Evaluating potential hazards to seafloor infrastructure associated with submarine morphodynamics

Helene Burningham, Jon French (UCL)

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Executive Summary

The seabed is subject to increasing exploitation and has seen a proliferation of offshore infrastructure associated with hydrocarbon and mineral resources, renewable energy generation, transport and telecommunications. Such activity encounters the risk of construction and/or operational problems due to a varied set of marine geohazards. Previous analyses of seabed geohazards to infrastructure have mainly focused on the roles of earthquakes, submarine landslides, turbidity currents, tsunami and high-pressure fluid or gas venting. A considerable body of work also exists on the risks associated with self-generated scour in the vicinity of engineered structures. However, shallow shelf environments also contain a range of sedimentary features, the dynamics of which can present a significant hazards to subsea infrastructure.

This report summarises work on the Evaluation of Seafloor Infrastructure Hazards Associated with Submarine Morphodynamics undertaken by UCL Coastal and Estuarine Research Unit on behalf of The Crown Estate. It presents a workflow for evaluation of seabed morphodynamic geohazards at various scales. Methods are outlined and demonstrated for a range of scales from the regional to more local areas of interest. These include initial assessment of potential seabed mobility, broad-scale bathymetric visualisation, and time-invariant and time-varying analysis of seabed morphological change at decadal to century scales. Areas for further work, including the potential to incorporate hazards arising from natural seabed morphodynamics into existing engineering risk assessments, are identified.
1. Introduction

1.1. Background

The seabed is subject to increasing exploitation for economically valuable hydrocarbon and mineral resource areas and the continental shelves in particular have also 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). 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 geohazards 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.
1.2. Scales and mechanisms of seabed morphodynamics

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, elucidation of these processes and their effect is more difficult owing to 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.

Analysis of seabed morphological change must necessarily start with a determination of the availability of potentially mobile sediments. In order to quantify expected magnitude of vertical bed elevation change in areas of mobile sediment, 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.

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) observes, bathymetric and seismic surveys often reveal a suite of features that are largely relict 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.
The requirement for a cover of mobile sediment provides the basis for an initial filter that might be applied in advance of the more sophisticated analyses described later in this report. This would be a two-stage process:

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 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 seafloors 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).

Sediment-mantled seafloors typically exhibit bedforms at a range of spatial scales. At a small scale, ripples and sand waves are typically organised in extensive fields. At a large scale, ridges and banks occur 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 seafloor 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 seafloor (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). This is reproduced here in Table 1.

**Table 1 Order of magnitude size and evolutionary timescale of selected offshore sand-dominated bedforms and landforms (after Knaapen, 2004). In this report, ripples and sand waves are considered to constitute a bedform scale, and ridges and banks to constitute a landform scale.**

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

At the smallest end of the bedform scale, features such as sand ripples and mega-ripples are of little interest from an engineering perspective of account of their low amplitude; they are also virtually impossible to resolve using conventional bathymetric surveys. Larger mega-ripples might generate time variation in seabed elevation that would most likely be under-sampled by sequential single-beam bathymetric surveys and thus contribute to the measurement uncertainty. Sand waves are of 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).

At the landform scale, the continental shelf around the UK comprises a range of static and dynamic features. 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). 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.

It follows from the above that the dynamics of sedimentary seabed surfaces in the relatively
shallow waters of continental shelves stems largely from the behaviour of organised bedform
and sedimentary landform features and in particular, their horizontal migration at different
rates. Much has been learned about submarine dunes and sand waves behaviour from
sequential multi-beam bathymetry surveys of relatively localised areas (e.g. Knaapen et al.,
2005b; Duffy and Hughes-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. Hence, change detection analyses must incorporate both a range of time
and spatial scales, in addition to an assessment of the uncertainties associated with the raw
bathymetric datasets.

Translation of morphodynamic assessments to an evaluation of hazard requires synthesis of
available geospatial bathymetric and seabed substrate data, the analysis of these to
establish magnitudes and directions of change, and some consideration of scale and
probability thresholds that allows the impact of change to be addressed in the context of
seabed infrastructure. The work outlined in this report proposes a suite of analytical
approaches and data considerations that would inform a formal evaluation of the hazards
presented by seafloor morphodynamic change, and outlines the workflow that would be
progressed to achieve this.

1.3. Report organisation

This report summarizes work on the Evaluation of Seafloor Infrastructure Hazards
Associated with Submarine Morphodynamics undertaken by the UCL Coastal and Estuarine
Research Unit on behalf of The Crown Estate. The report is organised into sections
describing a workflow for the assessment of the relevant geohazards (Section 2), and
demonstrating methods to deliver each stage of this workflow (Section 3). Summary findings
and recommendations are presented in Section 4. Although this research is primarily focused
on the UK continental shelf, the issues identified are largely generic and the work draws
upon a wider international literature where appropriate.
2. Submarine morphodynamic hazard evaluation and workflow

2.1. Modes of seabed behaviour and hazard to infrastructure

Given that much of the UK seabed is mantled by unconsolidated sediments, the vast majority of existing seabed infrastructure 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 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. 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 remainder of this report is primarily concerned with modes 2 and 3 above. A workflow for the scoping, disaggregation and quantification of these modes of seabed change is presented below. Key elements of this workflow are then demonstrated in Section 3.
2.2. Workflow for evaluation of seabed morphodynamic hazards

The primary considerations for a systematic analysis of seabed morphodynamic geohazards in areas of mobile sediment relate to data availability, and in particular the survey frequency (time frames and intervals) and resolution (discrete soundings versus multi-beam continuous bathymetric surfaces). These factors govern the type of analyses that can be undertaken. Where data for just a single time frame are available, a baseline analysis of spatial variance in seabed elevation is still possible. A suite of morphometric indices can be computed, and the derived data layers can guide analyses of risk to infrastructure without the need to explore the temporal dimension. The availability of surveys at multiple time intervals opens up additional kinds 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. In addition to survey frequency, survey resolution must also be appraised in order to understand the possible analyses and their likely outputs.

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 morphometric indices that we present in the present report. 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 quantify risk. Seabed dynamics are not considered directly, although the potential for dynamics is captured in the definition of these terrain units. These layers provide a context for the assessment of morphodynamic hazard, but the range of approaches outlined in this report show that hydrographic surveys can support a wider suite of morphological and morphodynamic assessments.

Figure 2 presents a possible workflow for the systematic analysis of hazards arising from seabed morphological change, and shows how this might feed into a subsequent determination of the risks to infrastructure. This risk quantification stage is outside the scope of the present report given that it requires detailed knowledge of specific infrastructural components and their vulnerability to different modes of seabed behaviour.
Figure 2. Workflow for the assessment of morphodynamic hazard to seabed infrastructure based on analysis of hydrographic and bathymetric datasets.

1. Seabed geology
2. Tide/wave bed stress
3. Regional seabed assessments
4. Seabed mobility map
5. Geomorphological assessment
6. Broad-scale bathymetry visualization
7. Area-of-interest (site scale) bathymetric datasets
8. Spatial resolution
   - Geostatistics (kriging)
   - Model performance
9. Interpolation uncertainty model
10. Seabed surface model
11. Temporal resolution
   - Multiple surfaces
   - Single surface
12. Seabed dynamics
   - Temporal statistics
   - Feature tracking
13. Morphometric and seabed variance
14. Morphodynamic hazard evaluation
15. Infrastructure properties
16. Risk assessment
17. No significant morphodynamic hazard
18. Potentially mobile
19. Immobile
3. Demonstration of hazard assessment methods

3.1. Regional assessment of seabed mobility

The first stage in the assessment of morphodynamic hazard to seabed infrastructure is the assessment of potential mobility. A seafloor region formed in lithified bedrock is unlikely to experience significant morphological change at the multi-decadal timescale, whereas the presence of unconsolidated sediments implies the potential for sediment transport and hence the likelihood for morphological change.

