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MORPHODYNAMIC EVOLUTION OF AN ESTUARY INLET

Harshinie Karunarathna[1], Jose Horrillo-Caraballo[2] Helene Burningham[3] and Dominic E. Reeve[4]

Abstract

This paper presents the application of a morphodynamic model based on 2D reduced-physics principles to investigate morphology change of a complex estuary inlet system in the United Kingdom. The model combines a simple governing equation with a set of measured bathymetry data in order to model morphology change. The modelling method suggests that this simplified approach is able to recognise principal medium term morphodynamic trends in the estuary. However, the length and quality of the estuary bathymetry data set limits the applicability of the model to inter-annual scale.

Key words: reduced-physics models, diffusion coefficient, Deben estuary, morphodynamics

1. Introduction

Estuary morphology change is a complex process that spans over a range of time and space scales. Timescales of change may vary from short term (hours to days), medium term (months to a few years), long term (decades to a few hundred years) and geological terms (several millennia). In the spatial dimension, the micro-scale morphodynamic phenomena are the development and evolution of ripples and dunes on the sediment bed. Changes to intertidal mud flats, channels and shoals are categorised as meso-scale evolution. Macro scale changes take place in tidal deltas, tidal flats and inlet channels. The changes to the entire estuary and the surrounding coastal areas are classified as mega-scale (De Vriend, 1996; Hibma et al., 2004).

Modelling and understanding 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, 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, (De Vriend and Ribberink, 1996; Friedrichs and Aubrey, 1996; Dronkers, 1998), are successfully used to model short term morphological change. Even though there have been attempts to use process-based models to simulate medium-long term morphology change (van de Wegen et. Al., 2011; Cayoca, 2001; Nahon et al., 2012), uncertainty in boundary conditions, lack of physical understanding of complex hydrodynamic-morphodynamic interactions and excessive computing requirements limit their success beyond the short term. On their own, neither of the above modelling approaches is adequate for forecasting medium term morphological evolution which is particularly required for sustainable management of estuaries.

[1]Zienkiewicz Centre for Computational Engineering, Swansea University, Bay Campus, Fabian Way, Swansea, SA1 8EN, UK, h.u.karunarathna@swansea.ac.uk
[2] Zienkiewicz Centre for Computational Engineering, Swansea University, Bay Campus, Fabian Way, Swansea, SA1 8EN, UK, j.m.horrillo-caraballo@swansea.ac.uk
[3] Coastal and Estuarine Research Unit, Department of Geography, University College London, Gower Street, London, WC1E 6BT, UK
[4] Zienkiewicz Centre for Computational Engineering, Swansea University, Bay Campus, Fabian Way, Swansea, SA1 8EN, UK, d.e.reeve@swansea.ac.uk

With that, alternative modelling techniques have been developed in the recent years. Among them, hybrid models that combine reduced-physics principles and either historic data or equilibrium approaches have proven to be successful in modelling medium term morhodynamic evolution of estuaries, which is useful for estuary planners and managers (Karunarathna et. al., 2008).

This paper investigates and discusses morphodynamic evolution of an estuary inlet driven by a complex regime of hydrodynamics using a two-dimensional 'reduced-physics' morphodynamic model. Section 2 of the paper describes the modelling approach. Section 3 introduces the selected test study site, i.e. the Deben estuary in the UK. Section 4 presents and discusses the application of the proposed modelling approach to the study site in order to investigate the model's ability to capture the morphodynamic evolution of the Deben estuary inlet. Section 6 concludes the paper.

2. Study Site

Deben estuary, located on the coast of Suffolk, eastern England, UK (Figure 1) is used in this study as the test site. The 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 Eestuary 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 meso-tidal and the mean spring tidal range varies from 3.2 m at Felixstowe Ferry to 3.6 m at Woodbridge (Hydrographic Office, 2000). The tidal reach of the Deben estuary is approximately 18 km, and the mean spring tidal prism is approximately $17x10^6$ m^3 (Burningham and French, 2006) with peak spring tidal discharge at the inlet of 1700 m^3/s. Based on measurements taken at a location 2 km upstream of the tidal limit, the mean flow of the River Deben (from 1964 to 2014) is around 0.8 m^3/s (NRFA, 2014). The tidal estuary is narrow, constrained by embankments constructed over the last 500 years to hold a single low tide channel flanked by narrow tidal flats and saltmarsh.

