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

Harshinie Karunarathna [a,*], Jose Horrillo-Caraballo [a], Helene Burningham [b], Shunqi Pan [c], Dominic E. Reeve [a]

[a] Energy and the Environment Research Group, Zienkiewitcz Centre for Computational Engineering, College of Engineering, Swansea University, Fabian Way, Swansea, SA1 8EN, UK
[b] Coastal & Estuarine Research Unit, Department of Geography, University College London, Gower Street, London, WC1E 6BT, UK
[c] School of Engineering, Cardiff University, Queen's Buildings, The Parade, Cardiff CF24 3AA, UK

A B S T R A C T

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.
© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

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 micro-scale 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

---

* Corresponding author.
  E-mail address: h.u.karunarathna@swansea.c.uk (H. Karunarathna).

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)

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

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. The diffusion coefficient is treated as a constant. If a time series of historic bathymetries $h(x_i, y_i, t_m)$ 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
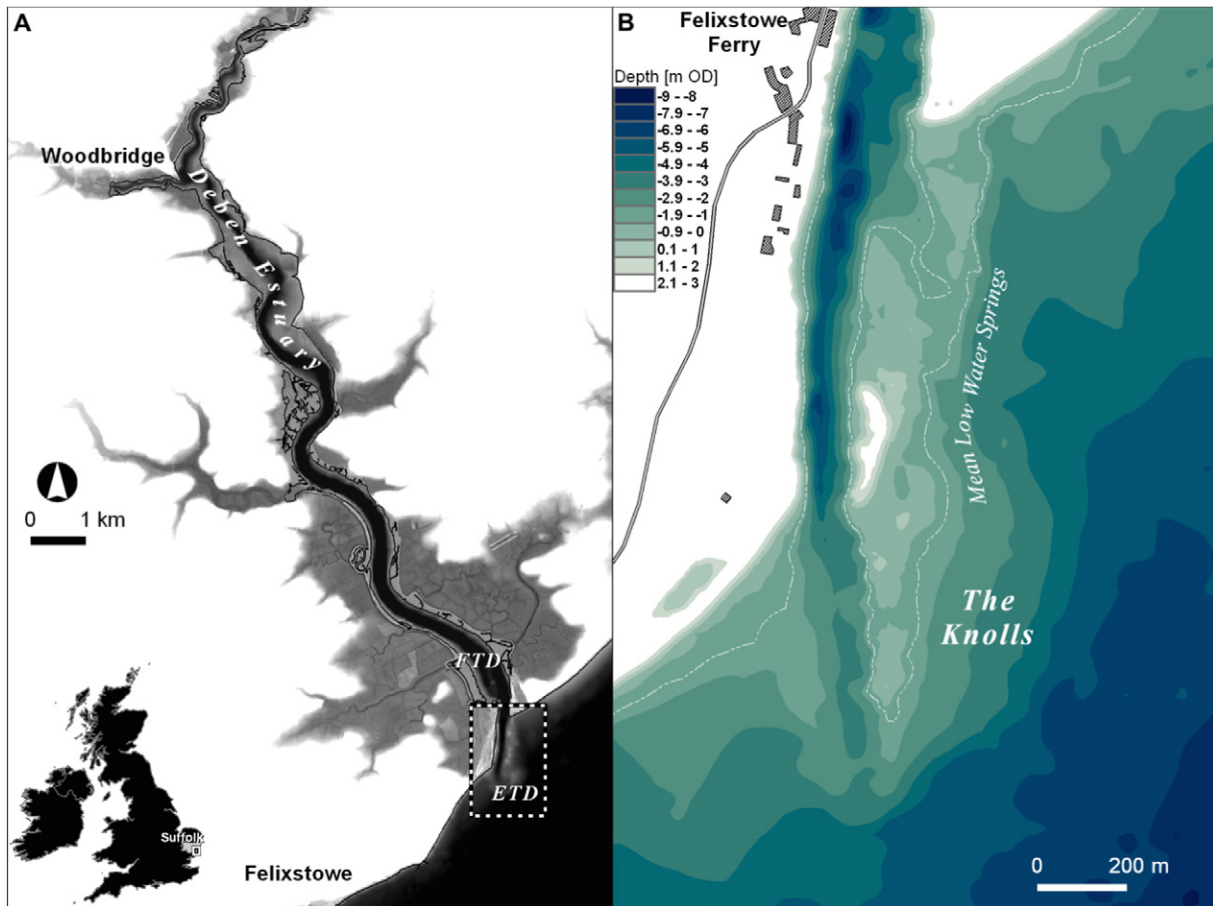
Fig. 1. A) Location of the Deben estuary, Suffolk, southeast UK highlighting the large area of reclaimed land and the position of the ebb- and flood-tidal deltas (ETD and FTD respectively); and B) detailed morphology of the Deben inlet and ebb-tidal delta in 2013.

inputs. Offshore of the mouth, the seabed comprises a mixture of mud, fine sand and broken shell. The main characteristics of the shoreface bathymetry are the influence of the ridges of London Clay and sub-marine river channels, which are now buried and filled with fine sediments (HR Wallingford, 2002).

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 length in the Deben estuary is approximately 18 km, and has a mean spring tidal prism of around 17×10^6 m^3 (Burningham and French, 2006) with peak spring tidal discharge at the inlet of 1700 m^3/s (Royal Haskoning, 2008). Based on measurements taken at Naunton Hall, 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 meaning that the estuary is well-mixed (NRFA, 2014). The tidal estuary is narrow, constrained by embankments emplaced over the last 500 years, holds a single low tide channel flanked by narrow tidal flats and saltmarsh. The estuary is tide-dominated and muddy (Fig. 1A) however, the inlet is subjected to a significant amount of littoral sediment transport driven by wave activities. Close to the inlet, the Deben estuary broadens a little and the low tide channel divides around a flood tidal delta before passing through a narrow inlet (c. 180 m wide) and entering the North Sea through the ebb tidal delta (The Knolls). Bathymetry within and between the channels around the flood tidal delta implies flood dominance to the northeast and ebb dominance to the southwest of Horse Sand. The flood tidal delta is occasionally exposed at low tide, but rather more intertidal structure is evident across the ebb tidal delta, which is also occasionally supra-tidal (Fig. 1B). The ebb tidal delta is the most morphologically dynamic part of the Deben estuary, and undergoes a slow process of inlet bypassing through ebb tidal delta breaching (Burningham and French, 2006).