Where a sedimentary cover exists, a more sophisticated pre-analysis of the likely mobility of the seabed can be undertaken. Bed mobility is determined by sediment grain size and the shear stresses exerted at the seabed by tidal currents and ocean waves. Information on these factors can be used to generate a sediment ‘mobility map’ that might be used to exclude areas of coarse ‘lag’ deposits that are effectively immobile under current tidal or wave conditions. Indicative grain sizes can be obtained from the standard sediment classifications used in the seabed sediment data products. Quantitative observations of the bottom stresses are usually not available from direct measurements as these are expensive and invariably restricted to sparse measurement campaigns at specific locations. As an alternative, current and wave output fields from numerical models can be used in conjunction with a bottom boundary layer model to produce estimates of bottom stress at the scale of the continental shelf.

An excellent example of how seabed sediment data and numerical tide and wave model outputs can be combined to produce regional sediment mobility maps is presented by Dalyander et al. (2015). They document the creation of a bottom stress and sediment mobility database for the United States coastal shelf. This uses near-bed tidal current stress estimates from 3D ocean and wave models to derived bottom stress estimates on a 1 km grid. Bottom stress is estimated for various exceedance percentiles and used to map the mobility of different grain size fractions. Both annually averaged and seasonal maps are produced. Estimation of bottom stresses is quite strongly dependent on various assumptions regarding the boundary layer (the portion of the water column adjacent to the seabed within which viscosity is important and transfers shear stress to the bed) and the bottom roughness. Bottom roughness is influenced by sediment grain size, as well as bedform at various scales. Model studies usually assign constant bottom roughness values as it is almost impossible to adequately capture the spatial variation that occurs both between and within model grid cells and also the time variation due to bedform evolution. Regional sediment mobility maps thus provide a first approximation to the spatial extent of sediment mobility but do not directly resolve the detailed behaviour of the seabed at the bedform or landform scales.

The preparation of a seabed mobility map derived from existing seabed substrate mapping or data resources is a useful first stage assessment. For the UK, the British Geological Survey (BGS) 1:250,000 Seabed Sediment data product has good coverage of the coastal shelf and can provide an initial baseline of potential seabed mobility. Bathymetric and seabed geology
data covering the shelf seas of Europe can also be obtained through the European Marine Observation and Data Network (EMODnet). EMODnet-Geology provides a harmonised seabed substrate dataset that draws from a range of national surveys, including the British Geological Survey. The spatial resolution of the EMODnet bathymetry and geology layers is suitable for landscape scale analysis and is increasingly being used in the assessment of seabed habitats and marine species (e.g. Vasquez et al., 2015; Rumolo et al., 2017).

Synthesis of knowledge and understanding from regional surveys is exemplified by the Southern Northern Sea Sediment Transport Study (SNSST, 2002) and the Outer Thames Estuary Regional Environmental Characterisation (Thames REC, 2009). In Figure 3, the interpretations documented by the Thames REC (2009) have been extended across a wider outer Thames/south Suffolk shoreface region to delineate distinct differences in morphology, seabed sediments and bedform- and landform-scale dynamics. Tidal flow in the western zone is notably constrained within the channels between banks; channel beds are largely stable, but bank migration is evident and can account for large-scale bed level change. The central zone is a largely flat platform with a few isolated large, elongated sand ridges and incised channels (formed by subglacial meltwater at the maximum extent of the Elster glaciation (c. 440ka BP) (Thames REC, 2009)) that are largely stationary at the landform scale. The eastern zone, further offshore, contains no large-scale sedimentary landforms, but the relatively flat region is covered in places by expansive dunes (bedforms up to 15 m high, with wavelengths over 100 m), the movement of which does lead to localized large-scale bed level change and spatial variance.

For the outer Thames, there is thus sufficient evidence to suggest that sediment thickness is variable, ranging from thin veneers in the east and north to metres thick elsewhere. The seabed system of this region can therefore be considered potentially dynamic, but some sediment types are likely to be more dynamic than others. On the basis of sedimentary characteristics alone, the large dunefields to the east have the greatest potential to move large volumes of sediment and present significant hazards to seabed infrastructure. The muddy sands and gravels to the west are much less likely to cause problems.
Figure 3 Synthesis of seabed characterisation and interpretation (morphosedimentary environments and sediment transport directions) for the outer Thames estuary / south Suffolk shoreface region, derived from British Geological Survey seabed sediment mapping, EMODnet bathymetry, SNSSTS (2002), and Thames REC (2009).

3.2. Broad-scale seabed bathymetry visualisation

The EMODnet Bathymetry Digital Terrain Model (DTM) is a composite bathymetric data product derived from the integration of multiple surveys from various countries. Depths are referenced to Lowest Astronomical Tide (LAT) at a gridded spatial resolution of 1/8 x 1/8 arc minutes. For the UK shelf seas, this equates to a linear, metric resolution of 110 to 230 m (Figure 4). The EMODnet Bathymetry DTM forms the basis of the European component of the recent GEBCO_2014 digital bathymetry of the world (Weatherall et al., 2015).
Visualization of the regional bathymetry provides an initial stage in the understanding of morphology and morphodynamic hazards. Spatial analysis of the DTM can provide insight into the seabed morphology and its potential for change. For example, calculation of seabed slope will usefully identify continental margins at risk from slope failure (i.e. mass movement), but even across shelf seas, can highlight steeper bank and channel margins that are actively shaped by contemporary tidal current and wave-driven sediment transport, where potential for bed level change is significant (Figure 5).
Figure 5 Bathymetric slope across the UK shelf derived from EMODnet bathymetric DTM.

3.3. Seabed morphometrics and spatial variance

Morphometric analysis uses spatial algebra on DTMs 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. Established terrain analysis metrics have 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. 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 (originally described by Riley et al. (1999)). The method has been variously evolved by others, but the TRI is generally calculated as:

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

[3]

where \( x_{oo} \) is the central cell elevation 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. The resulting metric, and interpretation of the spatial pattern in it, are scale (resolution) dependent. This is illustrated in Figure 6 where fine resolution bathymetry-derived TRI highlights local variance in bed level, whereas at a coarser scale, the TRI differentiates components of landforms (e.g. primarily margins).

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 particular, the Bathymetric Position Index (BPI) (the submarine equivalent of the TPI) calculated at regional and local scales has emerged as an effective approach to capturing spatial variance in morphology in terms of positive (e.g. crest), negative (e.g. channel) and flat terrain (Weiss, 2001) (Figure 7). The BPI has been adopted widely by the benthic ecology discipline as a means to effectively classify seabed habitats (Lundblad et al., 2006; Wilson et al., 2007; Verfaillie et al., 2009; Brown et al., 2011), and a suite of GIS tools has been developed to facilitate this process (Wright et al., 2012).

