Evaluation of seafloor infrastructure risk associated with submarine morphodynamics

Part 1 - Scoping

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1. Introduction

The seabed is subject to increasing exploitation for economically valuable hydrocarbon and mineral resource areas and the continental shelves in particular have seen a proliferation of offshore infrastructure associated with renewable energy generation, transport and telecommunications. Any activity at the seabed encounters the risk of construction and/or operational problems due to a varied set of marine geohazards. Geohazards incorporate a range of geological features and processes that are pertinent to some aspect of safety, commercial, economic or environmental risk (Hough et al., 2011). Offshore engineering projects therefore routinely include integrated assessments of seabed geology, ground conditions and processes, including the mapping of potential geohazard features and assessments of the likelihood of their occurrence. Most assessments start with seabed surveys and descriptive analysis founded on well-established principles of geomorphological mapping (Cooke and Dornkamp, 1990), often integrated with geophysical surveys and/or physical sampling to determine seabed geotechnical properties (Prior and Hooper, 1999). These surveys are supplemented by both qualitative and quantitative studies of the processes that trigger and drive seabed behaviour and best estimates of the magnitude and frequency of their past and likely future occurrence. In combination with knowledge of the vulnerability of the infrastructure or activity in question, this allows an integrated assessment of risk (Hough et al. 2011).

Existing approaches place particular emphasis on event-driven hazards such as earthquakes, submarine landslides, turbidity currents, tsunami and high-pressure fluid or gas expulsions and triggering factors such as seismicity, volcanism and human activities (see, for example, Locat 2001; Masson et al., 2006; Strasser et al., 2011). However, progressive changes in seabed topography can also be extremely damaging for structures and infrastructure elements such as pipelines and submarine cables. A considerable literature exists on the localised in situ interactions between structures and the bed, especially relating to the magnitude and implications of erosional scour and the behaviour of pipelines on and within sediment beds (e.g. Negor et al. 2014; Fredsøe 2016). The migration of sand waves has also attracted attention on account of the potential implications for pipelines (Morelissen et al., 2003) and other infrastructure. However, the progression from place-specific studies of seabed morphological change to a formal evaluation of the associated geohazard risks has not been accomplished to date. There are also some unresolved challenges regarding the disaggregation of various forms of morphodynamic behaviour into specific risks to infrastructure and how best to utilise available hydrographic data resources.

This report represents Work Package 1 of a study on the Evaluation of Seafloor Infrastructure Risk Associated with Submarine Morphodynamics undertaken by the UCL Coastal and Estuarine Research Unit on behalf of The Crown Estate. Work Package 1 involves a scoping study that sets out the context for the evaluation of risks to infrastructure arising specifically from morphological changes of the seabed and identifies the main challenges and areas where further method development is needed. The scoping study is organised into sections dealing with characterisation of the seabed through survey and interpolation onto bathymetric surface models (Section 2); the determination of morphological changes arising from different processes (Section 3); and an assessment of these approaches in a data and infrastructure context, including a preliminary outline workflow for evaluation of the risk to infrastructure from seabed morphological change (Section 4). Although this research is primarily focused on the UK continental shelf, the issues identified are largely generic and the scoping study draws upon a wider international literature where appropriate.

2. Characterisation of seabed morphology

The seabed is a naturally dynamic surface that evolves its morphology in response to processes acting over a wide range of spatial and temporal scales. In this respect, the geomorphology of the seabed is largely analogous to that of terrestrial land surfaces. Within the submarine environment, however, elucidation of these processes and their effect is more difficult owing to our reliance on incomplete mapping of the continental shelves and the fact that we typically have to rely on various forms of remote imaging in combination with inferences from descriptive geomorphological techniques. Advances in seabed survey technologies have clearly been considerable (Atallah and Smith, 2004; Brown and Blondel, 2008) although only a small proportion of the seabed (even that of the continental shelves) has been mapped by the current generation of high-resolution bathymetric and seismic survey techniques.

As Prior and Hooper (1999) note, the advent of new mapping datasets has, on the one hand increased the potential for geomorphology to contribute to engineering assessments of infrastructural risk, but on the other, presented new challenges for the recognition and interpretation of the characteristic sea floor features and their process origins. This applies to the determination of rates of progressive bed elevation change as much as to the analysis of the more obvious event-driven mass-movements triggered by seismicity or slope failure. Any analysis of seabed morphological change must necessarily start with some characterization of not just the bathymetry but also an analysis of the availability of potentially mobile sediments. In order to quantify expected magnitude of vertical bed elevation change, these changes must be greater than the uncertainty in sequential bathymetric surveys. It is therefore essential to quantify the uncertainty in both individual bathymetric measurements and in the generation of interpolated seabed terrain models on which morphological change analyses are based.

2.1. Seafloor substrate and potential mobility

Large-scale morphological evolution of the seabed occurs over long geological timescales under the influence of discrete events as well as more gradual changes due to sedimentation and erosion. As Mosher (2011) argues, bathymetric and seismic surveys of many areas will reveal a suite of features that are largely relict features and others that have a low probability of recurrence within the decadal time spans typically considered in relation to offshore engineering projects. Other areas are more dynamic, especially in shallower waters that experience higher tidal current and/or wave-generated shear stresses at the seabed and which have an abundance of potentially mobile sediment.

Change in seabed morphology and local elevation at decadal scales clearly requires the presence of mobile sediment. This requirement provides the basis for an initial filter that might be applied in advance of the more sophisticated analyses described later in this report. Such a filtering operation would involve two stages:

1. Available information on the nature of the seabed would be used to distinguish between zones characterized by more resistant bedrock surfaces and those with a sediment cover. For the UK continental shelf, the British Geological Survey (BGS) supply a suitable data product (1:250,000 Seabed Sediment) that maps seabed sediment cover and type.

2. Consideration would then be given to the likelihood of the sediment cover being mobile under contemporary water depths and tide and wave conditions. Few observational datasets exist for the interaction between tidal currents, waves and sediments and so this stage of the filtering operation needs to be informed by information extracted from numerical tide and wave models. Several such models have been implemented at the scale of the UK shelf, with recent efforts being motivated by a desire to better quantify regional sediment transport pathways and also refine estimates of offshore tidal and wave power generation potential (e.g. Hashemi et al., 2015). These models provide a means of estimating spatial variation in both time varying and peak tidal and wave-induced flow velocities close to the bed. These can be combined with appropriate drag coefficients based upon knowledge of the seabed sediment type and grain size (e.g. Soulsby, 1997) to refine the classification of sediment-rich seabed to include only those areas where surface sediments are likely to be mobile under particular hydrodynamic conditions (e.g. extreme events with a specific return period).

2.2. Seabed morphology

Sediment-mantled seabed typically exhibits bedforms that occur at a range of spatial scales. At a small scale, ripples and sand waves are typically organised in more extensive fields. At a large scale, ridges and banks occurs as more isolated individual features (Figure 1). Hereafter in this report, these scales are referred to as the bedform and landform scales respectively. These morphological features are found in a range of seabed settings that cover different water depths, shoreface position and estuarine-coastal context. Their morphology and dynamics tend to be forced by storm- and/or tide- generated currents that can drive both erosional and depositional formations (Stride, 1982; Swift et al., 1991). In sandy sediments, the suite and morphology of bedforms that develop will usually reflect i) the dominant sediment transport (bedload) direction; ii) sediment supply/availability; and iii) the relative magnitude of seabed (bottom) currents (Belderson et al., 1982; Dyer and Huntley, 1999).

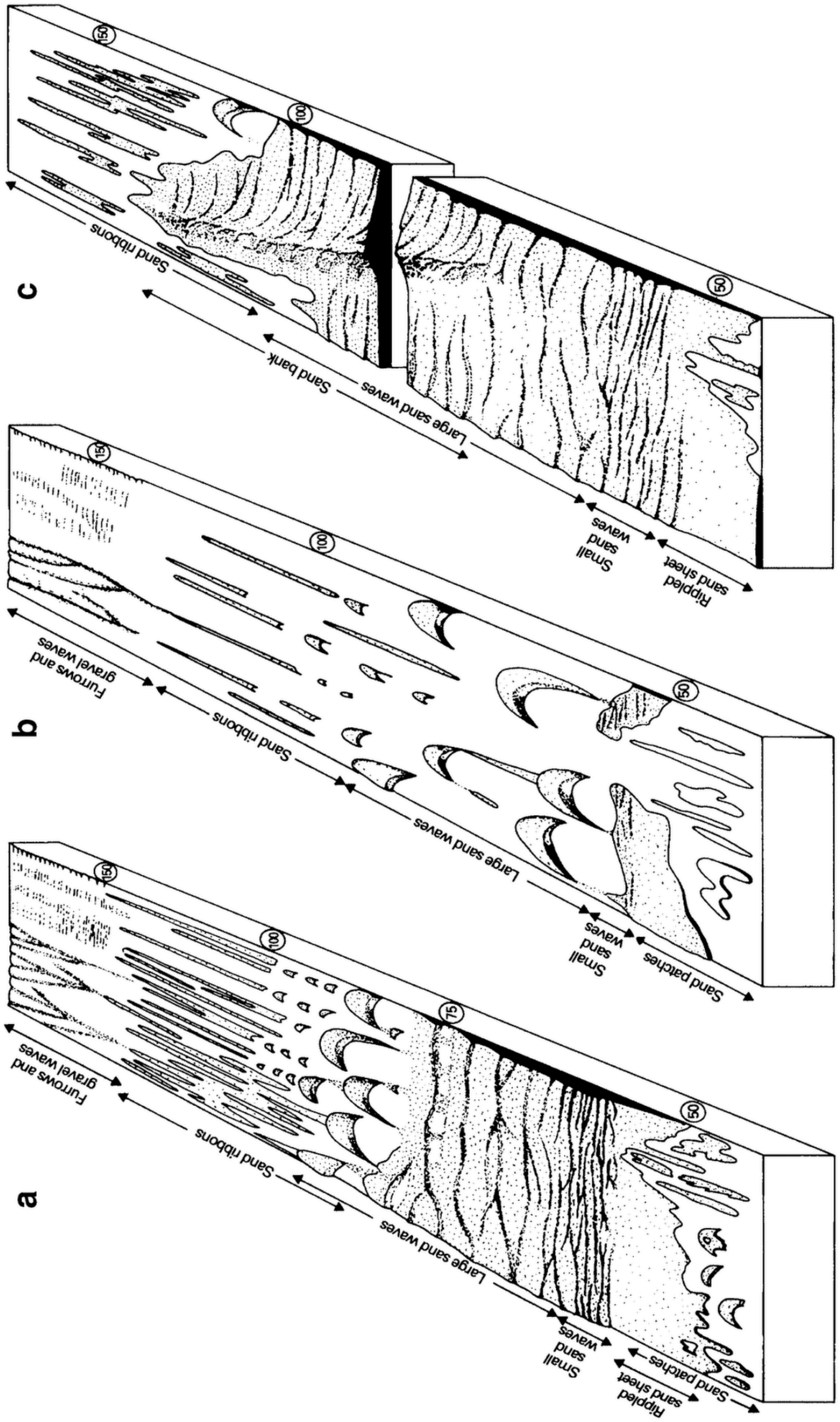

Figure 1 Seafloor bedform types organised in the context of tidal transport pathway (from rear to front of perspective views) for A) average conditions, B) supply-limited and C) abundant sand availability (source: Belderson et al., 1982).

Within a UK context, the banks and bedforms of the sand-dominated areas of the North Sea are especially well developed and have been the subject of numerous studies (e.g. Caston, 1972; Huntley et al., 1993; Hulscher and den Brink, 2001; Burningham and French, 2011). It is recognised that the features revealed in bathymetric surveys include both active and moribund features, with the latter tending to lie in deeper waters (Dyer and Huntley, 1999). Knaapen (2004) provides a tabulation of indicative spatial scales (wavelengths; amplitudes) and time scales (rates of horizontal migration) and this is reproduced here in Table 1.

