Geomorphological and hydrodynamic assessment of future flood defence management options at Hazlewood Marshes, within the wider context of the Alde & Ore estuary

Report to the

Alde & Ore Estuary Partnership

Commissioned by the Alde and Ore Association

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6 July 2014

Kenneth Pye Associates Ltd.
Scientific Research, Consultancy and Investigations

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Summary

This report summarises an assessment of 'Do Nothing' and Managed Realignment options at Hazlewood Marshes in the Alde-Ore estuary where the river walls were breached during the storm surge of 5th - 6th December 2013. It is concluded that 'Do Nothing' or large-scale managed realignment would have only a relatively small effect on water levels, current speeds and bed sediment transport within the river near Aldeburgh Marshes and Slaughden, Maximum flow velocities are unlikely to increase by more than 7% and the resulting increase in be shear stresses is unlikely to have a significant effect on bed sediment transport and the adjoining river walls. Water levels and current speeds between Iken and Snape are likely to reduce slightly, giving a small flood risk benefit to Snape. However, reduced tidal current velocities in this area might also cause a slight increase in subtidal and intertidal sedimentation rates. The spring tidal prism of the active estuary would increase by 6 to 7% but such a change would be unlikely to have a significant effect on the cross-sectional area of the estuary mouth and the potentially beneficial effects on high water levels in the inner estuary are therefore unlikely to be transient.

Managed realignment at Boyton Marshes could have a larger relative effect on the estuary since the surface elevation is lower than that of Hazlewood Marshes and the resulting increase in tidal prisms would potentially be larger (depending on the proportion of the site which is allowed to flood).

It is recommended that further investigative studies should be carried out before final management decisions are taken and/ or works carried out. These should include:

- further 2D hydrodynamic and sediment transport modelling using the most recent LIDAR / bathymetric DEM
- 3D modelling to fully characterise three-dimensional flows around meander bends
- additional field measurements of water levels and current speeds at key locations where little or no data presently exist, notably between Iken and Snape and within the Butley River
- additional bathymetric surveys should be commissioned covering the Butley River and the upper Alde between Iken and Snape
- the existing LiDAR / swath bathymetric DEM of the estuary used in the analysis described in this report should be improved by incorporation of 2012 data for additional areas.

1.0 Report scope and purpose

Between 5th and 7th December 2013 the East Coast of England was affected by a significant storm surge which caused significant flooding and erosion along the coast of East Anglia. The maximum surge at Lowestoft almost coincided with the time of predicted high water (observed HW at 22.30, predicted HW at 23.00 on 5th December), producing an observed high tide of 3.26 m OD, the biggest recorded event since the 1953 surge (reported by Rossiter (1954) to have attained 3.44 m OD). The 2.06 m skew surge (difference in height between the height of predicted and observed high water) recorded at Lowestoft on 5th December was also the largest recorded since 1964 (Pye & Blott, unpublished data).

The maximum high water level recorded by the EA tide gauge at Orford Quay was 3.06 m OD at 01.45 on the 6th December, 71 minutes before the time of predicted HW, and the estimated skew surge (difference in height between predicted and observed high water) was 1.66 m. No long term tide data are available for the Alde-Ore estuary, but statistical estimates for the adjoining open coast (McMillan *et al.*, 2011) would suggest this was between a 1 in 50 and 1 in 100 year event. However, this analysis probably overestimates the return periods since it is based on short term tidal records which do not capture high magnitude events like the 1953 surge (Pye & Blott, unpublished data). Water level estimates for the open coast also can provide only an approximation since non-surge high tidal levels outside the estuary mouth are 30 to 40 cm higher than in the lower part of the estuary (Table 1).

The high tide of 5th-6th December caused overtopping of the flood defences at several locations in the Alde-Ore estuary, and a number of breaches and partial breaches were created, including near Shingle Street and on Havergate Island in the lower estuary, on Orford Ness in the middle estuary, and at Hazlewood Marshes, Ham Creek and Iken Marshes in the upper estuary (AOEP, 2013; Figure 1). The breaches and near-breaches at Ham Creek and Iken were repaired quickly, but a decision on whether to repair or rebuild the walls at Hazlewood Marshes, which to date have been maintained by the Environment Agency (EA), has not yet been made. At Hazlewood Marshes the lower part of the Aldeburgh Golf Club River Course was flooded and water entered the gardens of seven properties on the estuary margins.

In February 2014 Kenneth Pye Associates Limited (KPAL) was engaged by the Alde & Ore Association (AOA), on behalf of the Alde & Ore Estuary Partnership (AOEP), to undertake an assessment of the future management options at Hazlewood Marshes in terms of their potential geomorphological and hydrodynamic implications for the immediate area and the wider estuary. The future management options include:

(1) 'Do Nothing' (un-managed realignment)
(2) Re-build the embankments on the existing alignment, possibly to a higher standard

(3) Re-build the walls on a new alignment further landward (managed realignment)
(4) Build new bunds around the margin of Hazlewood Marshes to protect properties
(5) Manage the breaches in the existing wall to control the inflow and outflow of tidal water, possibly in connection with Option (3) or Option (4)

A final decision regarding the most appropriate option awaits DEFRA / Environment Agency (EA) guidance on the possible legal requirement to protect or replace European designated habitats affected by natural ('force majeure') events such as the December 2013 surge, and a full consideration of environmental, economic and social factors. Much of the Alde - Ore estuary, including Hazlewood Marshes, is of national and European nature conservation importance (Figure 2).

This purpose of this report is to inform the decision making process by examining the potential effects of different options on water levels, flood risk, current speeds, sediment movement and potential longer-term morphological changes at Hazlewood Marshes and within the wider estuary.

The analysis has taken account of a number of questions raised by members of the AOA, AOEP and the local community, including:

- Would there be any significant increase in flow velocities in the vicinity of Slaughden Bend, with potential implications for the Aldeburgh Marshes wall and the AldeburghYacht Club / Slaughden Sailing Club frontage?

- Would there be any significant change in high water levels (and hence flood risk) in the estuary, notably at Aldeburgh, Iken and Snape?

- If the Hazlewood wall is not repaired and no other action taken, what morphological and habitat changes might be expected?

- What would be the likely impact of 'Do Nothing' or Managed Realignment (MR) on groundwater salinity around the margins of Hazlewood Marshes?

- What would be the effect of 'Do Nothing' or Managed Realignment at Hazlewood Marshes in combination with possible full managed realignment or overspill schemes at Boyton Marshes, Havergate Island, King's Marshes and Lantern Marshes?

2.0 Data sources and methods

2.1 Approaches

The issues identified in Section 1.0 have been addressed using two main approaches:

(1) a review of previous hydrodynamic modelling and conceptual geomorphological assessment undertaken as part of the Suffolk Estuarine Strategies(SES), Alde and Ore Futures programmes and other initiatives between the mid-1990s and 2012 (ABP Research & Consultancy, 1996; ABPmer 1997; HR Wallingford, 1999; Posford Duvivier, 1999a,b; Posford Haskoning 2002a,b; Black & Veatch, 2006; Halcrow 2011a,b,c); Pye 2005, 2008; Blott & Pye; Haskoning 2008, 2010; JBA Consulting, 2011a,b).

(2) new analysis of the broad-scale hydrodynamic regime and geomorphological relationships within the estuary.

2.2 Data sources

The following data sets have been used in the new analysis undertaken as part of this study:

- Predicted tidal level data for stations inside and outside the estuary taken from Admiralty Tide Tables (Table 1; UKHO, 2013)
- Tide gauge data for East Coast stations, including Lowestoft (obtained from the National Tidal and Sea Level Facility (NTSLF) website)
- Long-term sea level data, based on tide gauge records, taken from the Permanent Service for Mean Sea Level (PSMSL) web site
- EA tide gauge data for Orford Quay
- Water level data collected at several stations within the estuary by Gardline (2003; Figure 3)
- EA LiDAR data flown in 2012 at 1.0 m resolution, covering most of the active estuary and Orford Ness (Figure 3)
- EA LiDAR data flown in 2008 at 2 m resolution, covering both the active estuary and most of the reclaimed areas around the estuary (Figure 3)
- EA swath bathymetry surveys of sub-tidal areas (excluding the Butley River and upper part of the Alde and Ore) undertaken in 2012 and 2006
- EA composite topographic / bathymetric digital elevation model based on the 2012 LiDAR and swath surveys, covering most of the active estuary with data at interpolated 0.5 m resolution (Table 2; Figure 3)
- EA 2011 rectified digital colour aerial photography

- EA combined topographic and bathymetric cross-profiles for surveys in 1995, 2002 and 2006)
- EA flood defence crest level survey undertaken in 2009
- Admiralty Chart No. 5670-8 (Hydrographer of the Navy, 2011)
- The 'chartlet' of the entrance to the Alde-Ore estuary, based on Trinity House survey on 1st April 2014, available on the East Coast Pilot website
- Historical Ordnance Survey maps
- Historical aerial photographs (RAF 1945, Luftwaffe, 1942, University of Cambridge 1983)

2.3 LiDAR and bathymetric data processing

Four digital elevation model (DEM) datasets were supplied by the EA for this project (Table 2; Figure 3). An airborne LiDAR survey was conducted on 17th December 2012 covering the intertidal area of the Alde-Ore estuary between Shingle Street and 1 km upstream of Snape. The Butley River between its confluence with the Alde-Ore and Butley Mill was also covered. The data were processed by the EA Geomatics Group (EAG) to produce gridded DEMs with a resolution of 1 m. The estuary was divided into two polygons, supplied separately as P_8611 (upstream of Slaughden) and P_8612 (downstream of Slaughden) (Figure 2). During this processing, areas beyond what was presumably considered to be the area of interest were 'blanked' by EAG. With the exception of Lantern Marshes, King's Marshes and Havergate Island, elevation data for all reclaimed land in the estuary were removed from the dataset. This removal was achieved by roughly prescribing the alignment of the embankments at a resolution of c. 200 m. In several areas this resulted in parts of the intertidal estuary seaward of the embankments also being 'blanked' from the dataset in error.

A multi-beam swath bathymetry survey of the Alde-Ore estuary was also undertaken in 2012, between the mouth at Shingle Street and Church Reach, Iken. The Butley River was not surveyed. The exact date of this survey is unknown, although the initial processing of the data was undertaken in November - December 2012.

EAG processed these datasets using an interpolation routine to produce a combined DEM of the estuary bed at a resolution of 0.5 m. Unfortunately, the final DEM was trimmed by EAG at northing 257340 and eastings 637249 and 646291, and the estuary above Iken (easting 640000) and Butley Mill (northing 252000) were also trimmed. As a result, the combined LiDAR-bathymetry DEM of the estuary contained even more gaps in the intertidal area than the LiDAR surveys.

For the purposes of this study it was therefore necessary to combine the two LiDAR polygons flown in 2012 with the combined LiDAR – swath bathymetry dataset to produce the most comprehensive coverage of the estuary possible. An additional LiDAR dataset supplied by EAG, flown on 2-7 February 2008 at a resolution of 2 m, was used to fill the gaps in the 2012 dataset, and provide complete coverage of the intertidal and reclaimed areas of the estuary. This was accomplished using the Golden Software *Surfer* program *Mosaic* routine. Small areas of ponded water containing no data, which would have formed 'holes' in the DEM, were filled using a nearest neighbour algorithm. The final combined 2008-2012 dataset was saved at 0.5 m resolution in two parts: the upper estuary above Slaughden and the middle and lower estuary below Slaughden.

2.4 Tidal volume calculations

Volumes of water within the active estuary (and on the reclaimed marshes with defined Flood Cells) were calculated using the Surfer *Volume* routine. Volume calculations require an upper and lower surface to be defined. Admiralty predictions and measurements by Gardline (2003) show that tidal levels vary along the estuary (Table 1; Figures 4 & 5). For this study, volumes were calculated above the LiDAR / bathymetric DEM, and below either a horizontal or a sloping tidal surface, depending on position within the estuary (Table 3). In the absence of measured data for the innermost part of estuary, a horizontal surface was assumed for all areas upstream of Slaughden. Tidal levels were assumed to vary linearly between Slaughden and Gedgrave, near the Butley River mouth, and tidal volumes for this section of the estuary were calculated below a sloping surface. No measured tidal level data exist within the Butley River, but for the purposes of this study tidal levels were assumed to increase upstream along the Butley River at the same rate as along the main Alde-Ore channel. There are also no reliable measured tidal level data in the main channel between Flybury Point (at the mouth of the Butley River) and North Weir Point, although the available data suggest a slight reduction in tidal levels between the open sea and the area just inside the estuary mouth (Figure 5). For this study, a horizontal water surface between North Weir Point and the Butley River entrance was assumed. Horizontal tidal surfaces were also assumed within each flood cell on areas of reclaimed marshland

Tidal prism (volume of water entering or leaving the estuary on a given tide) was calculated by measuring the difference between the defined upper and lower tidal surfaces for a range of tidal levels attained at Slaughden / Aldburgh Marshes: (a) a storm tide reaching 3.5 m, (b) a storm tide reaching 3.1 m OD, (c) HAT, (d) MHWS and (e) MHWN (Figure 7). For the storm surge and HAT tides, LAT was chosen as the lower level for the tidal prism calculations since there is often a negative surge of up to 0.5 m before a large positive surge. For MHWS tides the lower limit for the tidal prism calculations was taken to be MLWS, and for MHWN tides lower level was taken to be MLWN. Tidal levels at intermediate positions between Slaughden and Gedgrave have been estimated using ratios of the distance between these two points (Table 3). Tidal prisms on reclaimed marshes (assuming the embankments were breached or removed) have been calculated using a horizontal surface at the same level as the active estuary in that part of the estuary. The distribution of tidal levels is the same at Gedgrave and Slaughen, and therefore a straight-line relationship exists between tidal levels estimated at the two stations (Figure 6). This allowed intermediate levels at Gedgrave to be calculated for any given level at Slaughden.

Total water volumes within the estuary, and within each flood cell, were calculated between the 2012 estuary bed level and each high tidal level using the Golden Software *Scripter* routine. Tidal volumes, and tidal prisms, were calculated for different parts of the estuary by defining 'blanking files' required for calculation in each area. Calculations were made for the area of the defined 2012 'active estuary' and for 13 individual flood cells. Some flood cells were further sub-divided into a, b, c etc. where internal embankments cross the flood cells (Figures 8 & 9).

2.5 Estuary cross-sections

Cross-sectional data were extracted from the 2012 combined DEM at positions in the estuary where EA strategic monitoring profiles are located and at selected other locations (Figure 10). The '*Slice*' routine in Surfer was used to extract the data at 0.5 m resolution. Data from historical EA surveys in 1995, 2002 and 2006 were combined with elevation data from 2012 in Microsoft *Excel*, and the data plotted for visual inspection. Channel widths, maximum depth, cross-sectional area below defined tidal levels and tidal prisms upstream of individual cross-sections were calculated in Microsoft *Excel* using specially written *Visual Basi*c macros.

2.6 Potential errors

Errors in the tidal volume calculations associated with the assumptions relating to local tidal levels are likely to be small (<5%) compared with those arising from errors and limitations in the data sets used to construct the DEM (estimated to be 10-15% for the estuary as a whole).

The average vertical accuracy of airborne LiDAR is of the order of ±15 cm but may be better or worse depending on the nature of the terrain, flight pattern and nature of data post-processing. At a local scale, apparent differences in elevation of 1m or more may arise due to the limited spatial resolution of the LiDAR data (which in this study was originally presented at 1.0 or 2.0 m pixel resolution and subsequently interpolated at 0.5 m resolution).

As part of this study, the 2012 LiDAR survey data were compared with EA ground topographic profile data across 'hard' and un-vegetated surfaces. Average elevation errors for two profiles, S1A6 across the hard-standing near the Slaughden Martello Tower and A55-S1A5 at Slaughden Quay, were determined to be 2 - 3 cm. However, the errors are likely to larger, of the order of 10 - 15 cm, across areas of un-flattened saltmarsh and freshwater marsh vegetation. The presence of vegetation usually leads to an over-estimation of ground elevation. Black & Veatch (2006) compared ground survey elevations with those derived from a 2003 LiDAR survey at 43 locations around the estuary and found that the LIDAR elevations were on average 12 cm higher than the ground survey elevations. The effect of such errors is to potentially underestimate tidal volumes, but only by a relatively small percentage since calculated volumes are affected to a much greater degree by the area of flood compartments; values for area can be calculated with relatively high accuracy (better than +/- 0.5%) using LIDAR DEMs.

The horizontal position of LiDAR datasets can also differ by up to 1 m, which has implications for the assessment of recession / advance of linear features such as saltmarsh cliffs, but such differences have a minimal effect on tidal volume calculations across large areas.

The accuracy of swath bathymetric surveys can vary considerably, depending on the equipment used, vessel speed, water depth, characteristics of the bed and the nature of post-collection data processing, but is typically of the order of +/- 25 cm. No information was provided regarding the methods used to collect and process the data provided for use in this study. However, a comparison with results from previous EA cross-sectional bathymetric surveys undertaken in 1995 and 2006 showed relatively good agreement in many areas where little or no change would be expected. No 2012 swath bathymetry data were available for the sub-tidal channel areas of the Butley River or the Alde above Iken, and sub-tidal depths and calculated total water volumes in these areas are therefore likely to be underestimated. However, the effect on tidal prism calculations is small.

Comparison of the 2002 EA cross-sectional bathymetric survey data with those for 1995, 2006 and 2012 revealed a number of anomalies and a decision was therefore taken not to use the 2002 data in the analysis.

3.0 Geomorphology of the Alde-Ore estuary

3.1 General form and evolution of the estuary

The present tidally active Alde-Ore estuary is relatively long and thin, with two main sections of quite different morphological character. The upper estuary upstream of Slaughden has an NNW – SSE orientation and is relatively wide, almost basin-shaped, compared with the middle and lower estuary to seaward of Slaughden (Figure 1). However, prior to embanking and reclamation the active estuary was much wider in its middle and lower reaches. The middle and lower parts of the estuary today have a general NNE-SSW orientation and cross-cut the generally SW-NE trend of the underlying and surrounding geological formations (Figure 11).

Two main rivers, both of modest size, drain into the Alde-Ore estuary, the River Alde and the Butley River. The Alde, which enters the estuary at its head near Snape, has two significant tributaries, the Ore and the Fromus, which join above the present tidal limit (the latter located at the Snape Barrier, just upstream of Snape Bridge). Prior to construction of the barrier in the late 1960s the normal tidal limit lay approximately 1 km further upstream near the confluence of the Alde and the Fromus, and a significant area of the upper Alde valley was subject to tidal flooding during surge tides.

The name 'Alde' is applied to the estuary north of Halfway-Reach, above Orford; between this point and the sea the estuary has traditionally been referred to as the 'Ore' (Steers, 1926; Arnott, 1973). Near the south end of Havergate Island the Ore is joined by the Butley River which flows in a general NNW direction towards Chillesford before turning west towards Butley. At the present time the normal tidal limit lies at Butley Mill, although this can be overtopped during extreme surge tides.

The sinuous thalweg (deepest part) of the main Alde-Ore channel has a length of approximately 30.1 km, compared with a linear estuary length of c. 21.7 km (7.33 km between Snape and Slaughden, 7.95k between Slaughden and the north end of Havergate Island, and 6.41 km between the north end of Havergate Island and the mouth). The thalweg varies in elevation along the length of the estuary, with alternating 'deeps' and 'shallows' (Figure 12). The most significant area of shallows occurs at 'The Horse' on the relatively straight reach south of Slaughden. This feature corresponds with a SW-NE trending 'high' in the underlying Crag bedrock (Figure 11). Elsewhere along the estuary 'deeps' occur mainly on the outside of meander bends (Figure 3) where high bed stresses are likely to be associated with three-dimensional helicoidal (corkscrew-like) flow which leads increased shear stresses on the channel wall and channel bed.

In the early- to mid-Holocene (postglacial period) the River Alde entered the sea via a west - east oriented channel near Slaughden (Figure 11). This old channel is cut into Pre-Pleistocene Crag and older sedimentary deposits and is partly filled by fossil alluvial muddy sediments which can be traced offshore (Mathers & Smith, 2002). In the later Holocene the mouth of the river was progressively deflected to the south by the build-up of gravel and sand transported along the open coast from the north. It is unclear whether a gravel barrier island ever existed in the area now occupied by Orford Ness, and subsequently became joined by development of the spit from the north, since the detailed age structure of the features have not yet been investigated in detail.

Historical accounts suggest that, in the eleventh century, when construction of Orford Castle was started, the mouth of the estuary (Orford Haven) lay much closer to the castle than at present. A map dating from the time of Elizabeth I (c. 1570-8) indicates the end of the spit ('The North ende Poynte') lay opposite what is now Hollesley. Norden's map of 1601, Kirby's map of 1736 and Hodskinson's map of 1783 and the Ordnance Survey One-Inch Sheet 208 published in 1895 also all show the mouth of Orford Haven approximately opposite Hollesley (Anon, 1966). This suggests that there was a period of marked southerly growth of the spit between the 13th and late 16th centuries, possibly driven by a high frequency of north-easterly storms and strong southerly sediment drift during the earlier part of the Little Ice Age. Maps and charts compiled since the mid-19th century show that the position and width of North Weir Point and the estuary mouth have varied markedly on annual to decadal timescales, reflecting the interaction of waves and tides in controlling alongshore and onshore-offshore sediment transport, but the estuary and protective spit feature have essentially maintained a condition of dynamic equilibrium.

The bed sediments of the estuary are dominated by gravel and sand near the mouth, but mud dominates in the inner estuary and on the higher intertidal areas. A comprehensive sediment survey of the estuary has not been carried out, but Black & Veatch (2006, Table 6.3) report the general sediment size characteristics of bed samples taken from 17 locations along the estuary. Bed samples taken between Havergate Island and the mouth consisted very largely of gravel, while those taken upstream of Barber's Point consisted of 45 to 99% mud. The fringing saltmarshes are composed mainly of mud, although sand and gravel deposits are often found within creek beds and along the toe of eroding marsh cliffs.