The southern North Sea wave climate is directionally bimodal - 46% from the northwest (0–90°N median wave height of 0.87 m) and 48% from the south (90–270°N median wave height 1.04 m) - measured at West Gabbard 2010–2013 (French and Burningham, 2015). 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 flat and saltmarsh.

Land reclamation, of more than 2000 ha of intertidal mudflats and saltmarshes (approximately 25% of the tidal area), completed during the early 19th century has considerably changed the Deben estuary (Beardall et al., 1991). Through these modifications there are now more than 25 km of defenses around the estuary protecting 16 compartments (which once were estuary floodplains) from tidal inundation (more than 1400 ha). According to the Suffolk estuarine strategies review (Posford Duvivier, 1999) many of the defenses are in a poor state and realignment to restore tidal action in the compartment areas has been considered. The stability of the inlet-associated shorelines and the behaviour of the ebb-tidal delta would likely be modified with any managed change in tidal prism.

4. Morphodynamic analysis

The Deben estuary inlet has been surveyed annually since 1991 primarily for the purposes of navigation. Historic bathymetries of the Deben estuary inlet (Fig. 2) reveal a morphodynamic transformation from year to year whereby the ebb tidal delta, incorporating tidal

channel and intertidal shoals shift progressively southward (as described by Burningham and French, 2006). In order to investigate potential spatial and temporal morphodynamic trends of the Deben inlet, we performed Empirical Orthogonal Function (EOF) analysis, using all annual bathymetries since 1991 until 2013. EOF analysis, which maps the observed data into a set of shape functions in the space and time domain, is widely used in analysing coastal morphological data. 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).

The EOF analysis reveals that the first six eigenfunctions contained 99% of data variance. Here we focus on the first six spatial and temporal eigenfunctions (Fig. 3). The first spatial eigenfunction (EOF1) corresponds to the mean bathymetry of the estuary. The prominent features that define the morphological characteristics of the inlet; ebb tidal delta, tidal channel and west bank inter-tidal flats are well captured in EOF1. The remaining eigenfunctions correspond to the morphological variation around the mean. The second spatial eigenfunction (EOF2), which contains 31% of the data variance around the mean, captures the dynamics of the inlet channel, the west face of the *updrift* margin, the southeast extent of the ebb-jet/distal shoals and the *downdrift* shoreline, south of Martello Tower T. The form of EOF2 implies sediment exchange between the ebb delta, southwest shoreline and intertidal channel. The third eigenfunction (EOF3), which captures 17% of the data variance around the mean, is dominated by changes across the south/southwest components of the ebb delta shoals (south of Martello Tower T), and to
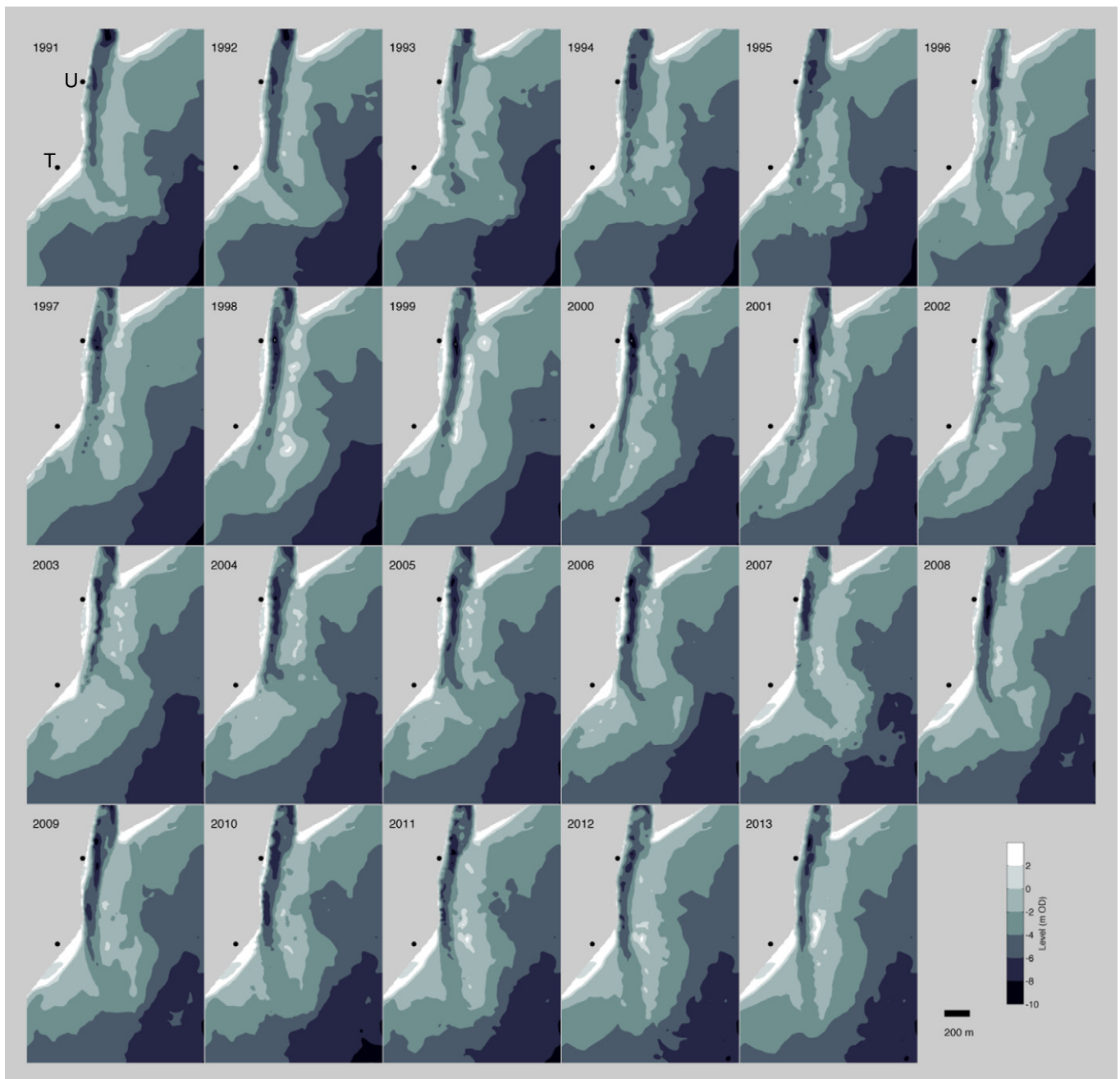