Table 1 Orders of magnitude of selected characteristics of offshore sand bedforms: wavelength, L, height, H, migration rate, c and the typical time scale, T, in which the patterns evolve (after Knaapen, 2004). The present report considers ripples and sandwaves to constitute a bedform scale and ridges and banks to constitute a landform scale.

Feature	Wavelength (m)	Amplitude (m)	Migration rate	Evolution time
Ripples	1	0.01	1m/hour	Hours
Mega-ripples	10	0.1	1m/day	Days
Sand waves	500	5	10m/year	Years
Long bed waves	1500	5	?	?
Shoreface connected ridges	4000	5	1m/year	Decades
Tidal sand banks	6000	10	1m/year	Centuries

At the smallest scale, features such as sand ripples and mega-ripples are of little interest from an engineering perspective of account of their low amplitude and, in any case, are virtually impossible to resolve using conventional bathymetric surveys. The larger mega-ripples do, however, generate time variation in seabed elevation that will most likely be under-sampled by sequential bathymetric surveys and thus contribute to the measurement uncertainty. Sand waves are more direct interest since they are known to migrate rapidly enough under the influence of tidal asymmetry and residual currents to move considerable distances within the lifespan of major infrastructure (Németh & Hulscher, 2002). They can generate large enough perturbations of the seabed elevation to affect navigation (e.g. Knaapen et al., 2005a) expose pipelines and cables, possibly resulting in free spans (Morelissen et al., 2003). Larger sand banks evolve their morphology at longer timescales and are quite variable in their behaviour depending on tidal and wave process environment and the geological context. Some appear extremely stable over decadal to centennial timescales, some show in situ variability in position, and others show progressive migration (Burningham and French, 2009; 2011).

At the landform scale, the continental shelf around the UK comprises a range of static and dynamic features. Dyer and Huntley (1999) presented a classification and description of the primary sedimentary structures found across the seabed of shelf environments, which in part also provides some indication of their generation and contemporary forcing. More recently, the BGS have outlined a new approach to seabed classification that differentiates between seabed forms (morphology) and seafloor process domains (geomorphology) (Dove et al., 2016). Encompassing the full suite of seabed environments, not just those associated with sedimentary deposits, this classification has the potential to provide a significant basis for the assessment of morphodynamic risk. Although the classification approach has been outlined, the mapping of the UK continental shelf has not been completed meaning no data product is readily available. The mapping might survey a purpose in future assessments of seabed dynamics, but here simply provides a conceptual framework.

It follows from the above that the dynamics of sedimentary seabed surfaces in the relatively shallow waters of the continental shelves stems largely from the behaviour of organised bedform features and, in particular, their horizontal migration at different rates. Much has been learned about the behaviour of submarine dunes and sand waves from sequential multi-beam bathymetry surveys of relatively localised areas (e.g. Knaapen et al., 2005b; Duffy and Clarke, 2005). However, engineering assessments of seabed behaviour are frequently reliant upon analysis of existing surveys conducted for other purposes to varying standards of accuracy using different techniques (see for example, Dyer, 2011). This is especially relevant to situations where larger tidal sand banks occur, since the long time scales over which this features form and evolve their morphology and position require analysis of historical bathymetric chart surveys as well as modern multi-beam sounding datasets. Prior to any form of change detection, therefore, it is essential to consider the uncertainties present in the raw bathymetric datasets.

2.2.1. Hydrographic surveys and derivation of bathymetric surfaces

As noted above, our knowledge and understanding of seabed morphology is determined by the resolution and frequency of bathymetric mapping. Modern hydrographic surveys are increasingly undertaken using high-resolution multi-beam sonar with a typical spatial resolution of 1 to 2 m and a precision of a few centimetres for a point measurement of depth (Brown and Blondel, 2008; Brown et al., 2011). In contrast, soundings and charted bathymetries associated with historic surveys have a much coarser spatial resolution (typically around 400 to 1000 m) and a lower fundamental measurement precision (1 foot (0.3048 m) was the smallest depth unit for most pre-metric surveys). Hereafter in this report, the term ‘high-resolution survey’ is used for multi-beam datasets and ‘low-resolution survey’ refers to older surveys obtained through single beam echo sounding or traditional lead line surveys.

It should be noted that errors are always present in any measurement (Taylor, 1996) and are the differences between the measured value and the true value. The International Hydrographic Organisation (IHO) highlight the fact that since the true value is never known it follows that the error itself cannot be known (IHO, 2008). The analysis of error thus becomes an analysis of uncertainty, that is a statistical assessment of the likely magnitude of this error. Current minimum standards for hydrographic surveys are outlined in IHO (2008) and these vary according to the purpose of the survey according to an outline uncertainty model that acknowledges that some sources of measurement error are independent of the water depth while others depend in some way on the depth. The IHO standard for total vertical measurement uncertainty, *TVU*, can be expressed as:

$$TVU = \sqrt{a^2 + (b \cdot d)^2} \qquad [1]$$

where *a* is the portion of the uncertainty that does not vary with depth, *b* is a coefficient representing the proportion of the uncertainty that does very with depth and *d* is water depth. Depending on the order of the survey, *a* can vary from 0.25 m to 0.50 m and *b* between 0.0075 and 0.013. IHO standards for positional accuracy vary according to the order of survey being undertaken. Acceptable positional uncertainties for bathymetry soundings (expressed as a 95% statistical confidence interval) range from 2 m for special surveys where there are critical implications for navigation, to 20 m + 10% of the depth for lower order surveys in water deeper than 100 m.

At the scale of an individual depth determination, measurement errors arise within the instrument system itself, as well as in related systems concerned with datum control (including correction for tidal variation that would otherwise affect vessel-mounted sensors), and positioning. The fidelity with which a complex continuously varying surface can be resolved is also dependent on the area of ensonification (i.e. the spatial footprint at the bed of a single measurement), which depends partly on depth but also on the beam angle. As, Mosher (2011) shows, variation in the area of ensonification can be large across the swath width of multi-beam sounding surveys and can affect the resolution of discrete objects (such as boulders or structures) on the seabed.

Fundamental measurement error is not the only source of uncertainty. In reality, the seafloor is a continuous surface that it is resolved by measurement at a finite set of points. For both the descriptive characterization of the seabed and the determination of temporal changes in depth or bed elevation, these raw bathymetric survey data are interpolated from irregular survey lines onto regular grids to generate a Digital Elevation Model (DEM). Essentially the same process applies to high-resolution digital multi-beam datasets, raw data from single beam surveys, and digitised hydrographic charts. Interpolation is performed with algorithms that use information from neighbouring points to perform some form of local averaging. Regardless of the algorithm used (inverse distance weighting, nearest neighbour etc.), the higher the density of the original soundings the more information available on which to estimate the bed elevation at a grid point and the higher the statistical confidence in its value. There is there an additional error in the interpolation of data (Mosher, 2011), which depends on the nature of the actual seabed surface, raw data density, the interpolation algorithm, and the distance between the interpolation point and the nearest measured point(s).

Interpolation of discrete depth measurements onto a regular grid (Figure 2) involves a choice of interpolation algorithm and resolution (output grid cell size). Deterministic interpolation approaches make simple assumptions about the relationship between point value of neighbouring points and distance to grid cell location. This usually follows the concept that values of closer points should have more bearing on the predicted result than values of points at some distance. The simplest expression of uncertainty in the results of this interpolation process is through the point-based residuals (i.e. difference between observed and modelled value at each input point). This is typically quantified using a metric such as the root mean square error (RMSE), given by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(Z_{est}^{i} - Z_{\mathrm{mod}}^{i}\right)^{2}}{N}} \qquad [2]$$

where Z_{est} and Z_{act} are the estimated (modelled) and actual (measured) values of the seabed elevation at location i and N is the number of measurements. Interpolation to a resolution higher than that of the original data reduces the statistical confidence of the fitted surface, and may create misleading artefacts. On the other hand, under sampling without first applying a low-pass filter may lead to the appearance of spurious regularities due to aliasing of under-resolved high frequency detail (Mosher, 2011; Dyer, 2011).

Grid cell size is thus usually selected with consideration to the spatial extent and point density of the input data. However, where comparison between surfaces representing different time frames is required, it can be difficult to find a satisfactory balance between spatial detail and data density. This is illustrated in Figure 3, wherein the data points for a sample dataset from 1933 have a spacing of 200 to 900 m, whereas a comparable 1995 dataset has an inherent spacing of 60 to 80 m. At the 100 m grid cell resolution, a linear bank is discernable in both surfaces, but sand wave structures are only apparent in the 1995 surface, although this region of the grid exhibits some change from one time frame to the next. At the 500 m and 1000 m resolution, the differences become less noticeable and the two surfaces become more similar in structure. The interpolation in this example is performed using a fairly simple inverse-distance weighted algorithm (see, for example, Davis (1986)). More sophisticated interpolators are discussed in Section 2.2.3.

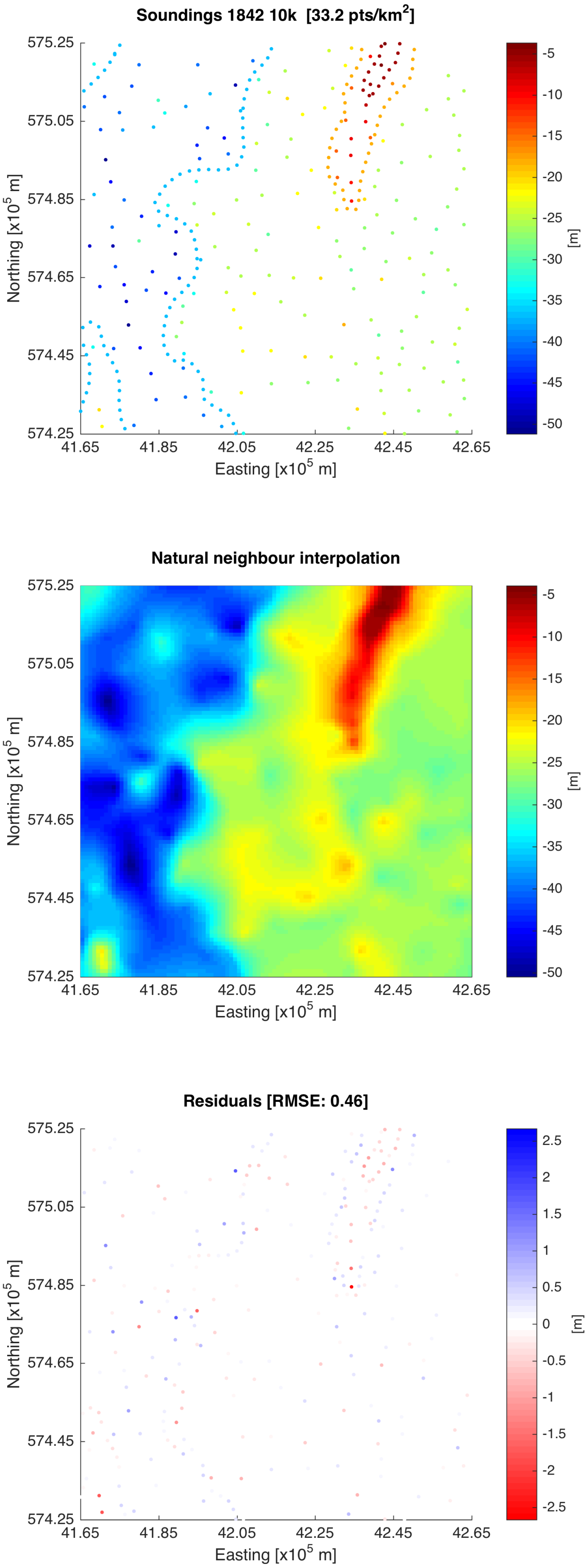

Figure 2 Illustrative sample of hydrographic data (digitised soundings from an 1842 chart), interpolated on to a 100 m grid, with input point-based residuals and the root mean square error (RMSE) calculated.