There has been more recent interest in the application of BPI analysis to the survey and description of seabed geomorphology (Kaskela et al., 2012). Following Lundblad et al. (2006), the BPI is calculated using equation [4]:

\[ BPI_{scale \ factor} = Z - focalmean(Z, OR, IR) \]  

[4]

where for each cell in the bathymetric grid \( Z \), the mean elevation (relative to a datum) of a region around this cell (defined by an inner radius (IR) from the cell to an outer radius (OR) from the cell) is subtracted from the elevation of the central cell.

As with other DTM-morphometry indices, BPI is scale dependent, based on the radius of the area of the focal mean (OR - IR) multiplied by the grid cell size. To date, the approach has been primarily used to classify seabed habitats, and has been successfully applied to both fine and coarse resolution bathymetric DTMs (Table 2). For example, Howell et al. (2011) derived fine- (OR=3, IR=1, scale factor = 300m) and broad- (OR=5, IR=1, scale factor = 1000m) scale BPI from 200 m gridded bathymetries in their assessment of Lophelia pertusa reefs on the Rockall Plateau.
Figure 6 Terrain (Topographic) Ruggedness Index (TRI) applied to a recent bathymetry (A) at high [20 m] (B) and low [100 m] (C) resolution.
Possibly the coarsest resolution reported is the habitat prediction modelling undertaken by Ross et al. (2015) on 750 m resolution GEBCO bathymetry, but their analyses are supported by work at a finer scale (200 m). At such a coarse resolution, landforms and seascapes can be effectively classified, but smaller scale features, even large bedforms, are not captured at all. Many applications utilise high-resolution multi-beam DTMs to classify specific habitats and species, and at this scale, bedforms are clearly identifiable.

Bathymetry resolution is the primary limitation on the capability of this approach; features that can be identified when viewing the bathymetry are those that can ultimately be classified by approaches such as BPI. For example, Figure 8 illustrates a range of morphological features that can be recognised in coarse resolution bathymetry, primarily those associated with the landform scale (e.g. banks/ridges, channels, flat seabed). At this resolution, finer detail such as bedforms is evident only as localised areas of irregular depths. Sand wave ‘fields’ (or ‘dunefields’) are evident across the wider seabed, but also occur as concentrated, coalesced structures that form the basis of ridge or bank landforms. They are larger than ripples but smaller than banks and ridges with heights of 1-10 m and wavelengths of tens to hundreds of metres (McCave, 1971; Bijker et al. 1998). As such, the morphology of these features can only be captured in much finer resolution bathymetry.
Table 2 A review of Bathymetric Position Index (BPI) parameters (OR outer radius; SF scale factor) used in the broad- (bBPI) and fine (fBPI) scale recent analysis of seafloor features.

<table>
<thead>
<tr>
<th>Application</th>
<th>Authors</th>
<th>bBPI OR</th>
<th>bBPI SF</th>
<th>fBPI OR</th>
<th>fBPI SF</th>
<th>DTM resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habitat prediction modelling and data resolution assessment: NE Atlantic</td>
<td>Ross et al. (2015)</td>
<td>33</td>
<td>24750</td>
<td>3</td>
<td>2250</td>
<td>750 m</td>
</tr>
<tr>
<td><em>Lophelia pertusa</em> reef habitat/species distribution: Rockall</td>
<td>Howell et al. (2011)</td>
<td>5</td>
<td>1000</td>
<td>3</td>
<td>600</td>
<td>200 m</td>
</tr>
<tr>
<td>Habitat prediction modelling and data resolution assessment: NE Atlantic</td>
<td>Ross et al. (2015)</td>
<td>33</td>
<td>6600</td>
<td>3</td>
<td>600</td>
<td>200 m</td>
</tr>
<tr>
<td>Mauritanian slope habitat</td>
<td>Jones et al. (2012)</td>
<td>11</td>
<td>1008</td>
<td>2</td>
<td>181</td>
<td>90 m</td>
</tr>
<tr>
<td>Seabed habitat classification</td>
<td>Verfaillie et al. (2009)</td>
<td>20</td>
<td>1600</td>
<td>3</td>
<td>240</td>
<td>80 m</td>
</tr>
<tr>
<td>Seabed habitat mapping: English Channel</td>
<td>Coggan and Diesing (2011)</td>
<td>6</td>
<td>450</td>
<td>3</td>
<td>225</td>
<td>75 m</td>
</tr>
<tr>
<td>Rocky reef habitat mapping: English Channel</td>
<td>Diesing et al. (2009)</td>
<td>6</td>
<td>450</td>
<td>3</td>
<td>225</td>
<td>75 m</td>
</tr>
<tr>
<td>Guam seabed habitat</td>
<td>NOAA-PIBHMС</td>
<td>17</td>
<td>1020</td>
<td>4</td>
<td>240</td>
<td>60 m</td>
</tr>
<tr>
<td>Cold-water coral distribution/seabed morphology: Rockall</td>
<td>Guinan et al. (2009)</td>
<td>9</td>
<td>270</td>
<td>3</td>
<td>90</td>
<td>30 m</td>
</tr>
<tr>
<td>Cold-water coral predictive mapping: Porcupine Seabight</td>
<td>Heindel et al. (2010)</td>
<td>5</td>
<td>131</td>
<td>2.615 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediments and sedimentary deposits: northwest Irish Shelf</td>
<td>Evans et al. (2015)</td>
<td>25</td>
<td>1250</td>
<td>6</td>
<td>400</td>
<td>10 m</td>
</tr>
<tr>
<td>Pagan Island seabed habitat</td>
<td>NOAA-PIBHMС</td>
<td>25</td>
<td>250</td>
<td>5</td>
<td>50</td>
<td>10 m</td>
</tr>
<tr>
<td><em>Lophelia pertusa</em> reef habitat/species distribution: Norwegian margin</td>
<td>Tong et al. (2016)</td>
<td>8</td>
<td>80</td>
<td>1</td>
<td>10</td>
<td>10 m</td>
</tr>
<tr>
<td>Lobster habitat</td>
<td>Galparsoro et al. (2009)</td>
<td>3-100</td>
<td>15-500</td>
<td>3</td>
<td>15</td>
<td>5 m</td>
</tr>
<tr>
<td>Gold coral habitat suitability: South Tyrrhenian Sea</td>
<td>Guisti et al. (2014)</td>
<td>1-55</td>
<td>3-165</td>
<td>3</td>
<td>2.5</td>
<td>3 m</td>
</tr>
<tr>
<td>Habitat suitability for demersal fish: Victoria, Australia</td>
<td>Monk et al. (2011)</td>
<td>52</td>
<td>8</td>
<td>2.5 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seafloor habitat mapping</td>
<td>Lanier et al. (2007)</td>
<td>150-300</td>
<td>15-50</td>
<td>2-10 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocky reef habitat mapping: English Channel</td>
<td>Diesing et al. (2009)</td>
<td>250</td>
<td>500</td>
<td>30</td>
<td>60</td>
<td>2 m</td>
</tr>
<tr>
<td>American Samoa seabed habitat</td>
<td>Lundblad et al. (2006)</td>
<td>70-83</td>
<td>70-250</td>
<td>10-20</td>
<td>10-20</td>
<td>1-3 m</td>
</tr>
<tr>
<td>Shoreface substratum, N Ireland</td>
<td>Plets et al. (2012)</td>
<td>100</td>
<td>100</td>
<td>20</td>
<td>20</td>
<td>1 m</td>
</tr>
<tr>
<td>Benthic habitat mapping: coastal waters of Maltese Islands</td>
<td>Micalel et al. (2012)</td>
<td>5</td>
<td>5</td>
<td>1 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Explanatory modelling of rocky seabed species distribution: Norway</td>
<td>Schläppy et al. (2014)</td>
<td>125</td>
<td>12.5</td>
<td>0.46 m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Figure 8 Morphological features illustrated across a range of bathymetric data: landforms such as banks and wide channels are clearly shown in coarse resolution bathymetries (A: EMOD bathymetry (187 m resolution); B: 100 m resolution composite (c. 1990) bathymetry) but bedforms and other smaller-scale features across/around landforms can only be fully appreciated in high resolution (e.g. multi-beam bathymetry (C to F: 2 m resolution)).
Calculation of BPI for regional-scale (e.g. EMODnet) bathymetric data, undertaken at broad (OR=25, IR=5, scale factor = 4671 m) and local (OR=3, IR=1, scale factor = 561 m) scales shows the potential of this approach in detecting the morphological components of a seafloor landscape (Figure 9). In this example, the broad scale BPI effectively draws out the primary bank and channel features that occupy the outer Thames region, with larger positive values denoting elevated banks and ridges, and larger negative values representing intervening channels. Flatter areas across the region are represented by low magnitude (positive or negative) BPI. At the fine scale, the banks are less distinct, but the narrow ridges further offshore are evident with large positive BPI. Bank margins are effectively highlighted, and the distinction between the top (medium-high positive) and base (medium-high negative) of these margins is clear. Although the wide flat areas persist with low magnitude BPI, a number of these sites (particularly offshore to the east) include very variable BPI likely reflecting large-scale bedforms, such as sand waves, rather than landforms.