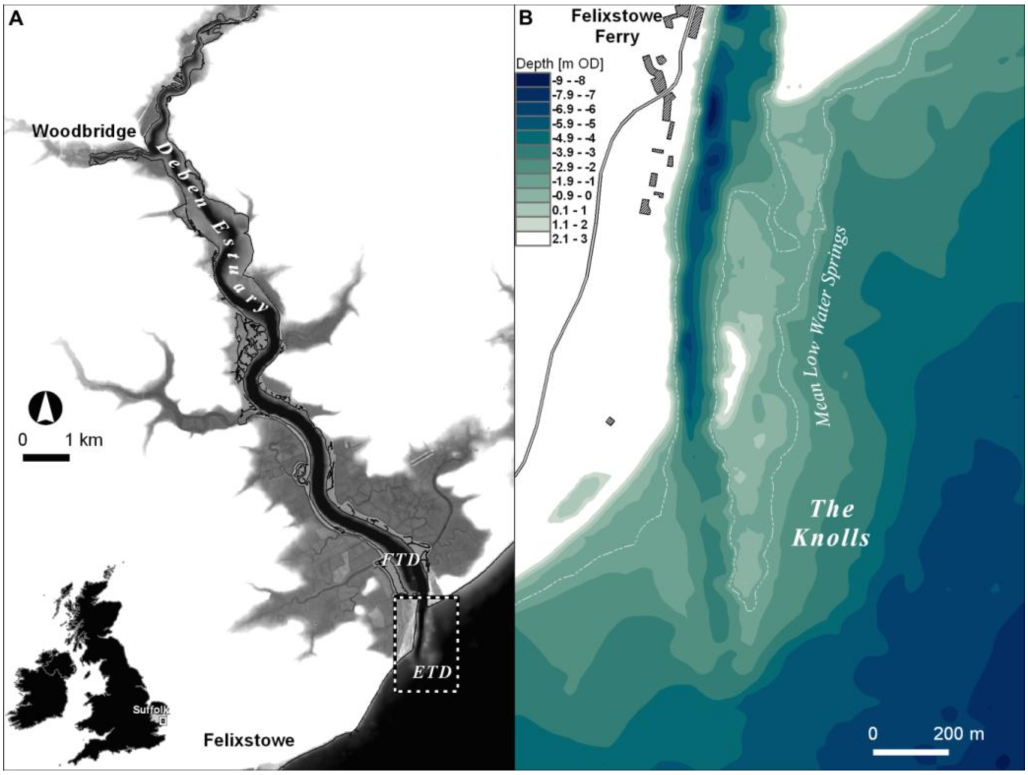

Figure 1. A) Location of the Deben Estuary and River Deben and B) detailed morphology of the Deben inlet and ebb-tidal delta in 2013 (Karunarathna et al., 2016)

The estuary is tide-dominated. However, the inlet is subjected to a significant amount of littoral sediment transport driven by wave activities. The ebb tidal delta is the most morphologically dynamic part of the Deben estuary. Waves from the northeast have long been associated with the net southerly littoral drift pattern in the area (HR Wallingford, 2002), although recent work has demonstrated the importance of the southerly climate in driving reversals in alongshore sediment transport direction (French and Burningham, 2015). In the estuary inlet there is limited wave propagation, but locally generated fetch-limited wind waves can be important across estuarine tidal flats and saltmarshes.

The inlet of the estuary undergoes significant morphodynamic changes as a result of the complex tidal and littoral processes. Historic bathymetry measurements carried over a period longer than two decades reveal a morphodynamic transformation from year to year whereby the ebb tidal delta, incorporating tidal channel and intertidal shoals, shift progressively southward (Burningham and French, 2006) as can be seen in Figure 2. Also, the ebb shoal has been found to go through a cyclic morphodynamic evolution process where alternate accretion and erosion across the shoal, particularly in the dynamic ebb jet region, had taken place. As a result, the ebb shoal becomes fragmented and reformed from time to time. Significant changes to the inlet channel have also been observed simultaneously. Sediment exchange between the ebb delta and the down-drift shoreline is also evident.