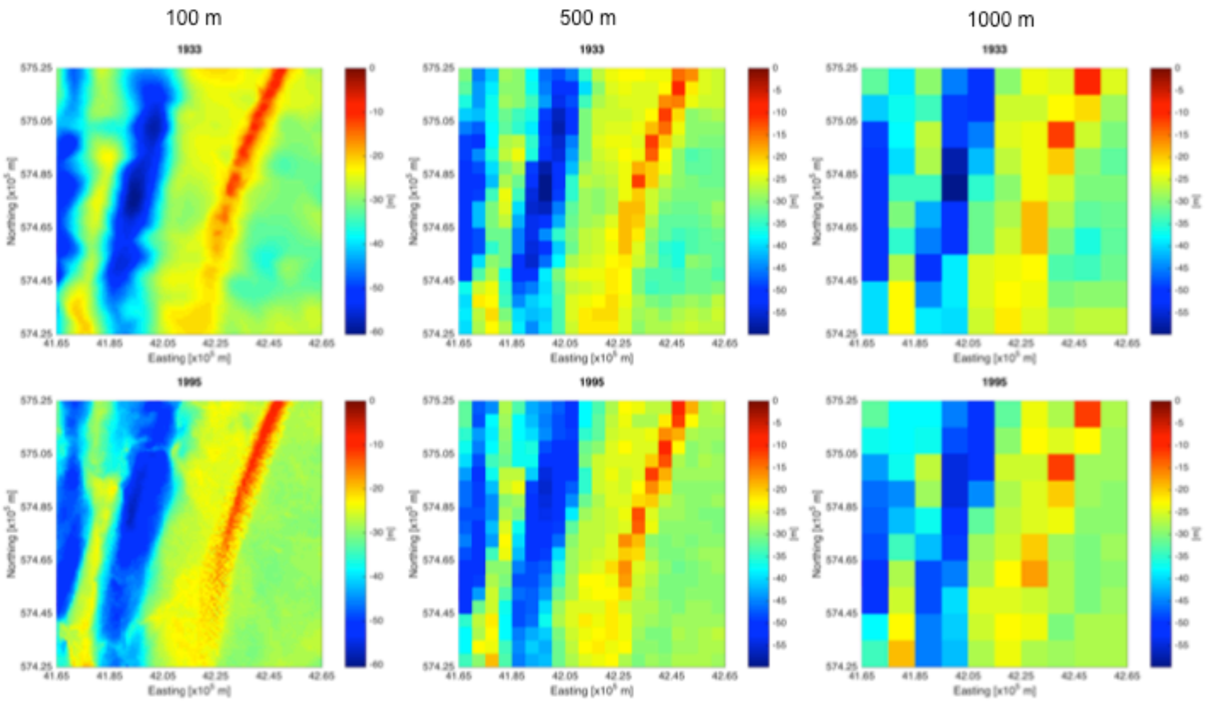

Figure 3 Comparison of interpolated bathymetric DEMS arising from raw datasets of varying spatial sampling density generated at different output (interpolation) resolutions. Upper three panels are derived from a 1933 survey that has a density of 25 soundings km^{-2}; lower three panels show equivalent DEMS generated from 1995 data with a density of 2708 soundings km^{-2}.

From a UK perspective, data access and resolution is very variable and the availability of high resolution datasets in particular is very patchy. The EU INSPIRE (Infrastructure for Spatial Information in Europe) initiative has prompted the dissemination of some survey data under the Open Government Licence. These data are freely available through the UKHO INSPIRE Portal. For some locations around the UK, time sequences of several high-resolution surveys are freely available, whilst other areas are covered by a single low-resolution survey or no data available at all. Hydrographic surveys from older published charts or soundings from original fair sheets, which usually require digitisation, are often needed in order to provide a temporal perspective.

Pre-processed bathymetric surfaces can be obtained through SeaZone (who provide a range of varying resolution products for different applications and budgets). Alternatively, the European Marine Observation and Data Network (EMODnet) has assembled a digital bathymetric model based on integration of GEBCO (General Bathymetric Chart of the Oceans) with hydrographic survey data. The bathymetric surface covers the entire UK continental shelf with a resolution of 1/8 minute (~0.002º), equivalent to around 120-230 m.

2.2.2. Morphology

The next stage of an analysis involves examining the interpolated seabed surface models to determine the existence or otherwise of morphological features that may give rise to bed elevation changes over areas and timescales of interest. As Figure 4 shows, landform-scale features such as sand banks and ridges (Swift et al., 1991; Dyer and Huntley, 1999) are readily identified on both high and low-resolution surveys. The detection of smaller-scale bedforms, from ripples to sand waves (Knaapen, 2004; Table 1, is far more limited by the resolution of the survey data and by the interpolation onto a bathymetric model. Older surveys might show evidence of sand waves in the form of increased local time-variation in depth measurements between successive surveys even when no clear morphological feature is directly resolved (see also Dyer, 2011).

The presence of sand waves, ridges or banks provides evidence for the transport of sediment, and the potential for morphological change. Seafloor environments where no such features are present are less likely to experience significant morphological change in the near-future in comparison to environments where local bed level variability is larger due to the presence of sand waves or banks. Spatial variation in bed elevation is therefore an indicator of potential variability over time at any one location.

Morphometric analysis uses spatial algebra on DEMs to extract specific topographic measures. Slope and curvature, the first and second derivatives of elevation or bathymetry respectively, can be used to identify broad trends and discrete features across seabed surfaces (e.g. Figure 5). Established terrain analysis metrics have been proved effective in the characterisation and classification of topographic surfaces (e.g. De Reu et al., 2013). These apply more refined algebraic expressions that seek to highlight peaks, troughs, flat areas and varying slopes (Figure 5). For example, Terrain or Topographic Ruggedness Indices (TRI) express the relative local difference in elevation or depth to capture different scales of features described by varying rates of change in elevation of depth (originally described by Riley et al. (1999)). The method has been variously evolved by others, but the TRI is generally calculated as:

$$TRI = \sqrt{\sum(x_{ij} - x_{oo})^2} \qquad [3]$$

where x_{oo} is the central cell value, x_{ij} are each of the 8 neighbouring cells for which the difference in elevation or depth to the central cell is calculated and averaged.

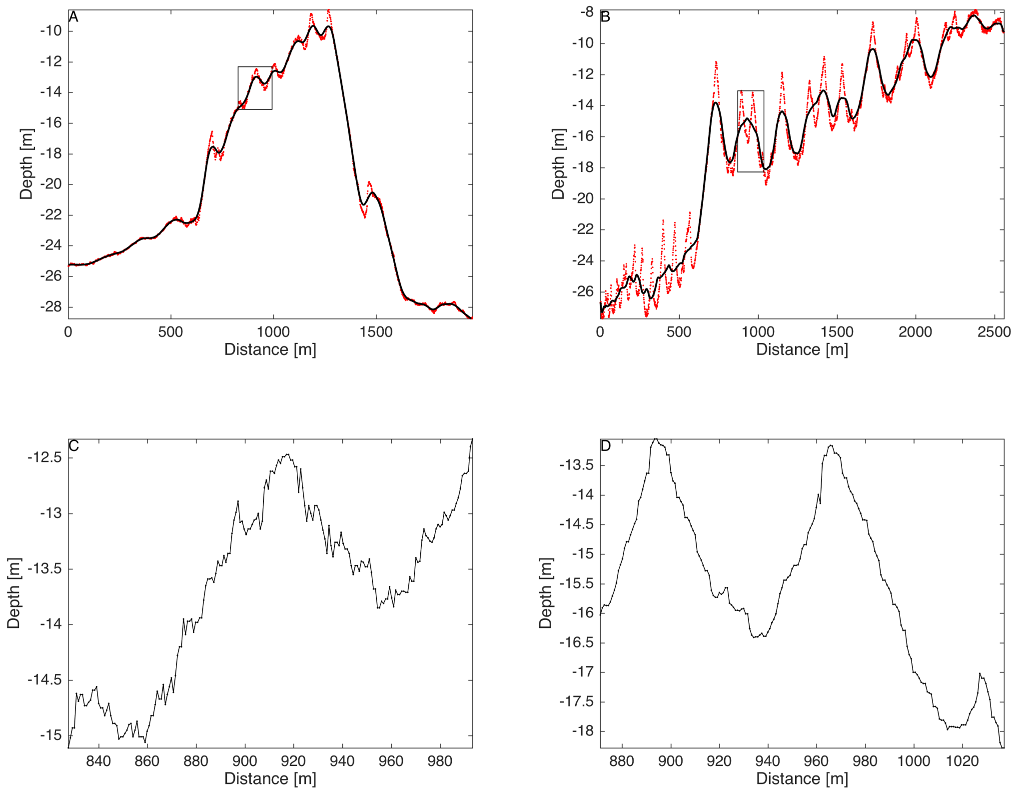

Figure 4 Illustrative morphological features at the landform (A and B) and bedform (C and D) scales: A) cross-section (west to east) of the north of Galloper Bank, North Sea; B) long-profile from open seabed to the north end of Galloper Bank (north to south); and sand wave and ripple structures across (C) and along (D) the bank.

Similar approaches have also been applied to bathymetric surfaces (e.g. Lundblad et al., 2006; Micallef et al., 2012), primarily in the field of seafloor habitat mapping and habitat suitability modelling. In the example shown in Figure 5, morphometric measures highlight the notable slopes across the 100 m cell size bathymetric surfaces, around the margins of the sand bank to the right, and the channelized regions to the left. These indices are far more effective on the 1995 seabed surface generated from high-resolution data than on the 1978 surface derived from low-resolution survey data. In particular, the 1978 DEM struggles to identify linear topographic features that are very prominent on 1995 DEM.