Fig. 2. Annual changes in the Deben ebb-tidal delta morphology, 1991 to 2013. Martello Towers T and U are provided for reference.
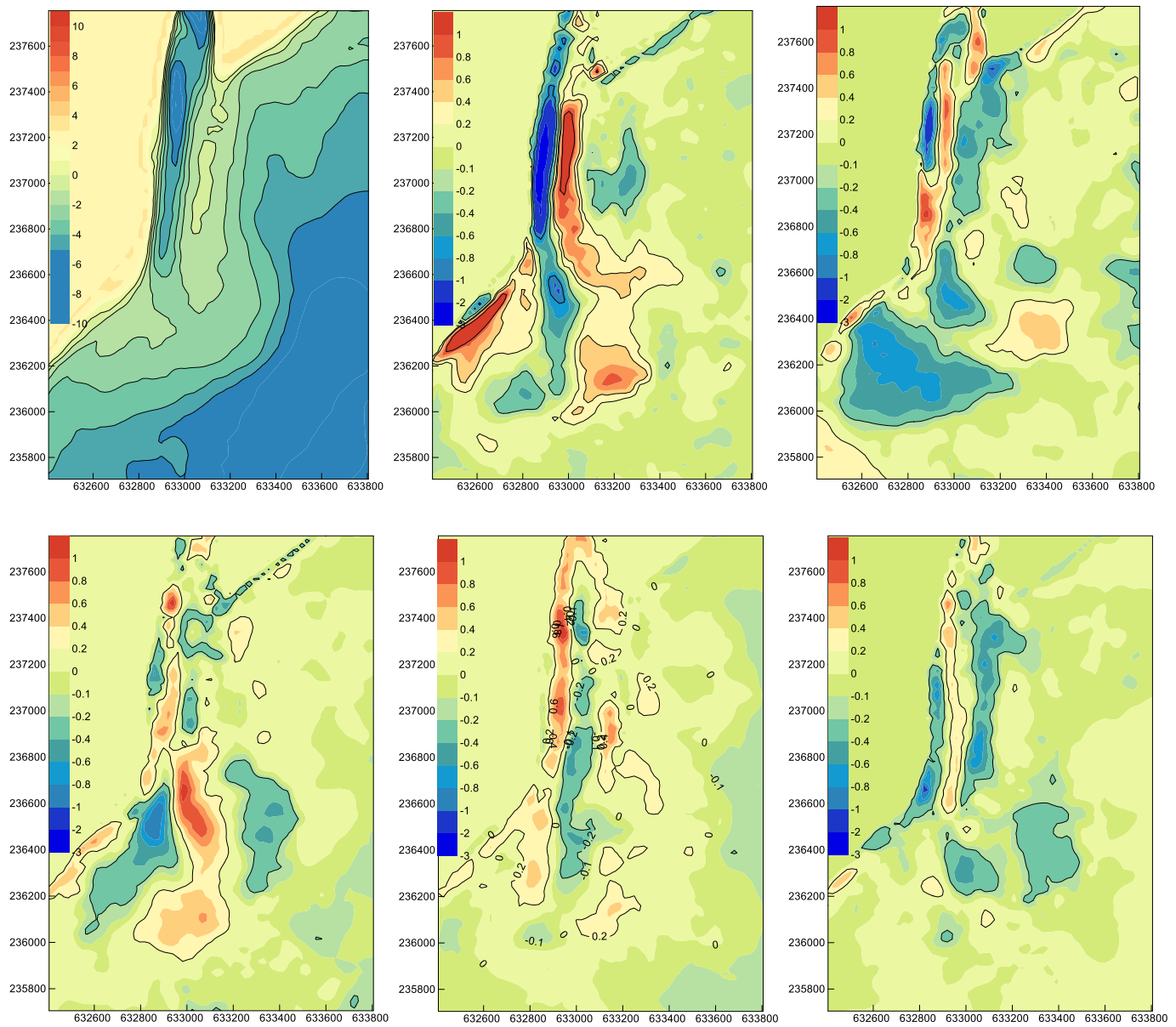
Fig. 3. First six spatial Empirical Orthogonal Functions of the Deben Estuary inlet bathymetries from 1991 to 2013. Clockwise from top left to bottom right EOF1 to EOF6.

some extent the bathymetric lows across the rest of the tidal delta and some sediment exchange between the inlet channel and ebb delta. The fourth spatial eigenfunction (EOF4) shows complementary spatial patterns to EOF2 in the *downdrift* shoreline and in the distal ebb shoal but, some contrasting patterns can be seen in the channel area and in some specific parts of ebb-jet and shoals. However, it should be noted that EOF4 contains only 11% of the variance around the mean. The fifth and sixth spatial eigenfunctions (EOF5 and EOF6) again capture further characteristics of the ebb delta, and in particular the ebb-jet and distal shoals but they collectively contain only 12% variance around the mean.

