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# Seabed dynamics in a large coastal embayment: 180 years of morphological change in the outer Thames estuary

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**Abstract** This article analyses the morphological history of the outer Thames seabed, covering over 3,000 km$^2$ from Aldeburgh (Suffolk), to Southend-on-Sea (Essex) and Margate (Kent). The region has been depicted on bathymetric charts since the sixteenth century, and has been formally charted since the eighteenth century. Charts published since the early 1800s incorporate sufficient grid reference or ground control detail for georectification onto a common coordinate system (British National Grid). The morphological history of the outer seabed was thus reconstructed through the digitisation and inter polation of soundings onto a regular grid (3Dsurface). The evolution of seabed morphology was examined using transects, bathymetric change maps and spatial statistics. The results show considerable spatial variability in seabed behaviour. Within the central Thames, banks have experienced significant depth changes can be associated with lateral shifts in individual banks. Some of the outer banks in this region exhibit progressive elongation. Shifts in bank position across the Suffolk shoreface appear to be more subtle, and there is evidence here of both onshore and offshore migration. There is no clear evidence of any regionally coherent response to large-scale historical forcing such as sea-level rise.

**Keywords** Estuary · Sandbanks · Tidal channels ·Shelf ridges · Morphodynamics · Geomorphology ·Bathymetry · Hydrographic survey · Marine habitats

## Introduction

The outer Thames region, occupying the southwestcorner of the North Sea, connects estuaries from theSuffolk (Orwell, Stour, Deben and Alde/Ore), Essex (Crouch/Roach, Blackwater and Colne) and Kent(Medway and Swale) shorelines, in addition to the river Thames itself (Fig. 1). The substantial spatialextent of the region (the seabed to the 20 m depth contour covers c. 3,000 km$^2$) accommodates a largerange of subtidal landforms. Sand banks and intervening channels, extending up to 80 km in length and 7.5 km in width, link the Thames estuary to the southern North Sea, whilst further north and closer to the main shorelines, a variety of more discrete seabed features are present (Fig. 1).

The sedimentology and broad geomorphology of the outer Thames seabed is substantially inherited from the palaeo- (Pleistocene) landscape and modifications associated with the Holocene marine transgression (D'Olier, 1972). Evidence of palaeochannelsrunning west to east is present on high resolution bathymetry, but the present regional morphology is

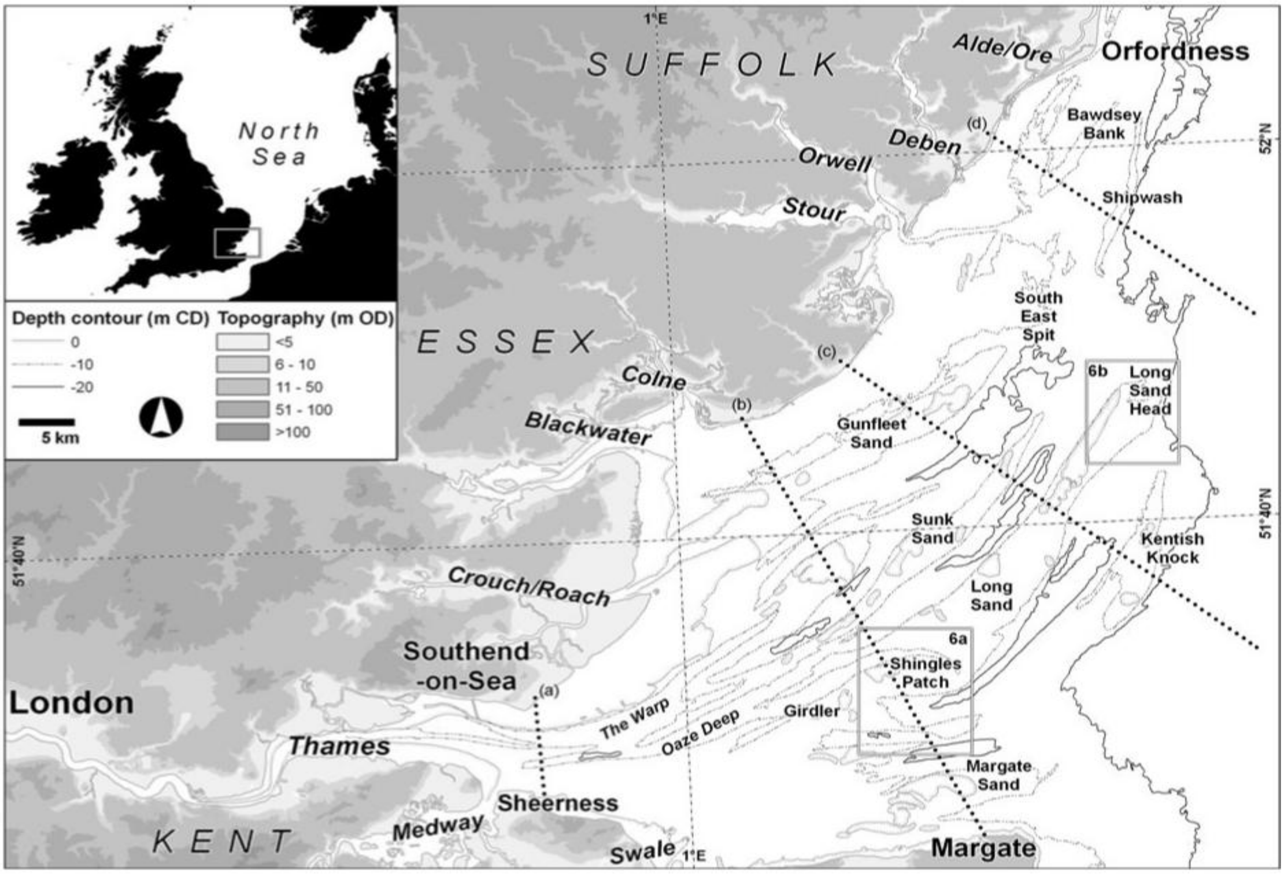



Fig. 1 Location and bathymetry of the outer Thames region. Dotted lines show the position of transects used in Fig. 3. Insets show the location of Figs. 6a and b.

dominated by tidal-stream aligned banks and ridges (Fig. 1). A London Clay (Eocene) basement outcrops in places, but much of the seabed comprises gravel and sand deposits and silt/mud channel fills; sediment texture and deposit thickness is spatially variable (HR Wallingford, 2002).

The area is important regionally, nationally and internationally for a number of reasons. Channels throughout the outer Thames provide crucial navigation routes to the ports of London, Tilbury, Felixstowe and Harwich, and the sediments across the seabed provide a major aggregate resource. Sandbanks in the region have become popular sites for offshore wind farm development, with a fully operational site at Kentish Flats (10 $km^2$ area), construction at Gunfleet Sands (10 $km^2$) and consent for a site in the vicinity of Kentish Knock (the London Array, c. 245 $km^2$). The extensive network of flats, banks and channels comprise a significant natural ecosystem that supports a wide range of habitats and species, recognised in the plethora of Marine Protected Areas (including Special Protection Areas (SPAs) and Special Areas of Conservation (SACs)) and inclusion in the Marine Conservation Zones Project. Habitats of note within the coastal zone include blue mussel beds, Sabellaria spinulosa reefs and seagrass beds, but much of the outer Thames is dominated by a complex network of habitats formed in subtidal sands and gravels. Here, wide ranging communities of marine polychaetes, crustaceans, echinoderms and molluscs exist, which support diverse and economically important fishing grounds.