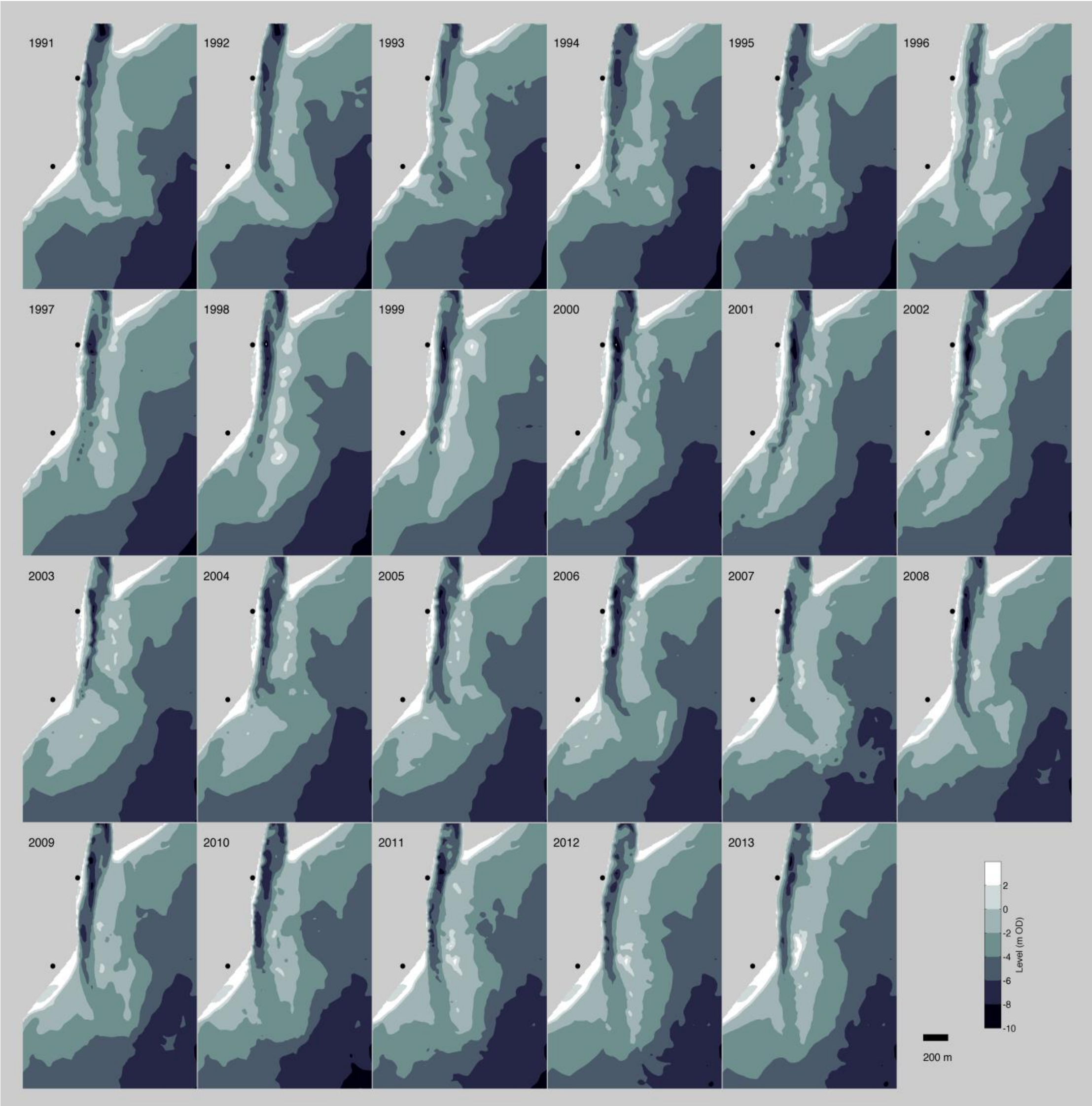

Figure 2. Annual changes in the Deben ebb-tidal delta morphology, 1991 to 2013 (Karunarathna et al., 2016)

3. Morphodynamic Model

We will take a reduced-physics modelling approach (Karunarathna et al., 2008; Reeve and Karunarathna, 2011) to investigate morphodynamic change of Deben estuary at meso-scale. 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

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

In Eq. (1), x and y are taken as cross-shore and longshore directions. $h(x,y,t)$ 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. $S(x,y,t)$ is a source function which describes the effects of all non-diffusive processes on morphodynamic change. It is assumed 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:

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

We then re-scale x and y in order to make the coefficients of the spatial derivatives are equal:

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

which gives h and S in terms of rescaled x and y to be $\hat{h}(\hat{x},\hat{y},t) = h(x,y,t)$ and $\hat{S}(\hat{x},\hat{y},t) = S(x,y,t)$respectively.

The Eq. (1) can then be rewritten, after dropping ^ for convenience, as

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

or in operator (D) notation as

$$h_t = Dh + S \tag{3}$$

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

The solution of Eq. (3) describes morphodynamic change of the estuary. However, both the diffusion coefficient K and the source function S are site-specific unknowns of the model that should be known a priori, to solve Eq. (3). In order to find the two unknowns, Eq. (3) can be inversely solved using historic estuary bathymetry data. However, the solution of Eq. (3) to find both K and S simultaneously is difficult. Therefore, here we will use a simplified approach where a constant diffusion coefficient is assumed *a priori*.