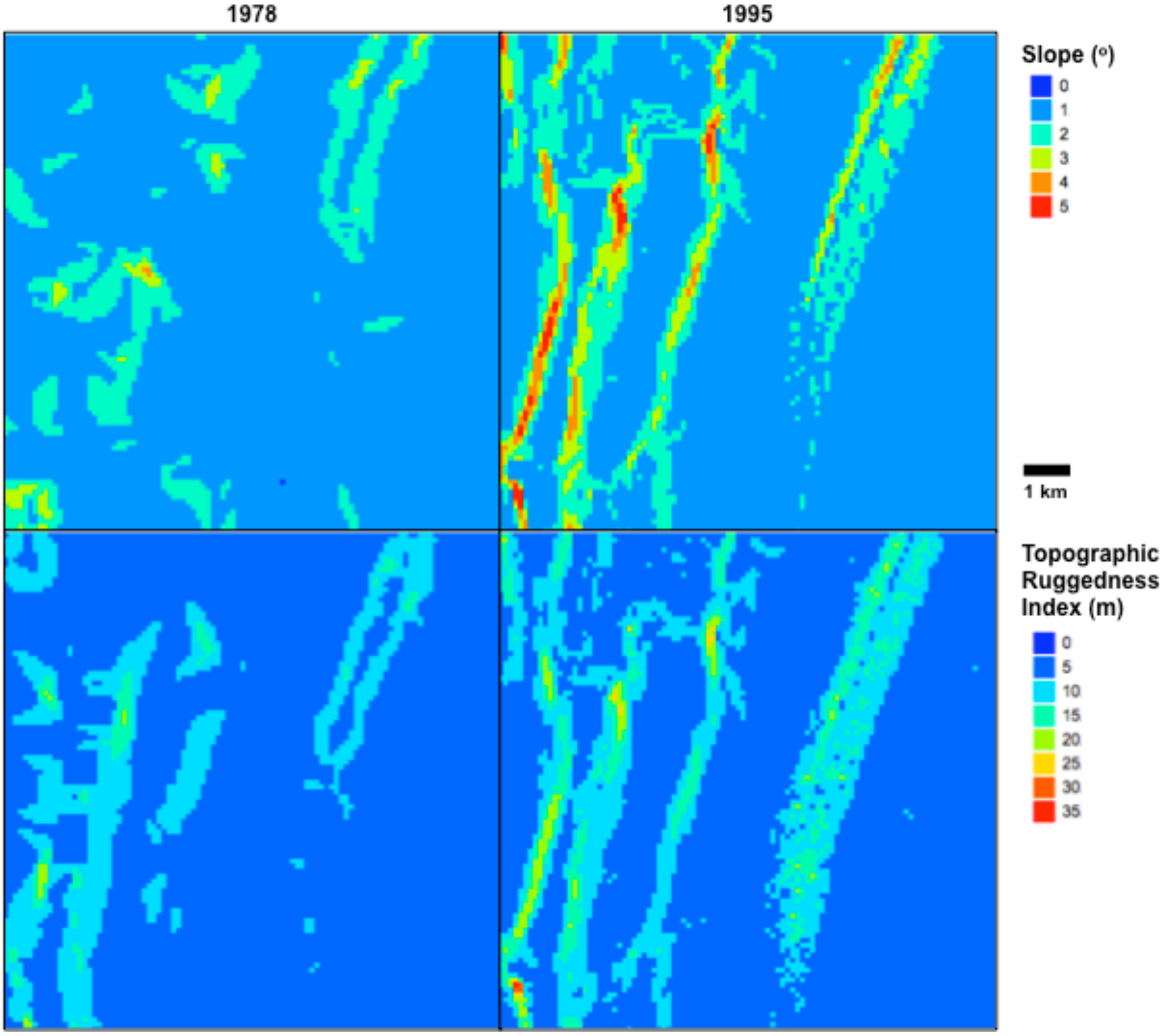

Figure 5 Slope and Topographic Ruggedness Index (TRI) metrics applied to interpolated seabed bathymetry surfaces derived from low-resolution (1978) and high-resolution (1995) hydrographic surveys.

2.2.3. Seafloor variance

There are several methods that can be applied to the generation of bathymetric surface models. In the illustrative examples presented so far, bathymetric DEMs have been produced using simple inverse-distance weighting. A more statistically rigorous treatment is made possible through the applicational of geostatistical techniques. that range from a simple application of neighbourhood statistics through to more complex geostatistics. Geostatistics is founded on the concept of the regionalized variable (Matheron, 1971), and the realization that closely-spaced neighbouring values exhibit a stronger spatial autocorrelation than ones further apart. A regionalized variable is one that exhibits continuity from point to point but has variability too complex to represent with any simple deterministic function. We know about the variable through measurements at a discrete set of locations. A key goal of geostatiscal analysis is the interpolation of such irregularly spaced data to unsampled locations in a way that is directly informed by their natural scales of spatial variability and which generates a statistically optimal surface along with accompanying estimates of the uncertainty at each point. This process is termed kriging (Davis, 1986; Oliver and Webster, 2014).

The spatial scale over which this holds for a bathymetric dataset can be determined experimentally through the fitting of an empirical (or sample) variogram, which describes how depth measurements are correlated with distance. The empirical variogram is calculated by:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (z_{xi} - z_{xi+h})^2 \qquad [4]$$

where z_{xi} and z_{xi+h} are the data values spatial positions x_i and x_{i+h}, and N is the number of pairs separated by Euclidean distance, h (Davis, 1986; Oliver and Webster, 2014). The resulting variogram cloud is then summarised on the basis of averaged distances and associated semivariance(Figure 6).

The empirical variogram is fundamental to geostatistics as it provides an estimate of the theoretical variogram and a basis for interpolation to unsampled locations through various forms of kriging. As shown in Figure 6, it is usual to model variogram using one a small set of standard curves. These curves generally have the property that, as distance increases, the semivariance levels off and spatial autocorrelation is no longer considered to be a function of distance. This asymptote of semivariance is termed the *sill*, and distance where this occurs is termed the *range*, and these parameters inform the model fit (which can be exponential, linear, spherical etc. in form). There may be an offset at the y-intercept, referred to as the *nugget*; this is usually assumed to be a non-spatial component and is sometimes used as an indication of measurement error.

Information gained from the variogram can then be used to generate a statistically optimal interpolation of the irregularly spaced sample data onto a regular grid (the process of kriging). In contrast to more simply mechanistic inverse distance weighting or natural neighbour algorithms, kriging also gives a measure of the uncertainty (variance) associated with the interpolated surface (Figure 7). This can be extremely useful, in combination with a conventional uncertainty analysis of the original measurements (IHO, 2008), to construct an overall uncertainty associated with a seabed surface model. This in turn, helps set the bounds for the kind of seabed changes that can be resolved through comparison of sequential DEMs and help in the filtering of signal from noise.

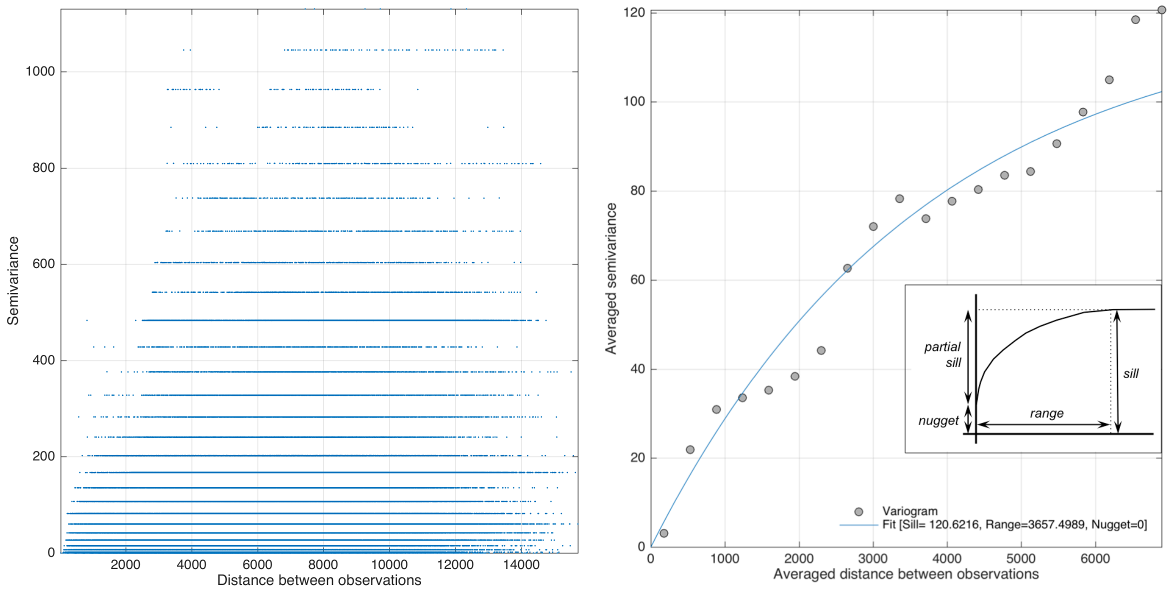

Figure 6 Spatial variance in a bathymetric dataset represented by the variogram cloud (left) and classical variogram with modelled (exponential) semivariance (right).

Application of kriging to real bathymetric datasets, especially large multi-beam datasets, can be a bit more complicated. Experimental variograms often do not conform well to idealised models and it can be difficult to objectively define a sill and range. Figure 6 illustrates the difficulties fitting an idealised model to an actual bathymetric dataset (a sample of soundings data from an 1842 survey), where the classical sill-range asymptote is not expressed particularly well. Here, there is no obvious nugget effect, and the transition to greater distances does not follow a classic variogram form. Computational overheads can also be very high with large datasets due to the need to calculate and store distances and differences across all unique pairs within a dataset (although various large dataset algorithms are available (see, for example, Cressie and Johannessen (2008) and Rennen (2009)).

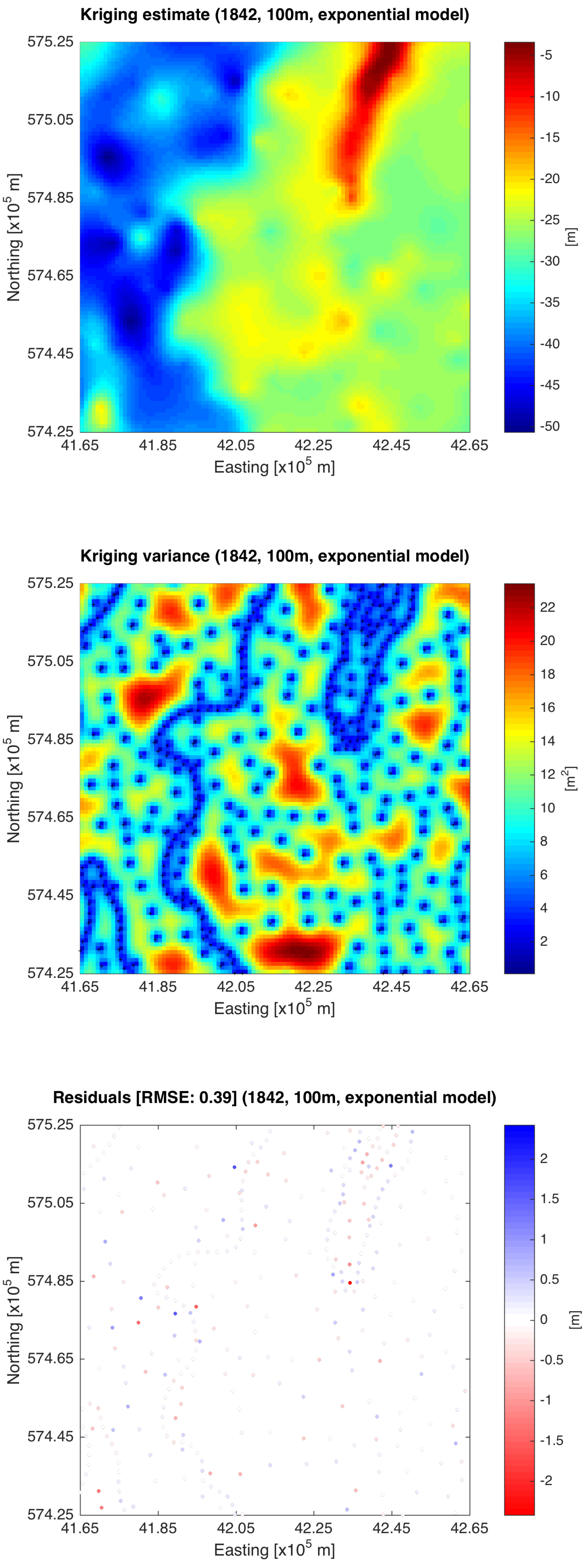

Figure 7 Kriging interpolated seabed surface model (upper panel), with spatial uncertainty (middle panel) and RMSE (lower panel).

3. Seafloor morphodynamics

3.1. Morphological change

Assessment of seabed morphological change requires the availability of sequential seabed models defined for at least two points in time. Change analyses using bathymetric DEMs are widely used to explore seabed morphodynamics and habitat mapping. However, the degree to which such information can be used to quantitatively inform evaluations of the associated risks to infrastructure depends on the nature and rate of change relative to the uncertainties inherent in the creation of the source DEMs.

Morphological change on the seabed can arise through processes giving rise to primarily vertical bed level change as well as by lateral migration of bathymetric highs and lows. In the former case, accretion might occur as a result of regional sedimentation, or extensive areas of downwearing are possible in the vicinity of tidal streams. Region-wide accretion or downwearing would likely be evident across all survey resolutions, but the scales of vertical change would need to exceed the uncertainty associated with survey and interpolation errors as well as any datum adjustments needed to tie together the individual surveys.