3.2 Tidal regime

The estuary experiences a mean spring tidal range of 2.2 to 2.3 m, meaning that it can be classified as 'mesotidal' (having a mean spring tidal range of between 2 and 4 m). The flood tidal wave moves southward along the Suffolk coast and there is a time difference of approximately 2.3 hours at low water and 1.75 hours at high water between the open coast at Slaughden and the inside of the estuary at Slaughden Quay. The time difference in high water between Orford Bar and the inner estuary near Iken Cliffs is approximately 1.64 hours (Gardline, 2003).

Available data indicate that the elevation of high waters decreases slightly between the open sea and the area just inside the estuary mouth, is relatively constant in the Butley River -

Gedgrave Marshes area, then increases again up the estuary to Slaughden Bend (Table 3; Figure 5). High water levels show relatively little difference between Slaughden and Iken Cliffs, but no data are available for the innermost part of the estuary close to Snape.

The tides within the estuary are slightly asymmetric, with the flood limb of the tidal hydrograph at Orford being steeper than the ebb limb, both for non-surge tides and surge tides.During the storm tide of 6th December 2013 the flood tide rose an average rate of 55 cm/hr, whereas the ebb tide fell at an average rate of 41 cm/hr. The tide level lay above 2.5 m OD for a period of 3.5 hours between 23.45 hrs and 03.15 hrs (Figure 13). The implications are that average flow velocities on the flood tide are likely to be higher than on the ebb tide, and the estuary may be expected to show a net tendency to import and retain fine-grained sediment. However, in the relatively shallow water areas near the estuary mouth ebb velocities often exceed the flood tide velocities, restricting the movement of shingle upstream into the estuary.

Current velocities vary with tidal height and with position in the estuary. Black and Veatch (2006 Table 6.5) reported values for maximum velocity at 11 stations in the estuary but did not specify if these are maximum depth-averaged, measured or modelled values. No separate figures were given for flood or ebb flows or for spring and neap tides. Their reported values range from 1.63 m/s at the mouth to 0.41 m/s at Iken Cliffs, but indicate little systematic variation between the Butley River and Aldeburgh Marshes (range 0.65 m/s to 0.53 m/s). These average values provide no indication of the maximum values experienced near the bed on the outside of meander bends, where the velocities might be considerably higher than the ‘average’. Black & Veatch (2006) did, however, report that bed shear stresses are highest between the estuary mouth and the southern end of Havergate Island where the channel splits into two parts, and are also high on Slaughden Bend. The potential energy available to move bed sediment is therefore likely to be greatest in these areas, although actual sediment movement will depend on the particle size and cohesive properties of the bed.

3.3. Freshwater input

The mean freshwater flow into the estuary from the Alde and Ore rivers above Snape (c. 0.62 $m^3 s^{-1}$) is relatively small compared with the mean tidal flow (reported by Gardline, 2003 to be 945 $m^3 s^{-1}$ for a spring tide and 514 $m^3 s^{-1}$ for a neap tide, respectively). Small quantities of freshwater are also discharged into the estuary from the Butley River and number of other small streams and springs around the margins of the estuary. The freshwater input gives to rise to reduced salinities in the inner estuary but no density stratification develops and the estuary overall can be classified as well-mixed (HR Wallingford, 1999). Freshwater flow, even during floods, is relatively unimportant in scouring the bed of the estuary and has no effect on the dimensions of the estuary mouth.

3.4 Waves

There is very limited penetration of open sea waves beyond the mouth of the estuary. Waves approaching the open coast from the southeast break and lose most of their energy on the sand and shingle banks which lie seaward of the estuary mouth. However, some regeneration of refracted waves occurs on the estuary side of the banks and these are responsible for northerly littoral drift of sediment along the western shore of the lowermost part of the estuary, mainly between Shingle Street and Barthorpe Creek.

Waves generated internally within the estuary by wind stress are fetch-limited and rarely exceed 0.5 m in height. Southwest winds cause internally generated waves to travel up the lower and middle parts of the estuary in a general northeasterly direction, while northeasterly winds generate waves which travel down these parts of the estuary in the opposite direction. In the inner estuary west of Aldeburgh Marshes the maximum wave fetch is approximately 4 km in a west to east / east to west direction. At Hazlewood Marshes the maximum fetch is approximately 3 km in a west-southwest direction.

Internally generated waves can be important in contributing to overtopping of the river walls during high tides, and are the dominant mechanism of sediment erosion and transport on the upper intertidal flats and at the edges of the saltmarshes. However, no short or long-term wave data were available for analysis in this study.

3.5 Channel cross-sectional morphology

Figure 13 compares estuary cross-sections for the estuary mouth in 2012 and nine EA strategic monitoring locations surveyed between 1995 and 2012. Table 5 provides a summary of the width, depth, cross-sectional area at these locations for each year of available data. Table 6 shows the maximum depth of water below defined tidal levels at each location and each year. Many of the surveyed profiles cross the channel at a slight oblique angle rather than perpendicularly. However, the data show that there is relatively little variation in the width and cross-sectional area of the channel in the lower and middle part of the estuary, although there is notable construction at profile A37-A38 (Orford Quay). In the inner estuary above Slaughden the estuary becomes wider and shallower but the cross-sectional area between MHWN and HAT level remains relative constant until it begins to decline again between Iken Cliffs and Snape.

The estuary mouth is constricted by shingle accumulations on either side at North Weir Point and Shingle Street and by a series of shingle shoals outside the estuary mouth. There is also a linear mouth bar which separates the channel into two parts (Figure 14). Due to the presence of this bar the cross-sectional area below HAT and MHWS at the mouth in 2012 was significantly smaller than further up the estuary at profiles A3-A5 and A9 – S1C12.

A survey by Trinity House on 1st April 2014 shows that the estuary mouth (position marked by section line KP1 shown in Figure 14) had moved approximately 80 m north compared with its position in 2012. The cross-sectional area of the mouth below HAT and MHWS was slightly larger than in 2012 although the cross-sectional area below MLWS was slightly smaller due to sediment accretion (Figure 15a). The temporal and spatial variability in the position and cross-sectional area of the mouth demonstrates the difficulty is attempting to establish simple relationships between entrance cross-sectional area, tidal prism, and 'morphological equilibrium' within the estuary as a whole.

EA profile A55 - S1A5 near Slaughden is oriented obliquely across the channel and does not capture the narrowest cross-section of the channel opposite Slaughden Quay. A perpendicular profile (KP2) derived from the 2012 composite DEM is shown in Figures 15b and 16). The channel width in this area is artificially constricted by the Quay and other structures. The maximum depth (< 9 m OD) is also less than at Profile A55 – S1A5, further round Slaughden bend; consequently the HAT cross-sectional area at profile KP2 in 2012 was only 994 m^2 (Table 7), less than that at the mouth (profile KP1).

At Orford Quay (Figure 17) the channel is also artificially constricted (Figure 15c). At profile KP3, which is perpendicular to the channel, the width of the channel at HAT level in 2012 (155.9 m) was even smaller (164 m) than at Slaughden Quay (199.1 m). However, the cross-sectional area (1314 m^2) of the channel in 2012 was larger than at Slaughden Quay due to the greater depth of water (12.11 m at HAT) on the outside bend of the meander at Orford Quay (Table 7).

The Ore divides into two around Havergate Island with the main flow taking place though the Gull on the north side of the Island (Figure 18). The Gull and the Narrows on the south side of the Island are of similar width but the Gull is much deeper (Figure 15d; Table 7). The cross-sectional area of the Gull at profile KP4 is approximately 30 - 35 % larger than that of the Narrows. The combined cross-sectional area of the two channels at MHWS level (1660 m^2) is considerably larger than that at the mouth, Orford or Slaughden (Table 7). This implies either a significant reduction in average current velocities around Havergate Island or a significant division between flood and ebb tidal flows on the two sides of the Island. Coriolis forces would favour flood tidal flow predominantly in The Narrows and ebb flow through the Gull.

Values for the channel width, water depth and cross-sectional area at different tidal levels have been determined at 73 locations along the length of estuary between the mouth and Snape, using the 2012 DEM and water surface model. Although there are variations in water depth along the estuary due to geological controls and the pattern of meander bends, a general trend of deepening is evident between Snape and the southern end of Havergate Island; seaward of this point the water depth starts to decrease again towards the mouth. The width of the active estuary is relatively large in the inner estuary but is much narrower downstream of Westrow Point (as identified on Ordnance Survey maps). There is a general trend for a slight reduction in width at all tidal levels between Westrow Point and the south end of Havergate Island, beyond which there is an average tendency for an increase in width towards the estuary mouth (Figure 19). The cross-sectional area shows an increasing trend between Snape and the middle part of the inner estuary, a declining trend between the mid part of the inner estuary and Westrow Point, a further increasing trend between Westrow Point and the southern end of Havergate Island, and a further declining trend further down the estuary towards the mouth (Figure 20).

3.6 Saltmarshes

Active saltmarshes form a fringe in front of the flood embankments along much of the remaining estuary, and more extensive active marshes remain along Barthorpe's Creek near Hollesley, in the upper parts of Stony Ditch on Orford Ness, and near Iken. The average surface elevation of the mature active marshes shows a general increasing trend up the estuary (Figures 21 & 22; Table 8), reflecting the general pattern of increase in high tidal levels.

Before embanking and reclamation saltmarshes were much more extensive in the estuary. Most of the embanking and land claim occurred before the 16th century, with much of it taking place in the Middle Ages, but numerous changes and improvements have been made in the past two centuries.

Areas of enclosed marsh become starved of new marine sediment and experience lowering of the land surface due to dewatering and consolidation, while active marshes outside the embankment outside the embankments continue to grow vertically in response to slowly rising sea level and continued sedimentation. As a consequence of these processes, many of the reclaimed former marsh areas around the estuary today lie well below the level of the active marshes and would therefore have a large accommodation space for tidal waters if the embankments are breached, lowered or removed.

The total area of the present tidally-active estuary (at HAT level) is approximately 14.5 x 10^6 m^2 (1450 ha), which represents about one third of the total potential estuary area which could exist if flood defences were not present) (Table 9).

The embankments around the estuary have been overtopped and breached by storms on many occasions in the past, but most have been re-built and improved. The storm surge of 31st January – 1st February 1953 created numerous breaches and caused extensive flooding around the estuary, but most of the land was subsequently drained and the walls re-built. Exceptions where no repairs were made, or subsequently failed, occur mainly between Iken and Snape in the upper estuary and around Barthorpe Creek in the lower estuary.

The wall around Lantern Upper Marsh was deliberately breached by The National Trust in 1999 to encourage regeneration of saltmarsh behind one of the narrowest parts of the Orford Ness spit (Warrington *et al,* 2013). In the same year the RSPB also created an area of mudflat and active saltmarsh by breaching part of the wall on Havergate Island. Areas of regulated tidal exchange have also been established on Havergate Island by the RSPB, and at Airfield and King's Marshes on Orford Ness by The National Trust, to create and maintain saline and brackish lagoons for the bird interest.

There have been a number of attempts to quantify change in the extent of active saltmarsh within the estuary, based on analysis of aerial photographs. A study by the University of Newcastle (Cooper & Cooper, 2000; Cooper *et al.*, 2001) identified 254 ha of saltmarsh within the Alde & Ore and suggested a loss of 3.9 ha (3%) between 1971 and 1998, although apparent change of this magnitude lies within the measurement error of the analysis techniques used. A more recent assessment by Phelan *et al.* (2011), based on analysis of 2006-09 aerial photography, suggested an area of saltmarsh within the Alde & Ore Water Framework Body of 424.4 ha. This illustrates the difficulty of identifying change in the extent of habits and morphological features through studies which specify different boundaries and use different analysis techniques.

Many of the active more 'mature' marshes within the Alde-Ore estuary are highly dissected by small tidal creeks and contain numerous artificial borrow pits and former oyster layings which contribute to a relatively high mud to vegetation ratio within the saltmarsh elevation window (approximately MHWN to about 0.2 m above MHWS). Areas of pioneer marsh at the transition to intertidal mudflat also often have a discontinuous cover of vegetation and it is often difficult to apply consistent rules when defining the saltmarsh 'limit'.

4.0 Hazlewood Marshes: future management options

4.1 General setting and character of Hazlewood Marshes

Hazlewood Marshes are backed by gently rising ground to the north and east and are anchored at their southwestern end (Barber's Point) by a low-relief bedrock outlier (BGS, 1996). The timing of initial reclamation is unknown but embankments along the present alignment are shown on the Ordnance Survey First Edition One-Inch and First Edition Six-Inch County maps (Figure 23). A small area of saltmarsh has existed on the northern side of Barber's Point at least since the mid-19th century, but marshes have been absent from the remainder of the west and south-facing embankments surrounding Hazlewood Marsh for the whole of this period.

At the present time the embankments are fronted by mudflats and scattered concrete facing blocks arising from periodic repairs to the seaward face of the river wall. The short section of wall north of Barber's Point is exposed to internally-generated waves from the west while the sinuous wall to the east of Barber's wall is exposed to waves from the southwest, west and southeast (Figure 24).

4.2 Effects of the December 2013 surge

Analysis of the EA LiDAR data and results of the 2009 defence crest level survey identified a number of areas where the crest level of the wall lay substantially below 3.0 m OD before the December 2013 storm tide (Figures 25 & 26). In the locations which were breached during the storm tide the crest level was locally as low as 2.5 m OD; tidal waters exceeded this level for approximately 3 hours (Figure 27).

The surge tide of 6th December 2013 created two complete breaches and a number of near breaches due to back-wall slips in the river walls (Figures 28 & 29). The eastern breach was located at a point where there was reportedly a clappergate sluice in the wall. The inner parts of Hazlewood Marshes (Figure 30) were inundated to a depth of up to 1.8 m and the tide reached the gardens of seven properties on the margins of the Marsh. Two holes of the Aldeburgh Golf Club's Riverside Club course were also inundated. The maximum water level attained in the estuary opposite Hazlewood Marshes is estimated to be 3.1 m OD but the levels attained around the margins of the Marsh may have been slightly lower.

4.3 Likely future changes

Figure 31 shows the extent of the areas which are predicted to be flooded by tides reaching levels of 1.4 m OD (between MHWS and HAT in this area) and 3.5 m OD (taken to be indicative of a 1 in 100 year surge tide). Most of the marsh area would be flooded by such tides and a significant amount of water would remain trapped within lower areas of the marsh after the falling tide. At the present time, tidal ingress to the marsh is limited by the small size of the two existing breaches. However, if the breaches are not repaired they can be expected to widen and deepen over time. Additional breaches are also likely to form. It is likely to take at least 5 to 10 years before a full tidal equilibrium develops between the flooded marsh and the outside estuary.

Pioneer saltmarsh development can be expected to begin around the margins of the Marsh within one to two years, and in the medium term (10 to 20 years) saltmarsh communities are likely to become established across most of the area between 0.9 and 1.7 m OD. The extent of the present potential saltmarsh elevation 'window' around the margins of the marsh is shown in Figure 32.

Over time the salinity of the soil and groundwater within and surrounding Hazlewood Marsh will increase. The effect will initially be seen close to the surface but will penetrate to greater depth over time. The extent to which this will impact on water extracted from boreholes in the surrounding area will depend on the depth from which water is extracted and the local pattern of freshwater flow in the sub-surface, relative to the landward position of the estuarine salinity 'front'. Specific detailed would be required to quantify the risk to individual boreholes.

4.4 Potential impacts of management options for Hazlewood Marshes on the wider estuary

4.4.1 Review of previous modelling

Early hydrodynamic modelling studies of the estuary by ABPmer (1996, 1997) and HR Wallingford (1999) were hampered by a lack of detailed bathymetric and hydrodynamic data. The results are therefore considered to be of limited value in the present context.

A more robust modelling investigation was carried out as part of the EA Suffolk Estuarine Strategies (SES) investigations by Black & Veatch (2006) using the RMA 10 numerical model, originally developed by the US Corps of army Engineers, and a bathymetric / topographic DEM of the estuary based on 2003 LiDAR and swath bathymetry data.

Although the model can run in 3D mode to simulate stratified flow, in this instance it was run in 2D mode using a fine element triangular mesh for the adjoining coastal areas and a curvilinear mesh for the estuarine channel areas. The model was calibrated and tested against field data collected over a 30 day period by Gardline (2003). Further validation exercises were also performed using hydrodynamic field data collected by University College London in 1995 and 1996, and qualitatively through consultation with estuary users.

On the basis that HR Wallingford (1999) had demonstrated the estuary to be well-mixed, with a calculated Richardson number of 0.0032, Black & Veatch considered it justifiable to run the RMA10 model in 2D depth-averaged mode. Vertical variations in velocity and shear stress were therefore not resolved.

The model was used to examine the potential impacts of a range of future management options, including managed realignment (MR) at Hazlewood marshes, on hydrodynamic conditions and likely sediment stability within different parts of the estuary between the mouth and Iken Cliffs. A summary of the modelling results is provided in Tables 10, 11, 12 and 13. The key findings relevant to the potential effects of MR at Hazlewood Marshes were:

- an increase of up to 8% in maximum velocities at Aldburgh Marshes
- a potential increase in maximum velocities of 3% in the main channel, decreasing down the estuary to 0% at the mouth
- a potential decrease in maximum velocities of 6% at Iken Cliffs
- a maximum increase in shear stresses on the defences of 12% at Slaughden, 10% in the main channel, and a potential reduction of 8% at Iken cliffs
- a slight reduction of 4cm in maximum water elevations at Aldeburgh marshes and a reduction of 6cm at Iken Cliffs
- the estuary would remain flood dominant over most of its length, with potentially significant effect only near Iken Cliffs where the existing degree of flood dominance might be reduced, potentially resulting in a lower rate of net sediment accretion
- the increase in maximum velocities and shear stresses at Slaughden arising from MR at Hazlewood Marshes would be much smaller than that arising from MR at Iken Marshes (21% and 50%, respectively) or Aldburgh marshes (18% and 24%, respectively)
- MR at Boyton Marshes is predicted to reduced maximum velocities at Slaughden by 6%, which might offset the increase of 6% predicted due to MR at Hazlewood Marshes
- MR at Boyton Marshes could reduce shear stresses on the sea defences at Slaughden by 10%, almost offsetting the 12% increase predicted due to MR at Hazlewood Marshes
- MR at Boyton Marshes is predicted to reduce maximum water levels by 2 to 5 cm in the lower estuary and by 1 to 5 cm in the upper estuary; this would be additive to the predicted 4 - 6 cm reduction in water levels in the inner estuary due effect of MR at Hazlewood Marshes

4.4.2 Results of new analysis

New analysis has been undertaken of potential tidal volume changes in the estuary using the 2012 DEM and tidal levels model described earlier in this report. Separate analyses have been carried out for (a) the active estuary in 2012 (i.e. before the December 2013 storm surge), (b) the reclaimed marsh areas within Flood Cells prior to December 2013, (c) potential future scenarios which include 'Do Nothing' or Managed Realignment at Hazlewood Marshes, and (d) a possible future management scenario which might also include some form of managed realignment at Boyton Marshes.

4.4.2.1 Tidal volumes in the active estuary and Flood Cells

Table 14 provides a summary of the tidal volumes below defined tidal levels within the estuary north and south of Slaughden, and in the estuary as a whole. The tidal prism for the estuary as a whole ranges from 11.96 x 10^6 m^3 for a neap tide to 53.28 x 10^6 m^3 for an extreme storm surge tide reaching 3.5 m at Hazlewood Marshes. This almost five-fold increase demonstrates the importance of storm surge tides in creating a very large volume of water which has to enter and leave the estuary, principally via the mouth. The amount of water which entered the estuary on 6th December 2013 was approximately 80% larger than the volume which would enter the estuary on a tide reaching HAT.

For comparison, Table 15 provides a summary of the potential tidal volumes, in the absence of flood defences, on the reclaimed marshes within each Flood Cell. The total potential tidal volume within these areas for a tide reaching HAT level (43.63 x 10^6 m^3) is approximately 73% larger than the present tidal prism in the active estuary (for a tide reaching HAT).

Table 16 shows the potential tidal volumes on individual reclaimed marshes as a percentage of the active estuary. Considering a tide reaching HAT level, the tidal volume for FC9 (Hazlewood Marshes) represents 6.7% of the volume of the active estuary north of Slaughden and 2.9% of the volume of the whole active estuary. The percentage potential tidal volumes at Hazlewood Marshes are relatively small compared with those for Iken Marshes or Aldeburgh Marshes (Figure 33), or for Gedgrave and Sudbourne Marshes (Table 16c; Figures 34 & 35).

4.4.2.2 Potential tidal prism and velocity changes associated with different options at Hazlewood Marshes

The 'Do Nothing' or full MR options at Hazlewood Marshes would increase the tidal prism of the upper estuary by 5.7% on mean neap tides, 6.9% on mean spring tides and 6.7% on an HAT tide (Table 16). On a surge tide such as the 6th December 2013 event the tidal prism would be increased by approximately 9.2%. The relationship between tidal prism and current speeds is not linear, and the increase in maximum velocities would probably be less than 5 to 9% between Hazlewood and the north end of Lantern marshes, and considerably less further down the estuary. A small reduction in flood tidal velocities upstream of Hazlewood Marshes would be expected, but would probably be less than the 6% reduction indicated by the Black & Veatch (2006) modelling. An increase of 9% in maximum velocities on a surge tide in the Slaughden area would result in an increase from c. 0.6 to 0.65 m/s. The bed shear stress would be expected to increase proportionately but the increase is unlikely to result in significantly greater mobilization of sediment. The maximum velocities experienced would remain much lower than those at Orford and close to the mouth

Table 17 shows the potential tidal volumes which would be associated with a number of possible future management scenarios other than ‘Do Nothing’ at Hazlewood Marshes (the options are shown schematically shown in Figure 36). The construction of a new wall some distance back from the old wall (Options A and B) would reduce the potential tidal volume by 62% and 27%, respectively (for a tide reaching HAT). The construction of bunds at the landward margin of the Marsh (Option C) would reduce the potential tidal prism by less than 5%. If the existing breaches were converted to managed overspill sills at MHWS level (option D) there would be a noticeable effect only infrequently on the very highest tides. Additional water storage space could be created up to a maximum of 0.73 x 10^6 m^3 on a tide reaching HAT, assuming that the marsh area was dry at the time of flooding, but as low as 0.14 x 10^6 m^3 if water from a previous high tide was impounded behind the sill. In the case of any of the Options B to D the effect on tidal prism and velocities in the Alde channel near Slaughden would be less than those predicted for the ‘Do Nothing’ or marginal bund options.