Previous studies of tidal channels and sand banks have commented on the organisation of features within the outer Thames estuary. Certainly, the number of channels present is suggestive of mutually evasive tidal streams, a commonly observed characteristic of macro-tidal estuaries (Robinson, 1956; Wright et al., 1975). Robinson (1960) inferred that most of the channels running through the outer Thames were flood channels, and that ebb channels were present only in the far southwest close to the Thames river entrance (Oaze Deep and The Warp). This is supported to some extent by Prentice et al. (1968) who showed that seabed biofacies within the Southend region extended seaward within channels of The Warp and Oaze Deep. Evidence from sand waves, found around the northern extents ('heads') of the central sand banks, and at each end of the Suffolk banks and offshore ridges, show abrupt reversals in asymmetry, and associated sediment transport directions, indicating that both flood and ebb tidal currents are actively moving sediment but that dominance is less clear-cut (Prentice et al., 1968; Langhorne, 1973; Caston, 1981; Harris, 1988). Accordingly, there remains some debate over the origin and maintenance of channels and banks in the outer Thames. A commonly mooted assumption is that the gross configuration is associated with underlying topography within the clay basement (Prentice et al., 1968; Harris, 1988). However, Harris (1988) observed that the broad bathymetric highs of the outer Thames banks, and the strong tidal signature of the intervening channels set the system apart from other large estuary mouths such as the Severn (southwest UK) or Moreton Bay (east Australia). In his 3-stage classification of degree of estuary infilling, he placed the Thames in the last (advanced infilling) stage and suggested that there is little vertical accommodation space left for sedimentary accretion, such that only lateral growth (of banks) could follow, with subsequent convergence with marginal tidal flats. Despite a number of studies of morphology, sediment transport and hydrodynamics across the southern North Sea over the last 50 years, there has been very little direct examination of historical seabed behaviour. The aims of this article are first, to describe the recent history (last 100–200 years) of the outer Thames as determined from analysis of published hydrographic charts and second, to evaluate the observed dynamics.

## Materials and methods

### Physical context

The mean tidal prism of the Thames at Southend-on-Sea is c. 6.1 9 $10^8$ $m^3$, which is considerably larger than the combined tidal prism of all other estuaries in the outer Thames (c. 4.2 9 $10^8$ $m^3$). Tidal regime is predominantly macro-tidal to the south (spring tidal range of 5.3 m at Southend-on-Sea and 4.3 m at Margate) and low meso-tidal to the north (2.3 mat Orfordness). Tidal currents in the southern North Sea are to the southwest during flood and to the northeast during ebb (McCave, 1979). Tidal dominance is spatially variable (Caston, 1979), but the net sediment transport direction is broadly to the south-southwest (Stride, 1963). Wave climate is bimodal, forced by dominant southwesterly winds and northeasterly storms. To the northeast of the region (West Gabbard), annual average significant height ($H_s$) and period ($T_z$) are 1.1 m and 4.1 s, respectively, which decrease to 0.3 m and 2.2 s in the centre of the region (Maplin Sands). Extremes inthe wave record, calculated as the 90th percentile in significant wave height, are about twice the mean: 2 mat West Gabbard and 0.6 mat Maplin Sands. Historical rates of mean sea-level risevaryfrom2.57 ± 0.33 mm year$^{-1}$ atLowestoft (in Suffolk, to the north of the outer Thames region) to 1.22 ± 0.24 mm year$^{-1}$ at Southend and 2.23 ± 0.13 mm year$^{-1}$ at Sheerness (Woodworth et al., 2009).

### Methods

Bathymetric data were obtained from UK Hydro-graphic Office published nautical charts. Chart 100 (published between 1812 and 1848) and subsequently chart 1610 (as published between 1855 and 1954) covered the entire outer Thames region at a scale around 1:150,000. Since the 1950s, chart 1610 has focused on a broader area at a smaller scale and coverage of the outer Thames is split between northern (chart 2052) and southern (chart 1183) extents. Most chart publications comprise soundings associated with previous surveys supplemented with local updates. Furthermore, the frequency of updates and publications is inconsistent over the last 200 years. As such, undertaking a comparison of all published material can generate an ambiguous representation of change. Hence, for the purposes of this study, charts separated by at least a 40 year interval were used to reconstruct the morphological history of the outer Thames. Chart 100 from the 1820s was considered in comparison to chart 1610 from the 1860s, 1910s and 1950s and charts 2052 and 1183 from 2000.

Charts were scanned whole on a large-scale scanner by the National Maritime Museum (Greenwich, UK) at 300 dpi. Raster images (TIFF format) of each chart were then georeferenced in ArcGIS 9.3 using ground control points and grid references (where present) to British National Grid (OSGB36). The RMS spatial error in the rectification process was <100 m for all charts except chart 100 (1824), which had RMS errors of 200 m. Soundings and contours were digitised from the charts into point and polyline layers: depths were initially referenced to the chart datum and units of each chart, and subsequently converted to depths relative to chart datum (CD). Data for chart 100 (1820s) were supplemented with soundings from chart 1406 (published in the early 1840s) due to lack of detail offshore. The Topo to Raster (TopoGrid) tool in ArcGIS 9.3 (see Jaffe et al. (2007)) was used to generate regular grids (raster surfaces) with a resolution of 200 m for each digitised bathymetric layer.

Bathymetric surfaces were converted to Ordnance Datum (OD) to enable direct comparison between charts. Chart datum on the 1820s and 1860s charts corresponded to mean low water springs (MLWS); CD on the 1910 and 1950s charts was one foot below MLWS, and the most recent chart used the level of lowest astronomical tides (LAT). A constant correction for each of these chart datums was not possible due to the spatial variation in tidal regime, so trend surface models of the difference between each CD and OD was used to convert the bathymetric surfaces to depth grids in metres relative to the common datum of OD, approximately mean sea-level (Burningham & French, 2008). Data have not been corrected for any possible changes in relative sea level or tidal regime over the last 200 years. A region of interest covering the outer Thames (Fig. 1) was defined for all subsequent analyses. Change was assessed on the basis of net change (difference map) between 1820s and present, changes between successive bathymetric layers, and linear time-series trend analysis. Spatial descriptive statistics of the five bathymetric layers were also produced. Transects crossing the outer Thames region were established at near-regular intervals along the northern and southern shorelines, from which 2D bathymetric profiles were extracted to provide a simple expression of seabed change. All analyses were conducted in Matlab (www.mathworks.com).