Then, the approximate inverse solution of Eq. (3) to determine the source function takes the form

$$S\left(x_i, y_i, t_m + \frac{T}{2}\right) = \frac{1}{T}\left[exp\left(-\frac{TD}{2}\right) h(x_i, y_i, t_m + T) - exp\left(-\frac{TD}{2}\right) h(x_i, y_i, t_m)\right] \quad (4)$$

in which, $h(x_i,y_i,t_m)$ and $h(x_i,y_i,t_m+T)$ are the estuary bathymetry at a location (x_i, y_i) at two consecutive time steps t_m and t_m+T respectively. T is the time interval between two time steps. If a time series of historic bathymetries $h(x_i,y_i,t_m)$ is available they can be used in pairs in Eq. (4) to determine a discrete time series of source functions. If the source functions determined by Eq. (4) have sufficiently coherent structure, they may form the basis for estimating suitable source functions for solving forward Equation (4) to make predictions of future morphological changes.

4. Application of the Model and Discussion

A morphodynamic model for the Deben estuary inlet is constructed using the modelling approach described in Section 3. The rich historic bathymetry dataset on the estuary inlet allows construction of a discrete time series of source functions for the estuary inlet. The aim of this work is to investigate the potential of the model to describe the morphodynamic process of the Deben estuary inlet.

The modelling process begins with the selection of a suitable sediment diffusion coefficient. Once a sediment diffusion coefficient is selected, a discrete time series of $S(x,y,t)$ can be obtained following the method explained in Section 3, using the time series of bathymetries $h(x_i,y_i,t_m)$ of the estuary inlet is available, Therefore, the selection of a suitable sediment diffusion coefficient is important to the success of the modelling approach. Here we turned to existing literature on sediment diffusion coefficients in similar settings. Masselink (1998) found that large scale sediment diffusion coefficients for micro-tidal sandy beach in Australia is in the order of 10^5 and 10^6 m^2/yr. Baugh (2004) and Baugh and Manning (2007) used a horizontal diffusion coefficient of the order 10^7 m^2/yr for morphodynamic modelling of the Thames Estuary, UK, which mostly consists of sand and mud. For offshore sand banks, Huthnance (1982), Flather (1984) suggested sediment diffusion coefficients of the order of 10^5 m^2/yr.

Considering sediment characteristics in the Deben estuary which primarily consists of sand-gravel deposits (Burningham and French, 2006), the sediment diffusion coefficient of $5\text{x}10^5$ m^2/yr was selected for this study which falls within the bounds found by other investigators in the past for other morphodynamic settings with similar hydrodynamic and sediment environments. A sensitivity analysis carried out on the value of sediment diffusion showed that +/- 10% variation of sediment diffusion coefficient did not have a significant impact on the source function construction.

The next step of the modelling approach is to determine the time-varying source function. In this, the measured historic Deben estuary inlet bathymetry data set (Figure 1) is used in consecutive pairs, with the sediment diffusion coefficient selected above, to solve Eq. 4 to determine a discrete time series of source function. Each consecutive pair of annual bathymetries from 1991 to 2013 (22 pairs altogether) gives twenty one discrete values for source function for every year. It is worth noting here that the source function $S(x,y,t)$ represents the contribution of all non-diffusive processes such as waves, tidal currents, fluvial flows and any anthropogenic controls to morphodynamic change of Deben inlet. As a result, the source function represents a significant proportion of morphology change.

It should be noted that freshwater input from rivers to the Deben Estuary is significantly smaller than the tidal prism. It is also known that the estuary is tide-dominated and that the inlet of the estuary is subjected to significant littoral transport processes. Based on this evidence, it is fair to hypothesise that the source function predominantly represents morphological change driven by tidal and littoral processes.

The sequence of source functions determined from bathymetry data are shown in Figure 3. Alternate positive and negative values of the source functions correspond to erosion/accretion of the estuary. In the source function maps, the structure of large scale morphodynamic features of the estuary such as the inlet channel, ebb shoal/delta and intertidal flats and down-drift coast are clearly visible. For example, significant channel infilling in 1995-1996 and fragmentation of the ebb delta in 2003-2004 (Burningham and French, 2006) are visible in the source functions of 1995-1996 and 2003-2004 respectively. Some smaller scale morphological structures such as movement of sand flats at and around the inlet are also apparent. The source function which captures the primary morphological features of the inlet signifies the non-diffusive contribution to morphodynamic process of the Deben Estuary inlet.