At a finer scale, accretion and erosion can result from current interactions with obstacles, and this is particularly evident around structures and components of seabed infrastructure (as illustrated in Figure 8) where depositional and scour features can extend some distance from the obstacle in the direction of dominant currents. The identification of these features from hydrographic surveys is very dependent on the availability of high-resolution data. Evidence from the analysis of seabed features within the vicinity of shipwrecks and subsea piles (for example see Caston (1979) and Quinn (2006)) suggests that accretion-scour marks can achieve extents comparable to the size of the obstruction depending on the local sediment properties and energy regime. Such features are unlikely to be detectable from single-beam and lead-line hydrographic surveys unless the survey was undertaken specifically for that purpose.

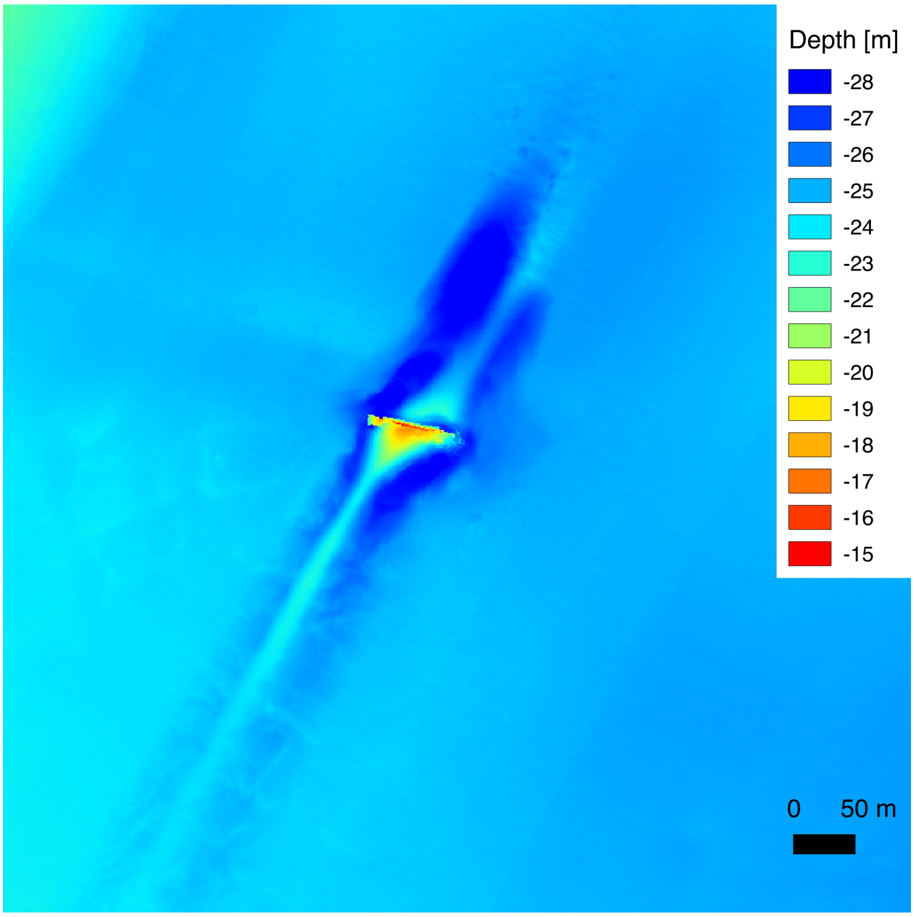

Figure 8 Bathymetric highs and lows associated with a seabed obstruction, which has led to distinctive deposition and scour features.

Morphological change can also be associated with the horizontal migration of sedimentary bedforms. Again, the potential for such changes to be detected is scale-dependent. Sequential multi-beam datasets acquired over short time intervals can be used very effectively to reveal local morphological changes associated with bedform movement. Figure 9 shows an example in which discrete sand wave features at a range of scales are captured well by bathymetric DEMs with a native resolution of 1 to 2 m. This allows precise analyses that effectively capture the magnitude and direction of bedform movement in addition to revealing the insignificant bed level changes in between these mobile bedforms. Key to interpretation of these results is an appreciation of the near-parallel banding of erosional and accretional signatures that are evidence of the transverse movement that occurs when bedforms migrate in the direction of a dominant sediment transport flux. Bedform-scale motions cannot be detected in coarser resolution bathymetries where the presence of under sampled features such as sand waves might be expressed as increased local variance. In most cases, older hydrographic survey data are not suitable for delineation of discrete bedform morphologies at anything less than the scale of the larger tidal ridges and sand banks and such analyses in sand-wave dominated environments will likely generate noisy estimations of change.

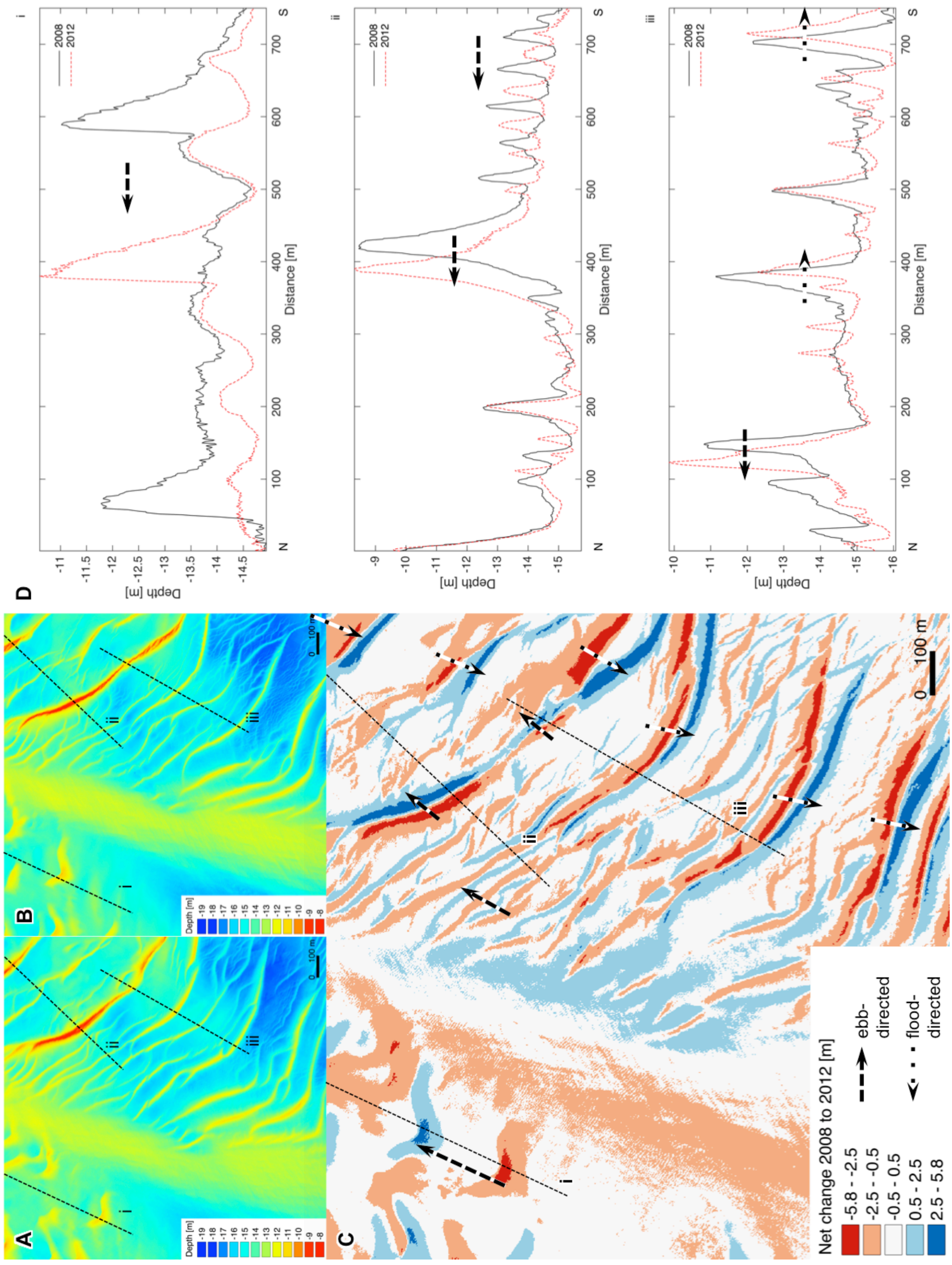

Figure 9 Short-term morphological change associated with sand wave migration driven by tidal currents. Change analysis of bathymetric surfaces from 2008 (A) and 2012 (B) reveal successive bands of erosion and deposition (C) that show spatial variation in direction of movement (D). To the west, features are moving northward, driven by the ebb tidal stream (D - i and ii); to the east, movement is southward, driven by the flood tidal stream (D - iii).

At the landform scale, seabed change is often manifested as patterns of erosion and accretion arising from lateral movements in tidal sand banks and intervening channels. As in the case of smaller scale bedforms, erosion-accretion banding at the landform scale can be diagnostic of the movement of a bathymetric high over a lower surface. Similar patterns of change can arise from the movement of channel features where a bathymetric low migrates through a surface. Figure 10 shows an example in which the large depth changes evident at an historical time scale (180 years) are dominated by linear patterns of erosion and accretion that reflect shifts in channel and sand bank position.

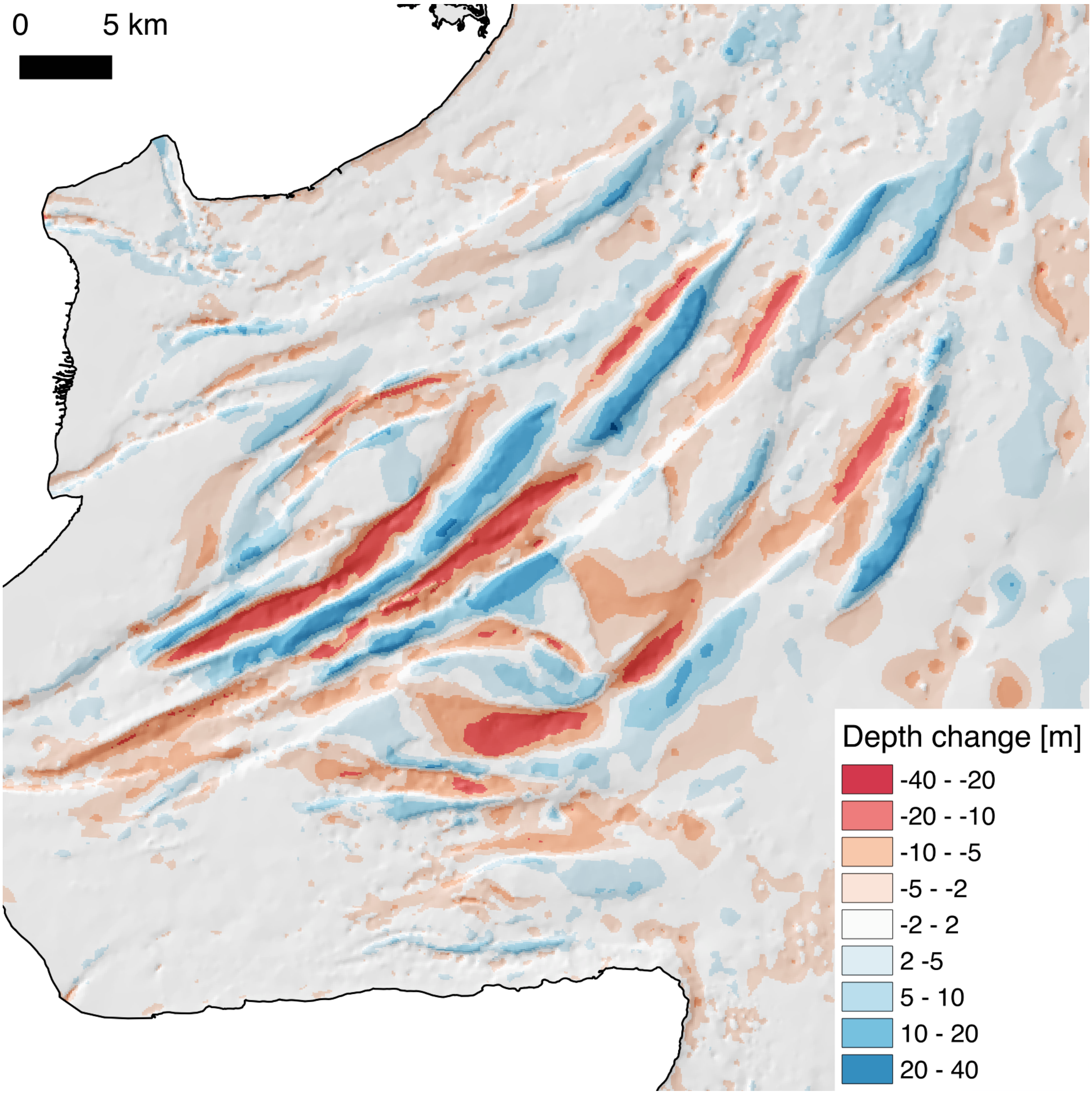

Figure 10 Seabed difference map for the outer Thames estuary based on comparison of seabed surface models for 1824 and 2003.