Sources of error in the bathymetric change analyses conducted here include those inherent in the original depth data (such as surveying errors) and errors associated with processing and conversion (such as georeferencing, digitisation and datum conversions). Calculating a combined error is a complex process: List et al. (1997) estimated a confidence interval of ±0.5 m in their analysis of the Louisiana barrier island coast (Gulf of Mexico), and van der Wal & Pye (2003) suggested ±0.58 m in their bathymetric change analysis of the Ribble estuary (northwest England). For the Thames, vertical errors are likely to be up to ±1 m, particularly with the inclusion of the 1820s data. A 200 m error on positioning of depth data presents a number of issues when considering vertical changes in regions where there are large changes in depth over a small spatial scale, such as along bank and ridge margins. As such, a cautious approach to interpretation is essential.

## Results

### Regional morphology and change

The 20 m OD contour bounds the seaward extent of the main depositional features of the outer Thames and the historical evidence suggests that there has been very little change in this boundary over the last 180 years (Fig. 2). Considered in the context of D'Olier's reconstructed Holocene shorelines (D'Olier, 1972), it is clear that there is some association between historical estuarine embayment configuration (particularly between Kentish Knock and north Kent) and the location of the palaeo-Thames channel. The 10 m OD contour is an effective delineator of the main banks and ridges, and again comparison of these over the historical term reveals a remarkable consistency in the broad configuration. Notable changes have occurred in the region of Long Sand Head, Kentish Knock, along Sunk Sand and at the south end of Long Sand. Changes around the narrow banks to the north are comparatively small, and the shoreface landward of the 10 m OD contour has been effectively stable, at least within the resolution of bathymetric change analysis over this timescale. The organisation of the shallower regions (banks and ridges) is less well connected to the physiography of the palaeo-shorelines. Kentish Knock is likely to

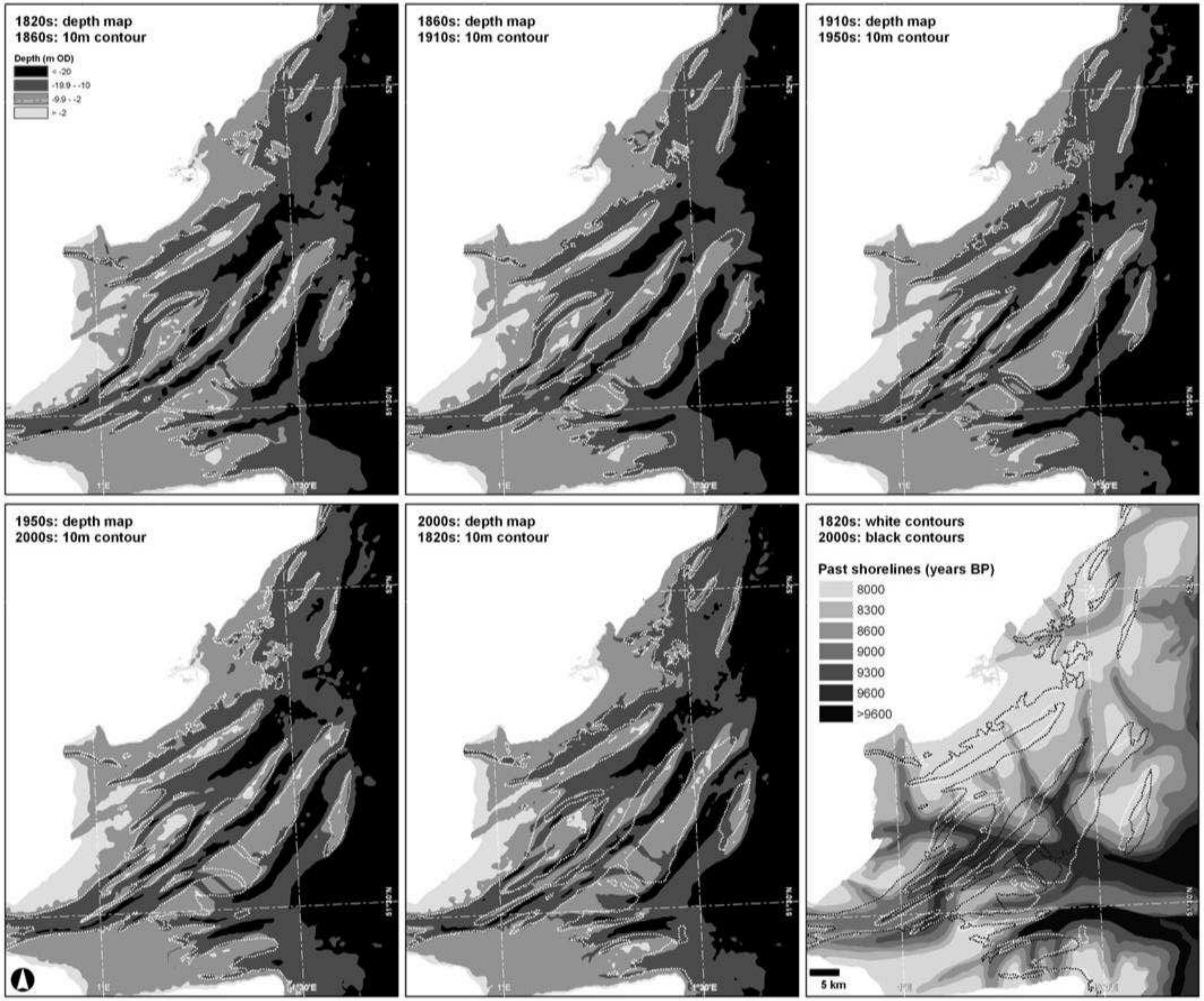



**Fig. 2** Changing seabed morphology across the outer Thames from the 1820s to 2000s. For reference, the 10 m **OD** contour of each successive state is shown for all, except 2000s where the 1820s contours are shown.

be associated with a topographic high that existed to the northwest of the bank's current position. The historical southeastward migration of this bank does appear to be the continuation of a long-term reshaping of a sedimentary feature associated with this topographic high. Similar associations between contemporary bathymetric and Holocene topographic highs are also evident around the Girdler/Shingles and Shipwash banks, suggesting that these too owe their origins to specific features of the palaeolandscape.