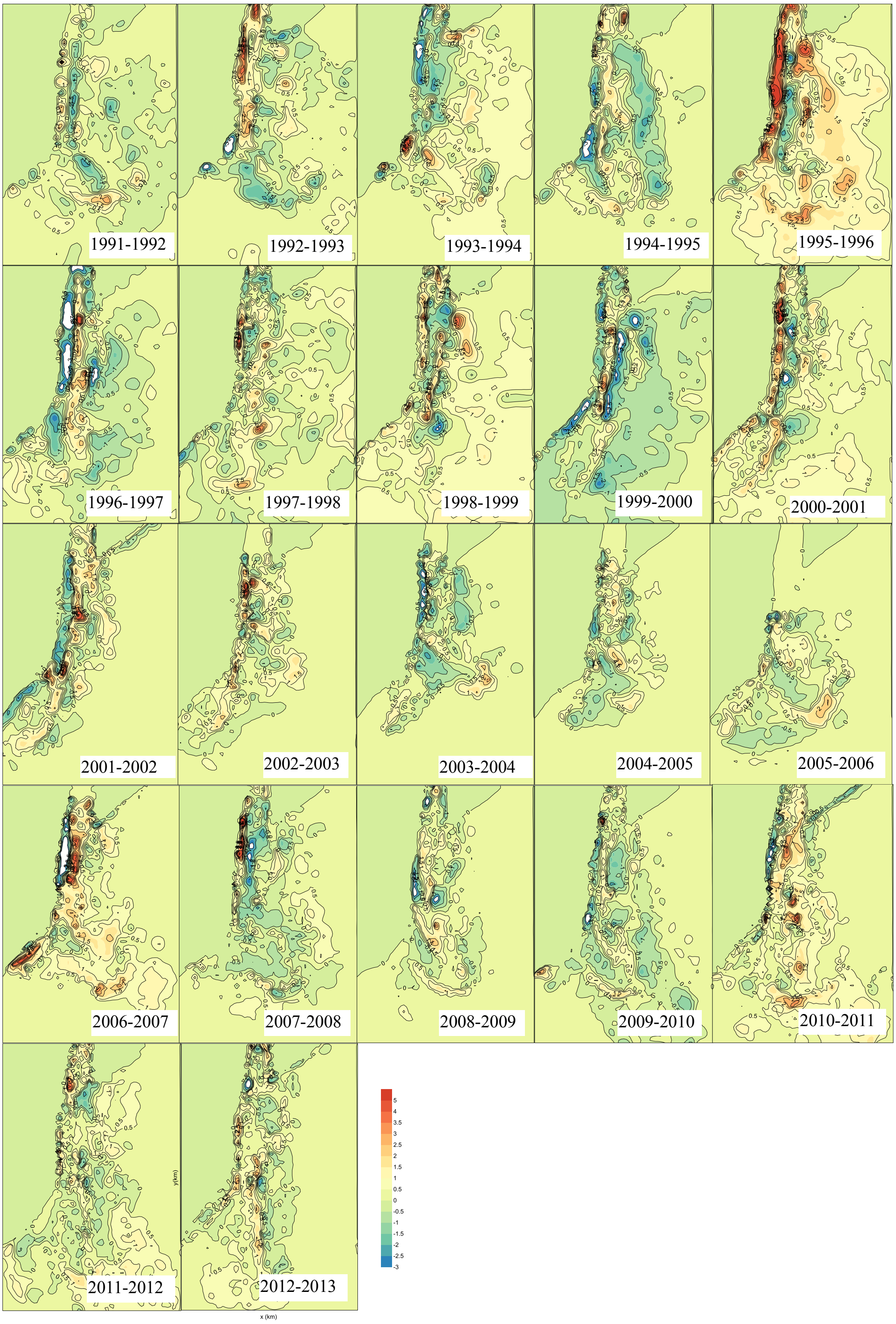

Figure 3. Discrete time series of annual source function from 1991 to 2013. The colour bar indicates m/year. Vertical and horizontal directions represent the long axis and cross axis directions of the estuary