The corresponding temporal variation in the bathymetries is explained through temporal eigenfunctions corresponding to each of the spatial EOFs. In Fig. 4, the first six temporal eigenfunctions of the Deben inlet bathymetry are shown. The first temporal eigenfunction is approximately a constant as it corresponds to the mean bathymetry. The second temporal eigenfunction shows a small negative trend from 1999 to 2001 and then a significant positive trend since 2002. The second spatial EOF captures the main channel and parts of the *updrift* shoals and *downdrift* shoreline. Therefore, the temporal variability of

EOF2 reflects sediment exchange between these components of the system, importantly pivoting around 2002. The timing of the shift from negative to positive trend occurs just before the ebb-tidal delta breaching and bypassing event observed in 2002/2003 (Fig. 2). EOF2 captures the change in morphological structure and focus of erosion/deposition between 1991 and 2001 and 2002–2013, and it also expresses, in the consistent post-2002 increase in EOF2, the renewed growth of the *updrift* shoals post-breaching event. The largest gradient (negative) in the third temporal EOF (EOF3) occurs between 1995 and 1999, with limited variation before and after this. However, temporal EOF3 changes from positive prior to 1997 to negative after 1997. EOF3 represents, primarily, the southwest portion of the ebb-tidal delta, and nearshore zone south of Martello Tower T. During the late 1990s, the main low tide channel eroded much of this region as it extended further south removing the inter-/sub-tidal foreland that previously existed here. Similarly to the previous EOFs, temporal EOF4 is stable at a value close to zero until 1995 when it peaks in 1999 before variably decreasing to a low in 2006, followed by an increase to 2013. This temporal EOF is the first to represent any significant cyclic variability as the time series for EOF2 and EOF3 both show a discrete shift over the time frame, whereas
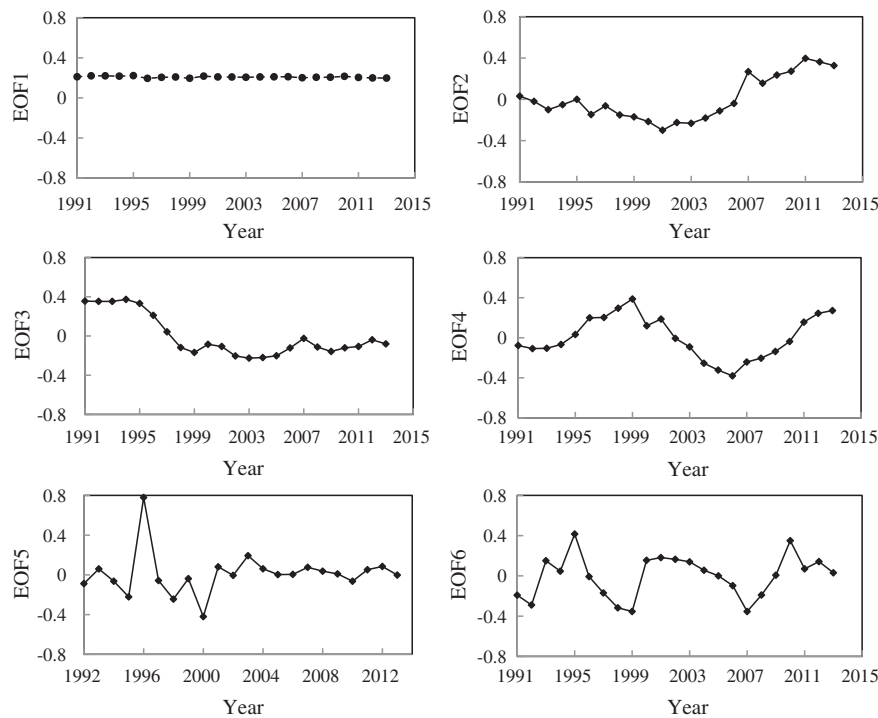
Fig. 4. First six temporal Empirical Orthogonal Functions of the Deben Estuary inlet bathymetries from 1991 to 2013.

EOF4 peaks, troughs and returns to a midpoint. EOF4 is largely focused on the ebb-jet region and distal shoals; the temporal sequence seems to capture the shifts in erosion and deposition of these shoals through the process of first, breaching, and second, onshore migration of the bypassed, downdrift shoal. Temporal EOF5 shows some cyclic variability but the values of EOF5 are close to zero except in 1996 and 2000. Temporal EOF6 also shows some cyclic behaviour, expressing local foci of accretion and erosion across the shoals, particularly within the dynamic ebb-jet region. As the bathymetric data do not cover an explicit bypassing cycle in its entirety, none of the temporal EOFs readily capture the full cyclic process.

The above analysis shows that morphodynamics of the Deben Estuary inlet is primarily driven by the changes to the inlet channel, ebb shoal/delta and the *downdrift* shoreline. The combined spatial and temporal eigenfunctions captured the historic changes of different morphological features of the inlet while identifying significant shifts and cycles of erosion and accretion that had taken place in the past.

5. Application of the model and discussion

The 2D reduced physics model presented in Section 2 is applied to the Deben inlet to assess its suitability to describe the historic inlet behaviour. The annual inlet bathymetries measured between 1991 and 2013 were used to build the model.

5.1. Sediment diffusion coefficient

As described in Section 2, a discrete time series of $S(x,y,t)$ can be obtained from Eq. (5) when a time series of bathymetries $h(x_i,y_i,t_m)$ of the estuary inlet is available. However, it should be noted that the source function depends on the diffusion coefficient through the operator D. In a complex hydrodynamic and sediment environment as in the Deben Estuary inlet, it is extremely difficult to determine a suitable diffusion coefficient. Here we take a constant sediment diffusion coefficient assuming the spatial variability of sediment coefficient at the Deben inlet is less significant and that sediment diffusion in transverse

and long-axis directions are not significantly different due to the complex 3D structure of the flow.

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 m²/yr. Baugh (2004) and Baugh and Manning (2007) used a horizontal diffusion coefficient of the order 10^7 m²/yr for morphodynamic modelling of the Thames estuary, UK, which mostly consists of sand and mud. Huthnance (1982), Flather (1984) and White (1995) suggest a value in the order of 10^5 m²/yr on offshore sand banks. Considering the sediment characteristics in the study area of the Deben estuary inlet which primarily consists of sand-gravel deposits (Burningham and French, 2006), the sediment diffusion coefficient of 5×10^5 m²/yr was selected for this study which falls within the bounds found by other investigators in the past for other coastal settings with similar hydrodynamic and sediment environments. A sensitivity analysis carried out using $\pm 10\%$ of the selected diffusion coefficient shows that it does not significantly affect the source function.