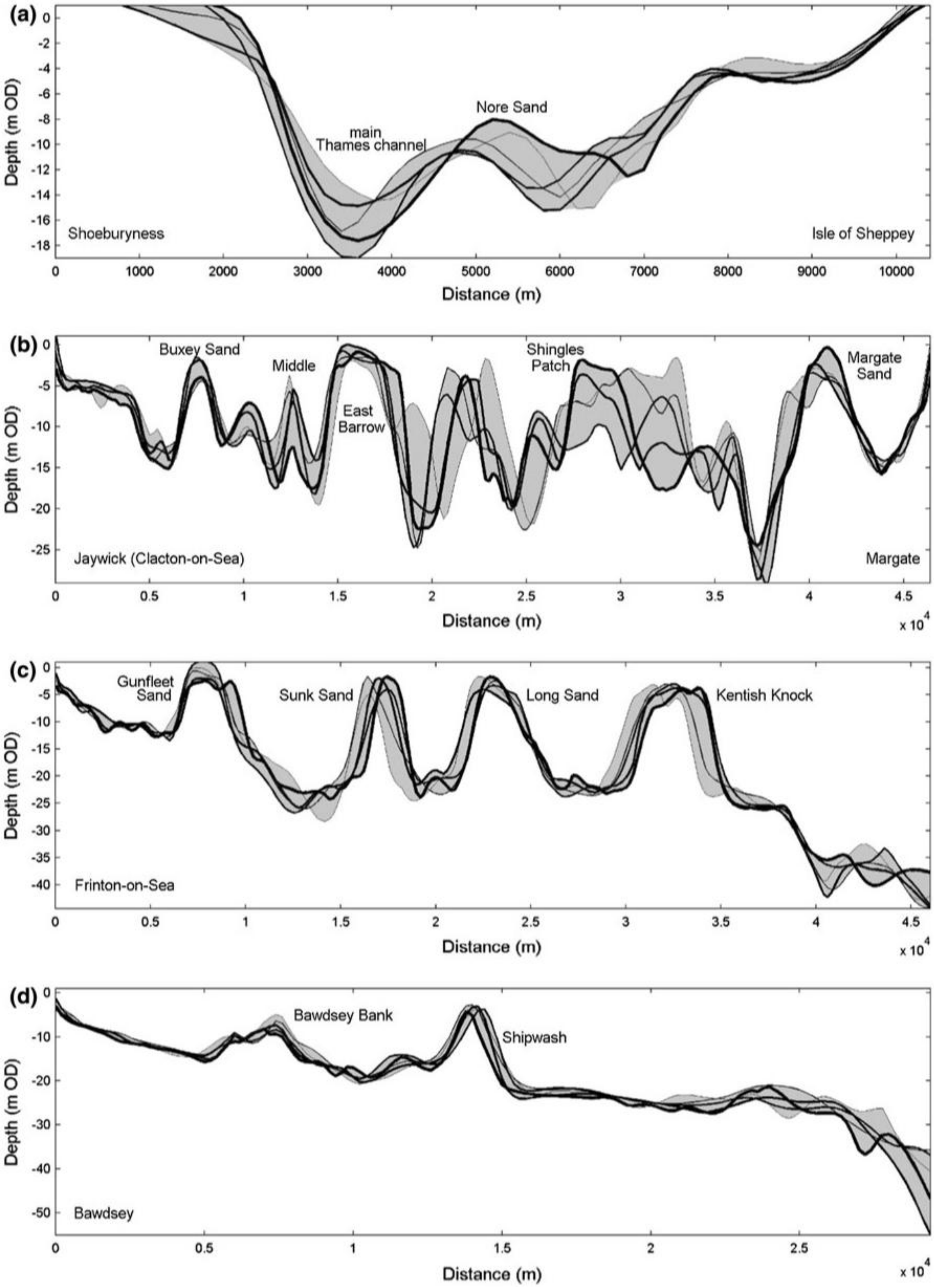
Cross-estuary transects, extending from the Essex and Suffolk coast, highlight the greater variability in seabed morphology within the central region (Figs. 1, 3). In transect (a) from Shoeburyness to the Isle of Sheppey, tidal flow is largely contained in one main channel (Sea Reach/The Warp), which is separated from the Medway Channel and Great Nore by Nore Sand bathymetric high (Fig. 3a). Cross-estuary position of the main channel shows little change over the last 180 years, although there is evidence of small-scale modification of the bank/channel boundaries and some overall deepening. Historical variability is greatest on transect (b) from Jaywick (Clacton-onsea) to Margate (Fig. 3b). Conformity in position increases toward the two shorelines, but across the central region, a significant degree of lateral movement in the bank systems is evident. Margate Sand has built up and narrowed (from the north) over the 180 years, whilst the bathymetric highs in the vicinity of Shingles Patch have become increasingly skewed to the north. Historically, the banks around the southern extent of Sunk Sand (between Shingles and the Barrows) appear to have shifted either side of the 2000s configuration, and there is significant associated variability in position of their flanking channels. To the west, this channel movement has been accompanied by an eastward shift of East Barrow, which has also vertically accreted over the same timescale. Buxey Sand has built up in the same way, but Middle (lying between Barrows and Buxey) has eroded vertically by approximately 9 m.

Transects to the north extend more directly offshore from the Essex and Suffolk shorelines. From Frinton, transect (c) crosses Gunfleet, Sunk and Long Sands, and Kentish Knock (Fig. 3c), and exhibits less temporal variability than transect (b). Sunk Sand, Kentish Knock and to a lesser extent Gunfleet Sands, show evidence of offshore migration whereas the changes at Long Sand are less specific. Depths to bank crests are variable; Kentish Knock and Long Sand appear to have sustained a relatively consistent vertical extent over the last 180 years, whereas it seems that depths have increased over Gunfleet Sands and decreased over Sunk Sands. The these banks comprise several discrete bathymetric highs over broader, more continuous banks, and much of the surface is characterised by large sand waves. Movement of these superimposed features contributes an additional complexity to the surface evolution over time and probably accounts for much of the historical changes identified. Further north, the sea floor is organised into a smaller number of narrow ridges. Transect (d) crosses the south end of Bawdsey Bank and through Shipwash (Fig. 3d). Here, there is greater variability in depths across the offshore seabed than inshore or even adjacent to the banks. But it is clear that, along this transect, depths over Bawdsey Bank have increased, and that both Bawdsey Bank and Shipwash have shifted landward since the 1820s.

**Spatial statistics**

Descriptive statistics of the historical seabed depth surfaces reveal a number of key characteristics (Fig. 4). First, the 180 year average seabed morphology (the mean gridded depth derived from a weighted average based on interval between successive surveys), is broadly aligned to the current organisation of banks and channels. This again illustrates the relative consistency of the historical configuration of seabed features in the outer Thames. At this scale, the submarine landscape is dominated by (i) long shallow banks and deep intervening channels in the central part of the region and (ii) thin near-linear hair-pin ridges to the north of the region, off the Suffolk coast. Second, the greatest variability (range and standard deviation) in seabed depth is associated with bank margins, demonstrating that historical changes in depth are primarily associated with lateral movements in bank and channel features.

Fig. 3 Cross-estuary bathymetric transects extracted from gridded surfaces, and their envelopes of variability. Transects run from a Shoeburyness to Minster, b Jaywick to Margate, c offshore from Frinton crossing Gunfleet, Sunk, Long Sands and Kentish Knock and d offshore from East Lane crossing Kettle Bottom—Bawdsey Bank and Shipwash. Transects are presented in increasing thickness from the 1820s (faint line) to present (bold line).


