a large range of time and space scales. For modelling long term morphological change geological and geomorphological evolution models are being used, and these are sometimes referred to as top-down models (Di Silvio, 1989; Stive et al., 1998; Dennis et al., 2000; Karunarathna and Reeve, 2008). These models, developed on either equilibrium concepts or behaviour oriented principles, are based on empirical rules or expert analysis of long-term morphological change. However, a lack of physical interpretation of the hydrodynamic and morphodynamic processes in these models imposes serious limitations to their application outside long term timescales. On the other hand, two- or three-dimensional hydrodynamic models combined with sediment transport and bed updating routines known as bottom-up models, (De Vriend and Ribberink, 1996; Friedrichs and Aubrey, 1996; Dronkers, 1998, Van der Wegen and Roelvink, 2012), are successfully used to model short term morphological change. They provided very good predictions of morphological evolution of estuaries at time scales up to a few months. Further, some other studies reported the application of process-based models in investigating medium to long term evolution of estuarine morphology. Van der Wegen and Roelvink (2012) investigated the impacts of sea level rise on tidal basin morphodynamics using an idealised rectangular basin using a 2D process based model. The model was able to capture some expected trends of future morphological evolution of a tidal basin with and without sea level rise. Bruneau et al. (2011) used a process-based morphodynamic modelling system to investigate the future evolution of a tidal inlet due to wave climate and sea level change. The model was able to qualitatively capture some important evolutionary features. Cayocca, 2001; Dastgheib et al., 2008; Nahon et al., 2012 and a few others also used numerous process-based models to predict

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morphodynamic evolution of tidal basins and estuaries with some success and identified the sensitivity of the results to initial conditions and the boundary conditions used for forcing models and hence the uncertainties associated with the predictions. All above studies were either limited to idealised estuaries and/or simplified forcing conditions, or have identified the limitations of using process-based models for simulating medium-long term morphodynamic evolution due to uncertainty in initial and boundary conditions.

The published literature reveals that on their own, neither top-down models nor bottom up models are adequate for forecasting medium term morphological evolution which is particularly required for sustainable management of estuaries.

The focus of this paper is to investigate morphological evolution of an estuary inlet driven by a complex regime of hydrodynamics and morphodynamics and to demonstrate the application of a two-dimensional 'reduced-physics' morphodynamic model to describe the historic morphodynamic change. Section 2 of the paper gives a description of the modelling approach. Section 3 introduces the selected test study site. Section 4 presents the analysis of the historic morphological evolution of the estuary using a set of bathymetry surveys spanning across two decades. Section 5 presents and discusses the application of the proposed modelling approach to the study site in order to investigate the model's ability of capturing the morphodynamic process of the Deben inlet. Section 6 summarises the main findings of the paper.

2. Modelling approach

Our focus here is on medium term (meso-scale) morphodynamic behaviour of estuarine systems that are critical to sustainable estuary management and flood defense. As a result, we adopt a reduced-physics modelling approach, which will be able to capture medium-large spatial scale and medium-long term morphodynamic variability. In this model, morphodynamic change is considered to be driven by two simplified processes: diffusive and non-diffusive sediment transport. The equation that governs the time evolution of the bathymetry of the estuary system is thus taken as a form of two-dimensional diffusion equation (Karunarathna et al., 2008; Reeve and Karunarathna, 2011):

$$\frac{\partial h(x,y,t)}{\partial t} = K_x(x)\frac{\partial^2 h}{\partial x^2} + K_y(y)\frac{\partial^2 h}{\partial y^2} + S(x,y,t) \tag{1}$$

in which $h(x,y,t)$ is bottom bathymetry of the estuary relative to a reference water level, $K_x(x)$ and $K_y(y)$ are the sediment diffusion coefficients in the x and y coordinate directions, respectively. The diffusion process in the equation will act to smooth sharp features of the bathymetry. $S(x,y,t)$ is a function that varies both in time and space which describes the aggregate effect of all non-diffusive processes on morphodynamic change. x and y are taken as cross-axis and long-axis directions.

