A Statistical and GIS-Based Approach for Morphodynamic Characterisation and Modelling

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1. Introduction

The transition from static snap-shot to event-orientated approaches in Geographic Information Science (GISc) (Worboys, 2005; Goodchild *et al*, 2007 and McIntosh and Yuan, 2005) opens up opportunities for morphodynamic characterisation and modelling approaches in coastal engineering. This is due to the dynamic nature of the marine morphodynamic system that evolves at varying spatial and temporal scales in response to differing inputs (hydrodynamic, meteorological and anthropogenic) and process interactions (hydrodynamics and sediment transport). The event-orientated concepts in GISc would enable the inputs and processes that result in a particular output (morphological response) to be captured and applied to further modelling.

Current applications of geographic information science and systems in morphodynamic modelling utilise the "snap-shot" view to:

- Visualise the output of modelling procedures.
- Calculate the height differences between raster representations of the seabed depth and derive approximate seabed volumetric changes.
- Digitise vector information from the seabed raster surfaces.

There are a number of existing morphodynamic assessment approaches in coastal engineering that aim to characterise the morphodynamic system in terms of the "cause-response" relationships. These can broadly be categorised into bottom-up or top-down concepts, which differ in how they account and represent the system processes. The limitation with the bottom-up methods is the system behaviour and process interaction is inferred, so it is only feasible for short-term (hours to days) and small spatial areas (unit kilometre squared) (De Vriend, 1991a; De Vriend, 1991b and De Vriend *et al*, 1993). In the top-down case the behavioural trends are derived for each system factor, however it is not always possible to correlate the "cause-response" relationship between the input and output variables (Reeve *et al*, 2001 and Wijnberg and Terwindt, 1995). Therefore, there is a gap in morphodynamic characterisation approaches to address spatial areas of up to tens of kilometres at multi-decadal time-scales.

This paper presents a proposed morphodynamic characterisation and modelling methodology to address the described gap by utilising the event-orientated concepts from GISc with existing morphological assessment methods.

2. Methodology

The methodology presented utilises event-orientated concepts to identify the system inputs and processes that result in specific morphological response.

The functionality of the geographical information system and the morphological modelling approach is demonstrated in Figure 16. The spatial and temporal behaviour are derived for each system factor using a morphological modelling approach (1). The derived behaviour is extrapolated to calculate the morphological response at a future time step based on forcing conditions (hydrodynamic and meteorological influences) (2). The modelled response is validated against a real-world case by modifying associated weightings to the forcing conditions (3). The "cause-response" relationship is then determined by systematically varying the forcing conditions, associated weighting and the spatial and temporal averaging and aggregation of the input forcing parameters to identify characteristic morphological zones (4). The identified seabed locations that have similar responses to the varying forcing influences are spatially aggregated (5) and form the inputs into a rule-based morphological prediction procedure (6 to 8).