(a)
Depth (m OD)
Nore Sand
main
Thames channel
Shoeburyness
Isle of Sheppey
Distance (m)
(b)
Buxey Sand
Middle
East
Barrow
Shingles
Patch
Margate
Sand
Jaywick (Clacton-on-Sea)
Margate
(c)
Gunfleet
Sand
Sunk Sand
Long Sand
Kentish Knock
Frinton-on-Sea
(d)
Bawdsey Bank
Shipwash
Bawdsey

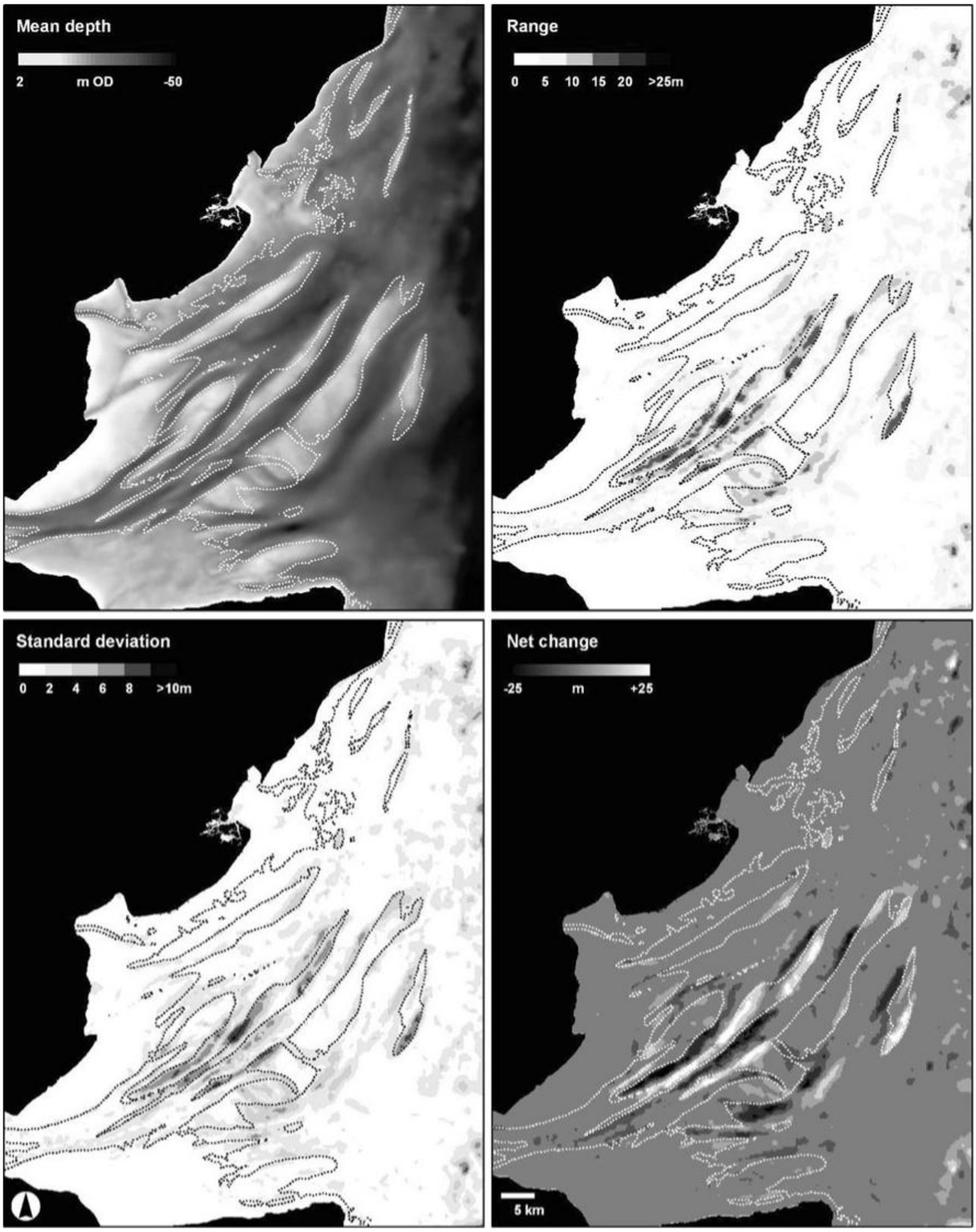



Fig. 4 Descriptive statistics (mean, range and standard deviation) of the changing bathymetry of outer Thames (1820s to present) and net change in seabed depth over this time (where positive values indicate net vertical accretion). The 10 m OD contour associated with the 2000s is shown for reference.