The ‘Do Nothing’ and MR options at Hazlewood Marshes would increase the potential storage space for flood water. For typical spring tides this could reduce high water levels by 3 to 5 cm but the effect on surge tides is expected to be relatively larger (4 to 7 cm). This is because the additional storage volume at Hazlewood Marshes for a tide reaching 3.1 m OD is 9.2% of the volume in the active inner estuary compared with 6.9% on a MHWS tide. A smaller beneficial effect at Aldeburgh and Sudbourne Marshes is also expected.

Under a ‘Do Nothing’ option the level of the breaches in the Hazlewood Marshes wall will gradually be lowered to a point where the marshes are able to completely drain, but this may take several years. If flood tidal waters are able to enter the marsh at mid tide level there will be a small lowering effect on water levels in the active estuary, but this is unlikely to have any significant effect on saltmarshes or navigation.

4.4.2.3 Effects of possible partial managed realignment at Boyton Marshes

As discussed in Section 4.4.1 of this report, previous hydrodynamic modelling by Black & Veatch (2006) suggested that possible managed realignment at Boyton Marshes might have effects on water levels, current velocities and shear stresses which might partially or wholly cancel out those predicted from MR at Hazlewood Marshes.

Boyton Marshes is located at the confluence of the River Ore and the Butley River, down-estuary from Havergate Island. A significant part of the area is now owned by the RSPB who, it is understood, are considering options for a partial managed realignment and/ or regulated tidal exchange scheme. A preliminary assessment for an outline scheme outline has been made by Dixon (2012). Parts of the river wall defences along the Lower Gull channel have lacked protective saltmarsh since the late 19th century and are under pressure from erosion by tidal flows and waves (Figures 37, 38 & 39).

A large area of Boyton Marshes lies low in the tidal frame and would be flooded at quite low tidal levels in the absence of defences. Figure 40a shows the extent of potential tidal flooding by tides higher than 0.2 m OD (MSL), if the defences were breached. The elevation window for potential saltmarsh development is restricted to a fringe around the western side of the Marsh (Figure 41). The potential tidal volume of Flood Cell 1b (as defined in Figures 8 & 9) below HAT level is 1.92 x 10^6 m^3, which compares with 0.73 x 10^6 m^3 at Hazlewood Marshes (Table 15). This represents 13.3% of the tidal volume of the mid and lower estuary south of Slaughden and 7.6% of the volume of the entire active estuary (Table 16). Management changes affecting the whole of FC1b would therefore be expected to have a bigger impact than those which might be undertaken at FC9 (Hazlewood Marshes).

The outline scheme presented in Dixon (2012) has been superimposed on the 2012 LiDAR DEM in Figure 42. For the purposes of further analysis it has been assumed that the scheme would involve the creation of two compartments, an outer one subject to unrestricted tidal exchange through a breach in the Lower Gull wall, and the inner one subject to regulated tidal exchange via a number of sluices in a new set-back wall.

Using the DEM and tidal level model described earlier in this report, the potential tidal volume of the outer compartment, for a tide reaching HAT, is calculated to be 0.83 x 10^6 m^3. The calculated volume for the rear compartment, with present morphology (i.e. excluding any new borrow pits, scrapes and islands, is 0.92 x 10^6 m^3 (Table 18) . The outer compartment is therefore only about 13% larger than Hazlewood Marshes in terms of potential tidal volume at HAT level. However, for tides reaching MHWN and MHWS levels the potential tidal volumes at Boyton are 25% and 74% larger, respectively, owing to the lower level of the Boyton site relative to the local tidal frame.

The volume of water entering and leaving the outer compartment on a highest astronomical tide would represent approximately 6% of the tidal volume of the estuary south of Slaughden, and approximately 3.5% of the volume of the entire active estuary (Table 16). These percentages are similar to those for the full MR or 'Do Nothing' option at Hazlewood Marshes.

The effects of MR at Boyton Marshes would likely to be greatest in the adjoining areas, with a likely increase in flood and ebb velocities in the Lower Gull and towards the mouth. In the short term there would be some reduction of velocities (estimated 3 to 5%) and water levels (estimated 2-3 cm) further up the estuary.

Short-term reductions in water levels, and locally, velocities, at Hazlewood and/or Boyton Marshes could be offset in the medium to longer term if the increase in tidal prism were to increase the flow velocities sufficiently to cause a widening of the mouth (and hence reduce the resistance to the upstream movement of the tidal wave). However, two factors make this relatively unlikely unless managed realignment is undertaken on a very large scale: (1) the mouth of the estuary is continually constricted by combined wave and flood tidal processes which transport sediment towards North Weir Point and into the estuary mouth, and (2) current velocities close to the mouth are already very high and even large-scale increases in tidal prism are likely to make only a relatively small difference to the mobility of shingle-dominated sediment in the mouth area.

5.0 Conclusions and recommendations

Adoption of the 'Do Nothing' option or a managed realignment option at Hazlewood Marshes would be likely to have only a relatively small effect on water levels, current speeds and bed sediment transport within the river near Aldeburgh Marshes / Slaughden. In this area the maximum flow velocities are predicted to increase by up to 7% but this would not be significant in terms of bed shear stresses, bed sediment transport and pressure on river wall structures. There would be likely to be a slight reduction in water levels and current speeds higher up the inner estuary (between Iken and Snape). This would give a small flood risk benefit to the Snape area but might lead to reduced tidal current velocities and a slight increase in sedimentation rates within the river channel. The increase in tidal prism of the active estuary for typical spring tides would be of the order of 6 to 7%. An increase of this magnitude would be unlikely to have a significant effect on the width / cross-sectional area of the mouth of the estuary and the beneficial effects on high water levels in the inner estuary are therefore unlikely to be transitory.

If managed realignment is undertaken on part of Boyton Marshes the effects are likely to be a slight reduction in water levels and current speeds further up the estuary. Boyton Marshes lie relatively low in the tidal frame and MR would create a relatively large tidal prism. If undertaken in conjunction with 'Do Nothing' or managed realignment at Hazelwood Marshes, the combined effect could lead to a significant reduction in surge tide high water levels in the estuary as a whole by creating additional storage space for water. However, some erosion of the intertidal flats and subtidal areas can be expected close to the sea wall breaches / ebb drainage channels due to locally increased water velocities. Little or no saltmarsh would be likely to form on Boyton Marshes for many years due to the low surface level of much of the site. MR at Boyton and 'Do Nothing' or large-scale MR at Hazlewood Marshes together would be more likely to have a detectable effect on current speeds in the lower estuary, with potential effects on the cross-sectional geometry of the mouth and subsequent adjustment of tidal flows and levels throughout the estuary.

Before final management decisions are taken and/ or works carried out it is recommended that:

- further 2D hydrodynamic and sediment transport modelling should be undertaken, using the most recently available LIDAR / bathymetric DEM, to examine the effects of MR and 'Do Nothing' options at Hazlewood Marshes, Boyton Marshes and other potential locations on water levels, current speeds, bed shear stresses and potential sediment transport within the estuary
- some 3D modelling should also be carried out to fully characterise three-dimensional flows around meander bends and quantify local shear stresses on the bed and banks of the estuary in these areas

- additional field measurements of water levels and current speeds should be made at key locations where little or no data presently exist, most importantly (a) in the inner estuary between Iken and Snape and (b) within the Butley River

- additional bathymetric surveys should be commissioned to improve subtidal data coverage in the Butley River and the upper Alde between Iken and Snape

- the existing LiDAR / swath bathymetric DEM of the estuary used in the analysis described in this report should be improved by incorporation of 2012 LiDAR data for the entire estuary, including areas outside the limits of the present tidally active estuary (EA Geomatics should be requested to provide the missing 2012 data).

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Tables

Table 1. Tidal levels on the open coast and within the Alde-Ore estuary from (A) predictions in Admiralty Tide Tables (UKHO, 2013) and (G) Gardline (2003) who deployed Aquadopp (acoustic Doppler) meters and Aanderaa (pressure transducer) tide recorders over a period 32 days between 21st August and 23rd September 2003. *The Gardline Alde-Ore Mouth values are considered to be unrepresentative as only nine days of data were obtained. Values in **bold** have been calculated by extrapolation using the trend at the relevant Standard Port.

	HAT	MHWS	MHWN	MSL	MLWN	MLWS	LAT	CD	MSTR	MNTR	Source
Open Coast, north to south											
Lowestoft	1.4	0.9	0.6	0.16	-0.5	-1.0	-1.4	-1.50	1.9	1.1	A
Aldeburgh	1.8	1.1	0.7	0.06	-0.7	-1.3	**-1.8**	-1.60	2.4	1.4	A
Martello Towers	**1.86**	1.56	1.04	nd	-0.25	-0.76	nd	nd	2.31	1.29	G
Orford Ness	1.4	1.2	1.1	nd	-0.8	-1.2	**-1.5**	-1.65	2.3	1.8	A
Orford Haven Bar	1.9	1.5	0.9	0.13	-0.7	-1.3	**-1.7**	-1.66	2.8	1.6	A
Bawdsey	2.0	1.6	1.0	0.09	-0.8	-1.5	**-2.0**	-1.77	3.1	1.8	A
Felixstowe	2.3	1.9	1.2	0.13	-1.0	-1.6	-2.1	-1.95	3.4	2.1	A
Harwich	2.4	2.0	1.4	0.12	-0.9	-1.6	-2.1	-2.02	3.6	2.3	A
Walton-on-the-Naze	2.5	2.0	1.2	0.08	-1.1	-1.8	-2.3	-2.16	3.8	2.3	A
Alde-Ore Estuary, mouth to head											
Orford Haven Bar	1.9	1.5	0.9	0.13	-0.7	-1.3	nd	-1.66	2.8	1.6	A
Alde-Ore Mouth	**1.78**	1.51	1.04	nd	-0.27	-0.75	nd	nd	2.25	1.31	G
Butley River Entrance	**1.57**	1.36	0.99	nd	-0.22	-0.60	nd	nd	1.97	1.21	G
Gedgrave Marshes	**1.56**	1.35	0.98	nd	-0.25	-0.63	nd	nd	1.98	1.23	G
East Havergate	**1.60**	1.38	1.00	nd	-0.25	-0.63	nd	nd	2.01	1.25	G
Orford Moorings	**1.64**	1.42	1.03	nd	-0.22	-0.61	nd	nd	2.03	1.25	G
Orford Quay	1.5	1.2	0.7	0.20	-0.5	-1.0	nd	-1.60	2.2	1.2	A
Main Channel	**1.67**	1.44	1.04	nd	-0.26	-0.66	nd	nd	2.10	1.30	G
Aldeburgh Yacht Club	**1.71**	1.48	1.08	nd	-0.23	-0.64	nd	nd	2.12	1.31	G
Slaughden Quay	1.5	1.3	1.0	0.19	-0.6	-1.0	nd	-1.60	2.3	1.6	A
Aldeburgh Marshes	**1.74**	1.50	1.08	nd	-0.27	-0.69	nd	nd	2.19	1.35	G
Iken Cliffs	1.6	1.3	0.8	0.20	-0.5	-1.0	nd	-1.60	2.3	1.3	A
Iken Cliffs	**1.72**	1.47	1.03	nd	-0.35	-0.80	nd	nd	2.27	1.38	G

Table 2. Data sources used to construct the composite digital elevation model (DEM) of the Alde-Ore Estuary. The areas covered by each dataset are shown in Figure 3. Where datasets overlapped, data were selected in the following priority order: A, B, C, D. All data were supplied by the Environment Agency (Geomatics Group).

Dataset	Data type	Data captured	EA Polygon	Resolution
A	Combined LiDAR and swath bathymetry	LiDAR: 17/12/2012 Bathymetry: 2012	P_8493	0.5 m (interpolated)
B	LiDAR	17/12/2012	P_8611	1.0 m
C	LiDAR	17/12/2012	P_8612	1.0 m
D	LiDAR	2-7/02/2008	P_5541	2.0 m

Table 3. Estimated tidal levels in different parts of the estuary used to calculate tidal volumes in this study. Levels in the upper (A) and lower (E) estuary are averaged from Gardline (2003) data, and intermediate tidal levels have been calculated using the relationship shown in Figure 6. Levels in areas B, C and D have been calculated using 0.75, 0.50 and 0.25 proportions respectively of the differences between A and E.

	HAT	MHWS	MHWN	MSL	MLWN	MLWS	LAT
A: Upper estuary above Slaughden	1.70	1.50	1.10	0.20	-0.30	-0.70	-1.60
B: Home Reach, Lantern Marshes	1.66	1.47	1.08	0.20	-0.29	-0.68	-1.55
C: Halfway Reach, Sudbourne, Kings North and upper Butley Marshes	1.62	1.43	1.05	0.20	-0.28	-0.65	-1.50
D: Orford, Kings South and Chillesford Marshes	1.57	1.40	1.03	0.20	-0.26	-0.63	-1.45
E: Lower estuary below Gedgrave Marshes	1.53	1.36	1.00	0.20	-0.25	-0.60	-1.40

Table 4. Some morphometric parameters for the Alde-Ore Estuary.

Parameter	Value
Length of thalweg from mouth to Snape tidal barrier	30.1 km
Perimeter of the active estuary at HAT	73.7 km
Perimeter of the active and reclaimed estuary at HAT	106.8 km
Perimeter of the active estuary as a proportion of the whole estuary	68.7%
Area of the active estuary at HAT	14.5×10^6 m^2
Area of the active and reclaimed estuary at HAT	43.2×10^6 m^2
Area of the active estuary as a proportion of the whole estuary	33.6%

Table 5. Morphometric parameters for eight cross-sectional profiles in the Alde-Ore estuary, based on EA linear topographic and bathymetric surveys (1995 and 2006) and swath bathymetry and LiDAR surveys (2012).

		Mouth	A3-A5	A9-S1C12	A37-A38	A49-S1A8	A55-S1A5	A65-A66	A71-A72	A74-A77	A79-A80
1995	Maximum Depth	nd	-7.67	-7.70	-10.24	-6.01	-9.18	-2.99	-1.53	-1.06	-0.63
	Width at HAT	nd	233	325	167	385	324	616	575	817	56
	Width at MHWS	nd	231	322	166	355	315	612	564	791	54
	Width at MHWN	nd	227	319	165	338	303	603	538	600	51
	Width at MSL	nd	215	264	163	250	245	584	309	64	32
	Width at MLWN	nd	195	253	162	217	215	505	171	37	21
	Width at MLWS	nd	172	245	161	201	196	313	107	18	0
	Width at LAT	nd	158	230	154	182	167	204	0	0	0
	Area at HAT	nd	1207	1728	1311	1451	1514	1735	928	594	91
	Area at MHWS	nd	1168	1673	1283	1379	1451	1612	815	435	79
	Area at MHWN	nd	1086	1557	1222	1254	1336	1370	609	214	58
	Area at MSL	nd	908	1329	1085	999	1094	832	221	39	19
	Area at MLWN	nd	816	1213	1011	886	978	558	107	14	6
	Area at MLWS	nd	752	1126	951	804	897	390	52	3	0
	Area at LAT	nd	621	936	822	639	733	166	0	0	0
2006	Maximum Depth	nd	-8.37	-8.22	-12.18	-6.19	-9.45	-3.16	-1.72	nd	-1.42
	Width at HAT	nd	232	325	167	387	327	618	574	nd	56
	Width at MHWS	nd	230	322	167	382	324	616	561	nd	55
	Width at MHWN	nd	226	319	166	351	303	605	539	nd	52
	Width at MSL	nd	214	263	163	271	258	595	340	nd	32
	Width at MLWN	nd	204	252	162	233	225	549	184	nd	14
	Width at MLWS	nd	172	243	159	204	203	421	93	nd	8
	Width at LAT	nd	158	223	153	182	160	216	51	nd	0
	Area at HAT	nd	1288	1772	1511	1505	1563	1836	973	nd	90
	Area at MHWS	nd	1248	1717	1483	1432	1498	1713	860	nd	79
	Area at MHWN	nd	1166	1602	1421	1302	1381	1468	654	nd	58
	Area at MSL	nd	990	1372	1285	1037	1137	928	247	nd	19
	Area at MLWN	nd	897	1256	1210	914	1016	639	119	nd	7
	Area at MLWS	nd	835	1169	1150	829	930	444	65	nd	3
	Area at LAT	nd	704	983	1023	664	770	209	1	nd	0
2012	Maximum Depth	-6.36	-7.28	-8.12	-10.49	-6.01	-9.53	-3.07	-1.76	nd	nd
	Width at HAT	213	230	323	164	383	326	617	575	nd	nd
	Width at MHWS	211	229	322	164	378	313	615	550	nd	nd
	Width at MHWN	206	225	318	163	339	304	611	497	nd	nd
	Width at MSL	199	191	263	160	237	256	594	316	nd	nd
	Width at MLWN	194	182	253	158	219	218	541	174	nd	nd
	Width at MLWS	185	175	242	155	203	191	339	111	nd	nd
	Width at LAT	158	162	223	148	184	158	238	14	nd	nd
	Area at HAT	1030	1144	1754	1314	1459	1542	1811	924	nd	nd
	Area at MHWS	994	1105	1699	1286	1391	1480	1688	815	nd	nd
	Area at MHWN	919	1023	1586	1226	1268	1366	1443	617	nd	nd
	Area at MSL	757	852	1365	1092	1017	1123	901	230	nd	nd
	Area at MLWN	669	768	1249	1019	906	1006	615	115	nd	nd
	Area at MLWS	602	705	1163	961	823	925	439	60	nd	nd
	Area at LAT	467	571	976	838	655	769	190	1	nd	nd

Table 6. Maximum depths below tidal levels to the bed at eight cross-sectional profiles along the estuary, determined from EA topographic and bathymetric line surveys (1995 and 2006) and swath bathymetry and LiDAR surveys (2012)

		Mouth	A3-A5	A9-S1C12	A37-A38	A49-S1A8	A55-S1A5	A65-A66	A71-A72	A74-A77	A79-A80
Level (m OD)	HAT	1.53	1.53	1.53	1.57	1.66	1.70	1.70	1.70	1.70	1.70
	MHWS	1.36	1.36	1.36	1.40	1.47	1.50	1.50	1.50	1.50	1.50
	MHWN	1.00	1.00	1.00	1.03	1.08	1.10	1.10	1.10	1.10	1.10
	MSL	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	MLWN	-0.25	-0.25	-0.25	-0.26	-0.29	-0.30	-0.30	-0.30	-0.30	-0.30
	MLWS	-0.60	-0.60	-0.60	-0.63	-0.68	-0.70	-0.70	-0.70	-0.70	-0.70
	LAT	-1.40	-1.40	-1.40	-1.45	-1.55	-1.60	-1.60	-1.60	-1.60	-1.60
1995	Depth at HAT		9.20	9.23	11.81	7.67	10.88	4.69	3.23	2.76	2.33
	Depth at MHWS		9.03	9.06	11.64	7.48	10.68	4.49	3.03	2.56	2.13
	Depth at MHWN		8.67	8.70	11.27	7.09	10.28	4.09	2.63	2.16	1.73
	Depth at MSL		7.87	7.90	10.44	6.21	9.38	3.19	1.73	1.26	0.83
	Depth at MLWN		7.42	7.45	9.98	5.72	8.88	2.69	1.23	0.76	0.33
	Depth at MLWS		7.07	7.10	9.61	5.33	8.48	2.29	0.83	0.36	-0.07
	Depth at LAT		6.27	6.30	8.79	4.46	7.58	1.39	dries	dries	dries
2006	Depth at HAT		9.90	9.75	13.75	7.85	11.15	4.86	3.42	nd	3.12
	Depth at MHWS		9.73	9.58	13.58	7.66	10.95	4.66	3.22	nd	2.92
	Depth at MHWN		9.37	9.22	13.21	7.27	10.55	4.26	2.82	nd	2.52
	Depth at MSL		8.57	8.42	12.38	6.39	9.65	3.36	1.92	nd	1.62
	Depth at MLWN		8.12	7.97	11.92	5.90	9.15	2.86	1.42	nd	1.12
	Depth at MLWS		7.77	7.62	11.55	5.51	8.75	2.46	1.02	nd	0.72
	Depth at LAT		6.97	6.82	10.73	4.64	7.85	1.56	0.12	nd	dries
2012	Depth at HAT	7.89	8.81	9.65	12.06	7.67	11.23	4.77	3.46	nd	nd
	Depth at MHWS	7.72	8.64	9.48	11.89	7.48	11.03	4.57	3.26	nd	nd
	Depth at MHWN	7.36	8.28	9.12	11.52	7.09	10.63	4.17	2.86	nd	nd
	Depth at MSL	6.56	7.48	8.32	10.69	6.21	9.73	3.27	1.96	nd	nd
	Depth at MLWN	6.11	7.03	7.87	10.23	5.72	9.23	2.77	1.46	nd	nd
	Depth at MLWS	5.76	6.68	7.52	9.86	5.33	8.83	2.37	1.06	nd	nd
	Depth at LAT	4.96	5.88	6.72	9.04	4.46	7.93	1.47	0.16	nd	nd

Table 7. Morphometric parameters for cross-sections KP1 (at the estuary mouth, crossing the highest part of the sand bank), and KP2 (at Slaughden Quay) derived from 2012 LIDAR / swath bathymetry

	KP1 (mouth)	KP2 (Slaughden)	KP3 (Orford)	KP4 (Havergate Island) (The Gull)	(Narrows)	(combined)
Maximum bed level (m OD)	-7.28	-8.88	-10.53	-9.48	-5.37	-9.48
Depth at HAT (m)	8.81	10.58	12.11	11.01	6.90	11.01
Depth at MHWS (m)	8.64	10.38	11.93	10.84	6.73	10.84
Depth at MHWN (m)	8.28	9.98	11.56	10.48	6.37	10.48
Depth at MSL (m)	7.48	9.08	10.73	9.68	5.57	9.68
Depth at MLWN (m)	7.03	8.58	10.27	9.23	5.12	9.23
Depth at MLWS (m)	6.68	8.18	9.91	8.88	4.77	8.88
Depth at LAT (m)	5.88	7.28	9.08	8.08	3.97	8.08
Width at HAT (m)	227.1	199.1	155.9	152.2	209.1	361.3
Width at MHWS (m)	225.5	198.0	155.0	144.9	193.3	338.1
Width at MHWN (m)	220.9	161.0	153.2	142.1	174.1	316.2
Width at MSL (m)	210.6	151.6	149.6	129.4	140.3	269.7
Width at MLWN (m)	197.3	139.6	145.8	123.7	127.3	251.0
Width at MLWS (m)	188.5	128.2	142.1	119.6	117.9	237.6
Width at LAT (m)	162.8	109.3	134.5	107.7	109.6	217.3
Width:depth ratio at HAT (m)	25.8	18.8	12.9	13.8	30.3	32.8
Width:depth ratio at MHWS (m)	26.1	19.1	13.0	13.4	28.7	31.2
Width:depth ratio at MHWN (m)	26.7	16.1	13.3	13.6	27.3	30.2
Width:depth ratio at MSL (m)	28.1	16.7	13.9	13.4	25.2	27.9
Width:depth ratio at MLWN (m)	28.1	16.3	14.2	13.4	24.9	27.2
Width:depth ratio at MLWS (m)	28.2	15.7	14.3	13.5	24.7	26.7
Width:depth ratio at LAT (m)	27.7	15.0	14.8	13.3	27.6	26.9
Area at HAT (m^2)	1072.8	994.3	1137.5	968.6	749.3	1717.9
Area at MHWS (m^2)	1034.3	955.9	1109.9	943.6	716.4	1660.0
Area at MHWN (m^2)	953.9	890.5	1052.9	891.9	653.2	1545.1
Area at MSL (m^2)	781.6	748.9	927.8	782.6	526.0	1308.7
Area at MLWN (m^2)	689.2	676.0	859.5	725.8	466.0	1191.8
Area at MLWS (m^2)	621.4	623.2	807.3	683.2	423.1	1106.2
Area at LAT (m^2)	480.5	518.0	693.5	594.4	332.7	927.1

Table 8. Active marsh elevations determined from the 2012 combined LiDAR / bathymetric DEM (interpolated 0.5 m spatial resolution). Median (50%) and upper and lower tails of the distribution (10% and 90%) are shown, based on the elevations measured over discrete areas of marsh, avoiding creeks, drains and hedges. Locations are shown on Figure 21.