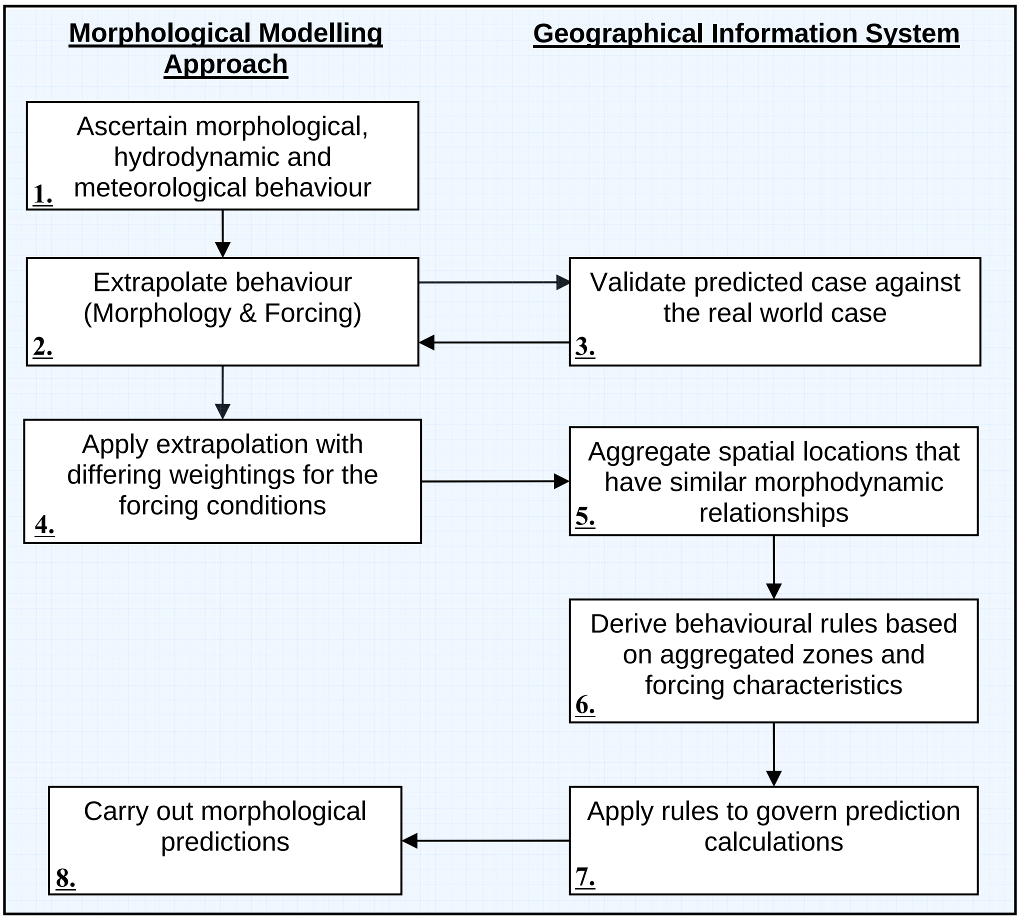

Figure 16: Proposed morphodynamic characterisation and modelling methodology.

2.1. Determining Morphodynamic Behaviour

The system behaviour is extracted from datasets of each factor using an Empirical Orthogonal Function (EOF) approach. The analysis method derives the dominant spatial and temporal eigenfunctions that account for the largest proportion of variance in the dataset (Larson *et al*, 2003 and Miller and Dean, 2007). The method has been widely used in coastal morphology analyses to identify characteristic patterns, often interpreting these in relation to the physical morphology (Wijnberg and Terwindt, 1995 and Miller and Dean, 2007). The application of the EOF method is this research involves separating the morphological data into spatial and temporal eigenvectors and associated weightings which can be linearly combined to recreate the original data based on equation 1 (Miller and Dean, 2007).

$$y(x,t)=\sum_{k=1}^{n} a_k c_k(t) e_k(x) \tag{1}$$

$$a_k=\sqrt{\lambda_k n_x n_t} \tag{2}$$

Where $e_k(x)$ is the spatial eigenvector, $c_k(t)$ is the temporal eigenvector or coefficient, a_k is determined by equation 2 and λ_k is the eigenvalue associated with the k^{th} eigenvector (where the spatial and temporal eigenvectors have the same eigenvalue), n is the lesser of n_x or n_t which are the count of spatial and temporal element respectively.

2.2. Characterising Morphodynamic Behaviour

The purpose of the validation step is to determine the appropriate morphological change function across the seabed (step 3, Figure 16). The objective of the characterisation step is to ensure that only the forcing climate that is applicable to an aggregated spatial zone is included in the change function for that zone when carrying out morphological predictions (steps 4 to 6, Figure 16).

2.2.1. Validation and Characterisation

A Geographical Information System (GIS) will be used to carry out the prediction validation (step 3, Figure 16) and enable the morphodynamic characterisation process in determining the appropriate morphological change functions for the morphological zones (steps 4 to 6, Figure 16). The system will facilitate validation by interpolating the calculated profiles into a surface and comparing the predicted output against the observed case. It will be used to highlight the distribution of the modelled difference, showing the locations where the prediction was closer to reality, due to lower differences. Future development will be to assess and determine how the calculated difference will act as a guide to modify the parameters from the forcing factor. The characterisation process would involve systematically varying the included forcing conditions and weightings to observe the locations that varied and to what degree, from which "cause-response" relationships will be established between the morphological and forcing factors.