BPI analysis can be taken further through the combining and thresholding of results at different scales to achieve a form of seabed classification. Application of the BPI classification varies between scales, but the approach to defining the limits and criteria is comparable, with most authors evolving the original criteria set out by Lundblad et al. (2006) to suit their features of interest. In the EMODnet bathymetry example shown here, a similar approach is followed with the criteria for BPI classification outlined in Table 3. In this case, bedforms such as sand waves are not directly identifiable but can be recognised on the basis of localised irregular depths, termed 'local features' here.

Integration of the broad- and fine-scale BPI with the slope calculation forms the basis of BPI classification. Using the criteria outlined in Table 3, the outer Thames seabed classification provides a good representation of seabed geomorphological features (Figure 10). This effectively distinguishes the broad-scale landforms: slopes between banks and channels, crests of narrow banks, broad bathymetric highs across wider banks, broader flats and local-scale features (such as sand waves). Achieving a consistent classification of the channels is somewhat challenging, but this does work as a collective feature (narrow and broad channels). Some parts of the seabed are left unclassified, but on inspection, these are primarily associated with the transitions between the broader scale features, i.e. bank and channel edges suggesting that the criterion for margins is too strict.

Geomorphometry analysis of the EMODnet bathymetry is an effective approach to characterise the main morphological features within a seabed environment at a regional scale. This would be particularly useful in locations that have received limited research to date, where a synthesis from the wider literature and regional reports is not possible.
Figure 9 Standardised Bathymetric Position Index (BPI) at broad (top) and fine (bottom) scales. Parameters used are outlined in the text.
Table 3 Criteria used to classify seabed morphology from the regional scale EMOD bathymetry using BPI and slope metrics (bBPI: broad-scale, fBPI: fine scale).

<table>
<thead>
<tr>
<th>Class</th>
<th>Notes</th>
<th>bBPI</th>
<th>fBPI</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local features</td>
<td>e.g. sand waves</td>
<td>-6 to 8</td>
<td>-8 to 10</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Bank edge (top)</td>
<td>high curvature, convex</td>
<td>&gt;6</td>
<td>&gt;0</td>
<td>0.25-1.6</td>
</tr>
<tr>
<td>Bank edge (base)</td>
<td>high curvature, concave</td>
<td>&lt;4</td>
<td>&lt;0</td>
<td>0.25-1.6</td>
</tr>
<tr>
<td>Broad channel/Depression</td>
<td>concave, flatter</td>
<td>&lt;3</td>
<td>&lt;5</td>
<td>&lt;0.8</td>
</tr>
<tr>
<td>Narrow channel</td>
<td>concave, steeper</td>
<td>&lt;2</td>
<td>&lt;0</td>
<td>&lt;1.2</td>
</tr>
<tr>
<td>Bank crest</td>
<td>local and regional peak</td>
<td>&gt;7</td>
<td>&gt;7</td>
<td>&gt;1.2</td>
</tr>
<tr>
<td>Broad bathymetric high</td>
<td>low curvature, convex</td>
<td>&gt;2</td>
<td>&lt;3 to 4</td>
<td>&lt;0.8</td>
</tr>
<tr>
<td>Broad flats</td>
<td>minimal topographic expression</td>
<td>-1.6 to 3</td>
<td>-3 to 4</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>Slopes</td>
<td>rapid change in depth</td>
<td>-</td>
<td>-</td>
<td>&gt;1</td>
</tr>
</tbody>
</table>

Figure 10 Seabed feature classification derived from Bathymetric Position Index (BPI) at broad and fine scales, and slope, using the classification criteria outlined in Table 3.
3.4. Area of interest (site-scale) bathymetry

Areas of interest earmarked for potential infrastructure development will be examined in detail as part of wider environmental impact assessments. The approach used might vary between developers, but efforts are invariably made to achieve a robust understanding of site geomorphology and morphodynamics. It is less usual for the bathymetric data used in these analyses to be comprehensively examined to quantify measurement, data and interpolation uncertainties. In the workflow presented in Figure 2, bathymetric data are used to inform the understanding of seabed dynamics, but an additional uncertainty model is produced to establish the confidence with which specific morphodynamic hazards can be identified. This uncertainty model includes both raw data (measurement) uncertainty and spatial (interpolation) uncertainty.

3.4.1. Uncertainty in bathymetric datasets

Hydrographic charts and bathymetric soundings covering areas of interest can usually be acquired from the 19th century to the present. Earlier chart-based records need to be georeferenced and digitised, whereas some late 20th century hydrographic surveys can be obtained as digital soundings. Sources, dates, coverage, datum and georeferencing accuracy of these resources will vary from site to site. To illustrate the process here, a data-rich area in the outer Thames estuary is used as a case example, for which a suite of bathymetric data covering the 1840s to present is available (Appendix 1). Charts were scanned and georeferenced to British National Grid (EPSG: 27700) using ground control points (fixed marks such as Martello towers) and grid references. Soundings obtained in latitude/longitude (WGS 1984 - EPSG: 4326) were transformed to British National Grid using the 7-parameter Helmert transformation (Ordnance Survey). The time frame considered was governed by the availability of surveys, and in many cases necessitated the merging of two or more surveys within a 10 year period to ensure coverage across the area of interest.

The datum to which depth soundings are referenced varies from MLWS (Mean Low Water Springs) in the earliest surveys to 1 foot below MLWS (Mean Low Water Springs) in the early 20th century surveys. Admiralty surveys have used LAT as the vertical datum since 1968. In order to make direct comparisons between different time frames, the depths were converted to seabed elevations relative to Ordnance Datum Newlyn (OD) using a region-wide, spatial trend model of the offset between each of these chart datum levels and OD. The tidal datum trend surfaces were constrained along the Essex and Suffolk coasts using the UKHO predicted tidal heights (UKHO, 2015) and far offshore by a zero-amplitude tide. The model achieved a good and consistent fit across the 3 datums (RMSE 0.129 to 0.137; $R^2$ 0.96 to 0.97).