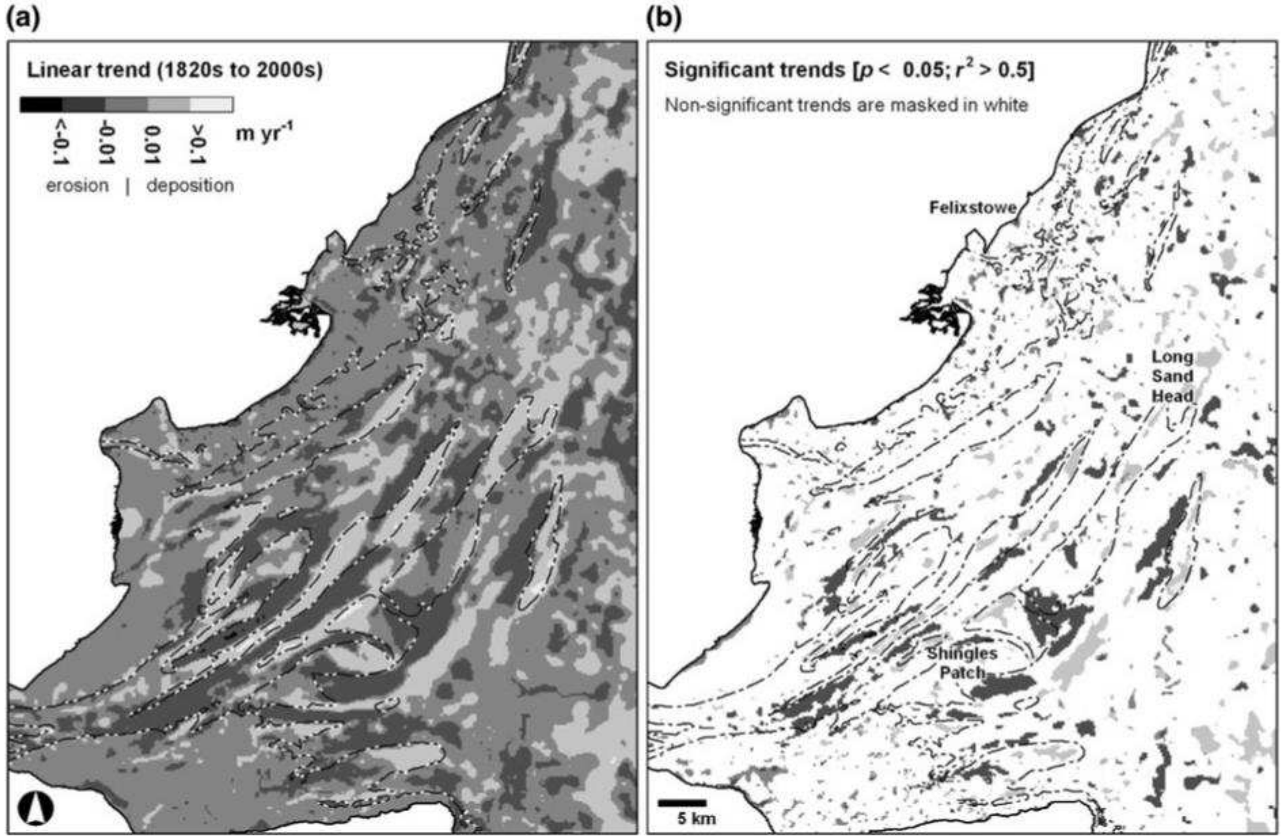



Fig. 5 a Spatial analysis of linear trends in seabed change over the 1820–2000 period; b linear trends are categorised into significant ($p < 0.05$ and $r^2 > 0.5$) where the underlying trends are visible, and non-significant where a mid-grey mask blanks the trends. The 10 m OD contour associated with the 2000s is shown for reference

The shifts evident in this analysis are significantly greater (>400 m) than the georeferencing-associated RMS errors (<200 m). Few areas exhibit no change, but the nearshore environments along the Essex and Kent coastlines exhibit the least change over the last 180 years. More generally, there is no indication of consistent downwearing or vertical accretion across the region as a whole. It is also interesting to note that net changes in seabed depths are more or less equivalent to gross changes, and that the present seabed morphology is distinctly different to that in the mid-1800s. Calculation of rate of change in seabed depth is possible (e.g. Kemp & Brampton, 2007). The simplest form of analysis is linear regression on a cell-by-cell basis, which assumes that site-specific (grid cell) changes are linear over time. The spatial pattern of these linear trends reveal increased rates of change in depth within the central and eastern parts of the region, and decreased rates inshore (Fig. 5a).

Where seabed morphodynamics are dominated by lateral shifts in bank position, mirrored linear trends are evident along opposite margins. Filtering these trends to consider only those that are statistically significant (with $r^2 > 0.5$ and $p < 0.05$) suggests that much of the temporal variability in depth across the wider seabed does not conform to a significant linear trend (Fig. 5b). In fact, the pattern of trends broadly echoes the main patterns in range and net change, but additionally reflects the strength and direction of historical trends. Rates of vertical change >0.1 m year-1 only occur where there are shifts in bank position. Pairing of positive and negative trends is significant, and arises due to the lateral movement of banks causing associated regions of large-scale accretion and erosion around opposite sides of banksand channels. This implies that the sediment budget of most banks is balanced. Trends in areas not associated with lateral movement are generally far smaller and/or not statistically significant.

## Historical seabed dynamics

Notable regions of progressive historical change include Kentish Knock, Shingles Patch, Oaze Deep, Margate Sand, South East Spit and the northerly extents of Long Sand and Bawdsey Bank. Kentish Knock exhibits accretion on its southerly and northerly wings, whilst erosion has occurred along its western boundary, indicating that change at this bank involves both migration (southeastward) and reshaping (becoming increasingly elongated). Accretion continues to the southwest of Kentish Knock along an imprecise bank connecting it to the southern banks of Long Sand. This is accompanied by a progressive deepening of the channel along the eastern margin of Long Sand. The bathymetric highs across this southern section of Long Sand appear to have shifted to the west, and this may be associated with the development of cross-bank 'swatchways' (also known as 'gats') in the region of Shingles Patch. The detailed morphological changes here reveal growth and decay of cross-bank channels (Fig. 6a); over the last 100 years, North and South Edinburgh Channels have formed across Long Sand in the vicinity of the former Thomas' New Channel (early nineteenth century), Bullocks Channel (mid-nineteenth century) and Duke of Edinburgh Channel (late nineteenth century). The progressive growth and diverging along-bank movement of the North and South Edinburgh Channels has facilitated the development of Shingles Patch, which is now the dominant bank feature in this region, in comparison to the Girdler and Shingles banks of the nineteenth century.

To the southwest, Oaze Deep is characterised by a strong negative (deepening) trend, and the lack of associated positive trends in neighbouring banks suggests that this region has been experiencing a negative sediment budget over the last 180 years. To the southeast around Margate Sand, the bathymetric high appears to have shifted eastwards, illustrated by the progressive vertical accretion across the eastern parts of the bank Margate Sand in contrast to downwearing across the western parts; this has occurred well within the 10 m contour that encircles the Margate Sand, Last and Margate Hook features.

Further north, to the southeast of Felixstowe, marked historical accretion has occurred at South East Spit (see Fig. 1 for location), which has served as a dredge material disposal ground since the 1970s. This has resulted in the seaward extension of the nearshore shelf along this section of coastline. Over the same period, Long Sand Head has extended to the northeast, accompanied by a significant change in bank configuration (Fig. 6b). Most of the progradation occurred between the mid-1800s and 1900s, with c. 2.5 km extension in the 10 m OD depth contour over the last 180 years. Since the 1950s, the head has broadened and developed raised margins around a notable trough aligned near parallel to the centre of the bank. This possibly reflects an initial stage of development of a flood-oriented channel. Northward extension is also evidence at Bawdsey Bank and to a lesser extent at Sunk Sand. At Bawdsey, the northward growth mirrors the erosional trend at its southern end.

## Discussion

Historical morphological change within the outer Thames exhibits a combination of progressive trend and less coherent variability. The strongest trends are associated with the cross-shore migration or along-bank extension observed across most of the banks within the central region. Even the more northerly banks on the Suffolk shoreface show similarly progressive, albeit smaller scale, evolutionary behaviour. In contrast, morphological change across large areas of the wider seabed (i.e. beyond the discrete channel-bank systems) is more variable both spatially and over time. Beyond the acknowledged errors associated with the analysis of historical datasets of this kind (especially those relating to changes in survey methodology and datum), the interpretation of morphological change is also impacted by the varying resolution of individual surveys. In particular, the interpolation of datasets comprised of discrete soundings into gridded datasets for the detection of seabed change necessarily introduces biases attributable to variations in attention to detail on the part of the original surveyors. In this analysis, the features of most interest are the discrete submarine landforms (banks and channels), which receive significant attention on all historical sources due to their importance in charting for navigation. In contrast, broader expanses of seabed are characterised by fewer specific bathymetric features. As such, they