	Elevation (m OD)			Number of	Centre of area	
	10%	50%	90%	data points	Easting	Northing
Alde-Ore River						
1	1.48	1.58	1.67	11712	637458	244463
2	1.49	1.56	1.64	15565	638967	245969
3	1.49	1.56	1.63	15523	639953	247167
7	1.36	1.46	1.54	31501	641688	247470
8	1.42	1.50	1.57	26861	641738	248297
9	1.48	1.54	1.60	47079	642822	248329
12	1.41	1.48	1.55	17017	643441	249732
13	1.49	1.54	1.60	79641	644498	251492
14	1.50	1.57	1.66	64920	645254	252867
15	1.56	1.62	1.68	31543	646166	254740
16	1.48	1.53	1.58	6006	645996	255733
17	1.51	1.60	1.75	53131	644833	255270
18	1.50	1.56	1.62	33200	644331	256425
19	1.63	1.71	1.80	3464	643183	257390
20	1.58	1.64	1.71	7947	642239	256863
21	1.63	1.69	1.76	19974	641692	257599
22	1.52	1.59	1.68	17737	641087	256132
23	1.60	1.71	1.81	13023	640253	256659
24	1.49	1.58	1.71	5277	640158	257121
25	1.71	1.85	1.97	5016	639483	257577
Butley River						
4	1.44	1.53	1.61	42927	639458	248594
5	1.46	1.53	1.64	26931	638645	250594
6	1.50	1.60	1.76	9284	638773	251446
Stony Ditch						
10	1.53	1.59	1.64	33908	644420	249552
11	1.49	1.55	1.68	9895	645084	249863

Table 9. Tide-covered areas (10^6 m^2) at HAT, MHWS and MHWN within the active estuary and potential tide-covered area on reclaimed (embanked) former marsh areas below HAT. Tidal levels vary along the estuary (see Table 1).

	HAT	MHWS	MHWN
Active Estuary (North)	6.19	5.59	5.26
Active Estuary (South)	8.32	6.85	6.20
Active Estuary (North and South)	14.51	12.44	11.46
Active + Reclaimed Estuary at HAT	43.19		
Total active estuary as a proportion of total floodable area at HAT	34%		

Table 10. Maximum velocities (m s^{-1}) in the Alde-Ore estuary under different managed realignment (MR) options. Results from hydrodynamic modelling by Black and Veatch (2006). NB Assumptions for MR are that the entire marsh area is subject to renewed tidal flooding

Option Reference			Monitoring Location								
			1	2	4	5	7	8	9	10	11
2-1	Existing	Maximum Velocity	1.63	0.65	0.68	0.51	0.78	0.46	0.52	0.53	0.41
			0%	0%	0%	0%	0%	0%	0%	0%	0%
2-2	Do Nothing Option	Maximum Velocity	2.14	0.56	0.79	0.60	0.95	0.48	0.42	0.28	0.22
			31%	-13%	15%	19%	22%	4%	-20%	-47%	-47%
2-3	MR at Iken Marshes	Maximum Velocity	1.66	0.66	0.71	0.53	0.85	0.52	0.63	0.62	0.34
			2%	1%	4%	6%	9%	11%	21%	17%	-16%
2-4	MR at Hazelwood Marshes	Maximum Velocity	1.63	0.66	0.69	0.51	0.80	0.48	0.55	0.57	0.38
			0%	2%	2%	1%	2%	3%	6%	8%	-6%
2-5	MR at Aldeburgh Marshes	Maximum Velocity	1.67	0.61	0.71	0.54	0.86	0.51	0.62	0.46	0.38
			3%	-6%	4%	6%	10%	10%	18%	-15%	-6%
2-6	MR at Boyton Marshes	Maximum Velocity	1.81	0.69	0.64	0.52	0.74	0.46	0.49	0.53	0.37
			11%	6%	-7%	3%	-5%	-1%	-6%	-1%	-9%
2-7	MR at Butley Marshes	Maximum Velocity	1.73	1.07	0.63	0.54	0.77	0.46	0.52	0.54	0.40
			6%	65%	-7%	6%	-2%	-1%	-1%	1%	0%
2-8	Slaughden bypass & Sudbourne Marshes	Maximum Velocity	1.77	0.56	0.81	0.60	0.99	0.63	0.39	0.41	0.35
			9%	-14%	19%	19%	27%	36%	-25%	-23%	-14%
			mouth	Butley River	Gedgrave Marshes	East Havergate	Orford	main channel	Slaughden	Aldeburgh Marshes	Iken Cliffs

Table 11. Shear stress (Pa) on the sea defences in the Alde-Ore estuary under different managed realignment options. Results from hydrodynamic modelling by Black and Veatch (2006)

Option Reference			Monitoring Location								
			1	2	4	5	7	8	9	10	11
2-1	Existing	Shear Average	8.019	0.802	1.483	1.460	1.273	1.126	0.919	0.916	0.583
			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2-2	Do Nothing Option	Shear Average	10.993	0.580	2.074	2.119	1.974	0.915	0.468	0.310	0.183
			37%	-28%	40%	45%	55%	-19%	-49%	-66%	-69%
2-3	MR at Iken Marshes	Shear Average	8.235	0.782	1.628	1.607	1.593	1.557	1.377	0.949	0.457
			3%	-3%	10%	10%	25%	38%	50%	4%	-22%
2-4	MR at Hazelwood Marshes	Shear Average	8.103	0.806	1.514	1.488	1.351	1.233	1.034	0.941	0.538
			1%	0%	2%	2%	6%	10%	12%	3%	-8%
2-5	MR at Aldeburgh Marshes	Shear Average	8.323	0.733	1.651	1.635	1.595	1.522	1.138	0.802	0.509
			4%	-9%	11%	12%	25%	35%	24%	-12%	-13%
2-6	MR at Boyton Marshes	Shear Average	8.834	0.808	1.352	1.279	1.151	1.017	0.828	0.812	0.526
			10%	1%	-9%	-12%	-10%	-10%	-10%	-11%	-10%
2-7	MR at Butley Marsh	Shear Average	8.559	2.792	1.410	1.376	1.221	1.058	0.860	0.874	0.568
			7%	248%	-5%	-6%	-4%	-6%	-6%	-5%	-3%
2-8	MR at Sudbourne Marsh with Channel	Shear Average	9.062	0.602	2.047	2.038	2.255	1.274	0.376	0.668	0.419
			13%	-25%	38%	40%	77%	13%	-59%	-27%	-28%
			mouth	Butley River	Gedgrave Marshes	East Havergate	Orford	main channel	Slaughden	Aldeburgh Marshes	Iken Cliffs

Table 12. Maximum water elevations (m OD) in the Alde-Ore estuary under different managed realignment options. Results from hydrodynamic modelling by Black and Veatch (2006)

Option Reference			Monitoring Location								
			1	2	4	5	7	8	9	10	11
2-1	Existing	Max Elevation	1.84	1.68	1.68	1.69	1.68	1.70	1.74	1.78	1.86
			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2-2	Do Nothing Option	Max Elevation	1.62	1.14	1.12	1.13	1.11	1.12	1.14	1.15	1.18
		Difference with Existing (m)	-0.22	-0.54	-0.55	-0.55	-0.57	-0.58	-0.60	-0.63	-0.67
2-3	MR at Iken Marshes	Max Elevation	1.82	1.62	1.59	1.60	1.58	1.61	1.63	1.66	1.70
		Difference with Existing (m)	-0.02	-0.06	-0.09	-0.08	-0.10	-0.10	-0.11	-0.12	-0.16
2-4	MR at Hazelwood Marshes	Max Elevation	1.84	1.67	1.66	1.67	1.66	1.69	1.72	1.74	1.79
		Difference with Existing (m)	0.00	-0.02	-0.02	-0.02	-0.02	-0.01	-0.02	-0.04	-0.06
2-5	MR at Aldeburgh Marshes	Max Elevation	1.82	1.62	1.62	1.62	1.63	1.66	1.70	1.72	1.75
		Difference with Existing (m)	-0.02	-0.06	-0.06	-0.07	-0.05	-0.04	-0.04	-0.06	-0.11
2-6	MR at Boyton Marshes	Max Elevation	1.80	1.64	1.65	1.65	1.66	1.70	1.73	1.75	1.81
		Difference with Existing (m)	-0.05	-0.04	-0.03	-0.04	-0.02	0.00	-0.01	-0.03	-0.05
2-7	MR at Butley Marsh	Max Elevation	1.81	1.60	1.65	1.65	1.66	1.71	1.73	1.75	1.83
		Difference with Existing (m)	-0.03	-0.08	-0.03	-0.04	-0.01	0.00	-0.01	-0.03	-0.02
2-8	Slaughden bypass & Sudbourne Marshes	Max Elevation	1.77	1.53	1.53	1.53	1.54	1.58	1.61	1.62	1.66
		Difference with Existing (m)	-0.07	-0.15	-0.15	-0.15	-0.14	-0.12	-0.14	-0.16	-0.20
			mouth	Butley River	Gedgrave Marshes	East Havergate	Orford	main channel	Slaughden	Aldeburgh Marshes	Iken Cliffs

Table 13. Ebb-Flood ratio in the Alde-Ore estuary under different managed realignment options. Results from hydrodynamic modelling by Black and Veatch (2006).

Option Reference			Monitoring Location							
			Mouth	Orford	Slaughden	Butley	Site 4	Site 5	Site 9a	Iken
2-1	Existing	Spring Peak	0.78	0.92	0.93	0.93	0.86	0.85	0.92	0.79
		Neap Peak	0.86	0.96	0.99	1.01	0.91	0.91	0.97	0.88
2-2	Do Nothing Option	Spring Peak	0.54	0.63	0.72	0.65	0.62	0.63	0.71	0.68
		Neap Peak	0.56	0.63	0.81	0.54	0.63	0.65	0.78	0.78
2-3	Setback at Iken Marshes	Spring Peak	0.74	0.86	0.84	0.98	0.82	0.77	0.84	0.64
		Neap Peak	0.84	0.95	0.90	1.02	0.92	0.87	0.90	0.71
2-4	Setback at Hazelwood Marshes	Spring Peak	0.70	0.80	0.75	0.95	0.87	0.83	0.91	0.91
		Neap Peak	0.60	0.89	0.91	1.00	0.93	0.91	0.96	0.96
2-5	Setback at Aldeburgh Marshes	Spring Peak	0.65	0.76	0.71	0.56	0.73	0.68	0.71	0.60
		Neap Peak	0.67	0.77	0.77	0.78	0.73	0.70	0.77	0.68
2-6	Setback at Boyton Marshes	Spring Peak	0.75	0.96	0.96	0.67	0.89	0.88	0.96	0.77
		Neap Peak	0.84	1.01	1.02	0.67	0.94	0.96	1.01	0.85
			mouth	Orford	Slaughden	Butley River	Gedgrave Marshes	East Havergate	Slaughden	Iken Cliffs

Table 14. Tidal volumes (10^6 m^3) below defined tidal levels within the active Alde-Ore estuary (north and south of Slaughden). The 'extreme surge' is taken to represent an approximate 1 in 100 year event.

	Extreme Surge	Dec 2013 Surge	HAT	MHWS	MHWN
upper level:	3.5 m OD	3.1 m OD	1.7 m OD	1.5 m OD	1.1 m OD
lower level:	-1.6 m OD	-1.6 m OD	-1.6 m OD	-0.7 m OD	-0.3 m OD
Total intertidal and subtidal volume below upper level					
Active Estuary (North)	25.08	22.34	13.15	11.97	9.81
Active Estuary (South)	43.07	39.20	26.96	25.56	23.14
Active Estuary (North and South)	68.15	61.53	40.11	37.53	32.95
Tidal prism between upper and lower levels					
Active Estuary (North)	22.77	20.02	10.83	8.57	5.66
Active Estuary (South)	30.51	26.64	14.41	10.16	6.30
Active Estuary (North and South)	53.28	46.67	25.25	18.73	11.96
Sub-tidal volumes below lower level					
Active Estuary (North)	2.31	2.31	2.31	3.40	4.15
Active Estuary (South)	12.55	12.55	12.55	15.40	16.84
Active Estuary (North and South)	14.87	14.87	14.87	18.80	20.99

Table 15. Tidal volumes (10^6 $m^{3)}$ below defined tidal levels on reclaimed marshes. *Note that FC11a (Lantern Marshes North) is now active and is included in the active estuary figures. The total shown below excludes Lantern Marshes North.

	Extreme Surge	Dec 2013 Surge	HAT	MHWS	MHWN
upper level:	3.5 m OD	3.1 m OD	1.7 m OD	1.5 m OD	1.1 m OD
lower level:	-1.6 m OD	-1.6 m OD	-1.6 m OD	-0.7 m OD	-0.3 m OD
FC1a (Hollesley Marshes)	2.33	1.94	0.71	0.57	0.28
FC1b (Boyton Marshes)	4.23	3.70	1.92	1.68	1.17
FC1c (Stonebridge & Butley Marshes)	8.87	7.71	4.09	3.58	2.38
FC2 (Upper Butley River)	0.81	0.56	0.04	0.02	0.00
FC3 (Chillesford Marshes)	5.74	4.98	2.63	2.29	1.54
FC4a (Gedgrave Marshes)	10.12	9.00	5.19	4.60	3.20
FC4b (Sudbourne Marshes)	26.60	23.39	12.73	11.20	7.98
FC5 (Iken Marshes)	12.43	10.66	5.19	4.48	3.08
FC6&7 (Upper Alde-Ore)	6.49	5.20	1.72	1.35	0.71
FC8 (Ham Creek)	1.41	1.10	0.28	0.20	0.06
FC9 (Hazlewood Marshes)	2.18	1.83	0.73	0.59	0.32
FC9A (Round Hill)	0.01	0.01	0.00	0.00	0.00
FC10 (Aldeburgh Marshes)	6.69	5.94	3.45	3.04	2.03
FC11a (Lantern Marshes North)*	0.78	0.65	0.23	0.17	0.07
FC11b (Lantern Marshes South)	5.42	4.69	2.16	1.80	1.09
FC11c (King's Marshes North)	2.03	1.74	0.74	0.60	0.33
FC11d (King's Marshes South)	2.77	2.43	1.23	1.07	0.75
FC12 (Havergate Island)	1.56	1.36	0.68	0.59	0.40
FC13 (Dovey's Island)	0.35	0.31	0.15	0.13	0.09
Total	100.06	86.54	43.63	37.78	25.42

Table 16. Tidal volumes below defined tidal levels on reclaimed marshes, as a percentage of (a) the active estuary south of Slaughden; (b) the active estuary north of Slaughden; (c) the total active estuary, north and south combined.

(a) Estuary South of Slaughden	Extreme Surge	Dec 2013 Surge	HAT	MHWS	MHWN
upper level:	3.5 m OD	3.1 m OD	1.7 m OD	1.5 m OD	1.1 m OD
lower level:	-1.6 m OD	-1.6 m OD	-1.6 m OD	-0.7 m OD	-0.3 m OD
FC1a (Hollesley Marshes)	7.6	7.3	4.9	5.6	4.5
FC1b (Boyton Marshes)	13.9	13.9	13.3	16.5	18.6
FC1c (Stonebridge & Butley Marshes)	29.1	28.9	28.4	35.2	37.8
FC2 (Upper Butley River)	2.7	2.1	0.3	0.2	0.0
FC3 (Chillesford Marshes)	18.8	18.7	18.2	22.6	24.4
FC4a (Gedgrave Marshes)	33.2	33.8	36.0	45.3	50.8
FC4b (Sudbourne Marshes)	87.2	87.8	88.3	110.3	126.5
FC11b (Lantern Marshes South)	17.8	17.6	15.0	17.7	17.3
FC11c (King's Marshes North)	6.6	6.5	5.1	5.9	5.2
FC11d (King's Marshes South)	9.1	9.1	8.5	10.6	11.9
FC12 (Havergate Island)	5.1	5.1	4.7	5.8	6.3
FC13 (Dovey's Island)	1.2	1.2	1.0	1.3	1.4

(b) Estuary North of Slaughden	Extreme Surge	Dec 2013 Surge	HAT	MHWS	MHWN
upper level:	3.5 m OD	3.1 m OD	1.7 m OD	1.5 m OD	1.1 m OD
lower level:	-1.6 m OD	-1.6 m OD	-1.6 m OD	-0.7 m OD	-0.3 m OD
FC5 (Iken Marshes)	54.6	53.3	47.9	52.3	54.4
FC6&7 (Upper Alde-Ore)	28.5	26.0	15.9	15.8	12.6
FC8 (Ham Creek)	6.2	5.5	2.6	2.3	1.1
FC9 (Hazlewood Marshes)	9.6	9.2	6.7	6.9	5.7
FC9A (Round Hill)	0.1	0.0	0.0	0.0	0.0
FC10 (Aldeburgh Marshes)	29.4	29.7	31.9	35.5	35.9

(c) Entire Estuary (north and south)	Extreme Surge	Dec 2013 Surge	HAT	MHWS	MHWN
upper level:	3.5 m OD	3.1 m OD	1.7 m OD	1.5 m OD	1.1 m OD
lower level:	-1.6 m OD	-1.6 m OD	-1.6 m OD	-0.7 m OD	-0.3 m OD
FC1a (Hollesley Marshes)	4.4	4.2	2.8	3.0	2.4
FC1b (Boyton Marshes)	7.9	7.9	7.6	9.0	9.8
FC1c (Stonebridge & Butley Marshes)	16.6	16.5	16.2	19.1	19.9
FC2 (Upper Butley River)	1.5	1.2	0.2	0.1	0.0
FC3 (Chillesford Marshes)	10.8	10.7	10.4	12.3	12.9
FC4a (Gedgrave Marshes)	19.0	19.3	20.6	24.6	26.8
FC4b (Sudbourne Marshes)	49.9	50.1	50.4	59.8	66.7
FC5 (Iken Marshes)	23.3	22.9	20.5	23.9	25.7
FC6&7 (Upper Alde-Ore)	12.2	11.1	6.8	7.2	5.9
FC8 (Ham Creek)	2.7	2.4	1.1	1.1	0.5
FC9 (Hazlewood Marshes)	4.1	3.9	2.9	3.1	2.7
FC9A (Round Hill)	0.0	0.0	0.0	0.0	0.0
FC10 (Aldeburgh Marshes)	12.6	12.7	13.7	16.2	17.0
FC11b (Lantern Marshes South)	10.2	10.0	8.6	9.6	9.1
FC11c (King's Marshes North)	3.8	3.7	2.9	3.2	2.8
FC11d (King's Marshes South)	5.2	5.2	4.9	5.7	6.3
FC12 (Havergate Island)	2.9	2.9	2.7	3.1	3.3
FC13 (Dovey's Island)	0.7	0.7	0.6	0.7	0.7

Table 17. Potential tidal volumes (10^3 m^3) at Hazlewood Marshes for different tides and alternative future management options: (a) 'Do nothing', (b-d) new 'set-back' walls on three possible generalised alignments; (e) allow the existing breaches to remain, but construct a sill at the level of MHWS, so that water remains at the level of MHWS on Hazlewood Marshes when the tide is out. Scenarios (a) to (d) assume the existing breaches will scour down, so that all the water drains from the marsh virtually entirely at each low tide

	Extreme Surge (3.5 m OD)	Dec 2013 Surge (3.1 m OD)	HAT (1.7 m OD)	MHWS (1.5 m OD)	MHWN (1.1 m OD)
'Do nothing' scenario	2.18	1.83	0.73	0.59	0.32
Set-back wall option A	0.70	0.61	0.27	0.23	0.14
Set-back wall option B	1.32	1.14	0.53	0.44	0.27
Set-back wall option C	1.93	1.65	0.70	0.57	0.31
Sill construction at MHWS	1.59	1.24	0.14	0.00	0.00

Table 18. Water volumes below different tidal levels on Boyton Marshes, subdivided into front and rear compartment by proposed realignment walls. Also shown are the tidal volumes which would flow in through the breach with realignment walls in place and standing water in a lagoon in the rear compartment.