In funnel-shaped macro-tidal estuaries, such as the outer Thames, mobile sediment tends to be organised within a suite of linear banks that are shaped and bounded by multiple tidal channels. Historical analyses have shown that these features shift laterally over decadal time scales (Thomas et al., 2002; Barnard and Kvitek, 2010; Burningham and French, 2011). Analysis of bed level changes from a sequence of hydrographic surveys provides the means to assess these landform-scale changes and identify the potential for channel and bank movement. Such assessments are largely undertaken as a surface change analysis that is then interpreted in the context of the contemporary morphology (Figure 11). The associations between morphology and change can be extremely valuable as a means of teasing out the dominant forcing factors and determining the most likely future behaviour.

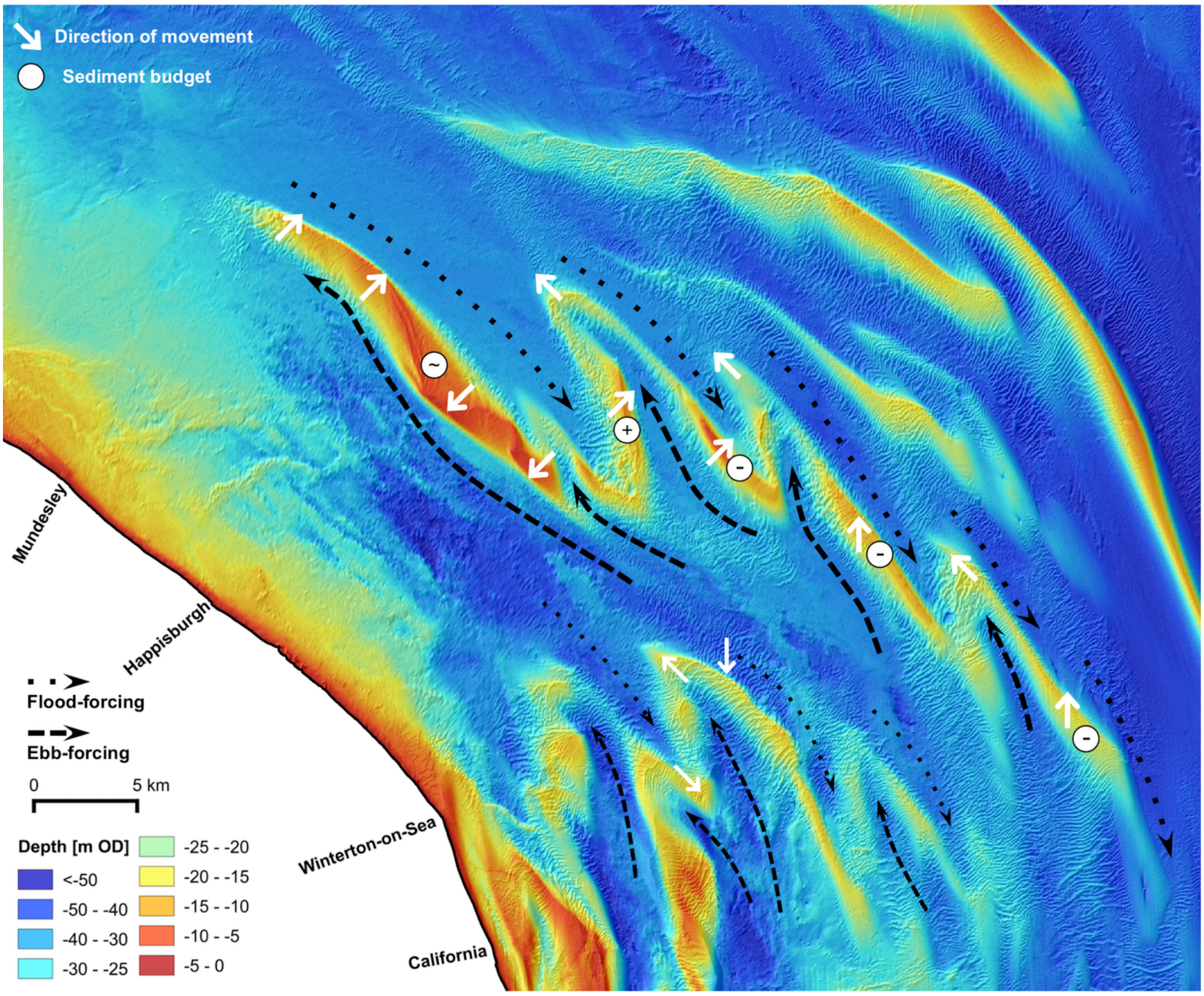

Figure 11 Conceptual model of historical morphodynamics of the Haisborough Sand bank system (source: Burningham and French, 2015).

3.2. Measures of morphological change

Difference calculations between bathymetric DEMs for different time epochs provide the basis of change maps such as Figure 12. The bathymetric surfaces need to be generated at equivalent resolution and their grids should be aligned. As already noted, the resolution of available surveys and their derived bathymetric surfaces has a direct impact on the scale of features that can be identified and evaluated. In Figure 12, difference maps between earlier (which in most cases implies low density) and more recent (which generally means higher density) surveys are shown for DEMs of various resolutions. Using a resolution appropriate to the more recent survey, the discrete patterns of change evident are possibly a product of interpolation across areas where limited data is available. But at a coarse resolution, interpretation of change becomes problematic due to the lack of clear morphology-change associations; these are implied in the finer resolution surface, even if aided by the interpolation process.

In situations where surveys are available for multiple time frames, it is possible to compute time-series statistics (Figure 13). The temporal mean can highlight morphological features that persist through time, whilst a temporal variance or standard deviation will highlight the seabed zones that have experienced increased variability through time. Although the net change (difference) maps shown in Figure 12 express the magnitude of change between one time frame and another, deriving a time-series trend (Figure 13) can effectively integrate changes experienced through time. A time-based linear regression of bed level change can reduce the impact of specific outliers and utilise all survey time frames to provide a rate metric that can be extrapolated into the future. Correlation and significance statistics of the regression can be used to classify the resulting map into zones of confidence levels (Figure 14).

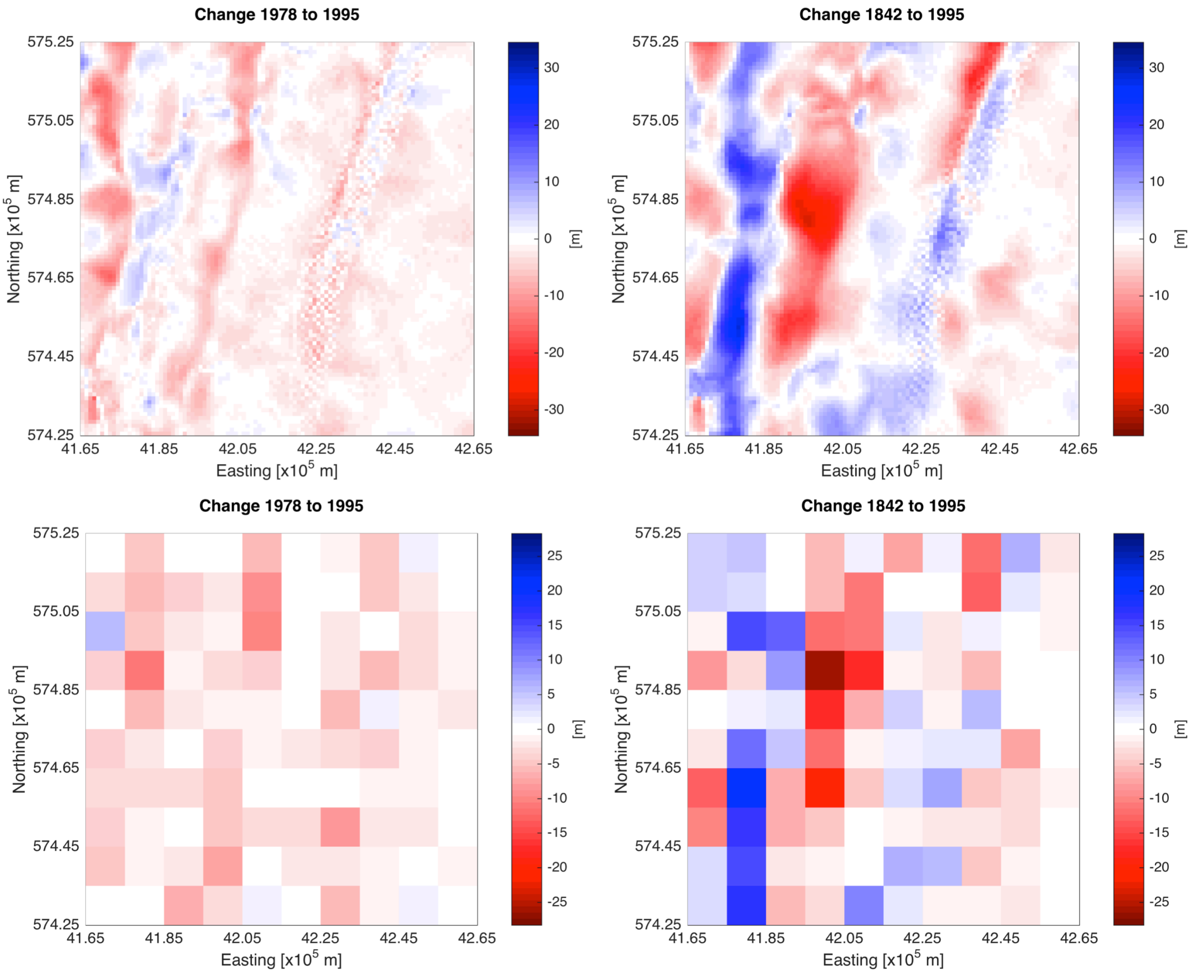

Figure 12 Bathymetric change maps created using illustrative bathymetric DEMs for 1978 to 1995 (left) and 1842 to 1995 (right) derived at 100 m (top) and 1000 m (bottom) resolution.