Here we assume that both $h(x,y,t)$ and $S(x,y,t)$ have well defined spatial Fourier transforms at each time t, and that $S = Df$ for some arbitrary function f. D is the Laplacian operator. That is:

$$D(f) = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2}$$

If x and y are rescaled in order to make the coefficients of the spatial derivatives are equal then, the rescaled x and y are given by

$$\hat{x} = \frac{x}{K_x(x)} \text{ and } \hat{y} = \frac{y}{K_y(y)}$$

Then, h and S in terms of rescaled x and y are given by

$$\hat{h}(\hat{x},\hat{y},t) = h(x,y,t)$$

$$\hat{S}(\hat{x},\hat{y},t) = S(x,y,t)$$

Then, Eq. (1) turns to:

$$\frac{\partial \hat{h}}{\partial t} = \frac{\partial^2 \hat{h}}{\partial \hat{x}^2} + \frac{\partial^2 \hat{h}}{\partial \hat{y}^2} + \hat{S}(\hat{x},\hat{y},t) \tag{2}$$

Dropping ^ for convenience, the governing equation may then be written as:

$$\frac{\partial h}{\partial t} = \frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + S(x,y,t) \tag{3}$$

or in operator (D) notation:

$$h_t = Dh + S \tag{4}$$

where $h_t = \frac{\partial h}{\partial t}$

The solution of Eq. (4) gives morphodynamic change of the estuary in time. However, both the diffusion coefficient K (through the operator D) and the source function S are site-specific unknowns of the model that should be known a priori, to solve Eq. (4).

In order to find the two unknowns K and D, Eq. (4) can be solved in an inverse fashion. Here, we can use a sequence of historic bathymetries, that is, $h(x,y,t)$ at a set of discrete times to solve Eq. (4) to determine the diffusion coefficients and the source function. However, the solution of Eq. (4) to find both unknowns simultaneously is difficult and is an unstable inverse mathematical problem. Therefore, here we will use a simplified approach described below:

The approximate inverse solution of Eq. (4) to determine the source function takes the form (Karunarathna et al., 2008)

$$\begin{aligned} &S\left(x_i, y_i, t_m + \frac{T}{2}\right) \\ &= \frac{1}{T}\left[exp\left(-\frac{TD}{2}\right) h(x_i, y_i, t_m + T) - exp\left(-\frac{TD}{2}\right) h(x_i, y_i, t_m) \right] \end{aligned} \tag{5}$$

in which, $h(x_\mathrm{i},y_\mathrm{i},t_\mathrm{m})$ and $h(x_\mathrm{i},y_\mathrm{i},t_\mathrm{m} + T)$ are the estuary bathymetry at a location $(x_\mathrm{i}, y_\mathrm{i})$ at two consecutive time steps t_m and $t_m + T$ respectively. T is the time interval between two time steps. The diffusion coefficient is treated as a constant. If a time series of historic bathymetries $h(x_\mathrm{i},y_\mathrm{i},t_\mathrm{m})$ is available they can be used in pairs in Eq. (5) to determine a discrete time series of source functions. A detailed description of the inverse mathematical technique used to derive Eq. (5) is given in Spivack and Reeve et al. (2001) who assumed that the time variation of the source function within one time step is small.

If the source functions determined by Eq. (5) using historic bathymetries are sufficiently coherent in structure, they may form the basis for estimating suitable diffusion coefficients and source functions for solving forward Eq. (4) to make predictions of future morphological changes.

3. Test study site

The modelling approach is applied to the Deben estuary inlet and it's highly morphodynamically active ebb tidal delta. Located on the coast of Suffolk, eastern England, UK (Fig. 1), the Deben estuary occupies a northwest-southeast trending valley that extends from the town of Woodbridge to the sea just north of Felixstowe (Burningham and French, 2006). The Deben estuary is an area of outstanding ecological importance resulting in international (European) and national designations including RAMSAR, Special Protection Area (SPA), Site of Special Scientific Interest (SSSI) and is within the Suffolk Area of Outstanding Natural Beauty - (River Deben Association, 2014). The estuary is narrow and sheltered in its configuration, and receives minimal fresh water

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