	Extreme Surge	Dec-13 Surge	HAT	MHWS	MHWN
Level in upper estuary	3.5	3.1	1.7	1.5 m	1.1
Level at Boyton Marsh	3.13	2.78	1.53	1.36	1.00
Water volumes on the compartments					
Front compartment	1.67	1.48	0.83	0.74	0.56
Rear compartment	1.99	1.75	0.92	0.81	0.58
Both compartments	3.66	3.23	1.75	1.55	1.14
Water volumes entering breach					
'Do nothing' scenario	4.23	3.70	1.92	1.68	1.17
No lagoon in rear compartment	3.66	3.23	0.83	0.74	0.56
Lagoon at 0.6 m OD in rear compartment	3.32	2.90	0.83	0.74	0.56
Lagoon at 1.5 m OD in rear compartment	2.77	2.35	0.83	0.74	0.56

Figures

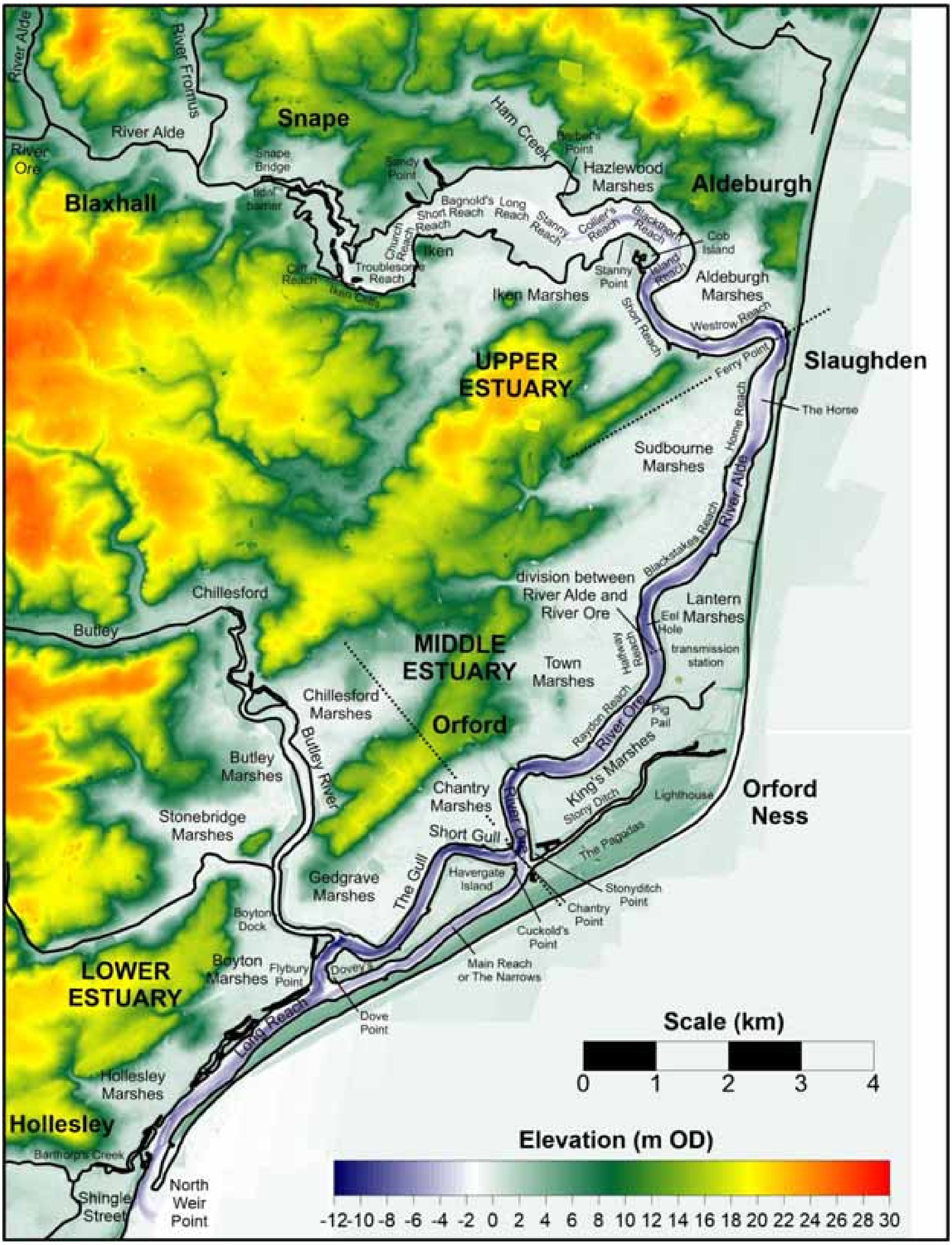


Figure 1. Location map showing the main places mentioned in the text

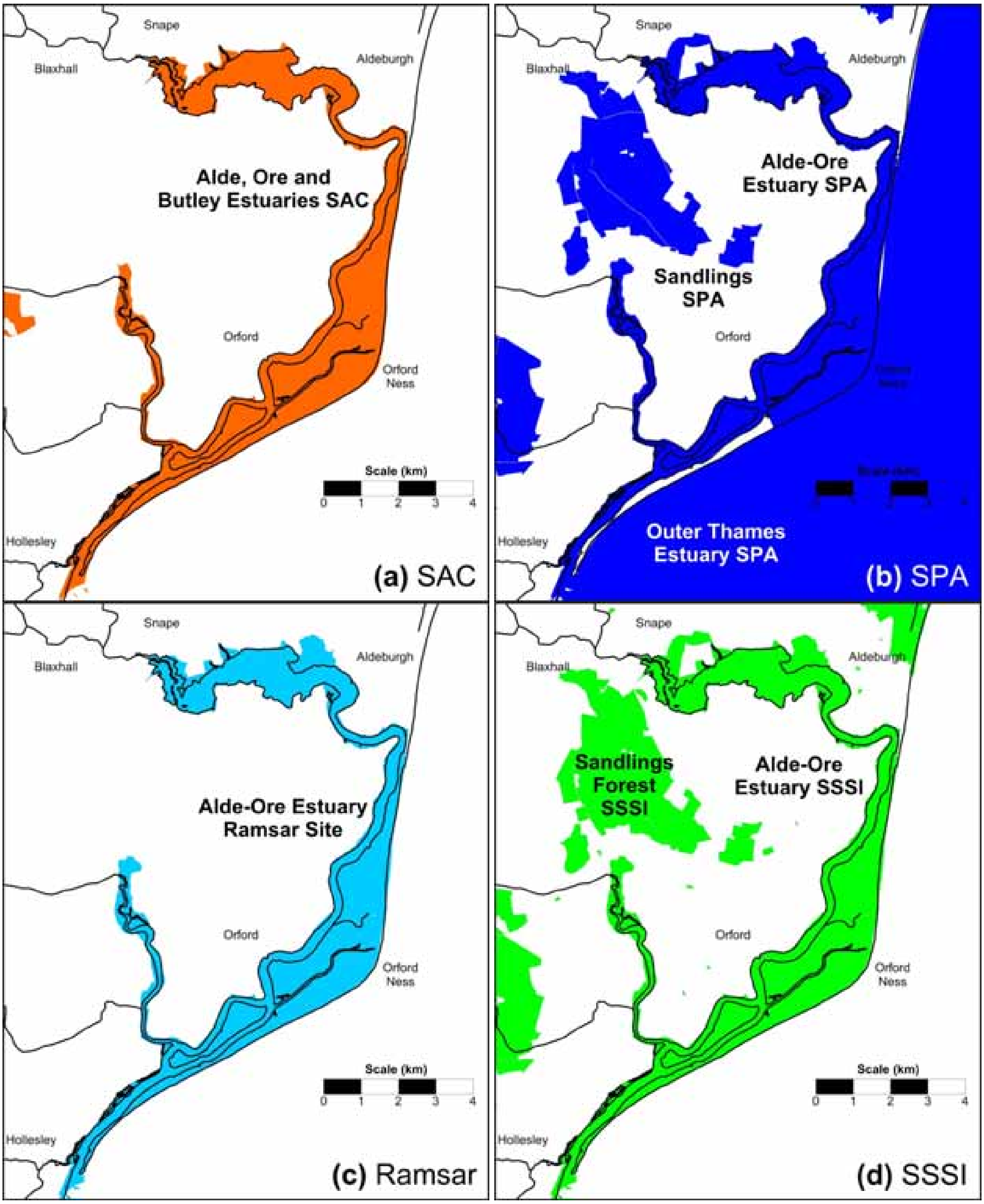


Figure 2. Conservation designations in the Alde-Ore Estuary: (a) Special Areas of Conservation (SAC); (b) Special Protection Areas (SPA); (c) Ramsar sites; (d) Sites of Special Scientific Interest (SSSI)

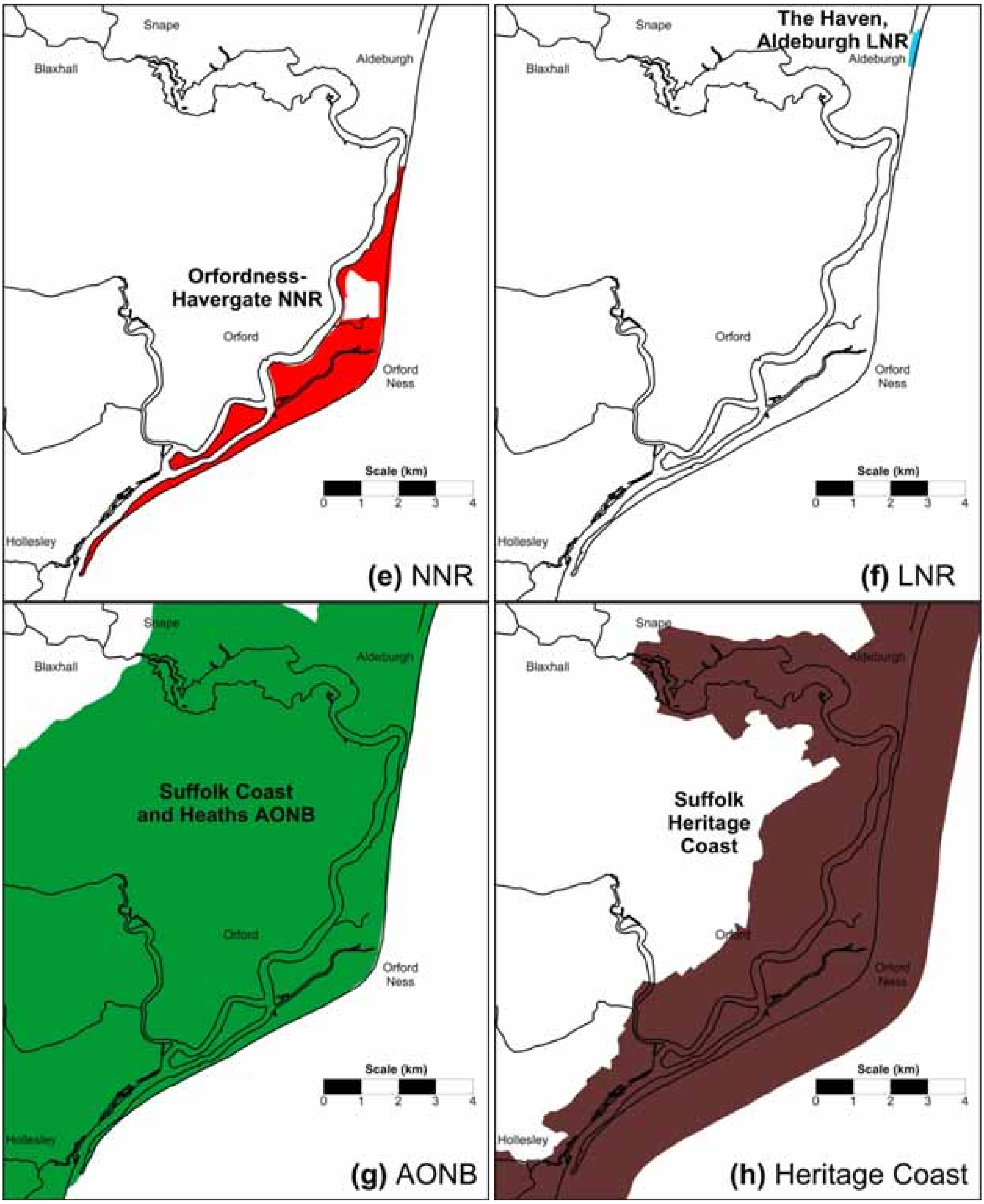


Figure 2 continued. Conservation designations in the Alde-Ore Estuary: (e) National Nature Reserve (NNR); (f) Local Nature Reserve (LNR); (g) Areas of Outstanding Natural Beauty (AONB); (h) Heritage Coast.

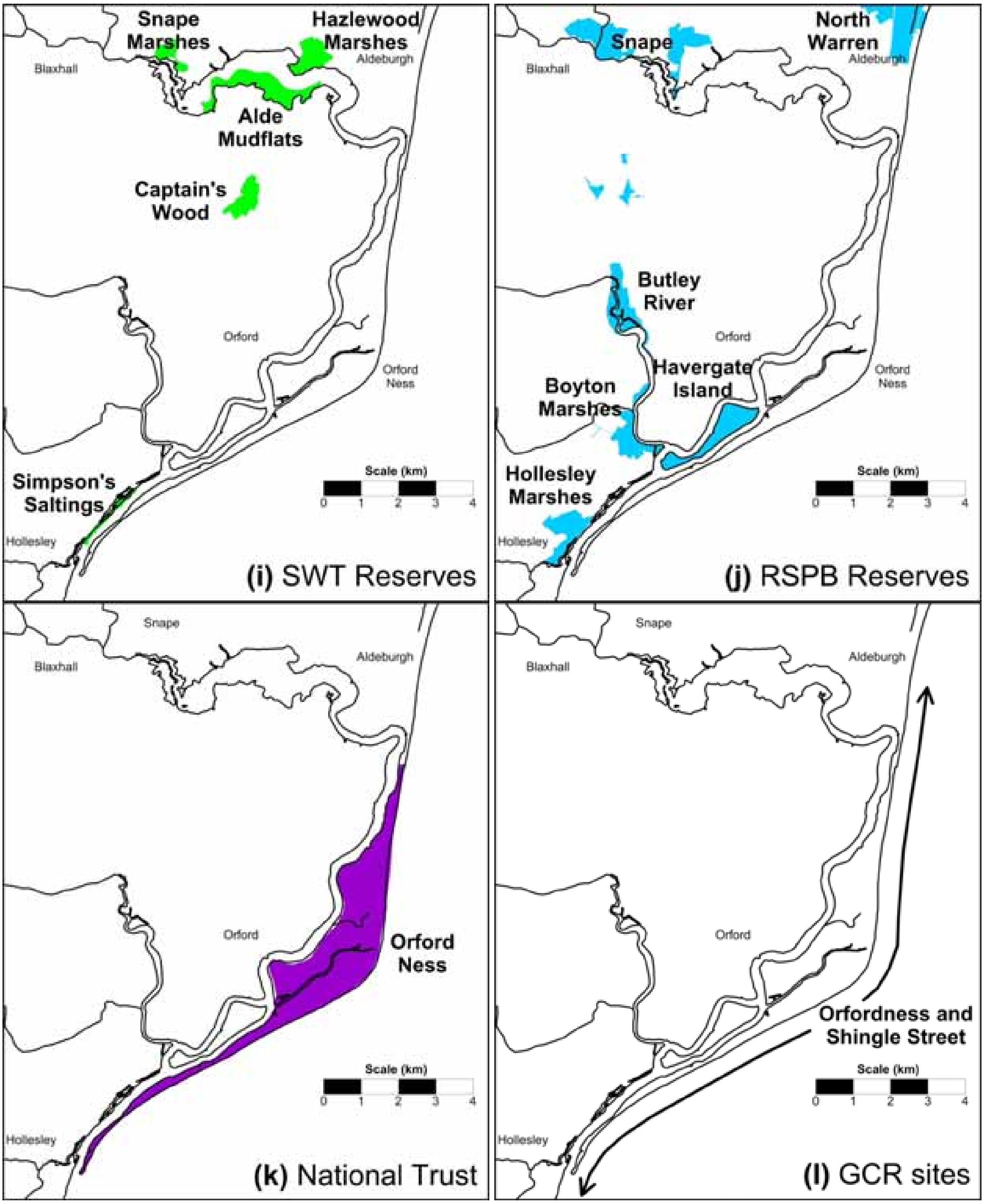


Figure 2 continued. Conservation designations in the Alde-Ore Estuary: (i) Suffolk Wildlife Trust (SWT) reserves; (j) Royal Society for the Protection of Birds (RSPB) reserves; (k) National Trust ownership; (l) Geological Conservation Review (GCR) sites

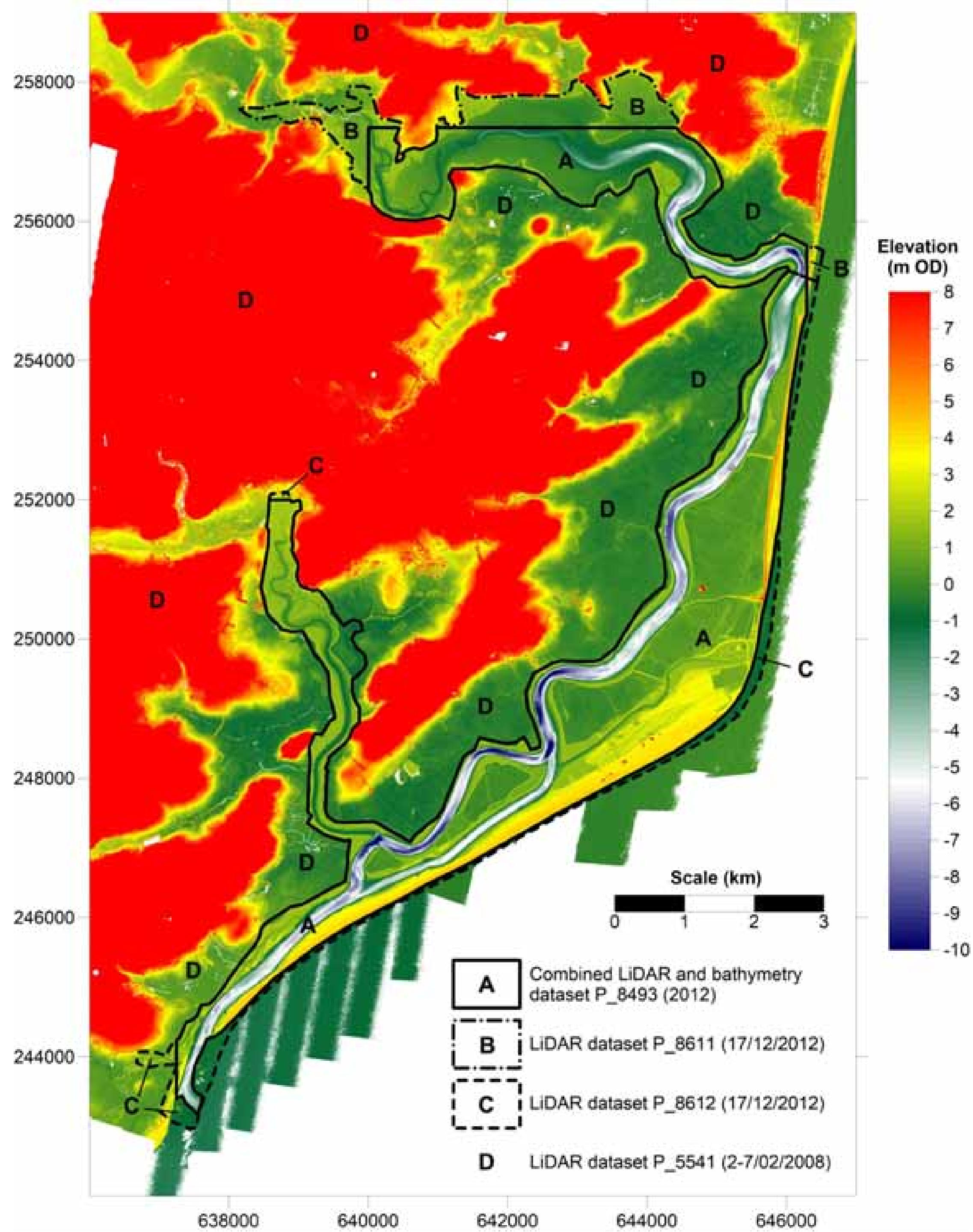


Figure 3. Data sources used to construct a composite digital elevation model (DEM) of the estuary. Where datasets overlap, data were selected in the following order of priority to construct the DEM: A, B, C, D. All data were supplied by the Environment Agency (Geomatics Group)