Errors are always present in any measurement (Taylor, 1996) and are the differences between the measured value and the true value. Since true values for a property such as depth cannot be known, it is more meaningful to think in terms of measurement uncertainties. These can be approximated using the indicative uncertainty standards for Order 1 (a,b)
surveys as defined by the International Hydrographic Organization (IHO, 2008). A simple model for the maximum permitted total vertical uncertainty (TVU) is given by equation [5]:

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

[5]

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 vary with depth and \( d \) is water depth. For Order 1(a,b) surveys in shallow water less than 100 m deep, \( a \) is given as 0.50 m and \( b \) between 0.0075 and 0.013.

Measurement uncertainty is likely to vary with survey era, and to some extent, this can be reflected in the unit (resolution) of measurement. For example, historical bathymetric surveys undertaken using a lead-line approach rarely offer sub-fathom (1.8 m) precision in water depths of greater than 11 fathoms (20.1 m); the precision for shallower water was 1 foot (0.3 m) until the metrication of hydrography in the late 1960s and early 1970s. Since then, echo soundings have been precise to 0.1 m, and more recent multi-beam surveys are reported to 0.01 m. The TVU effectively accounts for the modern precision, but is less effective for older surveys where the resolution is coarser than the TVU. To account for this, the uncertainty in the underlying bathymetric data \( \delta_{\text{data}} \), is approximated through a quadratic sum of TVU and unit resolution \( U_r \), given by equation [6]:

\[ \delta_{\text{data}} = \sqrt{\text{TVU}^2 + U_r^2} \]  

[6]

The resulting bathymetric measurement uncertainty model \( \delta_{\text{data}} \) therefore varies spatially (associated with depth) and temporally (accounting for survey resolution). Uncertainties linked to the distribution and density of soundings, and the variation in these through time, are addressed in the calculation of bathymetric surfaces and their associated interpolation uncertainties.

### 3.4.2. Generation of seabed surface models

The calculation of morphometric indices and quantitative rates of seabed elevation change are most easily performed using data on regular grids. Multi-beam bathymetry data are generally supplied as regular grids, with soundings at a horizontal interval of 1 to 5 m. Single-beam surveys, and older chart-based soundings are rarely regularly spaced and are not available at such high resolution. A key element of the workflow thus involves the generation of regular grids at a consistent resolution across a common area of interest. This procedure requires a) choice of a common grid resolution appropriate to the suite of data and b) the interpolation of the bathymetry datasets onto this regular grid. Unless multiple time frames of multi-beam surveys are available, high-resolution data generally require down-sampling (i.e. resampling) to reduce the spatial resolution to that which can be effectively achieved in the other data. Spatial interpolation is used on older survey data to model the bathymetric
surface across the domain of the data and predict values at locations within the grid where soundings are not available.

Most conventional spatial interpolation techniques incorporate implicit recognition of the fact that nearby points are likely to be more strongly correlated than those further away and use this in some form of distance weighting (Davis, 1985). Geostatistical interpolation takes this further, with reference to the theory of regionalized variables (Matheron, 1965; Isaaks and Srivastava, 1989; Oliver and Webster, 2014). This method starts with the estimation of variograms to describe the degree of spatial dependence in the data. When modelled using one of a variety of theoretical functions, these can be used to inform a spatial interpolation using kriging. Kriging generates a statistically optimal interpolation and also estimates the uncertainty (variance) in the interpolated surface at each point on the interpolation grid. Together with information on the uncertainties in the underlying measurements, this can be used to generate an uncertainty model for the datasets.

Kriging is a powerful interpolation technique that makes excellent use of the available data – once in the estimation and modelling of the variograms, and a second time in the interpolation to unsampled locations. However, solving the kriging equations directly involves inversion of an $N \times N$ variance-covariance matrix $\Sigma$, where $N$ data values require $O(N^3)$ computations to obtain $\Sigma^{-1}$. In other words, the computational time increases in proportion to the cube of the number of data points, $N$. Kriging is thus well suited to the interpolation of small or sparsely-sampled datasets but straightforward application of kriging to bathymetric datasets where $N$ may be of the order of $10^4$ or even $10^5$ (in the case of multi-beam surveys) quickly becomes impractical. Under these circumstances, a pragmatic approach based upon the estimation and modelling of variograms using a sub-sample of the data points and kriging within local neighbourhoods is typically used (e.g. Cressie, 1993).

A pragmatic approach is usually required for the processing of bathymetry datasets that typically range from $N = a$ few thousand to $N = 10^3$ to $10^4$ (or greater). First, the region-wide trend on seabed elevation is estimated using a least-square trend surface. In the case studies presented below, a simple linear model is fitted. Removal of this trend from the raw data grids leaves a set of seabed residuals that can be assumed (as a first approximation at least) to be free of bias. The second stage involves the estimation of experimental variograms for the residual datasets. Given the large $N$, variogram estimation is performed on a random sub-sample of points.

The experimental variogram is then modelled. Our case studies use an exponential function for the semivariance, $\gamma(h)$, given by equation [7]:

$$\gamma(h) = c(1 - \exp\left(\frac{-3h}{a}\right))$$  [7]

where $a$ and $c$ are constants and $h$ is the spatial lag distance. An exponential model asymptotically approaches a sill value at a spatial lag represented by the range and its rapid variation near the origin makes it a good model for properties such as bed elevation that may
exhibit significant local variability. Variogram estimation was performed isotropically, that is without reference to direction.

The final stage is to use the modelled variogram to inform a simple kriging computation using the de-trended residuals of the measured seabed elevation onto a regular grid. In the examples presented here, a 100 x 100 m grid was used and kriging calculations were performed using a local neighbourhood defined by a variable radius around each interpolation point. The appropriate neighbourhood radius has to be determined by trial and error with consideration given to the density of the soundings in the dataset as well as the range of the variogram. For some of the sparser (older) datasets, a radius equivalent to the range of the semi-variogram (typically a few km) was found to give reasonable computation times. For the denser (more recent) datasets, computation could only be undertaken with a neighbourhood extending over a portion of the range (typically about 750 m).

The kriging results are then re-combined with the regional trend that was removed initially to give consistent regular grids of seabed elevation for the assessment of morphology and change. For each of these grids, the kriging also yields a surface of the interpolation variance at each point – effectively an interpolation uncertainty model. Figure 11 summarises the main elements of this part of the workflow.

![Diagram](image)

**Figure 11** Detail of secondary workflow for the generation of seabed surface and associated uncertainty models using kriging.
Geostatistical analysis of de-trended bathymetric datasets commences with the estimation of variograms. Figure 12 shows an example of empirical and fitted variograms for 1840 and 1990 survey datasets for a site in the outer Thames estuary. These are based on sub-samples of 2000 data points, and generally approach a sill at a range of a few km. It should be noted the exponential function used to model the variogram here is one of a class of unbounded models that do not have a finite range. The practical range can be taken as the range at which 95% of the variance is reached. The practical range is remarkably similar between the Thames estuary datasets (2.4 to 2.8 km) despite the large difference in survey datasets (as shown in Figure 14).

Figure 12 Example empirical and fitted variograms for 1840 and 1990 sounding datasets.