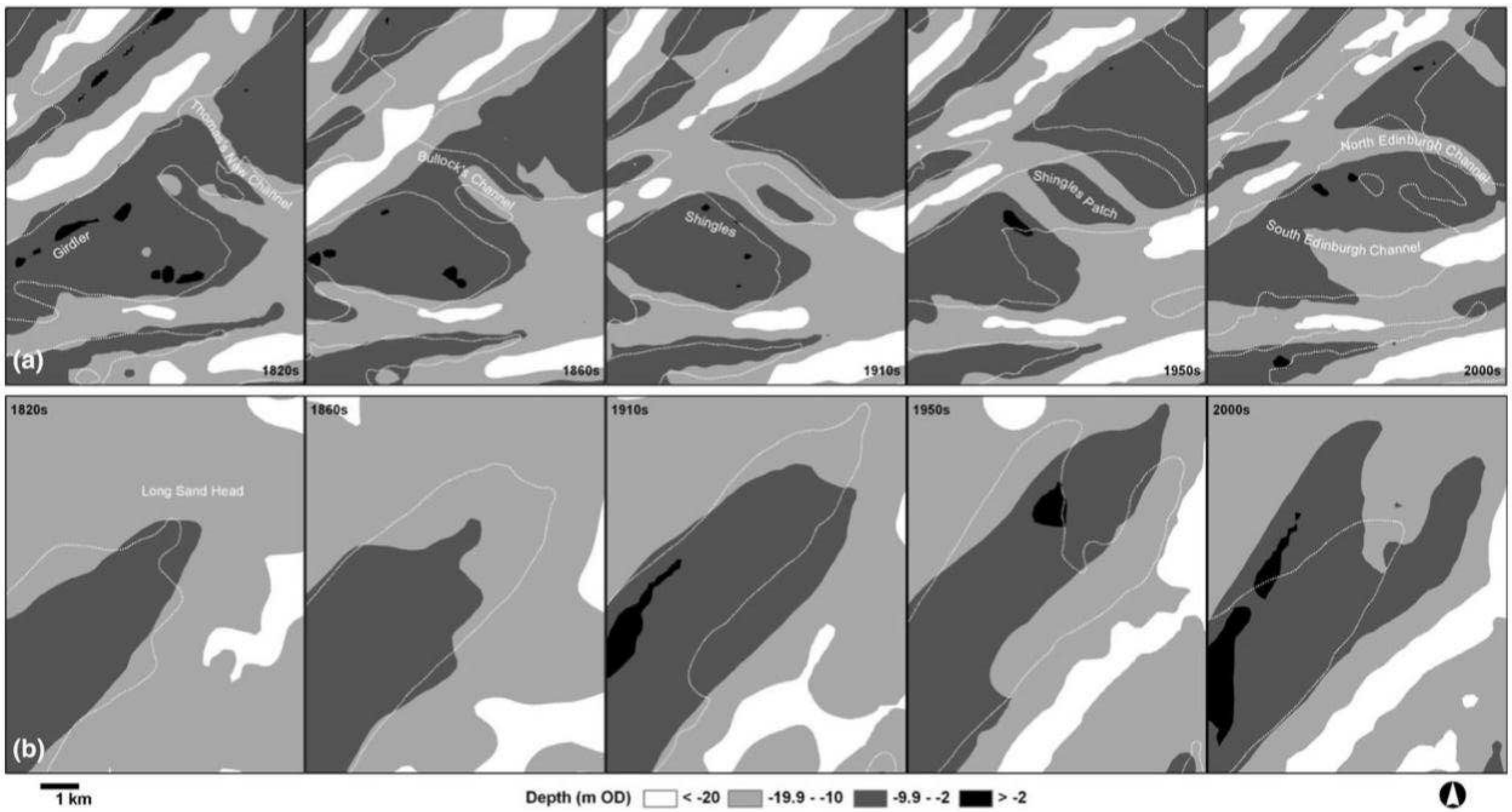



**Fig. 6** Changing seabed morphology in the **a** Shingles Patch and **b** Long Sand Head regions from the 1820s to 2000s. For reference, the 10 m **OD** contour of each successive state is shown for all, except 2000s where the 1820s contours are shown.

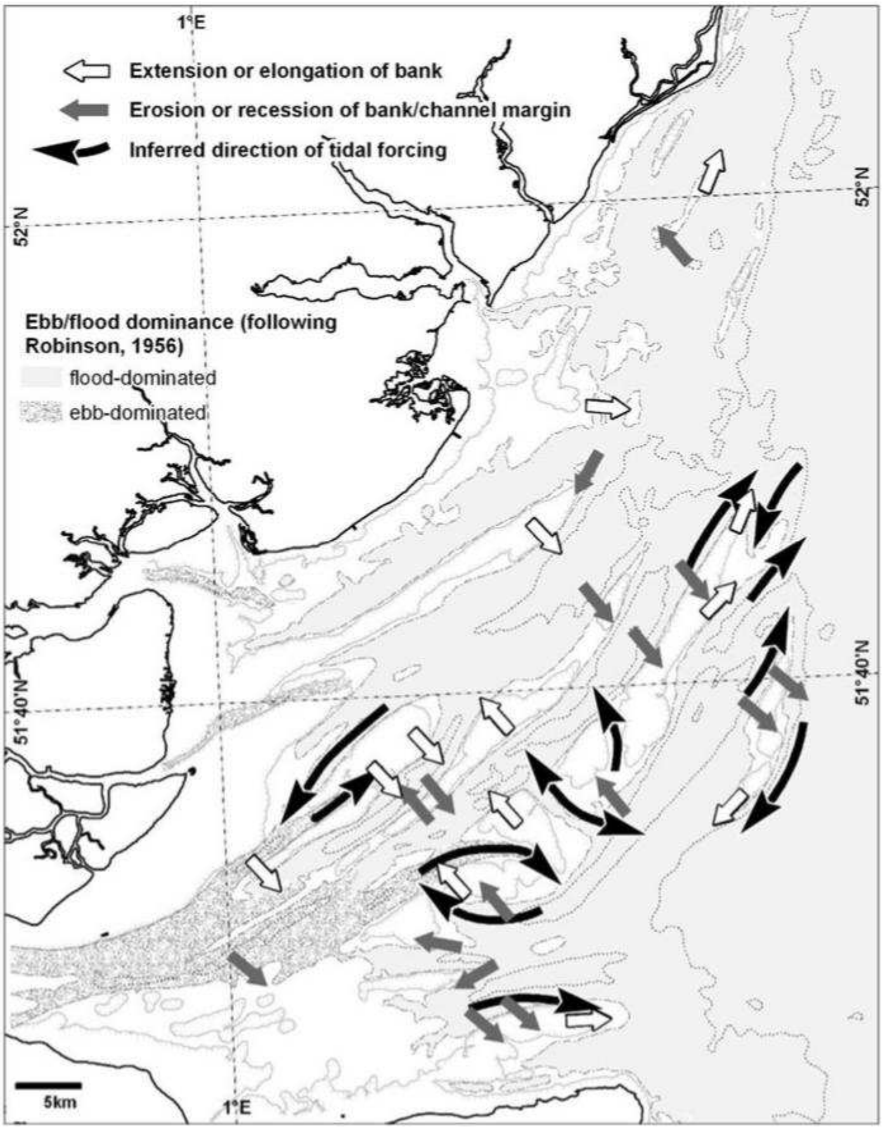



Fig. 7 Channel tidal (ebb/ flood) dominance(following Robinson(1956)), summarymorphological change and inferred tidal forcing across the outer Thames seabed.

have generally been of less interest from the perspective of navigation and tend to be more sparsely sounded within bathymetric surveys. It is not surprising therefore to find strong signals of progressive change in the features that are represented most accurately (banks, ridges and channels) and a more diffuse and noisy expression of change over featureless areas of seabed. Within this context, linear regression and correlation analysis of sequential bathymetric surfaces (Kemp & Brampton, 2007) provides an effective tool for isolating and quantifying statistically significant morphological changes from the background noise.