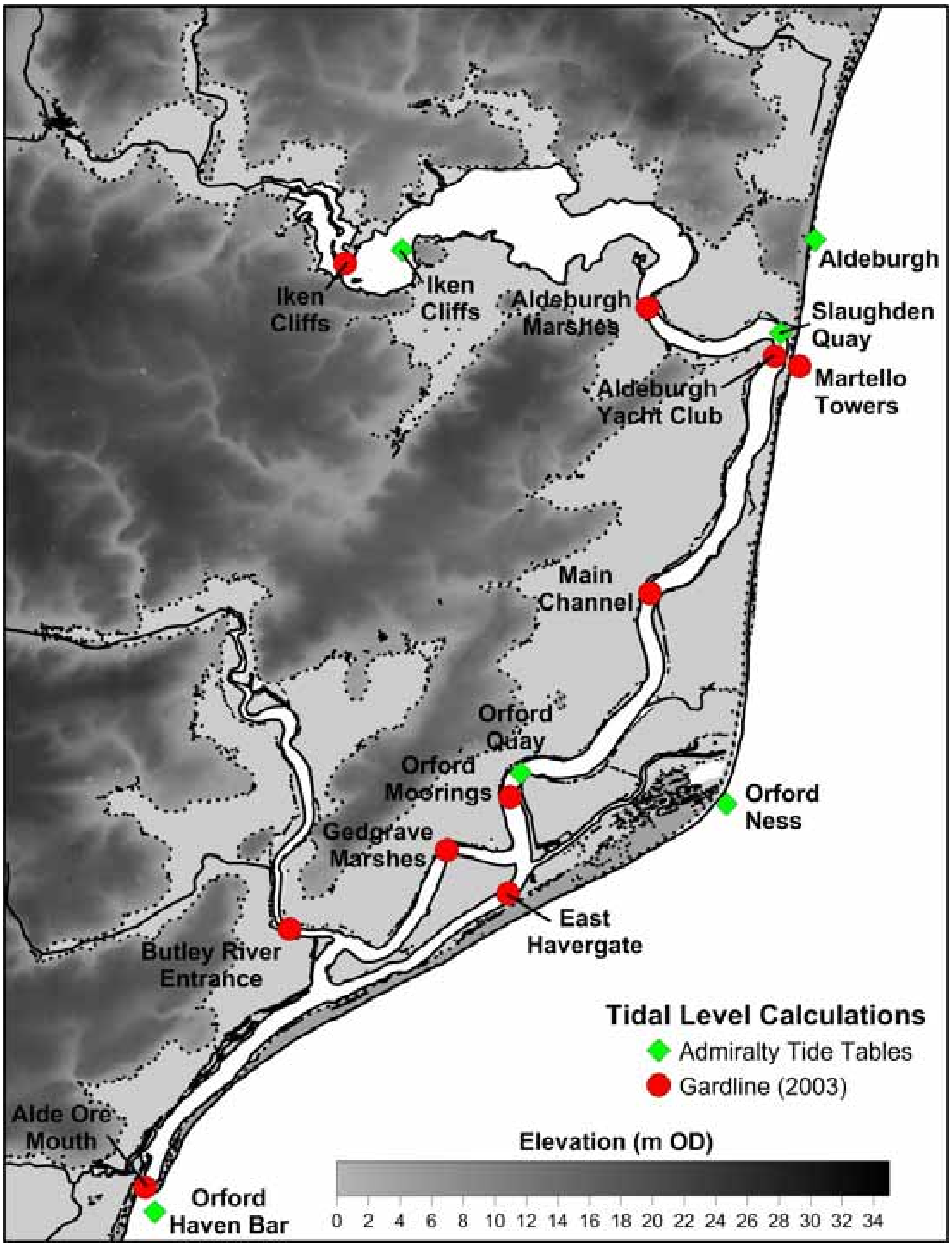


Figure 4. Location of tidal level prediction points given in Admiralty Tide Tables and measurement stations established by Gardline (2003)

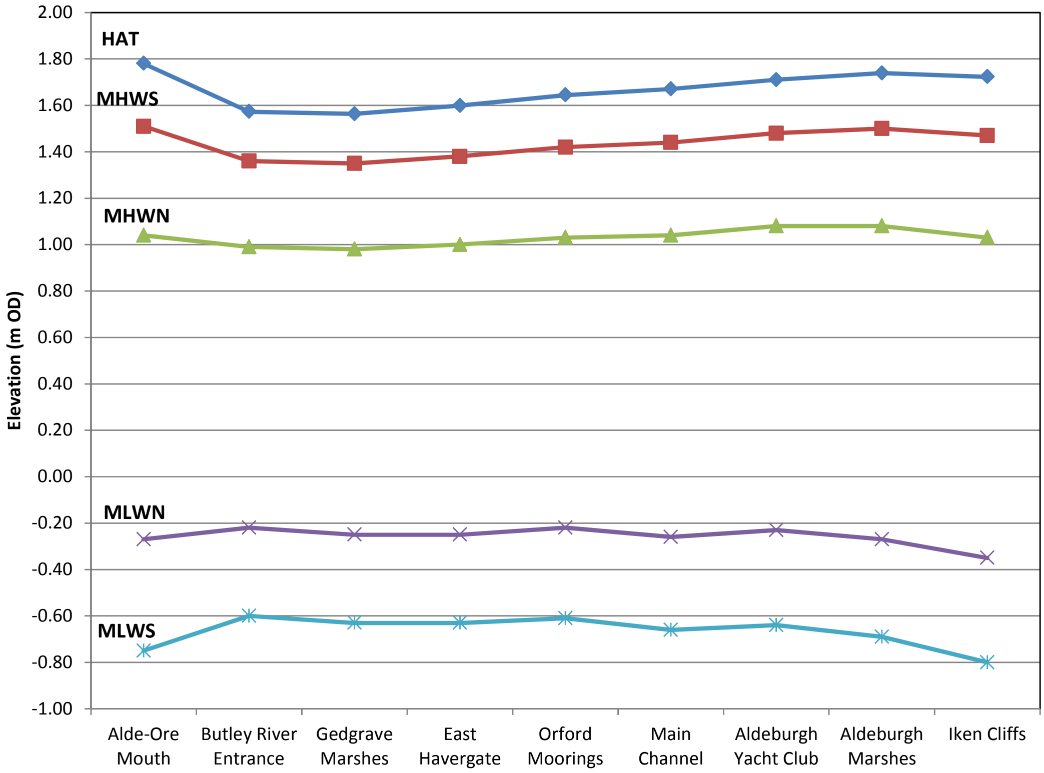


Figure 5. Variations in tidal levels along the estuary indicated by data from Gardline (2003)

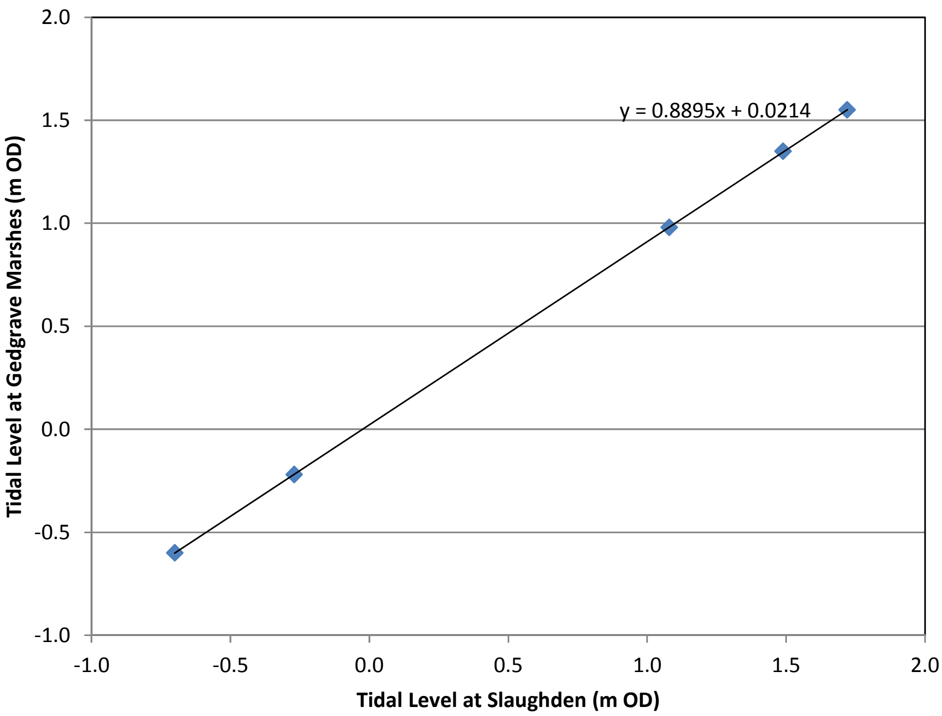


Figure 6. Relationship between tidal levels at Slaughden and Gedgrave Marshes, based on observations made by Gardline in 2003 (data shown in Table 1). This relationship has been used to calculate the tidal levels at different points along the middle and lower estuary

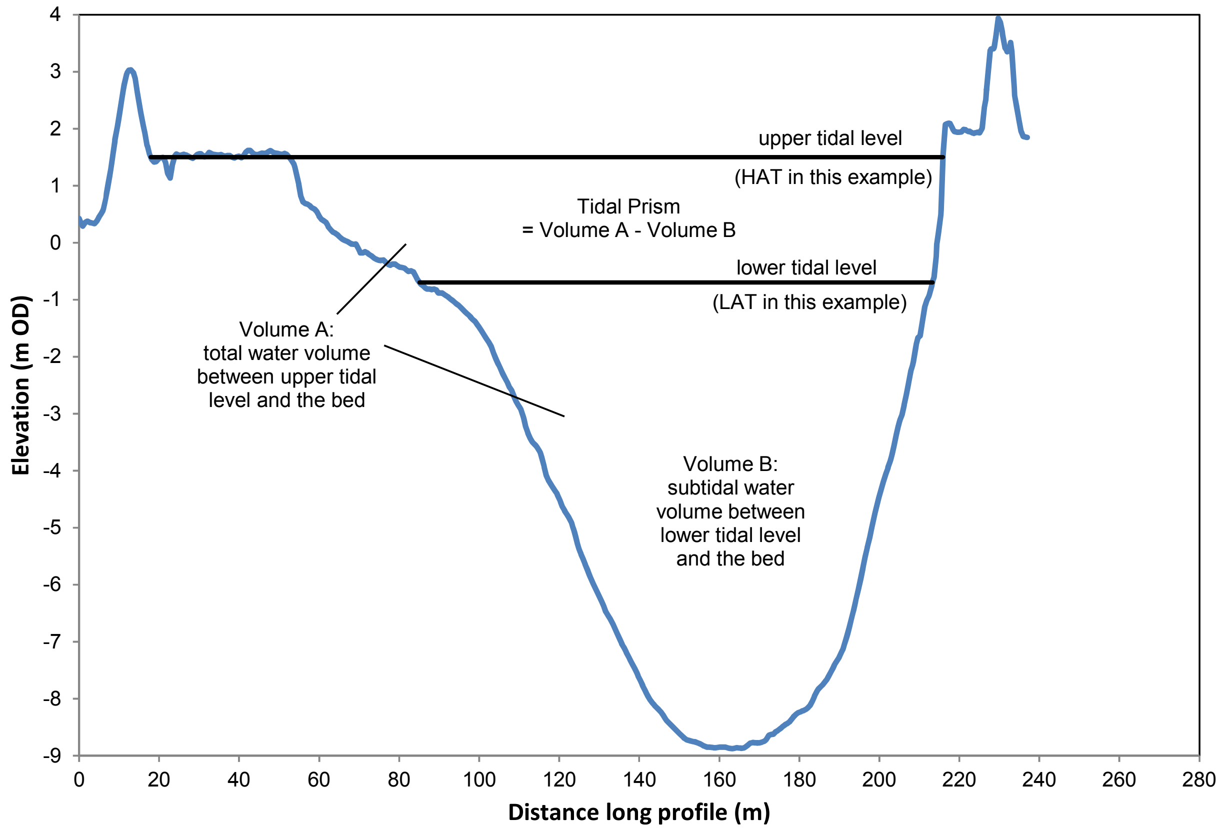


Figure 7. Definition sketch showing the calculation of tidal prism from measurements of tidal volume between the upper and lower tidal levels. Cross-section at Slaughden is shown, but calculations are performed on the DEM in three dimensions for each 0.5 x 0.5 m grid point.

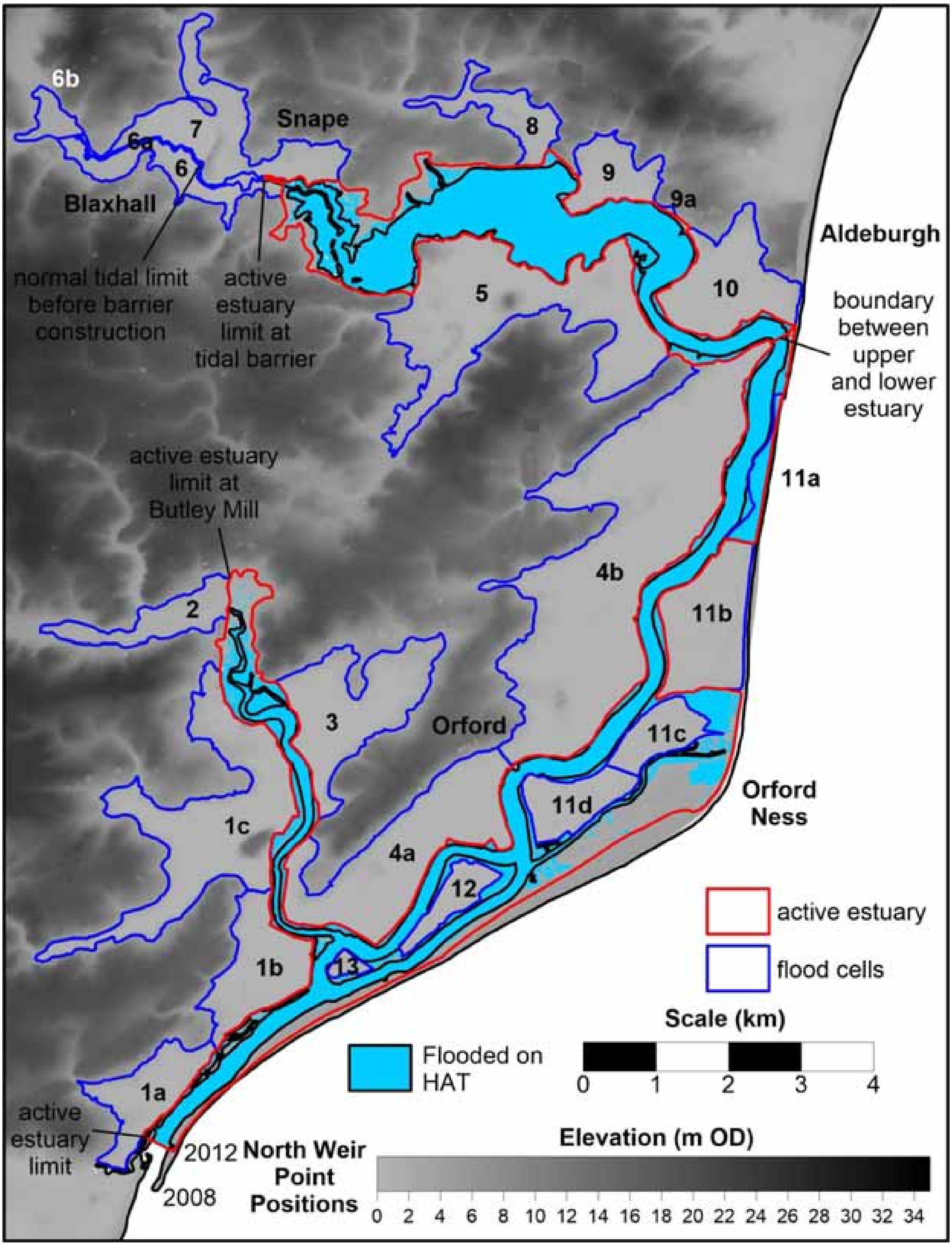


Figure 8. Map showing the limits of the active estuary, flood cell boundaries defined by the 3.5 m OD contour, and the areas which would have been flooded, prior to December 2013, by a tide reaching 1.7 m OD at Hazlewood Marshes. See Table 15 for flood cell names

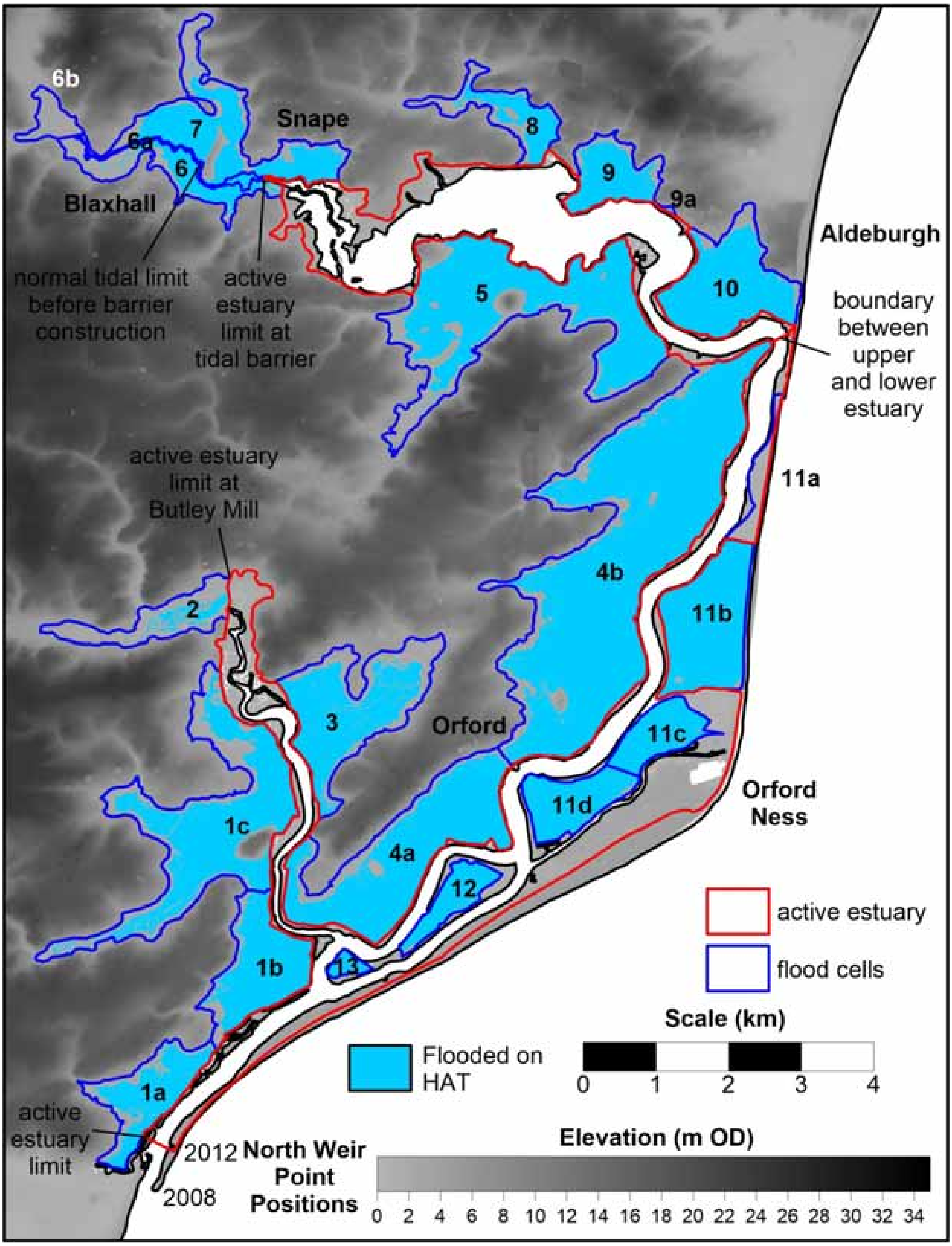


Figure 9. Map showing the limits of the active estuary and areas within the flood cells which could potentially be flooded (in the absences of defences) by a tide reaching 1.7 m OD at Hazlewood Marshes. See Table 15 for flood cell names