3.4.3. Morphometrics and seabed variance

Application of the Bathymetric Position Index at the site-scale using contemporary, single or multibeam soundings can provide an additional characterisation of the seabed environment, as a means to understand the potential for morphological change. Channels and banks within the immediate area of interest undoubtedly have the potential to present some hazard to seabed infrastructure. As noted before, morphometric indices are scale dependent, meaning that the process should be carried out independently of applications at a broader scale. For example, BPI was calculated for a region of the mid-Suffolk shoreface using the most recent available data, which was interpolated to a 50 m grid. With the increase in resolution, the BPI scale factors were duly modified, calculated at a fine (OR=3, IR=1, scale factor = 150 m), broad (OR=20, IR=4, scale factor = 1000 m) and mega (OR=50, IR=5, scale factor = 2500 m) scale. Classification of seabed morphological features based on the criteria outlined in Table 4 delivered the geomorphic map shown in Figure 13. The approach is particularly capable of distinguishing between broad flat areas (which would likely pose no threat to seabed infrastructure) and a range of discrete morphologies from large bedforms to
landforms that could contribute some hazard. The BPI classification process could be refined and modified further, which would undoubtedly achieve a more thorough cross-correlation between DTM and the BPI indices produced. The key point though is that geomorphological features can be successfully differentiated at the regional and local scale using contemporary bathymetric datasets, which is a useful stage in the assessment of potential geomorphic and morphodynamic hazards.

Table 4 Criteria used to classify seabed morphology from high resolution (50 m) bathymetric surfaces using BPI and slope metrics (mBPI: mega-scale, bBPI: broad-scale, fBPI: fine scale).

<table>
<thead>
<tr>
<th>Class</th>
<th>Notes</th>
<th>mBPI</th>
<th>bBPI</th>
<th>fBPI</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local features</td>
<td>e.g. sand waves</td>
<td>-4 to 7</td>
<td>-4 to 4</td>
<td>-11 to 10</td>
<td>&lt;3.5</td>
</tr>
<tr>
<td>Bank edge (top)</td>
<td>high curvature, convex</td>
<td>&gt;1</td>
<td>&gt;1</td>
<td>&gt;0</td>
<td></td>
</tr>
<tr>
<td>Bank edge (base)</td>
<td>high curvature, concave</td>
<td>&lt;0</td>
<td>&lt;1</td>
<td>&lt;2</td>
<td></td>
</tr>
<tr>
<td>Broad channel/Depression</td>
<td>concave, flatter</td>
<td>&lt;1</td>
<td>&lt;5</td>
<td>&lt;4</td>
<td>&lt;0.8</td>
</tr>
<tr>
<td>Narrow channel</td>
<td>concave, steeper</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>&lt;0</td>
<td>&lt;1</td>
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<tr>
<td>Bank crest</td>
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<td>&gt;6</td>
<td>&gt;3</td>
<td>&gt;5</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Broad bathymetric high</td>
<td>low curvature, convex</td>
<td>&gt;3</td>
<td>&gt;3</td>
<td>&gt;5</td>
<td>&lt;2</td>
</tr>
<tr>
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<td>&lt;0.5</td>
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Figure 13 Seabed feature classification derived from Bathymetric Position Index (BPI) at mega, broad and fine scales, and slope, using the classification criteria outlined in Table 4.
3.5. Morphodynamics

3.5.1. Determination of seabed change over time

Analysis of bathymetric change can be undertaken when two or more independent surveys cover the area of interest. The digital terrain (bathymetry) models (DTMs) generated can be analysed to calculate vertical net change (accretion or erosion), and linear trends for each cell across the bathymetric surface across a multi-temporal record. Change maps (i.e. the spatial expression of net change between two different time frames) are then recalculated with the application of a threshold of uncertainty. Indicative uncertainty models that represented the gridding ($\delta_{\text{gridding}}$) and measurement ($\delta_{\text{data}}$) uncertainty for each bathymetric surface are combined using a quadratic sum:

$$\delta_{\text{combined}} = \sqrt{(\delta_{\text{data}})^2 + (\delta_{\text{gridding}})^2}$$

[8]

to provide a spatially-varying measure of uncertainty that combined the error of each of the two time frames. This assumes that the two sources of error are independent of each other, which is a reasonable assumption. Measurement uncertainty reflects the quality of the data, whereas gridding uncertainty reflects the level of confidence in the interpolation process. Where interpolation is used to convert irregularly spaced or poor spatial resolution soundings onto a regular grid, gridding uncertainty is given by the interpolation variance at each point (a product of the kriging interpolation process). This reflects the density and distribution of soundings and spatial variance in measurement, thereby capturing the relative changes in spatial detail of surveys from different time periods and surveying methods. Where high-resolution soundings (i.e. multi-beam) are interpolated or resampled to a coarser grid, the gridding uncertainty is given by the root mean square of residuals between observed and modelled depths. Both representations of gridding uncertainty are spatially explicit. The combined uncertainty model is smoothed (e.g. using a Gaussian filter) to reduce local spikes in uncertainty estimates, to compensate for lateral errors associated with the georeferencing process. Filtered change maps then exhibit only those changes (cell by cell) that exceeded the cell-specific uncertainty.

Illustrative output from the combined treatment of measurement and interpolation uncertainty adopted here is shown in Figure 14. This shows how early 19th century surveys suffer from relatively large interpolation uncertainties that dominate the combined uncertainty in the gridded (100 m interval) data product. The data are sparse in relation to the output grid and this is reflected in the spotty appearance of the interpolation error. This spottiness also reflects the fact that the kriged surface honours the data points exactly and has a variance of zero at these locations. It is thus quite easy to appreciate the data density from Figure 14A. Overall uncertainty, as expressed as a root mean square error (RMSE) is surprisingly high at around 5.3 m, but this is skewed by the high errors where the data are sparser. In contrast, the equivalent process for the 1990 data yields a lower RMSE of around 1.6 m. Interpolation error is still the dominant term, and the mean is again skewed by localised uncertainties in
more sparsely surveyed areas. The various component surveys are quite evident in Figure 14B. It should be noted that the measurement errors are effectively the same for both time epochs as the same ‘worst case’ IHO (2008) model for total vertical uncertainty is used. This probably over-states the measurement error for the 1990 survey and it might be reasonable to use a slightly tighter confidence interval for these and similarly recent data.

Figure 14 Error uncertainty model development for A) 1840 and B) 1990 data for an area of interest in the outer Thames estuary (note variable colour bar scales).
3.5.2. Century-scale morphological trends

At the site scale, incorporation of historical bathymetries from time frames across the last 200 years into an analysis of change is best handled using a trend-based approach. For each data point (each cell within DTMs produced following the procedure outlined above), the correlation and linear trend between time and depth reveals the average tendency of the seabed across the historical timescale. This integrates changes through time rather than focusing solely on the net change between the earliest and most recent time frames. Illustrated using the outer Thames example, bathymetric surfaces from 1840, 1880, 1910, 1930, 1950 and 1990 exhibit a marked spatial pattern of seabed depth trend. Some areas show, on average, up to 0.25 m/yr vertical erosion or accretion over the historical time scale (Figure 15 A/B). In this example, trends tend to reach a maximum absolute magnitude along the margins of the bank systems, whilst the wider seabed is characterised by a weaker bed level trend. This implies that, in this case, larger scale seabed dynamics are primarily associated with sand bank movement. This is an important finding in the evaluation of morphodynamic hazard to seabed infrastructure; trend results are a useful indication of seabed tendency in the long term that might form the basis of prediction of future change at a point.