Historical sea-level rise, rates for which vary between 1.2 and 2.6 mm year$^{-1}$ in this region, equates to a net rise of around 22–47 cm over 180 years. In terms of the wider seabed, this is well within the error of the bathymetric datasets and changes derived from analysis of these. Furthermore, bathymetric changes in the vicinity of the major bank and channel systems are typically at least an order of magnitude larger. The tidal regime of the outer Thames region has been modified over a longer historical time-scale by twelfth to eighteenth century estuarine intertidal reclamation and by a more recent increase in tidal range and the frequency of exceptionally high tides (van der Wal & Pye, 2004). Although estuary tidal prisms were reduced substantially by reclamation and seawall construction, most of these changes occurred prior to the early 1820s. It is difficult to gauge the extent of any indirect, lagged, effects of these interventions on the outer Thames seabed over the last 180 years. Reclamation effectively represents an acceleration of the longer term decrease in tidal prism associated with late Holocene marine infilling, but over the more recent historical period, increases in the level of high tides and tidal range will have contributed positively to tidal prism. As such, any change in tidal forcing over the last few centuries is not clear-cut, and certainly not overwhelmingly dominated by an increasing or decreasing trend. From a morphological perspective, some of the channels and banks examined here exhibit tidal-current associated changes, particularly in the initiation and growth of cross-bank channels, but with no suggestion of shallowing or narrowing of longstanding tidal channels. Consideration of channel morphology in the context of Robinson's (1956) classification of ebb- and flood-dominance, suggests that the organisation of tidal flow has remained similar over the last 180 years (Fig. 7). It is clear that the tidal inner-Thames exerts the strongest ebb-tide control over the outer Thames as a whole; the tidal prism of Thames alone is almost 1.5 times that of all other estuaries combined. Changes in tidal forcing associated with the inner-Thames are hence more likely to influence the long-term seabed dynamics of the outer Thames.

Dredging and disposal activities, which are primarily limited to the late 20th, are locally evident, but associations between dredging and erosion-dominated behaviour, or disposal and accretion-dominated behaviour are inconsistent across the outer Thames. South East Spit (dredge material disposal ground) shows evidence of progressive accretion, whilst northeast of Long Sand Head (dredging area) shows some vertical erosion. But dredging licences have applied to a broader region of seabed across the northern extents of Long Sand and Kentish Knock, and to the east of Shipwash, yet these regions do not exhibit significant nor consistent erosion. It is not possible to infer impacts of the construction of wind farms on seabed dynamics, but it is worth noting that the London Array (planned to straddle Kentish Knock and the northern extents of Knock Deep and Long Sand) will occupy one of the most geomorphologically interesting and morphodynamically active areas of the outer Thames seabed.

The historical morphological behaviour in the central region of the outer Thames is dominated by bank migration. Here, deposition and lateral extension along one bank/channel margin is largely mirrored by erosion and recession on the opposite margin (Fig. 7). At the feature scale, it would seem that sediment budgets are relatively balanced, and that sediment released through reworking of one area supplies the accretional behaviour elsewhere. There are some features that stand apart from this, most notably Long Sand Head, which exhibits continued northerly elongation that is not directly balanced by adjacent recession. Although sand is present across much of the outer Thames and southern North Sea seabed, it is more often than not mixed with gravel and/or consolidated clay (HR Wallingford, 2002). The supply of these sediments from further afield to the banks system is likely limited to the very fine suspended fraction. Sediment supply from the littoral shoreline, particularly the eroding sedimentary cliffs of Suffolk and Norfolk, will include sand-grade material, but the pathways to the south Suffolk and central Thames banks are not clear. Certainly, there is no evidence of the strong sediment budget links between shoreline and shoreface that occur further north, for example at Sizewell (Robinson, 1980) and Scroby banks (Park & Vincent, 2007).

Harris (1988) proposed that the submarine morphology of the outer Thames is characteristic of an estuary in the final stages of infilling. The presence of mutually evasive flood and ebb channels across the central region is indicative of excess sediment that can be transported by currents in both directions. It is possible that the broad consistency in bank and channel configuration across the outer Thames is a consequence of strong ebb and flood tidal flows between the inner-Thames estuary and North Sea. Cloet (1954) noted that the lack of significant migration at Goodwin Sands (in terms of its position between the southern North Sea and the Straits of Dover) was directly related to the interplay of ebb and tidal currents. In this concept, dynamic behaviour of the bank is essential to the maintenance of its location on the seabed, where evading ebb and flood currents drive sediment transport and morphological change. The importance of ebb and flood tidal flows through the outer Thames system is evident from the presence of both ebb- and flood-dominated channels (Fig. 7). Many of the morphological changes that have occurred can be directly linked to the formation, development and cessation of the terminal portions of these channels. There is no indication that there have been any significant changes to this dynamic behaviour over the period considered here, in that the morphological changes and sediment transport processes of the nineteenth century are comparable to those of the nineteenth century.

Many estuarine systems in the final stages of infilling exhibit strong structural controls on deposition, morphological evolution and seabed dynamics due to constraints on accommodation space and influence on hydrodynamics. This is evident in glacially influenced estuaries that infilled rapidly in the mid- to late-Holocene, particularly those that exist within small (e.g. Burningham, 2008) or structurally complicated (e.g. Fitzgerald et al., 2000) valleys. In large, open-mouthed estuaries that exist within depositional, coastal plain contexts, accommodation space is inherently defined by the degree of infilling. Sedimentation in mature estuaries of this type is therefore a function of sedimentation history, the rate of continued sediment supply and the increases in accommodation space afforded by sea-level rise. The outer Thames exhibits dynamic equilibrium behaviour: the combined role of ebb and flood tidal currents is evident in the persistence of, at least over decades and centuries, a consistent suite of channel and bank features. Sediment continues to be introduced to the outer Thames from the inner Thames and neighbouring estuaries, in addition to shoreline erosion (HR Wallingford, 2002), and sediment is actively transported within the system, as manifested in significant areas of sandwaves on and around the margins of the main banks. Historically, therefore, the outer Thames displays a morphodynamic balance in which the sea-level rise and sediment supply controls on infilling are relatively equal and morphological change is largely restricted to the redistribution of sediment.

The implications of this morphodynamic evolution on the substrate and associated benthic communities are potentially important. Sediment redistribution across the outer Thames, associated with the significant shifts in channel and bank features, must inevitably be associated with some reorganisation of marine habitats. Such processes are a likely factor influencing historical shifts in fishing grounds. Further investigation is needed to assess the medium term change in sedimentary environments and benthic habitats as a consequence of seabed dynamics at the scales reported here.

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