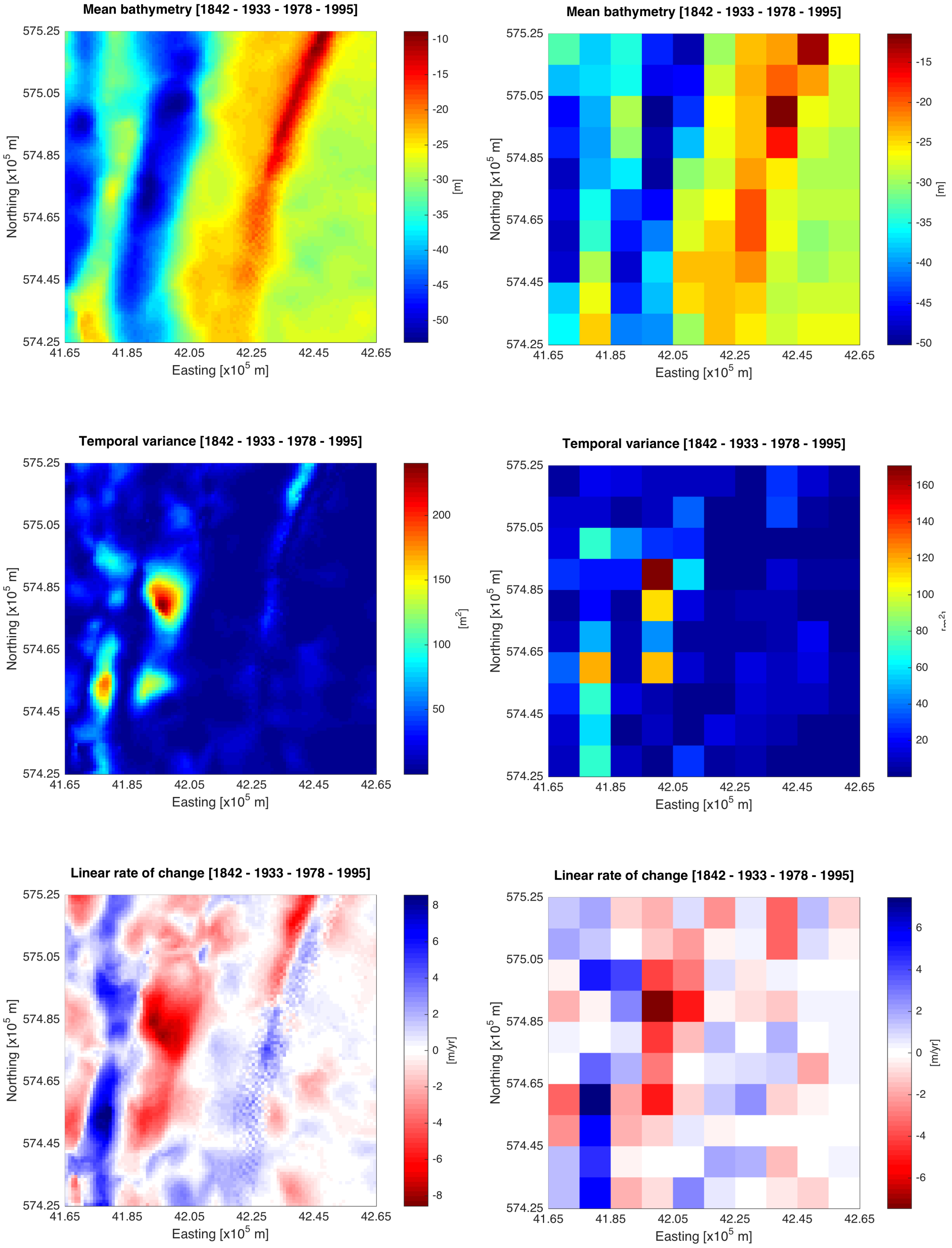

Figure 13 Temporal statistics derived from bathymetric change analysis (data from 1842, 1933, 1978 and 1995) at 100 m (left) and 1000 m (right) resolution.

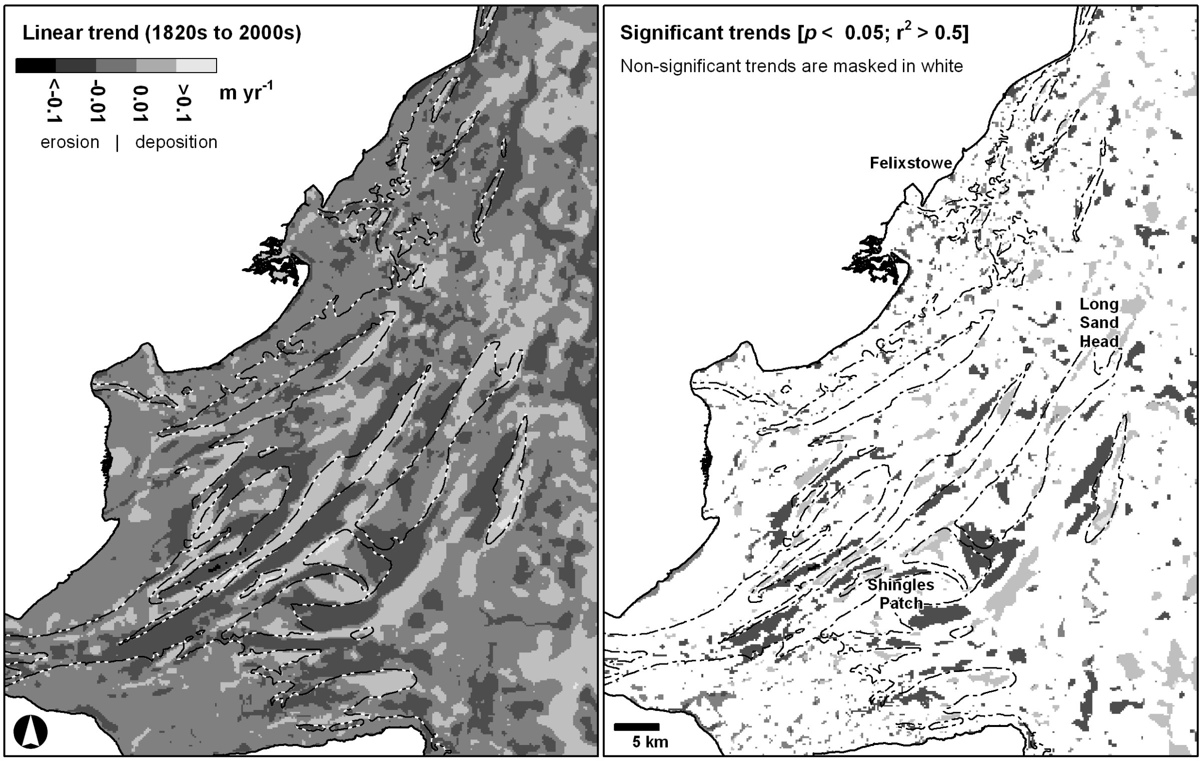

Figure 14 Linear trends in seabed dynamics over the 1820–2000 period in the outer Thames estuary (a) that are then reclassified on the basis of statistical significance ($p < 0.05$ and $r^2 > 0.5$) (source: Burningham and French, 2011).

3.3. Automated detection of correlated morphological change

The methods for assessing morphological change presented so far are largely based on an interpretive evaluation of change and morphology. In this case, identification of migratory features is largely based on an integrated interpretation of different spatial expressions of morphometry and change, and derivation of the direction and rate of lateral movement is undertaken manually as part of this. However, there is also considerable interest in the automated detection and quantification of changes associated with the migration of discrete features at both bedform and landform scales.

A number of studies have applied spatial cross-correlation to the analysis of bedform migration (e.g. Duffy and Hughes-Clark, 2005). Made possible by the advent of multi-beam bathymetric data, cross-correlation is used to find the location in a dataset where a peak in correlation between the two signals is found. Applied across two bathymetric DEMs, the location of the peak allows offsets in both x and y dimensions to be calculated. Figure 15 illustrates this using an idealised model of seabed morphology and shows how bed level changes that are a product of seabed feature movement can be identified through spatial cross-correlation between successive time intervals.

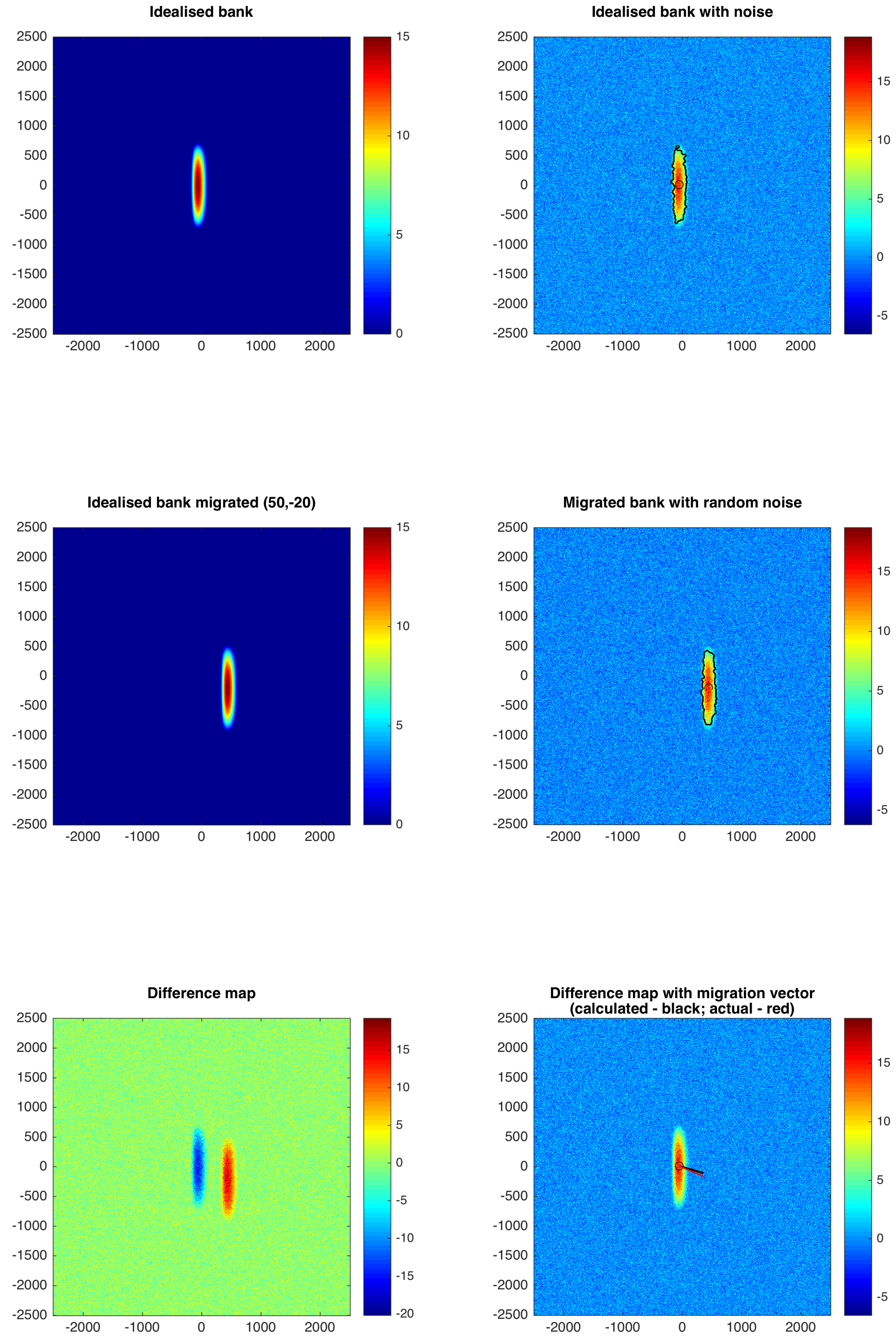

Figure 15 Illustration of automated feature tracking for an idealised bathymetric surface with a single migrating bank landform.