At sites where sequential surveys are not available, historical trend is often limited to just an evaluation of net change between the earliest and most recent surveys. Demonstrated here as a comparison to the bathymetric trend analysis, the net changes between 1840 and 1990 do reflect similar spatial patterns in erosion and accretion to the trend maps (Figure 15C). For this particular illustration, the results show that the patterns of time-averaged behaviour are equivalent to the average of change between 1840 and 1990, suggesting that movement of banks and channels are progressive through time. Filtering of the net change using the spatially-explicit uncertainty model indicates that these key patterns all exceed the thresholds of uncertainty for the 1840 and 1990 datasets (Figure 15D). In this example, the magnitude of change is quite substantial in places, exceeding 15 m of absolute bed level change over the 150 year history. It is possible that some of these patterns reflect the increasing survey resolution from the sparse and exploratory surveys of the early 19th century to the high resolution sounding of modern surveys. Certainly, an increase in definition of the channels could promote an enhanced erosion signature in these locations, but the magnitude of change around the banks, and the parallel/aligned pattern of erosion and accretion is a distinct signature of lateral shifts in position (lateral migration) at the landform scale.
3.5.3. Recent (decadal-scale) change

Assessment of recent, decadal-scale change can sometimes offer a more appropriate insight into seabed behaviour and dynamics that is relevant to seafloor infrastructure. For some regions of the shelf seas, limited availability of multiple surveys might preclude analysis at the decadal scale. Where hydrographic surveys have been undertaken since the 1950s, however, these can provide an analysis of change at time-scales similar to the life-times of subsea structures such as cabling and foundations. Illustrated in the context of the outer Thames estuary, the magnitudes of change are generally smaller at the multi-decadal time scale (Figure 16A) than at a centennial timescale (Figure 15C). The patterns of change are comparable, however, with foci of erosion and accretion along bank/channel margins. Application of the spatially-explicit uncertainty model has a particularly acute affect on the results of this change analysis (Figure 16B), demonstrating that the vast majority of low order
change (magnitude < 5 m) is less than the confidence threshold. In this specific example, this is due to the low spatial density of soundings from 1950s hydrographic surveys leading to larger interpolation (spatial uncertainty) errors. It is important that these bathymetric dataset limitations are considered as part of morphodynamic analyses, particularly where confidence in the magnitude of bed level change is needed.

Figure 16 Calculated vertical change in seabed depth (A), filtered in (B) to show just those changes that exceed the spatially-varying uncertainty model.

3.5.4. 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. 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.

Figure 17 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.

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 DTM s, the location of the peak allows offsets in both x and y dimensions to be calculated.
Figure 17 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.

In many situations, particularly in complex bathymetries, spatial cross-correlation analysis is unsuccessful in capturing the changing position of bank features. In these situations, banks can be identified as discrete objects within the DTMs, using a defining contour. The centroids of these objects can then be tracked through the time frames to capture any distinct spatial shifts in position. This can also be supported by an analysis of cross-feature depth transects that highlight lateral movements in landforms, and at appropriate resolution, bedforms too. Landform-scale centroid analysis of Kentish Knock (Figure 18) reveals almost 2.5 km of southward movement, and some smaller scale (around 500 m) shifts to the west. The bank has also increased in length by over 4 km during this period. Much of this change appears to have occurred during the 19th century, but there is strong evidence to indicate that the movement continues in recent decades.

![Figure 18](image)

Figure 18 Historical change in the position of Kentish Knock (left) driven in part by lateral migration of channels and banks, as shown in cross-bank bathymetric transects (left).
Discrete sand wave features at a range of scales are captured well by bathymetric DTMs 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 (Figure 19). Central to the 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 19 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).
3.6. Evaluation of risk to infrastructure

To translate the mapping of submarine geomorphology and quantitative estimates of bed level change and morphodynamic behaviour from a hazard-based evaluation into a risk to infrastructure analysis requires further stages of assessment and synthesis (Figure 20). At a regional or shelf scale hazards can be based on morphosedimentary interpretation of seabed sediments and sedimentary environments and geomorphic mapping following classifications such as the Bathymetric Position Index (BPI)). These resources provide the means to interpret the dynamic potential associated with different seafloor environments. For example, flat and featureless areas are likely at low risk of change whereas slope regions, and areas where large dune fields are present, present a higher risk of change where sediment transport is likely active, and erosion and deposition very probable. At a more local scale, where an assessment of change can be undertaken as outlined here, the hazards can be quantified as magnitudes or trends of change. With consideration then of the structural and engineering properties of seafloor infrastructures, it is possible to develop criteria that can inform a rigorous analysis of risk associated with seabed morphodynamics.

![Figure 20 Schematic outlining the procedure for translating hazard to risk.](image)

Morphodynamic risks are those associated with the transport, erosion and deposition of sediment associated with wave- and tide-forced seabed dynamics. Risks associated with scour around installed structures (for an overview see Whitehouse, 1998) are a consequence
of introducing structures to the seafloor environment, not the pre-existing process and morphodynamic regime associated with landform and bedform movement. Hence, scour itself would be explored as part of a separate construction engineering assessment. But it is useful to note that a design scour depth is usually allowed for in monopile foundation design and construction (assuming that scour protection is not installed at the base). The local scour is usually determined from one of various empirically-determined relationships between the equilibrium scour depth and the diameter of the (usually cylindrical) structure (e.g. Sumer et al., 1992). Slightly different relations are obtained for situations involving currents only (which usually results in a deeper scour) or cases involving waves or waves and currents (both of which are associated with shallower equilibrium scour depths). Predicted local scour depths are used in fatigue limit state and ultimate limit state calculations to determine safe structure dimensions and foundation depths.

Seabed elevation changes of the kind that result from the morphodynamic processes considered here effectively contribute an additional wider-area scour (or burial) term. The magnitudes of change and trend derived in these analyses would form the basis of a criteria-based judgement of risk. For example, turbine engineering reports suggest that around 40-50% of the length of 4-6 m diameter monopiles is driven into the seabed (Kaiser and Snyder, 2012), with the monopile length around 7 times the diameter (van der Tempel et al., 2010). In these reviews, monopile foundation is documented to be as shallow as 10 m (Kaiser and Snyder, 2012). Documented turbine scales and monopile foundations for wind farm arrays in UK shelf waters are substantially larger, with turbines in the Thames embedded in the seafloor by around 20-40 m\(^a\).

The criterion for risk to subsea cabling and pipelines is less clear. Pipelines may incorporate foundation elements, so would be susceptible to erosion similarly to the monopiles (though possibly vulnerable to smaller scales of erosion due to shallower foundations). Langhorne (1980) noted that bed level changes of up to 5.5 m over a 3 year period had impacted a pipeline crossing the sand wave field around Haisborough Sand (Norfolk shoreface), but that this did not present a significant concern. Cabling is designed to accommodate some degree of flexibility and movement, but undermining can cause significant vortex-induced vibrations if the cables become suspended and excessive burial (above-cable accretion) can lead to increased temperatures, and associated performance problems depending on the cable rating.

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\(a\) https://www.seawayheavylifting.com.cy/projects/greater-gabbard-monopiles


CERU 40
4. Summary and recommendations

4.1. Principal findings

Previous approaches to the analysis of seabed geohazards to infrastructure have 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 hazard to subsea structures and related components such as pipelines and submarine cables. This report has outlined a range of time-independent and time-dependent approaches to the understanding and representation of the seabed in terms of its spatial variability and time varying morphodynamics.