2.2.2. Prediction

The derived behaviour and association between the system factors is used to derive a rule-based morphological model which specifies the range of conditions that influences a particular area of seabed (steps 7 and 8, Figure 16).

2.3. Study Area and Data

A study area located off the East Anglian coast between Winterton-on-Sea and Orford Ness and extends fifty kilometres offshore was selected (Figure 17). It is bounded by WGS84 geographic grid coordinates 52.763N, 1.673E and 52.005N, 2.397E for the northwest and southeast corners respectively. The area forms an important navigation route into the ports at Great Yarmouth and Lowestoft and is made up of a number of bank and channel systems that are known to be mobile (UKHO, 2002, 2003 and 2004). The bathymetric dataset comprised sixteen digitised bathymetric survey charts between 1846 and 1992, which formed the analyses set and a side-scan sonar survey output from 2002 which was used for validation.

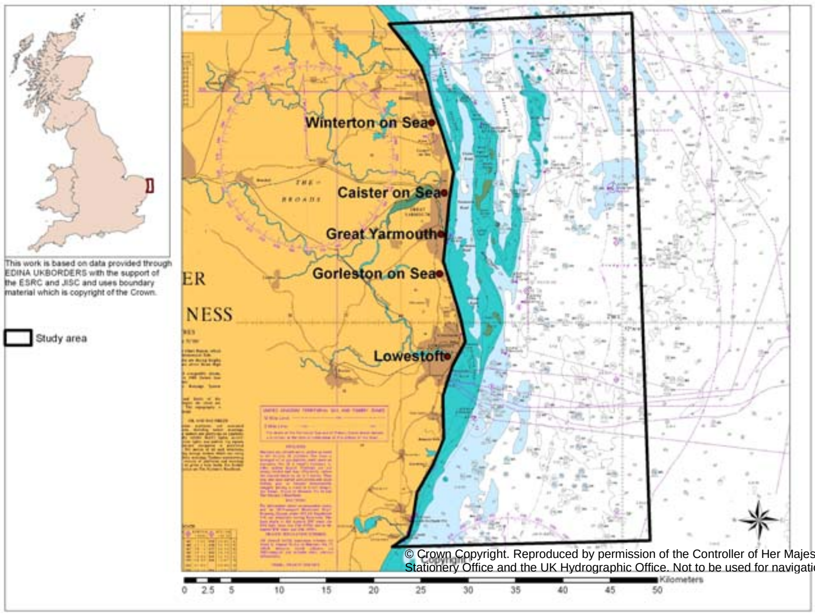

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Figure 17: Study area.

3. Implementation Tests and Results

In order to investigate the applicability of the proposed methodology, initial experiments were undertaken as described in steps 1, 2 and 3 (Figure 16) for morphological data only. The purpose was to explore the capability of identifying morphological behaviour and predicting future conditions. As well as demonstrate the need to include forcing influences in morphological prediction calculations.

The temporal mean, range, minimum, maximum, standard deviation and coefficient of variance of the seabed depth were calculated for each cell in ArcGIS 9.1™, to derive an overview of the morphological behaviour within the study area (Reeve *et al*, 2001). EOF analyses undertaken in MATLAB™ were used to decompose the morphological data into spatial and temporal trends from which the seabed was reconstructed using equation 1 based on the largest eigenfunctions. To predict future morphological states the identified temporal eigenvectors were extrapolated based on a best-fit line. The coefficient derived from the extrapolated temporal trend was utilised in equation 1 to predict the bed depth at a future time step.

The results of the summary statistics for the study area support the local observation that the banks and channel systems are mobile (Figure 18 A to C). The largest change with a height range of up to thirty-three metres primarily occurs in the offshore banks and channels. The least change of approximately zero to five metres occurs closer to the shoreline (Figure 18 A). A similar distribution pattern is observed between the range and standard deviation results, which indicate that the offshore bank and channels are more variable than the nearshore features. This is possibly due to the sampling density of the original survey and the digitisation and interpolation process. Alternatively the offshore bank and channel have a differing dynamic equilibrium phase to the nearshore features, which do not coincide with the survey periodicity.