5.2. Source function

Using the historic bathymetry dataset (Fig. 2) described in Section 4, a time series of $S(x,y,t)$ was derived using Eq. (5). Each consecutive pair of bathymetries from 1991 to 2013 gives twenty one discrete annual source functions (Fig. 5) which represent the effects of all processes, other than sediment diffusion, contributing to bathymetric changes of the Deben Estuary inlet. This includes advection and circulation from tidal currents, fluvial flows and waves, effects of climate change, and anthropogenic changes. As a result, the source function represents a significant proportion of sediment dynamics and hence morphology changes in the inlet.

Alternate positive and negative values of the source function correspond to accretion and erosion respectively. In Fig. 5, large scale morphodynamic features of the estuary such as the inlet channel, ebb shoal/delta and intertidal flats and *downdrift* coast are clearly visible. For example, significant channel infilling in 1995–1995 and fragmentation of the ebb delta in 2003–2004 (Fig. 3) are indicated in the source functions determined by 1995–1996 and 2003–2004 bathymetries
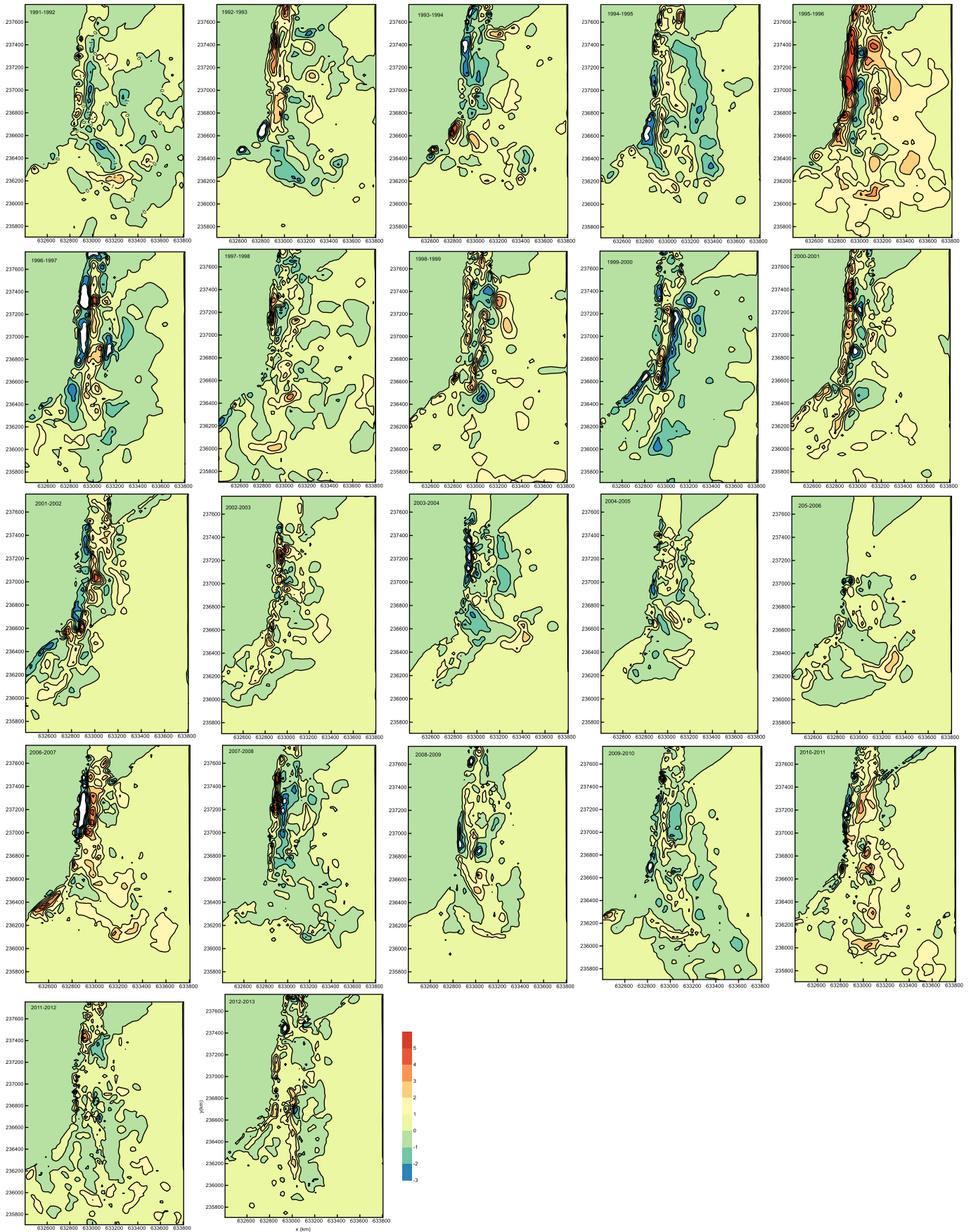
Fig. 5. Source functions determined from Eq. (5) using historic annual bathymetry measurements of the Deben estuary inlet from 1991 to 2013. The colour bar indicates source function in m/year.

respectively. Some smaller scale morphological structures 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.

As explained earlier, the source function represents morphological change arising from a collection of processes (e.g. river flow, littoral processes, tides and anthropogenic effects). However, river input to Deben Estuary is significantly smaller than the tidal prism. Also, no known post-1991 anthropogenic interventions were found. It is known that the estuary is tide-dominated and that the inlet of the estuary is subjected to significant littoral transport processes. Therefore, it is fair to consider that the source function primarily contains morphological change driven by tides and littoral processes.

If the sequence of source functions captures significant patterns of change in time then, the modelling approach used here will provide a useful tool to describe morphodynamic changes of the inlet. To determine whether they contained coherent patterns we analysed them into their EOFs.

The EOF analysis of the source function shows that twenty two eigenfunctions are needed to contain 100% data variance. However, the first eight eigenfunctions collectively contained 72% of the data variance and the remaining functions collected only a few percentage of the variance in each function. It should be noted that more EOFs are required to explain the variance than often seen (e.g. 3 is usually enough for beach profiles, 6 was needed to explain Deben inlet bathymetry in Section 4) which reflects the complex structure of the variations captured by the source functions. We will investigate only the first eight eigenfunctions (Fig. 6) of the source function in detail. These eigenfunctions should be able to provide patterns of morphodynamic variability of the inlet, mainly due to tides and littoral transport process in space and time. As a result, any impact of inter-annual scale wave climate hence littoral transport regime should be seen in the EOFs.