As the discrete sequence of annual source functions capture significant morphodynamic structure in time, the modelling approach used here will be a useful tool to describe morphological changes of the Deben estuary inlet. To determine whether the source functions contained coherent patterns we used Empirical Orthogonal Function (EOF) analysis. EOF analysis, which maps sequences of data into a set of shape functions in the space and time domain, is widely used in analysing coastal morphological. These shape functions are termed eigenfunctions and their form is determined from the data itself rather than being specified *a priori*. When applied to coastal and estuarine bathymetries, numerous morphological features and their evolution in time can be inferred via EOF analysis (Pruszak 1993; Larson et al. 2003; Kroon et al. 2008). Even though EOF analysis lacks any physically deterministic derivations, the technique has proved to be successful in identifying patterns in coastal and estuarine data (Winant et al. 1975; Wijnberg and Terwindt 1995; Reeve et al. 2001, 2008; Kroon et al. 2008). As the source functions derived for the Deben Estuary inlet provide morphodynamic structures of the inlet, EOF will be a useful tool to determine any spatial and temporal patterns in it.

The EOF analysis of the source functions shows that twenty two eigenfunctions are needed to contain 100% data variance. However, the first eight eigenfunctions collectively contains 72% of the data variance and the remaining functions collected only a few percentage of the variance in each function. Table 1 gives the % data variance around the mean value represented by the first eight eigenfunctions.

Table 1 - % data variance of eigenfunctions of the source term of Deben estuary inlet

Eigenfuction	% Data variance	Cumulative % data variance
2	29	29
3	13	42
4	8.5	50.5
5	6.5	57
6	6.0	63
7	5.4	68.4
8	3.7	72.1

It should be noted that in this case more EOFs are required to explain the variance in the source function than often needed (usually 4-6 as found in literature), which reflects the complex structure of the variations captured by the source functions. The first eight spatial eigenfunctions are shown in Figure 4.

The first spatial eigenfunction (EOF1) reflects the mean value of the source function. Morphodynamic activities in the inlet channel, ebb shoal and the west bank tidal flats are the primary features captured in EOF1. The second spatial eigenfunction (EOF2), which contains 29% of data variance around the mean, compliments all features captured in EOF1, including the inlet channel, ebb shoal and west bank intertidal flat but show opposite trends to that of EOF1. Therefore, EOF1 and EOF2 collectively capture alternate erosion and accretion of the channel and ebb shoal due to non-diffusive natural morphodynamic forcing. The lower ebb shoal and ebb jet area and downdrift coast of the third spatial eigenfunction (EOF3), which captures 13% of variance around the mean, shows contrasting trends to that in EOF1 but upper part of the inlet channel featured in EOF3 complements EOF1. The features of inlet channel and ebb shoal/delta seen in the fourth spatial eigenfunction (EOF4- variance is 8.5% around the mean) is significantly similar and mostly complements the features captured in EOF1.The next two spatial eigenfunctions (EOF5 and EOF6) also capture the ebb delta and the inlet channel and a similar structure can be seen in both of them however, it should be noted that EOF5 and EOF6 collectively capture only 12.5% of data variance around the mean. The subsequent functions do not show any particular structure and only show small scale fragmented localised features. The most notable feature in EOF7 is the up-drift area of the ebb shoal.