The cross-correlation approach works best on clear signals, and has been developed most actively for applications involving the migration of bedforms that have a dominant wavelength (e.g. Duffy and Hughes-Clark, 2005). However it has proven challenging even at the bedform scale, meaning that investigations of seabed bedform migration are still typically reliant upon the extraction of representative transects or use image enhancement techniques for the detection of key morphological sub-features (e.g. crest lines) to determine movement rate and direction (e.g. Van Landeghem et al., 2012). The success of the cross-correlation approach decreases as noise levels increase and in the presence of structurally complex or significantly evolving morphologies. Resolution is less of an issue assuming that comparable local spatial relationships are present in successive images. Although the potential can be demonstrated through an idealised bathymetric model, application of the approach to real bathymetries may be difficult.

4. Evaluation of morphodynamic risk to infrastructure

Given that much of the UK seabed is mantled by unconsolidated sediments, the vast majority of existing seabed infrastructure licenced by The Crown Estate is located in areas that are at least theoretically susceptible to morphological change of the seabed. From an infrastructure perspective, the key vulnerabilities relate to various distinct modes of seabed behaviour:

1) Localised scour in the vicinity of structures that function as obstacles to dominant flow fields. Perturbation of the bed may be sufficient to cause undermining of foundations or exposure of connected linear infrastructure elements such as pipelines and cables. Scour of this kind can be predicted and mitigated quite effectively using existing scour models (including both empirical and numerical simulations; Morelissen et al., 2003; Fredsoe, 2016) and the risk mitigated by scour control measures or allowed for in the structure design.

2) Time variation in seabed elevation of sufficient amplitude to exposure structure foundations, cause unsustainable free-spans in pipelines or cables, or possibly even bury and hinder access to other critical infrastructural components. At least two scales of seabed behaviour are relevant here: i) horizontal propagation of low amplitude (of the order 5 m) at rates of the order 10 m/yr; and ii) horizontal shifts in the position of larger tidal ridges and sand banks, where bank heights may be of the order of 20 m, but rates of net migration are usually quite low (of the order 1m/yr). These aspects of seabed dynamics are naturally occurring and harder to anticipate and mitigate against. They are also likely to be restricted to particular areas of the continental shelf and it is therefore important to be able to identify these areas, characterize the likely contemporary behaviour at a decadal scale (sand waves) and a multi-decadal scale (tidal ridges and sand banks), and generate quantitative estimates of likely amplitudes of bed level change over the time span of a specific infrastructural asset.

3) Progressive accretion or scour over wider areas that is not associated with discrete bedforms or larger submarine landforms. These changes may affect areas of seemingly featureless seabed, including areas between sand wave fields or larger sand banks, and may arise through spatial variation in net sediment transport pathways. Wide area changes are sometimes evident as low amplitude change in historic surveys, often exhibiting a degree of spatial organisation that implies that may not solely be the result of survey and interpolation noise. Given that these changes are small in magnitude, however, it they may be hard to resolve with any certainty from comparisons using older low-resolution datasets.

The primary considerations for a risk-perspective analysis of seabed morphodynamics are related to data availability, and in particular the survey frequency (time frames and intervals) and resolution (discrete soundings versus multi-beam continuous bathymetric surfaces). As explained thus far, these factors govern the type of analyses that can effectively be undertaken, and frame the likely value acquired from the analyses. The evaluation of risk to infrastructure is then related specifically to the properties of subsea installations, and nature of the hazard that they would be impacted by (e.g. burial versus scour). As shown, data from a single time frame can be analysed to provide a baseline spatial variance in seabed elevation. In combination with a range of morphometric indices, this suite of indices has the potential to generate a suite of derived data layers that can guide risk analyses without the need to explore the temporal dimension. The availability of multiple surveys at a range of time intervals opens up additional forms of analysis. These include the creation of simple vertical elevation change maps and extend to more sophisticated disaggregation of change into the various mechanisms outlined above. These can include site specific bed level variation as well as automated feature migration tracking.

Much of the existing seabed infrastructure has a local scale more closely aligned with bedform structures rather than landforms. They are features that would be detectable on high resolution, multi-beam or bathymetric Lidar surfaces, but unlikely to be captured on single beam surveys. Uncertainties in bed level, which can include both vertical and horizontal errors, are greater for i) older surveys and ii) coarser resolution surfaces. This implies that scales of morphological variance and morphodynamic change that can surpass the uncertainty in these measurements will likely be greater than the scales of seabed infrastructure. For modern, high-resolution data, uncertainties are much reduced and detectable quantities are smaller than the scales of seabed infrastructure. Therefore, similar to the question of survey frequency, survey resolution must also be appraised in order to understand the possible analyses and results produced.

Hough et al. (2011) have demonstrated the potential of integrated geomorphological mapping in the assessment of seabed geohazards. They advocate the creation of a suite of geospatial data layers that focus on geomorphological mapping (and by definition geomorphological assessment) and includes some of the indices and morphometry we have outlined here. In their suggested approach, geomorphological interpretation of bathymetric surfaces and their morphometric derivatives is key to an assessment of ‘terrain units’ that underpin their ability to define geohazards and gauge risk. Seabed dynamics are not considered directly, although some appreciation of the potential for dynamics is captured in the definition of these terrain units. In short, these layers provide some context for the assessment of morphodynamic risk, but the range of approaches outlined in this report show that hydrographic surveys offer a wider suite of morphological and morphodynamic assessments, given a specific survey resolution and frequency context.

As explained, the procedure for the evaluation of spatial variance and morphological change is dependent on the resolution, quality and temporal context of data available. Figure 16 outlines a possible workflow that would follow a requirement to evaluate risk to seabed infrastructure from morphodynamics. The suite of analytical tools that are described and illustrated in this report can each be applied, given consideration of the survey resolution and frequency, the quality and uncertainty in the data, and the infrastructure properties that underpin their risk.

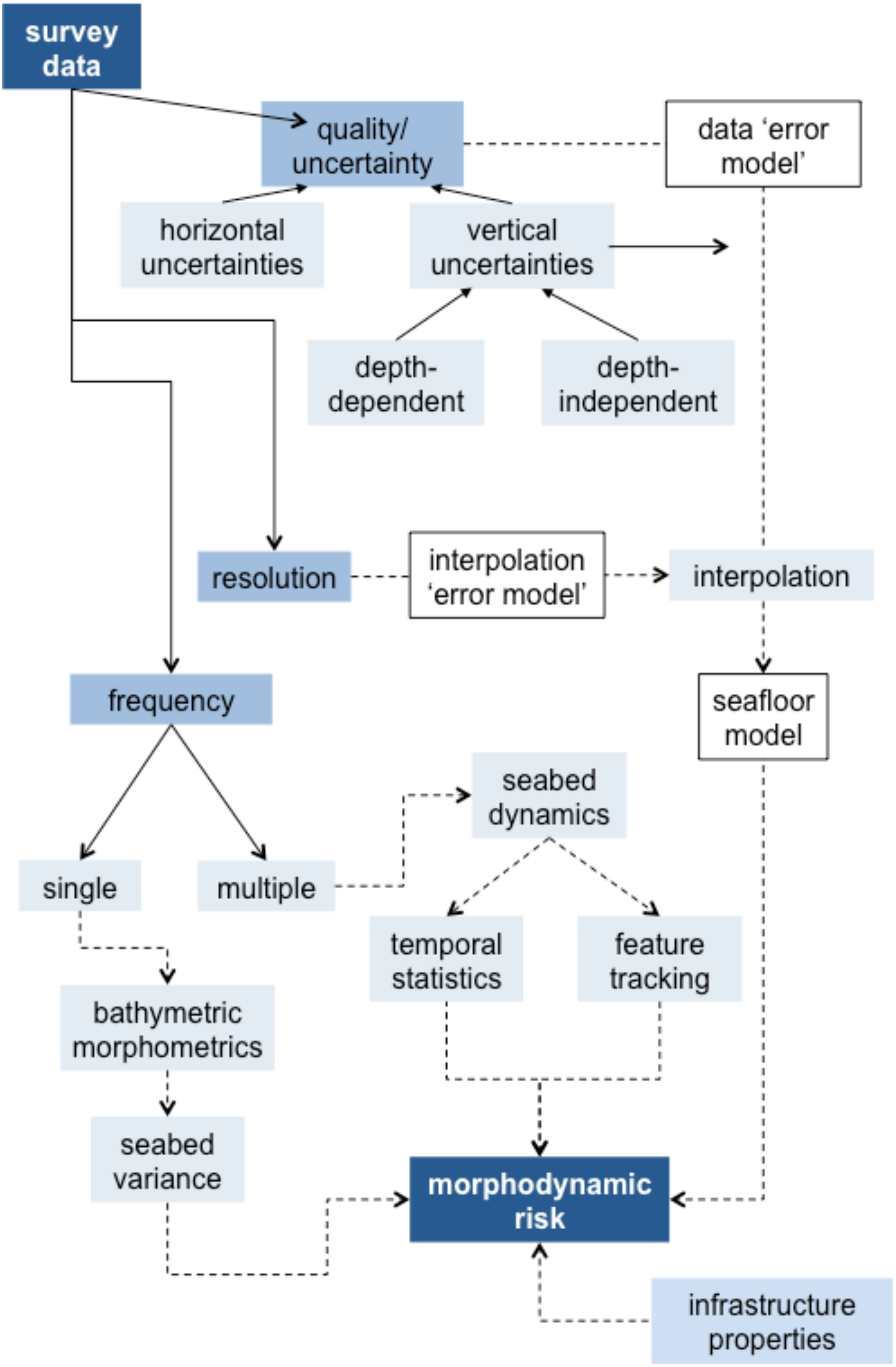

Figure 16 Outline workflow for the assessment of morphodynamic risk to infrastructure based on analysis of hydrographic datasets.

5. Summary

Previous approaches to the analysis of seabed geohazards to infrastructure have been largely focused on the roles of earthquakes, submarine landslides, turbidity currents, tsunami and high-pressure fluid or gas venting. But across shallow shelf environments, a range of dynamic sedimentary deposits and tidal channels can present a significant morphodynamic risk to subsea structures and related components such as pipelines and submarine cables. This report has identified and outlined a range of time-independent and time-dependent approaches to the understanding and representation of seabed dynamics and bathymetric variation. It has demonstrated that, even for single time frames and coarse resolution data, some expression of bathymetric variance can be derived to inform an indicative assessment of the likely risk from non self-generated changes in seabed elevation. With increasing spatial and temporal resolution, a broader range of dynamic properties can be ascertained.

This Work Package 1 report has scoped out the challenges and methods available, and outlined a preliminary workflow for the assessment of morphodynamic risk to seabed infrastructure. Work Package 2 will demonstrate the feasibility and effectiveness of the various methods and test the robustness of the workflow. This work will be undertaken with reference to a small selection of case studies where various kinds of seabed infrastructure are present.

Glossary

Bedforms	A range of depositional forms (e.g. ripples, sand waves) that develop in non-cohesive, mobile sediments as a product of bedload sediment transport driven by bottom (seabed) currents.
Bedload	Sediment transported at, or in contact with, the seabed.
Interpolation	Prediction of values at unsampled locations.
Kriging	A geostatistical approach to estimating values of a property (such as seabed elevation) at those locations that have not been sampled. Ordinary kriging uses a weighted average of neighbouring samples to estimate the unknown values at each desired unsampled location. Weights are optimized using a model of the empirical semi-variogram model. The technique also provides a "standard error" which may be used to quantify confidence levels.
Landform	A geomorphological unit with a characteristic morphology (as well as other physical attributes) produced by a distinct set of processes, which contributes to the overall topography (or submerged bathymetry) of the planetary surface.
Semivariance	When dealing with regionalized variables, the semivariance expresses the strength of the relationship between points separated in space (such as depth measurements across a seabed). The semivariance is simply half the variance of the differences between all possible points spaced a constant distance (or 'lag') apart.
Variogram	A function describing the spatial dependence of samples within a dataset, i.e. how data are related with respect to their relative separation in space. A variogram provides a measure of how much two sample measurements will vary in value depending on the distance between them. Measurements taken far apart are likely to vary more than those taken close to each other.

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