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 ebb shoal area of the third spatial eigenfunction (EOF3), which captures 13% of variance around the mean, shows trends contracting to EOF1 but EOF3 features seen in the upper reaches of the inlet channel complement 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 complements the features captured by EOF1.·The next two spatial eigenfunctions (EOF5 and EOF6) also captured the ebb delta and the inlet channel 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 but show small scale localised features.

Channel erosion/infilling, alternate 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. However, of morphodynamic variability captured by the spatial eigenfunctions cannot be fully explained without examining the corresponding temporal eigenfunctions.
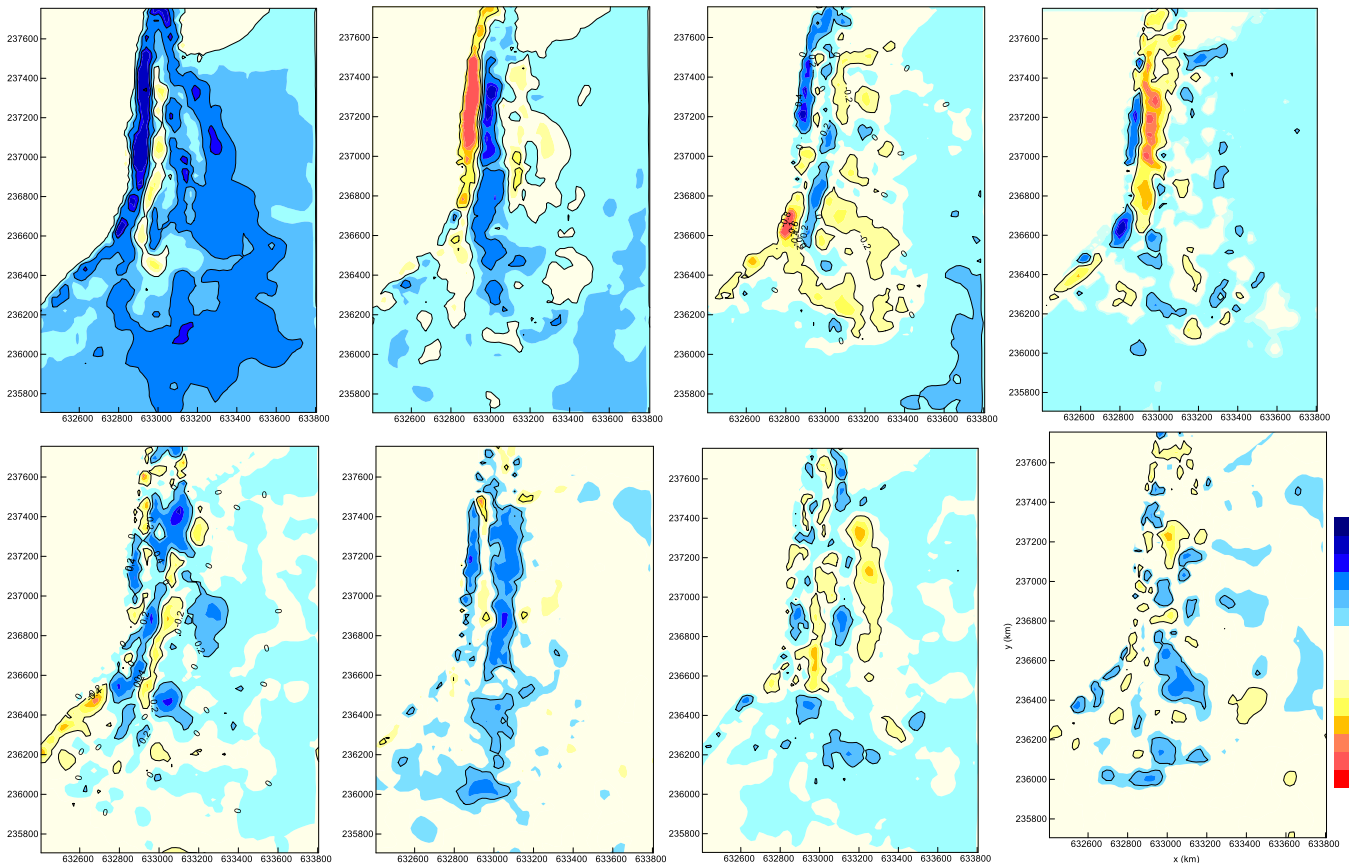

Fig. 6. First eight spatial Empirical Orthogonal Functions of the source functions shown in Fig. 5 (top figures from left to right – EOF1 to EOF4; bottom figures from left to right – EOF5 to EOF8).

Fig. 7 shows first eight temporal eigenfunctions which describe the time variation of the corresponding spatial eigenfunctions shown in Fig. 6. Temporal EOF1 which corresponds to time mean source function is nearly a constant as expected. Temporal EOF2 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 reveal that ebb shoal breaching has taken place in 2002–2003 period. The variability of temporal EOF3, which captures opposite trends to that of EOF2, 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. Temporal variability of EOF4 is significant between 1992 and 1997 only. Subsequent EOFs show some cyclic variability but, those two EOFs captures only 12% of data variance. Further analysis of the results shows that even though the first eight EOFs 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. However, a comparison of Fig. 4 (temporal EOFs of the measured bathymetries) and Fig. 7 (temporal EOFs of the source functions) reveals that while the Deben 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 the inter-temporal variability of the source function, averaged over a suitable timescale would be appropriate to model the morphodynamics of the Deben inlet.

6. Summary

This paper presents an analysis of a complex estuary inlet system using Empirical Orthogonal Functions (EOF) and assesses the suitability of a 2D reduced physics model to explain historic morphodynamic behaviour of the inlet. The model describes the evolution of sea bed bathymetry and reduces the complex and multi-faceted estuary morphodynamic process into 'diffusive' and 'non-diffusive' components. The study site is the Deben Estuary inlet located on the east coast of the United Kingdom.