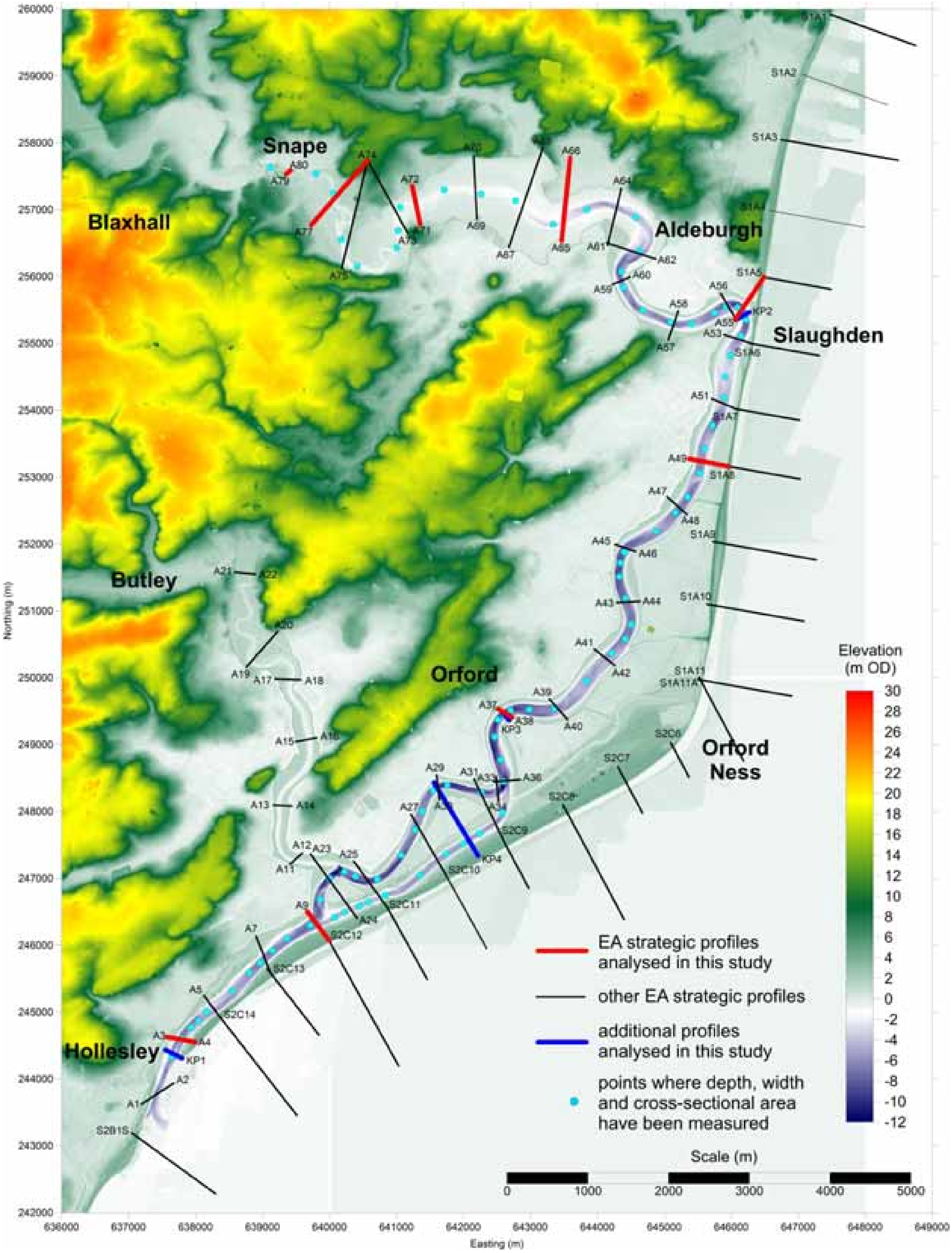


Figure 10. Locations of strategic topographic and bathymetric profiles surveyed by the Environment Agency since the early 1990s. Profiles analysed in this study are highlighted in red. Base DEM: 2012 composite LiDAR-bathymetry

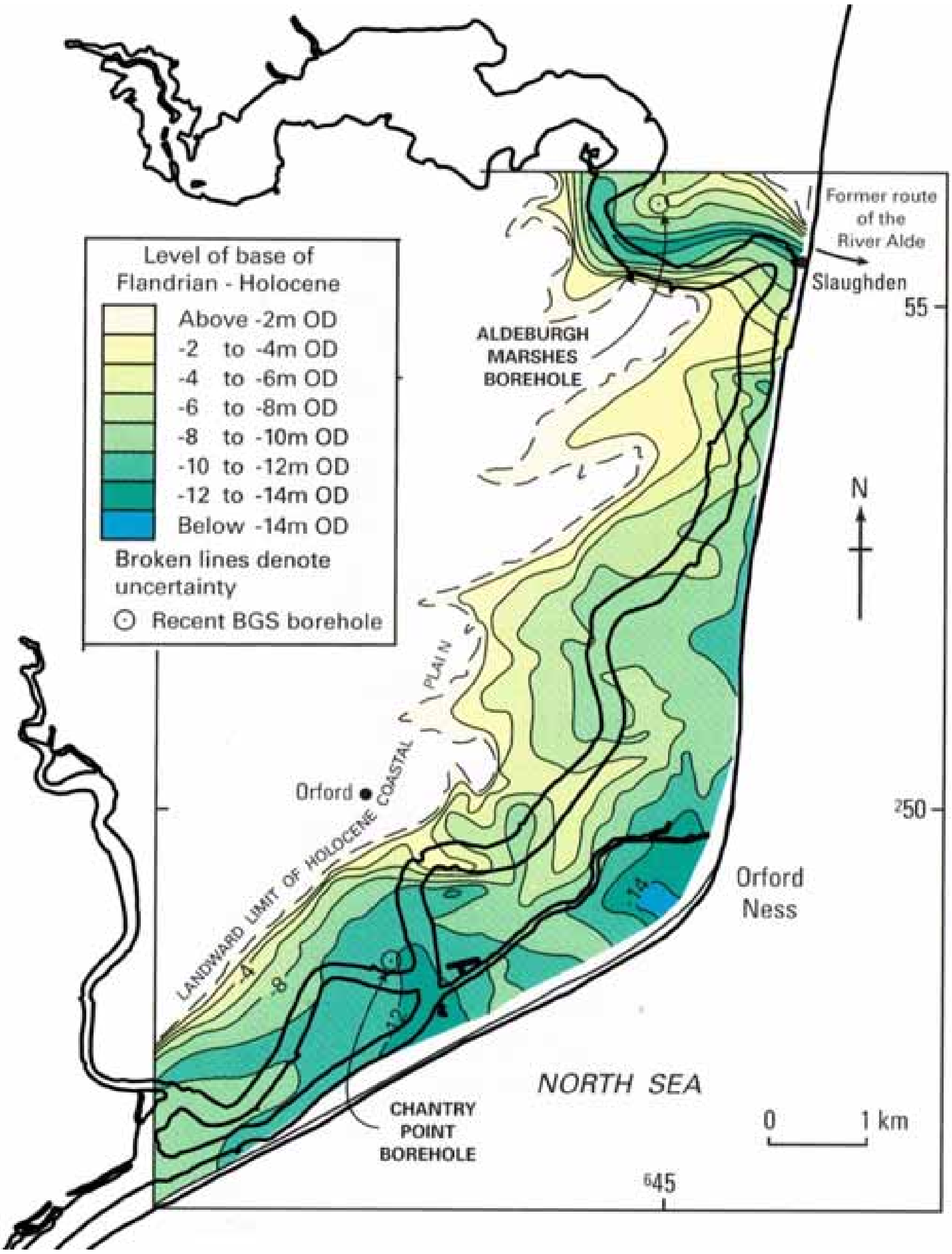


Figure 11. Map showing course of the Alde-Ore estuary in relation to the basal surface of Holocene-age (postglacial) sediments (based on Mathers & Smith, 2002)

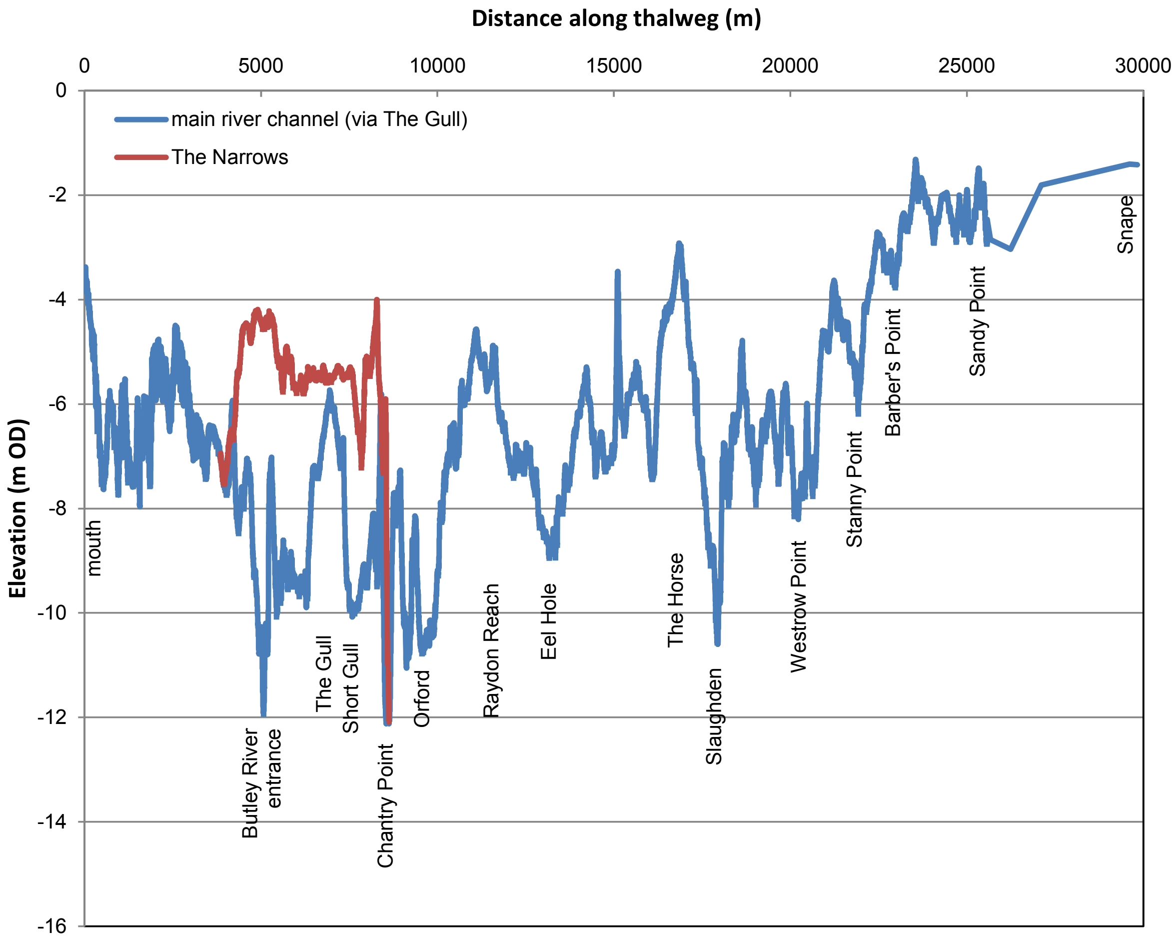


Figure 12. Depth of the thalweg (deepest point of the bed) of the Alde-Ore between Orford Haven Bar and Snape, determined from EA 2012 swath bathymetry data and cross-section survey data

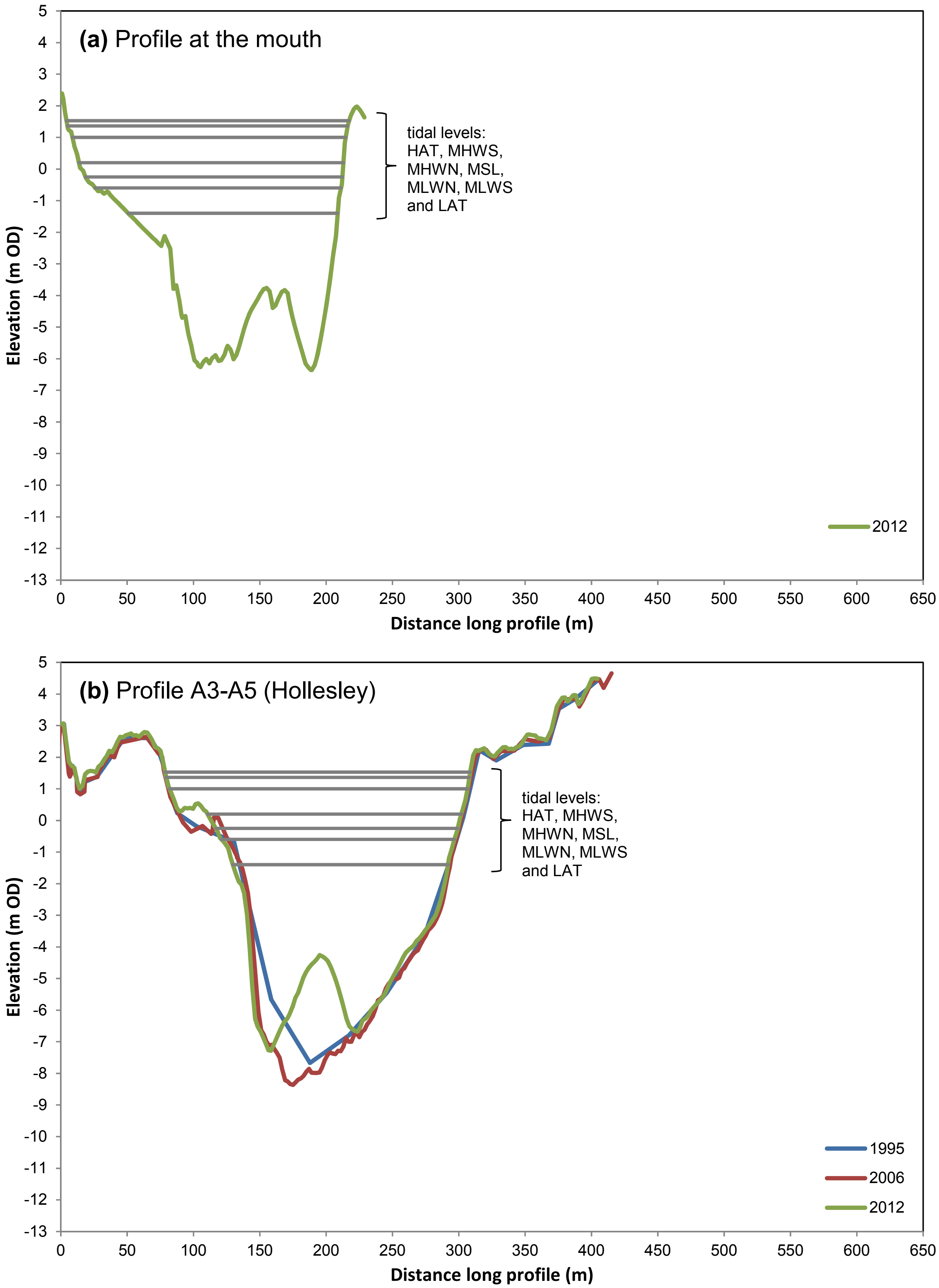


Figure 13. Cross-sections of the Alde-Ore estuary, from Environment Agency linear topographic and bathymetric surveys (1995 and 2006) and swath bathymetry and LiDAR surveys (2012). Data for the 2002 linear survey are regarded as unreliable and have been omitted.

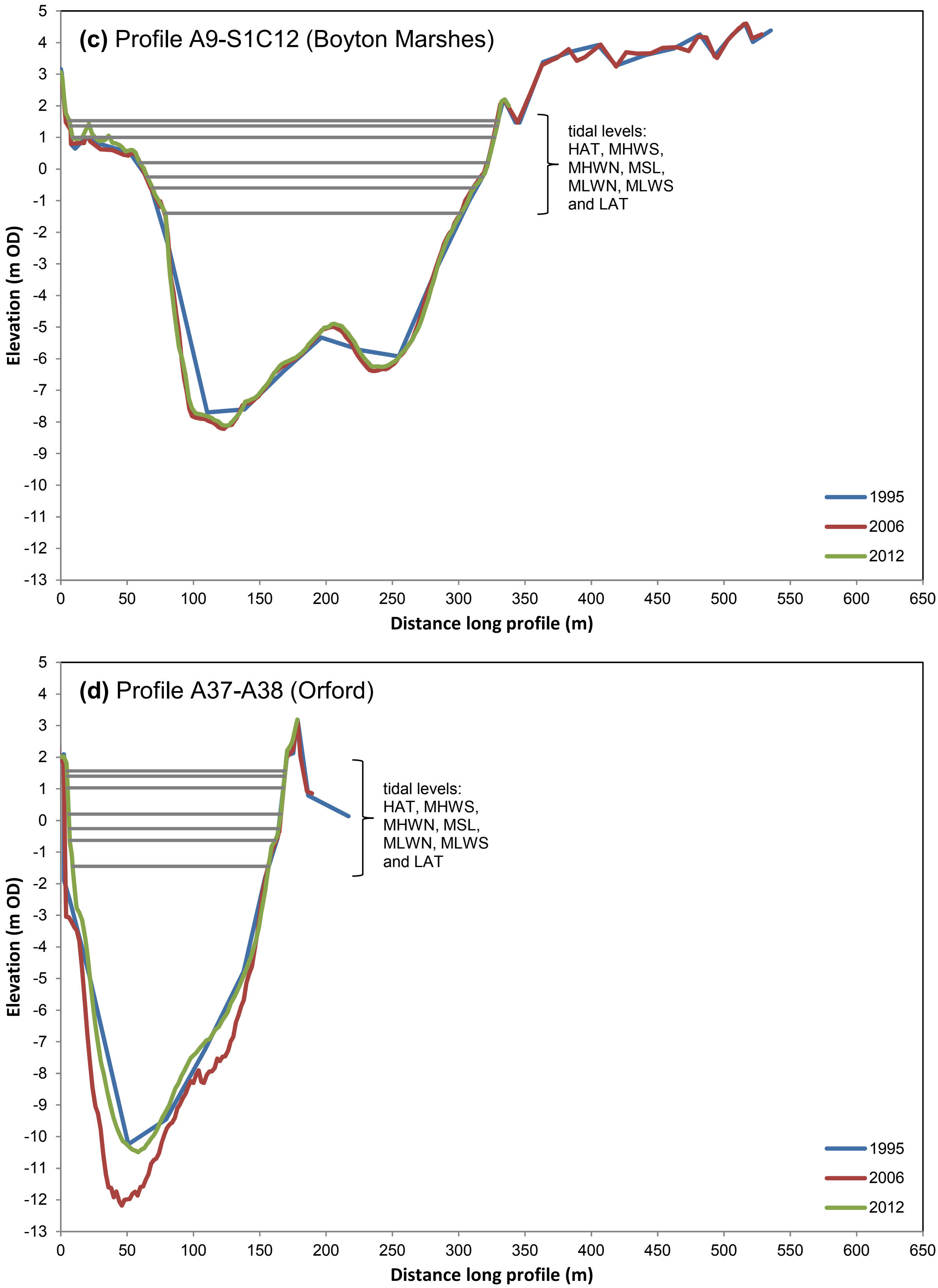
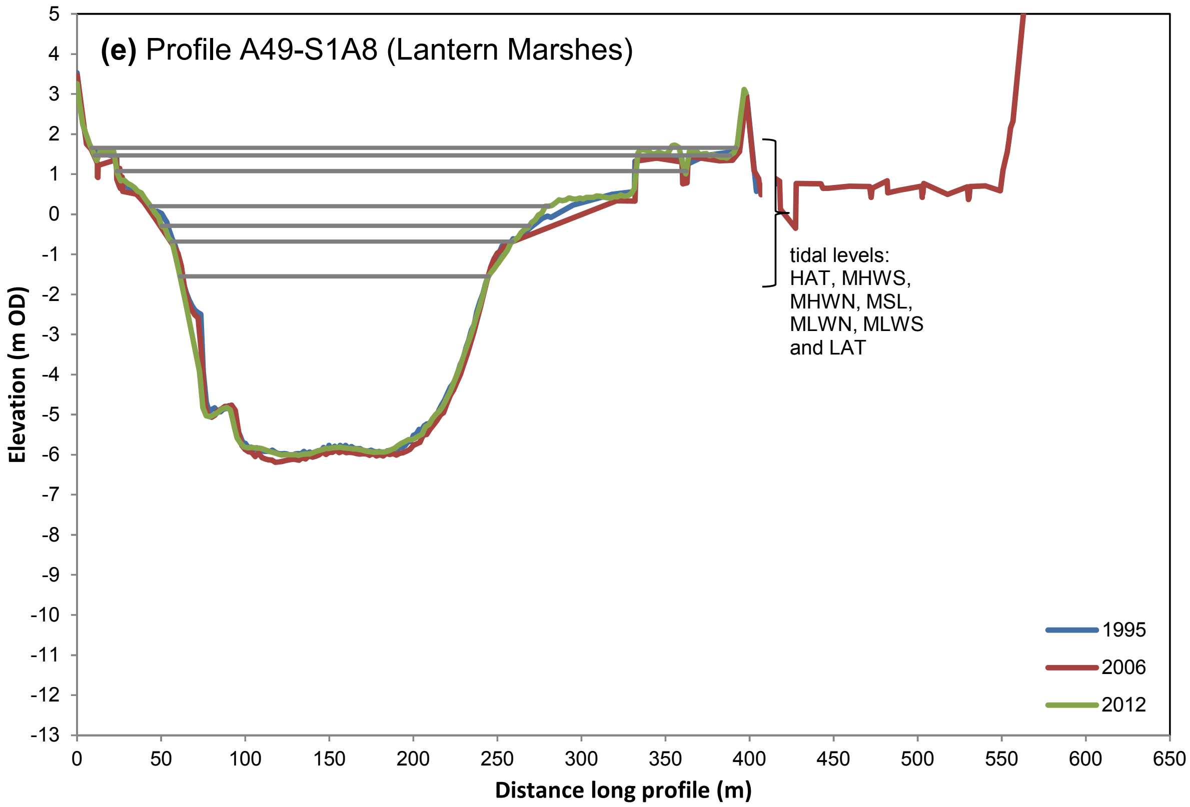
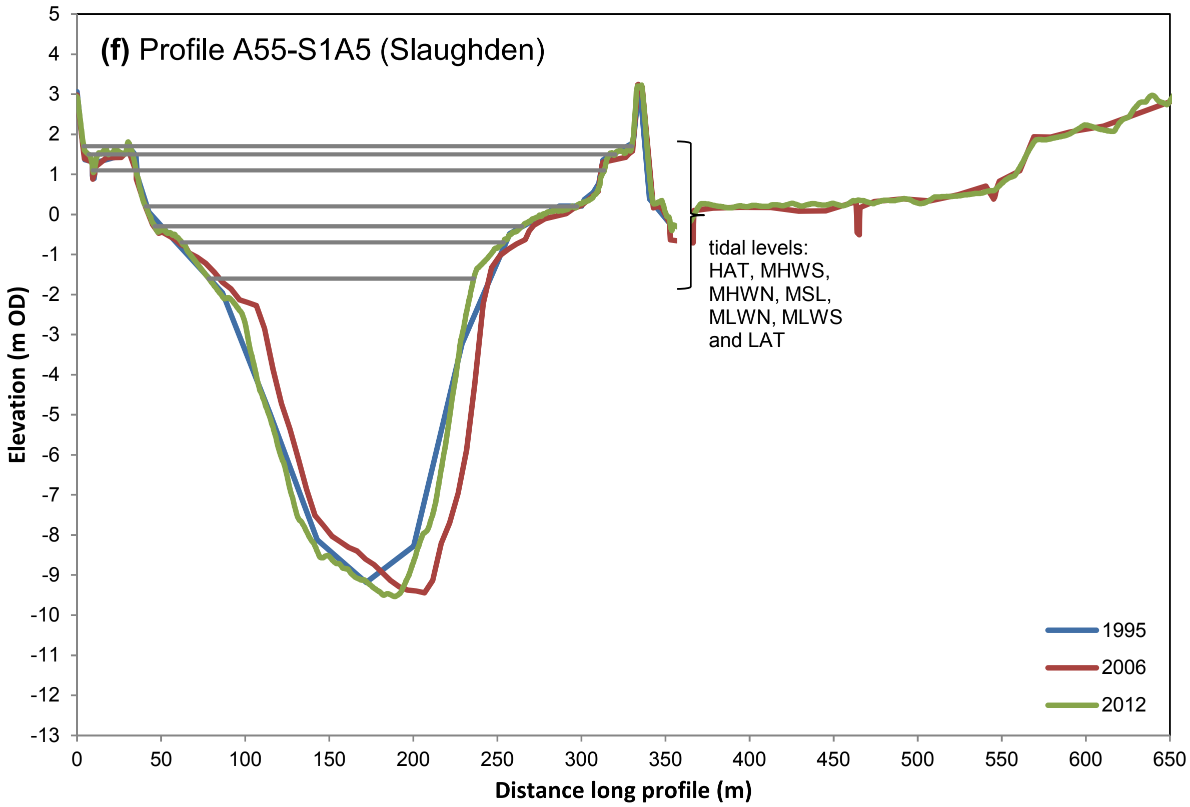


Figure 13 continued.