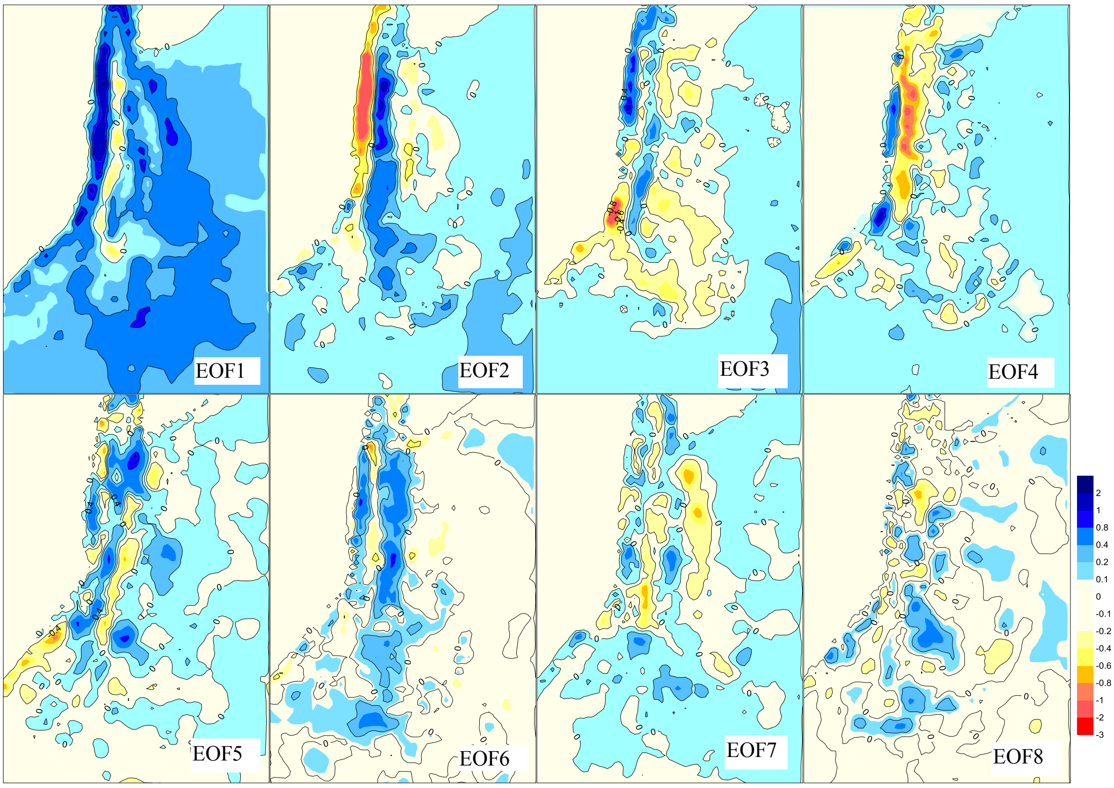

Figure. 4. First eight spatial Empirical Orthogonal Functions of the source functions shown in Figure 4

Alternate channel erosion/infilling, erosion/accretion of ebb delta and distal shoal are the primary features of morphodynamic variability in the Deben inlet (Fig. 2). The coherent spatial patterns shown in spatial EOFs of the source function, which are similar to historic morphological changes observed in the Deben inlet, assure that the source functions have been able to successfully capture the historic variability of the inlet.

The spatial variability of the source functions captured by spatial eigenfunctions cannot be fully explained without examining the corresponding temporal eigenfunctions, which describes their time variation. Figure 5 shows first eight temporal eigenfunctions corresponding spatial eigenfunctions shown in Figure 4. The linear trend lines and R^2 values are shown in the figures for clarity.

The first temporal eigenfunction (TEOF1) is nearly a constant as it corresponds to the mean value. Subsequent functions give variation around the mean. The second temporal eigenfunction (TEOF2) which captures inlet channel and ebb shoal/delta shows some cyclic variability, indicating alternate erosion/accretion of channel/ebb delta as a result of sediment exchange due to non-diffusive sediment dynamics but, the intensity of the variability has been diminished after 2003. The historic records reveals that ebb shoal breaching has taken place in 2002-2003 period. The variability of the third temporal eigenfunctions, (TEOF3), which captures opposite trends to that of TEOF2, also shows cycles which has comparatively higher magnitudes after 2004 than earlier years. This indicates sediment exchange between ebb delta, west bank and more offshore areas, (spatial EOF3), after 2004. Also, TEOF3 shows a noticeable upward trend over the entire 23 year period between 1991 and 2014, which may be indication of overall long term sediment accumulation in the distal shoal and/or down-drift shoreline area. Temporal variability of the forth eigenfunction (TEOF4) is significant between 1992 and 1997 only. The fifth and sixth temporal eigenfunctions, (TEOF5 and TEOF6), also show some cyclic variability as they also captures the ebb delta and the inlet channel but it should be noted that they collectively captures 12.5% of data variance only. The remaining functions did not show any significant spatial structure and it is therefore difficult to interpret their temporal variability.

Further analysis of the results shows that even though the first eight TEOFs have some cyclic variability on their own, they did not show any significant cohesion between them. This observation leads us to believe that temporal variability of different morphological elements of the inlet as a result of non-diffusive processes is random and largely uncorrelated, which may be attributed to frequent and complex variability of the littoral process and contributions from numerous other processes (tides, river flow) to non-diffusive morphodynamic change at varying degrees.