- The analysis confirms that EOF is a useful approach to investigate morphodynamic change of the Deben inlet where an excellent historic bathymetry data are available. The method correctly captured the features that dominate the morphology of the inlet and their morphodynamic behaviour. The analysis also confirms that some morphodynamic features of the estuary undergo cyclic changes, while significant meso-scale changes are evident. However, the length of the data set is not sufficient to investigate meso-scale changes in detail.
- 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
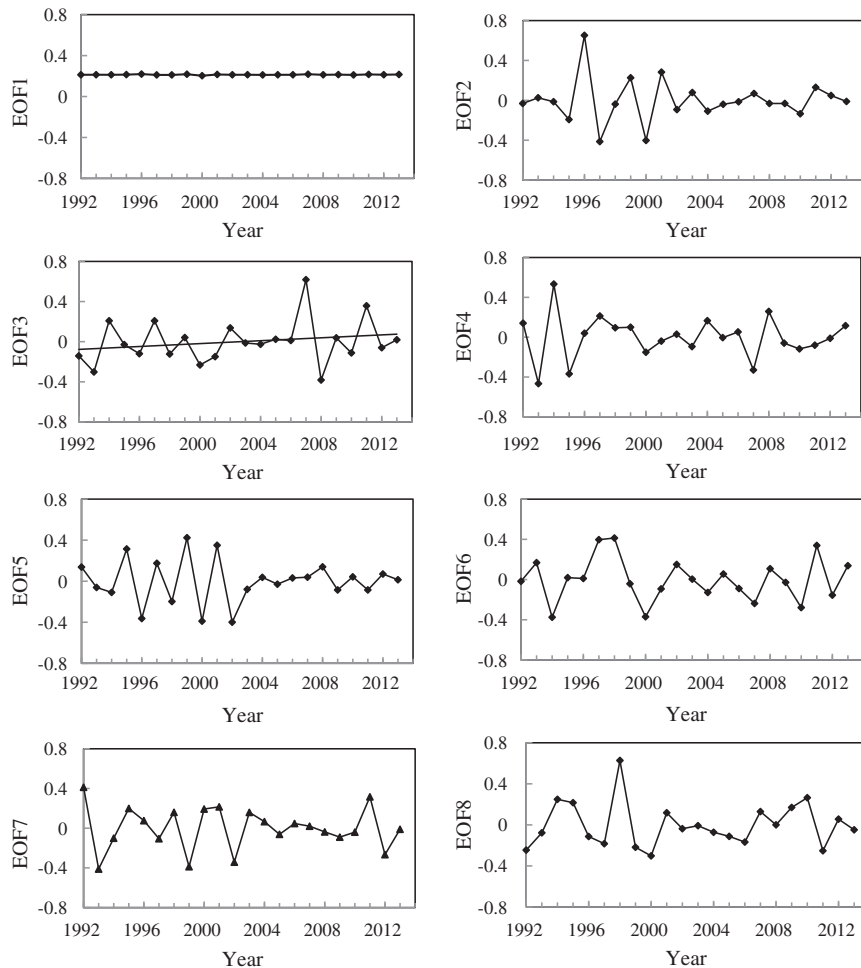

Fig. 7. The first eight temporal Empirical Orthogonal Functions of the source functions shown in Fig. 5.

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 the evolution of Deben inlet but does not directly recognise meso-scale variability observed in the measured data.

- 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. Even though the temporal EOFs of the source function show annual scale change, EOFs of historic annual Deben inlet bathymetries show variability predominantly at timescales of several years to a decade. Taking this into account, the 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. This is the subject of an ongoing study.

- 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. For example, if annual bathymetry surveys are used to determine site-specific model unknowns, then morphodynamic forecasts at less than one year period proves to be meaningless. Also, in the event of future morphodynamic forecasts, past and current environmental or anthropogenic forcings that govern the morphodynamic process should remain largely unchanged.

- Complexity of the Deben site e.g. variations in sediment type, channel orientation, complex littoral transport regime, provides a severe challenge for any model. Obtaining a better idea of the relative importance of different processes will be important and to do this will require less drastic simplification of the morphodynamic evolution equations.

- Finally, it is worth nothing that the success of this study and more generally, our understanding of meso-scale change of coastal morphology, rely on regular coastal monitoring over the period of many decades to provide the measurements with which to develop, calibrate and validate computational models.

Acknowledgement

References

Baugh, J., 2004. Implementation of Manning Algorithm for Settling Velocity to an Estuarine Numerical Model. (Technical Report No. TR 146). HR Wallingford Ltd., UK.

Baugh, J., Manning, A.J., 2007. An assessment of a new settling velocity parameterization for cohesive sediment transport modelling. Cont. Shelf Res. 27 (13), 1835–1855.

Beardall, C.H., Dryden, R.C., Holzer, T.J., 1991. The Suffolk Estuaries. Segment Publications, Colchester (77 pp.).

Bruneau, N., Fortunato, A.B., Dodet, G., Freire, P., Oliveira, A., Bertin, X., 2011. Future evolution of a tidal inlet due to changes in wave climate, sea level and lagoon morphology (Óbidos lagoon, Portugal). Cont. Shelf Res. 31, 1915–1930.

Burningham, H., French, J., 2006. Morphodynamic behaviour of a mixed sand-gravel ebb-tidal delta: Deben Estuary, Suffolk, UK. Mar. Geol. 225, 23–44.

Cayocca, F., 2001. Long-term morphological modeling of a tidal inlet: the Arcachon Basin, France. Coast. Eng. 42, 115–142.

Dastgheib, A., Roelvink, J.A., Wang, Z.B., 2008. Long-term process-based morphological modeling of the Marsdiep tidal basin. Mar. Geol. 256 (1–4), 90–100.

De Vriend, H.J., 1996. Mathematical modelling of meso-tidal barrier island coasts: part I. Empirical and semi empirical models. In: Liu, P.L.F. (Ed.)Advances in Coastal and Ocean Engineering Vol. 2, p. 115e149.

De Vriend, H., Ribberink, J.S., 1996. Mathematical modelling of meso-tidal barrier island coasts, Part I: process based simulation models. In: Liu, P.L.F. (Ed.)Advances in Coastal and Ocean Engineering 2, pp. 151–197.