The analysis of seabed geomorphology and morphodynamics to inform and evaluate hazards to subsea infrastructures can be achieved using both time-independent and time-dependent approaches. The key objective in these approaches is to capture and understand bathymetric variability over space and time. This is demonstrated for the outer Thames estuary, and at three case studies, using a range of bathymetric datasets at different spatial resolutions, in isolation and as part of a time-series analysis. Bathymetric variance in time and space can inform the evaluation of morphodynamic hazards affecting seabed-mounted structures in a multitude of ways. The key findings that emerge from the workflow and analysis presented here are:

1) There is clear merit in using of open access datasets (such as EMODnet) as a primary step to establish a broader context. Application of a suite of spatial analyses to carefully constructed bathymetric DTMs can be an effective first step to i) characterizing the geomorphology of potentially mobile sedimentary seabed in terms of static morphometric indices and quantitative determinations of change; and ii) assessing hazards that could impact seabed infrastructure posed by morphological change at decadal to longer historical timescales. This is an approach that could be applied across the entire UK shoreface (and beyond), using the readily available EMODnet data for the high level analysis, and available high-resolution datasets for the finer-scale analysis.

2) One of the disadvantages of the EMODnet bathymetry data, and composite data products more generally, is the lack of transparency regarding the original data sources and their measurement uncertainties. Despite the metadata provided, the derivation of the composite data product is difficult to follow and reconstruct. As shown in Figure 21, more than 20 surveys are integrated into the outer Thames region EMODnet data product. This could be quite a challenge to unravel for broader-scale bathymetric coverages. This has implications for the extent to which the quantification of uncertainty (measurement and interpolation) is possible. Given that the vast majority of bathymetry data covering the UK shelf are sourced through the UKHO INSPIRE portal and MEDIN Bathymetry Data Archive Centre (UKHO Inspire), reconstruction of the measurement uncertainty is possible.
through review of the individual survey metadata. Estimation of the interpolation uncertainty, beyond the application of an idealised model, would require collation of the source data, de-conflicting, and application of interpolation algorithms (i.e. reproducing the data product). This largely negates the time-efficiencies offered by the original data product.

Figure 21 Survey dates (years) and geographic extents of the source data used to construct the EMODnet bathymetry product for the outer Thames estuary region (http://www.emodnet-bathymetry.eu).

3) Geostatistical methods are invaluable for using information embedded in the spatial scales of seabed elevation variability to generate robust and statistically optimal gridded data products using kriging-based interpolation. Given the very large size of modern bathymetric datasets, a pragmatic approach to geostatistical analysis is essential. In this case, this was achieved through fairly simple broad-area de-trending, large random sub-sampling for the experimental variogram estimation and the use of ad hoc neighbourhoods for kriging interpolation.

4) Kriging can inform the generation of combined uncertainty models that incorporate both measurement uncertainty (inasmuch as this can ever be known) and interpolation uncertainty. These can be used to help identify and understand issues relating to the data density and distribution, and perhaps more usefully, provide a direct estimate of overall
uncertainty in the determination of seabed elevation and its change over time. Bathymetric studies have hitherto used rather arbitrary constant measurement uncertainty ranges based on consideration of survey method and the unit of measurement (e.g. van der Wal and Pye, 2003). In contrast, we present a spatially-explicit model of uncertainty that is specific to each bathymetric surface (and time frame) considered. This ensures that the criterion used to gauge the significance of seabed change is specific to the datasets and the geography.

5) Significant insight can be gained from geomorphological analysis of single time frame surveys using morphometric approaches. BPI classification applied at both the regional and case study scale has worked well here to capture key seabed features (bank components (top, crest, margins), open flat seabed, channels and depressions, possible sand wave fields). Work published elsewhere has demonstrated similar capability using higher resolution bathymetric data. If such data were acquired during the early stages of infrastructure planning and environmental impact assessment, BPI analysis and classification would provide an important overview of seabed geomorphology, including identification of landforms and bedforms that have the potential to exhibit dynamic behaviour. This could be undertaken as an exploratory step to establish a need for a full time-series analysis.

6) Examination of seabed behaviour over recent (decadal) and longer (century-scale) histories captures aspects of morphological change and system dynamics that can be used to: i) understand the geomorphology and morphodynamics and ii) supplement existing risk analyses, including conventional assessments of risks posed by local scour. A net change analysis, considering bed level change between successive time periods, identifies areas experiencing accretion or deposition. Magnitudes of change can be directly compared with infrastructure scale. Integration of multiple time frames makes it possible to track the position of discrete features over time, particularly where banks and channels are migrating across a wider seabed. In addition, trend analyses across these multiple time frames reveal the average tendency in bed level. Although linear trends have been derived here, non-linear trends can also be examined given a suitable survey frequency.
4.2. Recommendations for further work

Although we have presented a basis for the integrated assessment of seabed geomorphological hazards, the evaluation of the associated risks to seabed infrastructure remains incomplete. Several strands of investigation are needed to embed seabed hazard evaluations within risk assessments. There is thus potential for further research in this area. The key recommendations for further work are:

1. **Shelf-scale classification of the UK seabed.**
   
   At a landform scale, the morphometric and BPI analyses of coarse resolution bathymetric DTM is an effective first step in the assessment of seabed geomorphology. In combination with filtering of mobile and immobile substrates, it would be possible to examine seabed geomorphology and potential for geomorphology-associated hazard to infrastructure at the UK shelf scale. This would effectively deliver a first stage morphodynamic hazard assessment of the entire marine estate and could be undertaken without further primary data acquisition (historical or modern).

2. **Geomorphology and morphodynamic hazard assessment for areas of interest linked to on-going and new licence applications.**
   
   Locations such as The Wash, The Greater Wash, The Irish Sea and the Dogger Bank areas in the North Sea have been identified as possible sites for wind farm development. Isolated studies of seabed dynamics have been undertaken in parts of these areas, and elsewhere, seabed substrate, geomorphology or habitats have been classified and described. Application of the approaches outlined here would serve as a robust analysis to support decision-making, but also provide the opportunity to evolve the methodology and develop specific guidance documentation in order to embed it into practice.

3. **Refinement and embedding of morphodynamic hazard analysis within standard marine environmental impact and infrastructure engineering assessments.**
   
   Refinement of the process to include risk analyses would benefit from stakeholder consultation to evaluate the vulnerability of monopile foundations to erosion and accretion. Discussion with engineers involved in the design, construction and installation of turbines and other seabed infrastructure would allow the analysis to be developed into a rigorous risk assessment. Furthermore, consideration of cabling and other seabed infrastructures requires a more substantial review of the scale of structure, and the magnitude of change that would present some or significant risk. Progress in these areas would allow the translation of the principles and methods presented here into integrated engineering tools that, by better quantifying risks from seabed change, might improve infrastructure designs and lower costs. For example, existing engineering accommodates assessment of obstruction-associated scouring, but with appropriate discussion and development, these bed level change calculations could integrate variability associated with the dynamics of bedforms and landforms.
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.

DTM Digital terrain model; a 3D representation of a terrain, surface or seabed derived from elevation or bathymetry data.

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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### Appendix

#### A1. Review of data sources covering the outer Thames estuary

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<th>Coverage</th>
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*Units: FA - fathoms, FT - feet, dM – decimetres, cm - centimetre

**UKHO Inspire**: UKHO Inspire Portal & Bathymetry DAC [aws2.caris.com/ukho/]