The results of the EOF analysis and extrapolation prediction for the morphological data indicate that the observed eigenfunctions (spatial and temporal) which describe the largest proportion of variance in the data identifies the cross-shore profile shape for year 2002 (Figure 19). However a root-mean-square error of 2.88 (m) indicates that there is some difference between the predicted and observed bed height, which is also demonstrated in Figure 19. This leads to the assertion that although the morphological factor has a spatial behaviour, the forcing conditions and stochastic events also contribute to morphological evolution.

4. Conclusion

The morphodynamic environment is known to evolve at varying spatial and temporal scales. The objective of the current research is to spatially and temporally characterise morphological responses to hydrodynamic and meteorological conditions in order to enable morphological prediction at multi-decadal temporal and regional spatial scales. The event-orientated approach in GISc presents opportunities to identify the forcing influences which determine a specific morphological response and can be applied to rule-based prediction calculations.

The first step of capturing morphological behaviour using morphological modelling approaches indicate that it is not sufficient to predict future morphological states based on observed morphological trends only. Instead there is a need to include the hydrodynamic influences and use the relationship between the variables to predict future states.

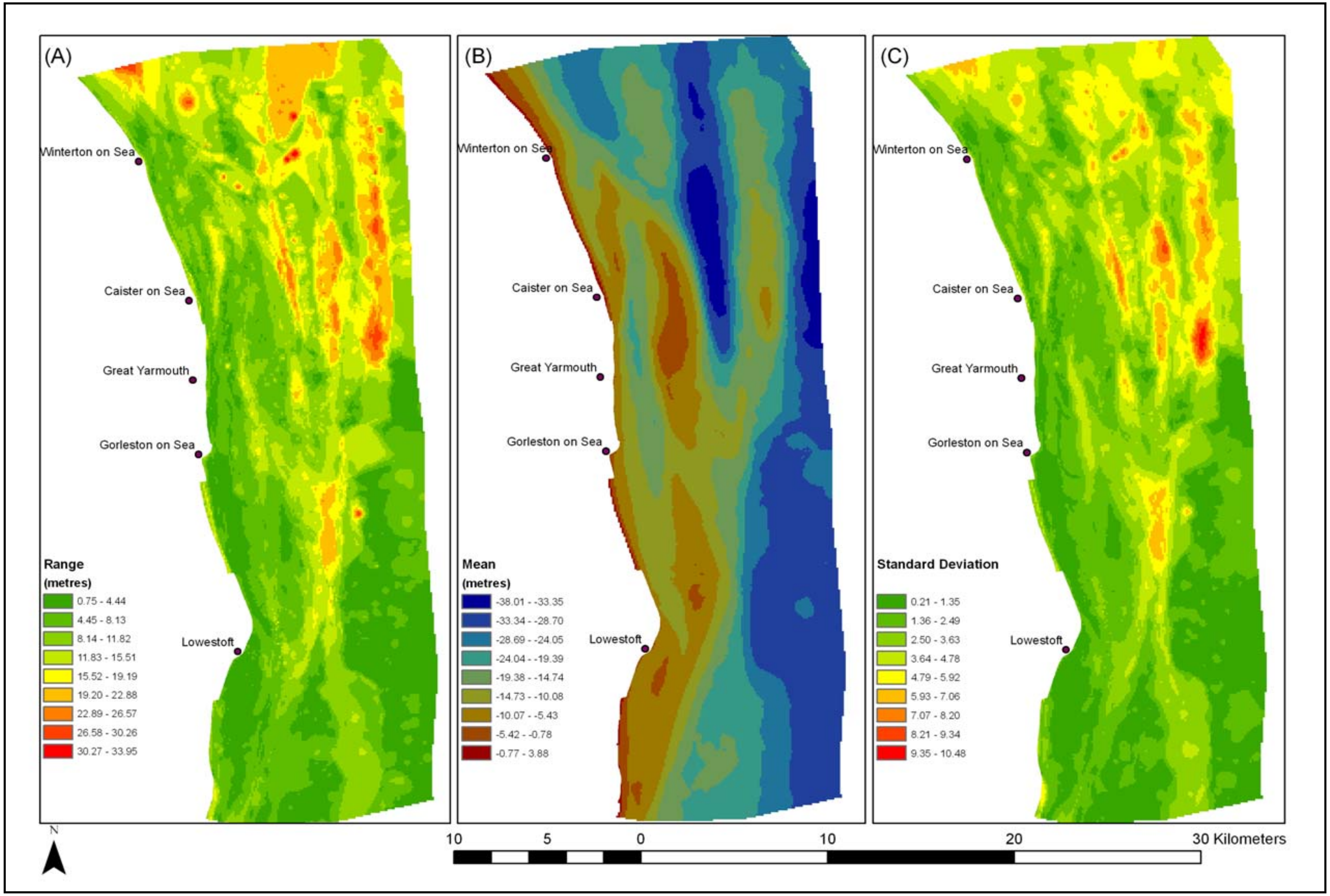

Figure 18: Results of the temporal a) range, b) mean and c) standard deviation statistics assessments for each grid cell for the 1846 – 1992 datasets.

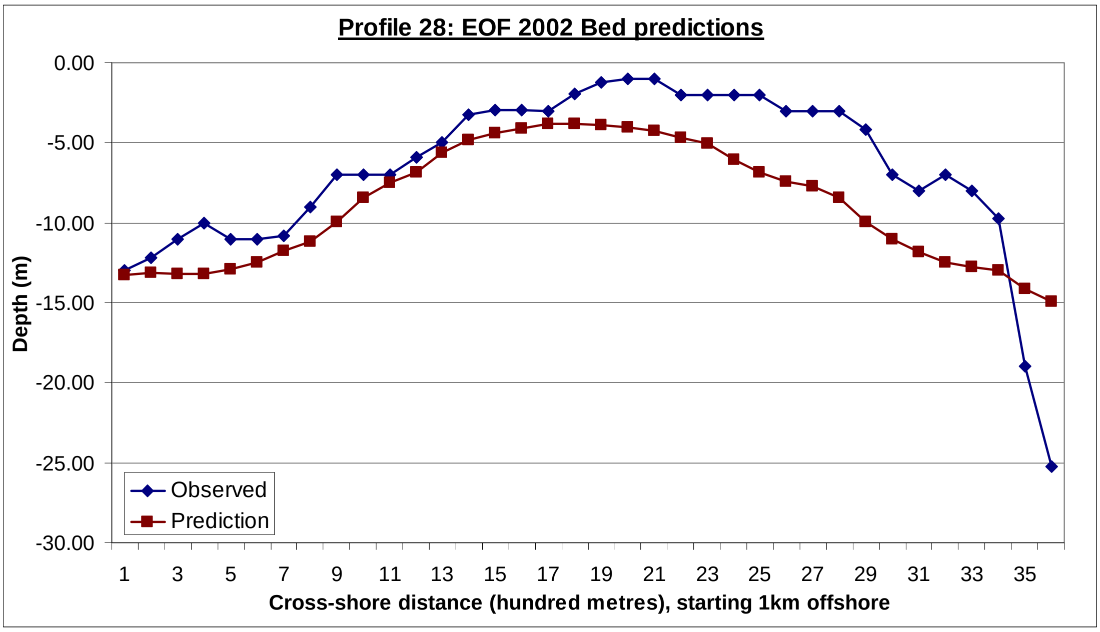

Figure 19: Comparison of the observed and predicted profile for the year 2002 derived using the EOF method for profile 28.

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Biography

Anna-Marie Bakare is a second year PhD in the department of Civil, Environmental and Geomatic Engineering, UCL. She holds a BSc (Hons) in Archaeology from UCL and an MSc in Geographic Information Science from UCL. Her interests are in marine GIS implementation and morphological modelling.

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