Dennis, J.M., Spearman, J.R., Dearnaley, M.P., 2000. The development of regime models for prediction of the long term effects of civil engineering activities of estuaries. Phys. Chem. Earth Part B 25, 45e50.

Di Silvio, G., 1989. Modelling the Morphological Evolution of Tidal Lagoons and Their Equilibrium Configurations. XXII Congress of IAHR, IAHR, Ottawa, Canada.

Dronkers, J., 1998. Morphodynamics of the Dutch Delta. In: Dronkers, J., Scheffer, M. (Eds.), Physics of Estuaries and Coastal Seas. Balkema, Rotterdam, p. 297e304.

Duong, T.M., Ranasinghe, R., Walstra, D.-J., Roelvink, D., 2016. Assessing climate change impacts on the stability of small tidal inlet systems: why and how? Earth Sci. Rev. 154, 369–380.

Duvivier, P., 1999. Suffolk estuarine strategies: river Deben. Strategy Report: Volume 1 Main Report. Environment Agency: Anglian Region (CP505(163). 61 pp. (plus appendices)).

Flather, R.A., 1984. A numerical model investigation of a storm surge of 31 January and 1 February 1953 in the North Sea. Q. J. R. Meteorol. Soc. 591e612.

French, J., Burningham, H., 2015. Wave-driven sediment pathways on the gravel-dominated Suffolk coast, eastern UK. In: Wang, P., Rosati, J.D., Cheng, J. (Eds.), Proceedings of Coastal Sediments (15 pp.).

Friedrichs, C.T., Aubrey, D.G., 1996. Uniform bottom shear stress and inter tidal hypsometry of intertidal flats. In: Pattiarachchi, C. (Ed.), Mixing Processes in Estuaries and Coastal SeasCoastal and Estuarine Studies Series. American Geophysical Union, Washington, p. 405e429.

Hibma, A., Stive, M.J.F., Wang, Z.B., 2004. Estuarine morphodynamics. Coast. Eng. 51, 765e778.

Huthnance, J.M., 1982. On the formation of sand banks of finite extent. Estuar. Coast. Shelf Sci. 15, 277e299.

Hydrographic Office, 2000. Admiralty Tide Tables: United Kingdom and Ireland (Including European Channel Ports). Hydrographer of the Navy (440 pp.).

Karunarathna, H., Reeve, D.E., 2008. A Boolean approach to prediction of long-term evolution of estuary morphology. J. Coast. Res. Vol. 24 (2B), 51–61.

Karunarathna, H., Reeve, D.E., Spivack, M., 2008. Long term morphodynamic evolution of estuaries: an inverse problem. Estuar. Coast. Shelf Sci. 77, 386–395.

Kroon, A., Larson, M., Moller, M.I., Yokoki, H., Rozynski, G., Cox, J., Larroude, P., 2008. Statistical analysis of coastal morphological data sets over seasonal to decadal time scales. Coast. Eng. 55, 581–600.

Larson, M., Capobianco, M., Jensen, H., Rozyanki, G., Southgate, H.N., Stive, M., Wijnberg, K.M., Hulscher, S., 2003. Analysis and modelling of field data on coastal morphological evolution over yearly and decadal time scales, part 1: background and linear techniques. J. Coast. Res. 19 (4), 760–775.

Masselink, G., 1998. The effect of sea breeze on beach morphology, surf zone hydrodynamics and sediment re suspension. Mar. Geol. 146, 115–135.

Nahon, A., Bertin, X., Fortunato, A.B., Oliveira, A., 2012. Process-based 2DH morphodynamic modeling of tidal inlets: a comparison with empirical classifications and theories. Mar. Geol. 291-294, 1–11.

NRFA, 2014. National River Flow Archive. http://www.nwl.ac.uk/ih/nrfa/.

Prumm, M., Iglesias, G., 2016. Impacts of port development on estuarine morphodynamics: Ribadeo (Spain). Ocean Coast. Manag. 130, 58–72.

Pruszak, Z., 1993. The analysis of beach profile changes using Dean's method and empirical orthogonal functions. Coast. Eng. 19, 245–261.

Reeve, D.E., Karunarathna, H., 2011. A statistical–dynamical method for predicting estuary morphology. Ocean Dyn. 61, 1033–1044.

Reeve, D.E., Li, B., Thurston, N., 2001. Eigenfunction analysis of decadal fluctuations in sandbank morphology. J. Coast. Res. 17 (2), 371–382.

Reeve, D.E., Horrillo-Caraballo, J.M., Magar, V., 2008. Statistical analysis and forecasts of long-term sandbank evolution at Great Yarmouth, UK. Estuar. Coast. Shelf Sci. http://dx.doi.org/10.1016/j. ecss.2008.04.016.

River Deben Association, 2014. Deben Estuary Partnership. ([accessed 29 July 2014], 2014). http://www.riverdeben.org/category/deben-estuary-partnership/.

Royal Haskoning, 2008. Suffolk Shoreline Management Plan Review: Estuaries Assessment. Report 1398. ABP Marine Environmental Research Ltd., Southampton, UK.

Stive, M.J.F., Capobianco, M., Wang, Z.B., Roul, B., Buijsman, M.C., 1998. Morphodynamics of tidal lagoon and the adjacent coast. In: Dronkers, J., Scheffer, M. (Eds.), Physics of Estuaries and Coastal Seas. Balkema, Rotterdam, p. 397e407.

Van der Wegen, M., Roelvink, J.A., 2012. Reproduction of estuarine bathymetry by means of a process-based model: western Scheldt case study, the Netherlands. Geomorphology 179, 152–167.

Wallingford, H.R., 2002. Southern North Sea Sediment Transport Study (Phase 2). HR Wallingford Report, EX, p. 4526.

White, T.E., 1995. Field tests of cross-shore sand transport models in oscillatory flow. US Army Corps of Engineers. Technical Report CERC-9513.

Wijnberg, K.M., Terwindt, J.H.J., 1995. Extracting decadal morphological behaviour from high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis. Mar. Geol. 126, 301–330.

Winant, C.D., Inman, D., Nordstrom, C.E., 1975. Description of seasonal beach changes using empirical eigenfunctions. J. Geophys. Res. 80 (15), 1979–1986.