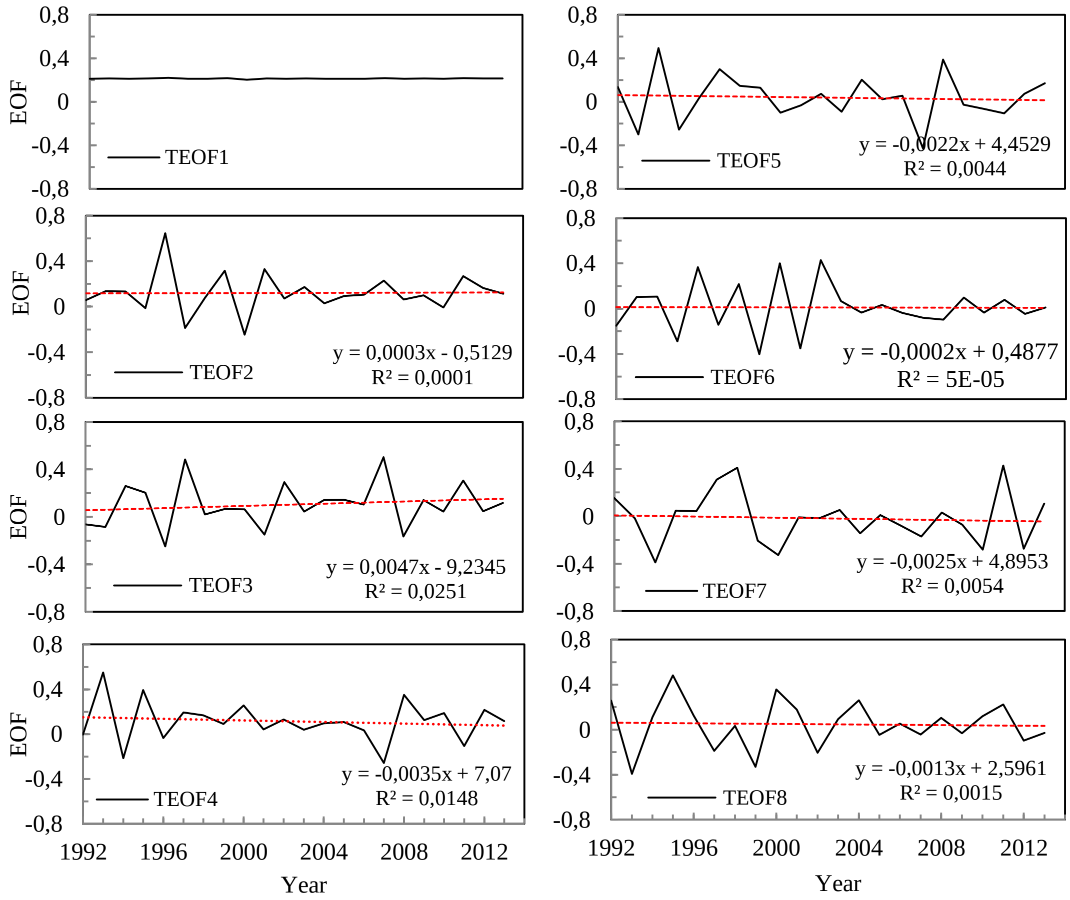

Figure 5. The first eight temporal Orthogonal Eigenfunctions of the source function shown in Figure 3. Black lines give Temporal EOFs and red lines give linear trend lines.

The EOF analysis of the Deben source function reveals that while the inlet as a whole undergoes clear meso-scale morphological changes, the source function (non-diffusive processes) captures short term (inter-annual scale) changes of primary morphological features. Therefore, it is clear that inter- annual variability of the source function, averaged over a suitable timescale would be appropriate to model the morphodynamics of the Deben inlet.

4. Conclusions

This paper presents the results of the application of a 2D reduced physics model to explain historic morphodynamic behaviour of the Deben estuary inlet in the UK. The model describes the evolution of seabed bathymetry and reduces the complex and multi-faceted estuary morphodynamic process into ‘diffusive’ and ‘non-diffusive’ components. Following points are noted from this study:

(i) Mapping the historical morphological changes onto a simple reduced physics model has demonstrated the importance of non-diffusive processes to the morphological evolution of Deben inlet. The source function show some complex and uncorrelated trends of variability of different inlet features which may be resulting from the combined effect of complex littoral process with other environmental forcings such as tidal variation and river inputs. However, the source function captured primary morphodynamic features of the inlet and identified inter-annual scale morphodynamic change that governs its evolution but does not directly recognise meso-scale variability observed in the measured data.

(2) Although the focus of this study is to investigate the validity of the reduced physics model in describing the historic morphodynamic characteristics of the Deben Estuary inlet, the method has potential to forecast future morphologies of the inlet by suitable parameterisation and extrapolation of the source term. The eigenfunctions may be used for this purpose. EOFs of the source function, averaged over a suitable timescale and extrapolated into the future, would be appropriate to model future changes of the Deben inlet.

(3) Limitations of the modelling approach should be noted. The method required substantial bathymetry data as the spatial and temporal resolution of the results depend on the quality, frequency and length of the dataset. Also, in the event of future morphodynamic forecasts, past and current environmental or anthropogenic forcings that govern the morphodynamic process should remain largely unchanged.

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