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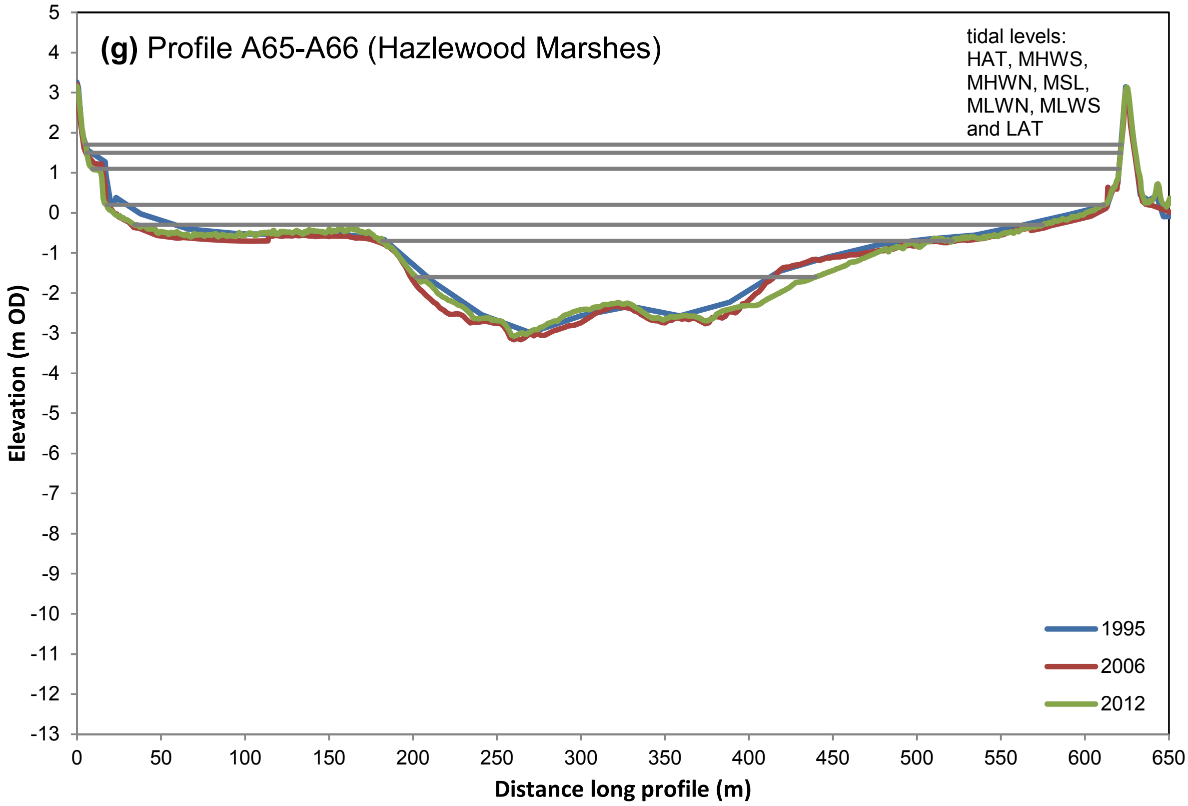

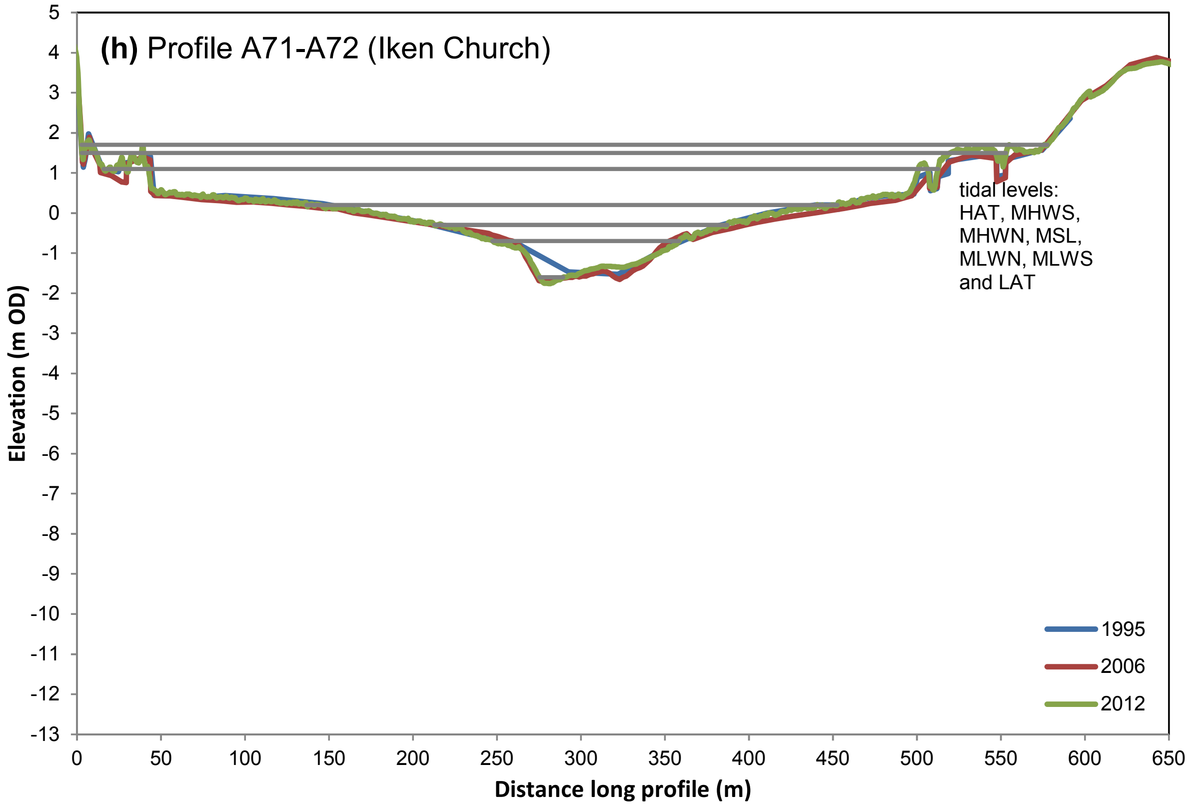

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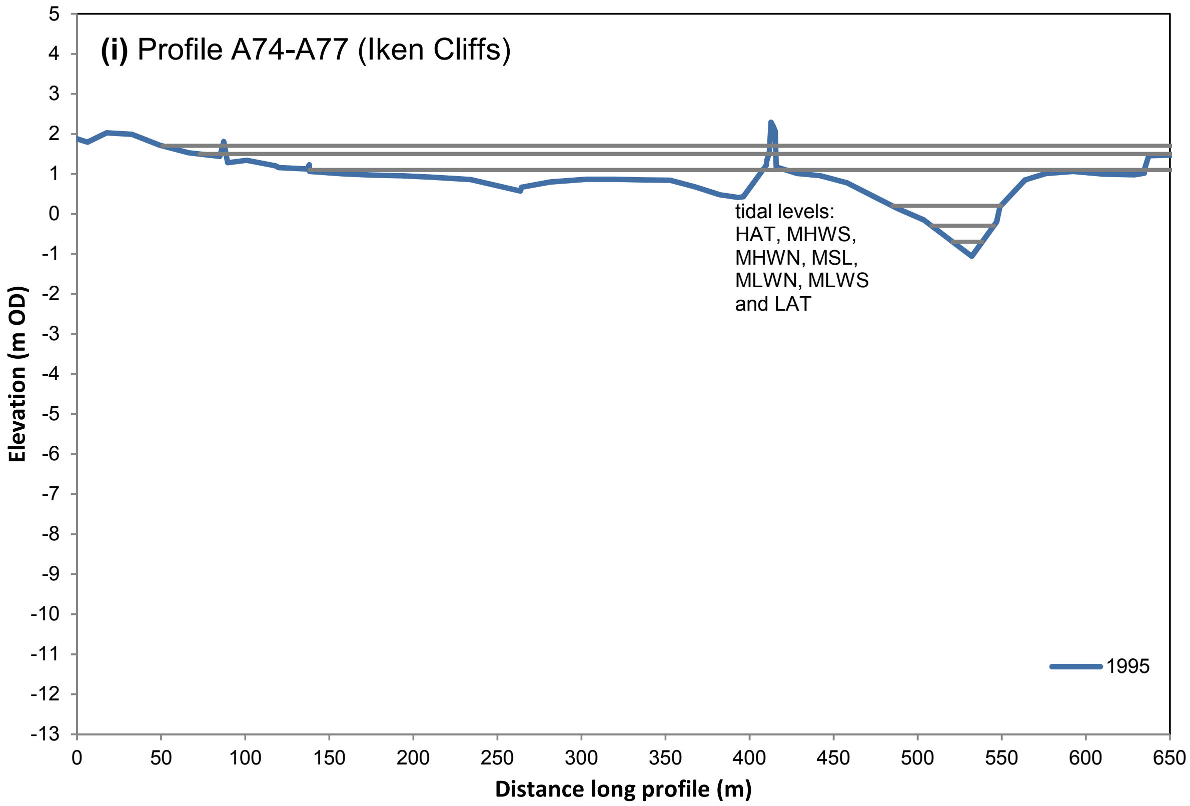

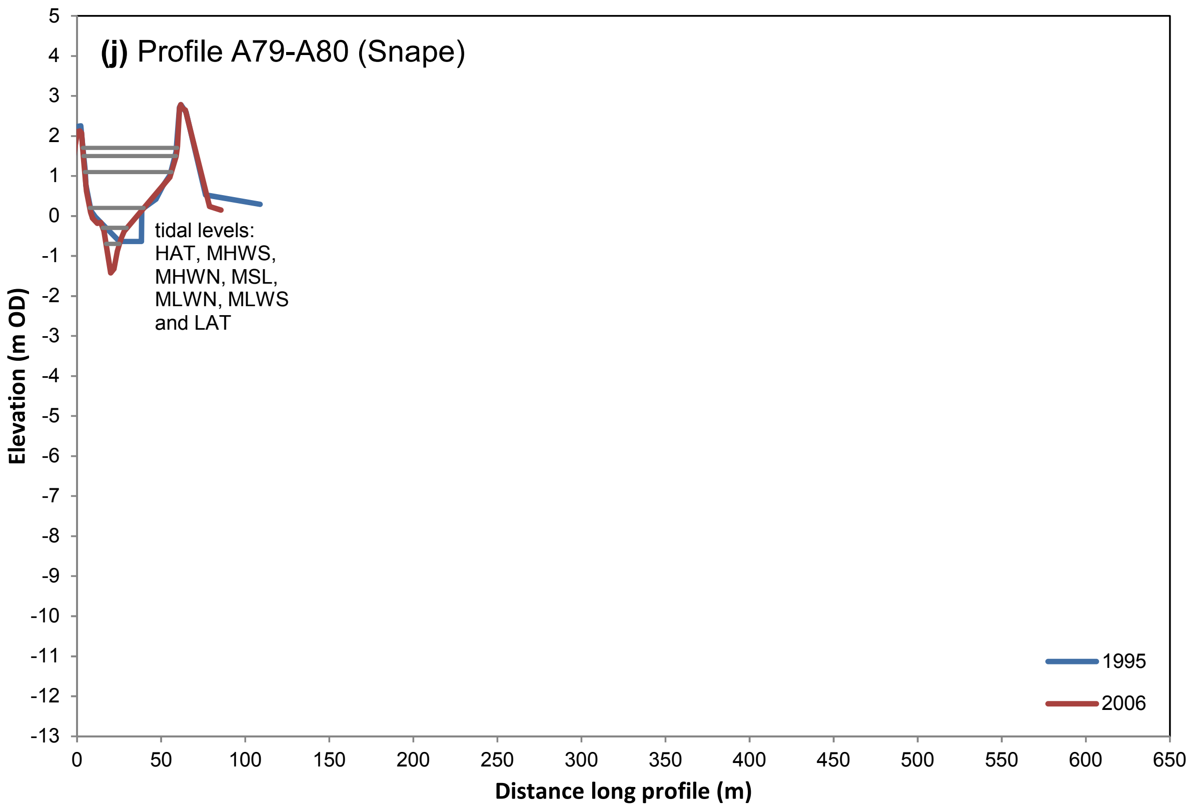

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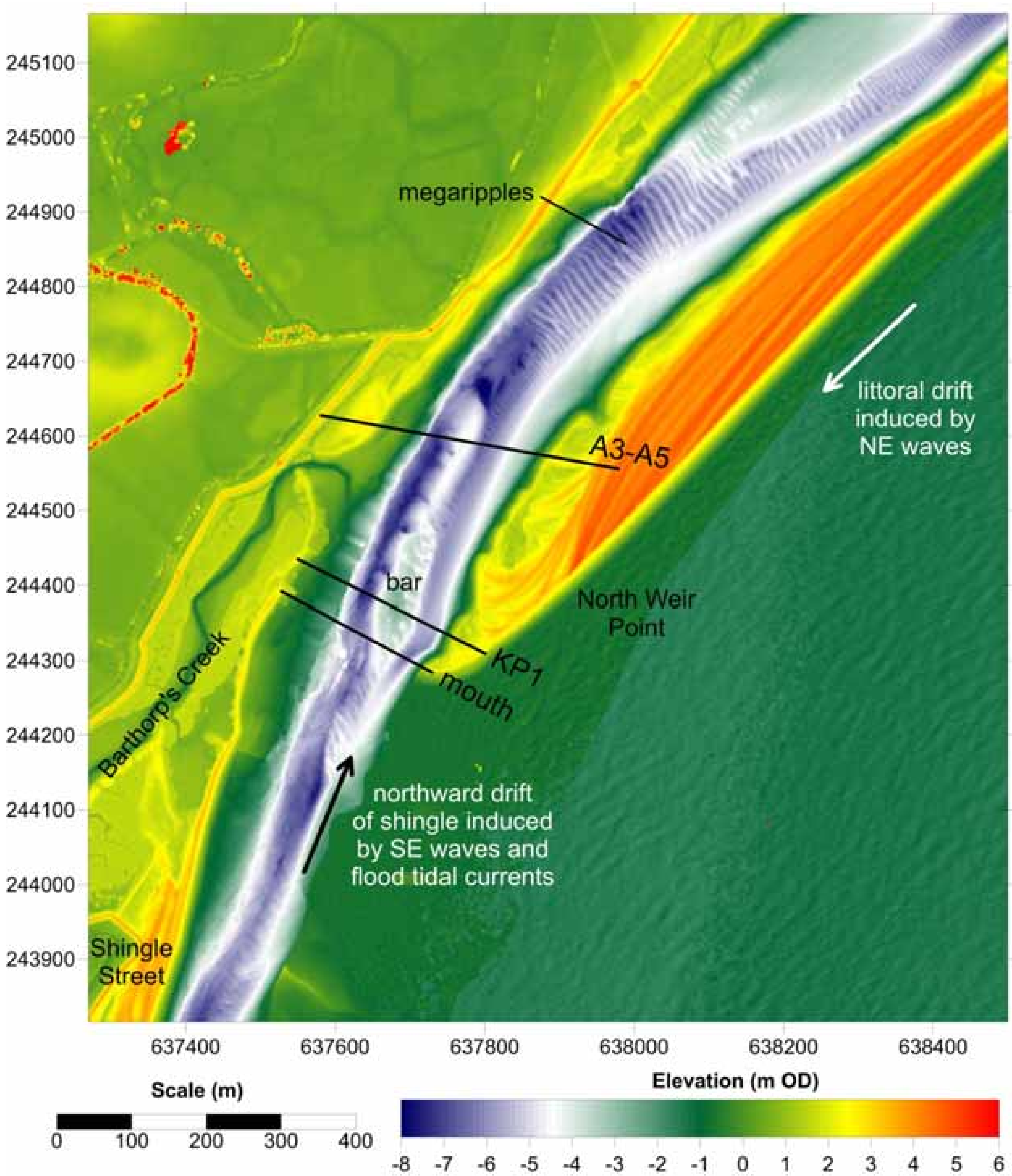


Figure 14. 2012 DEM of the mouth of the Alde-Ore showing the locations of cross-sectional profiles and the presence of a linear mouth bar. Note the megaripples on the bed, indicating high near-bed current velocities, approximately 400 m upstream. Profile KP1 is located at the end of North Weir Point shown by the April 2014 Trinity House survey

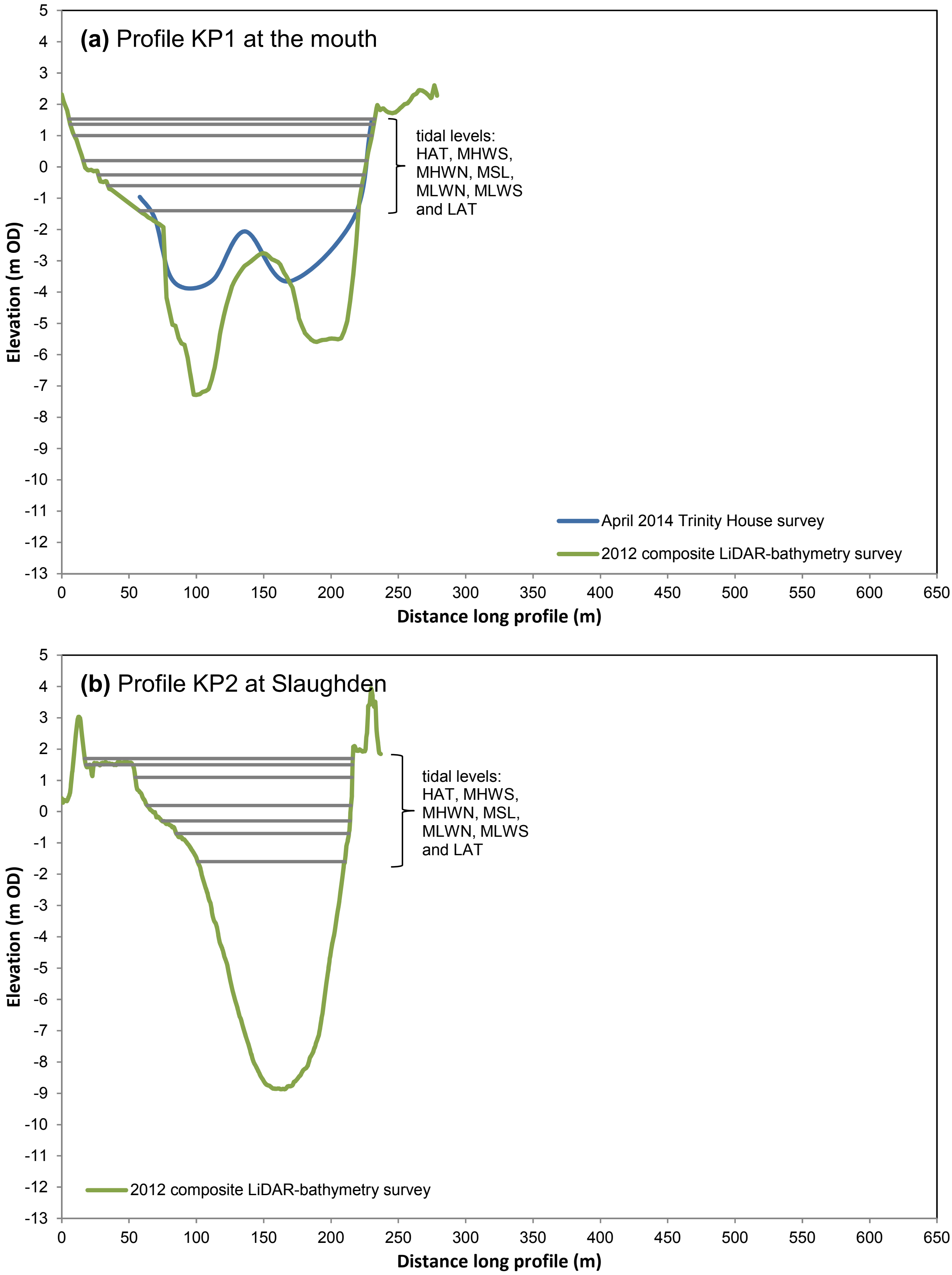
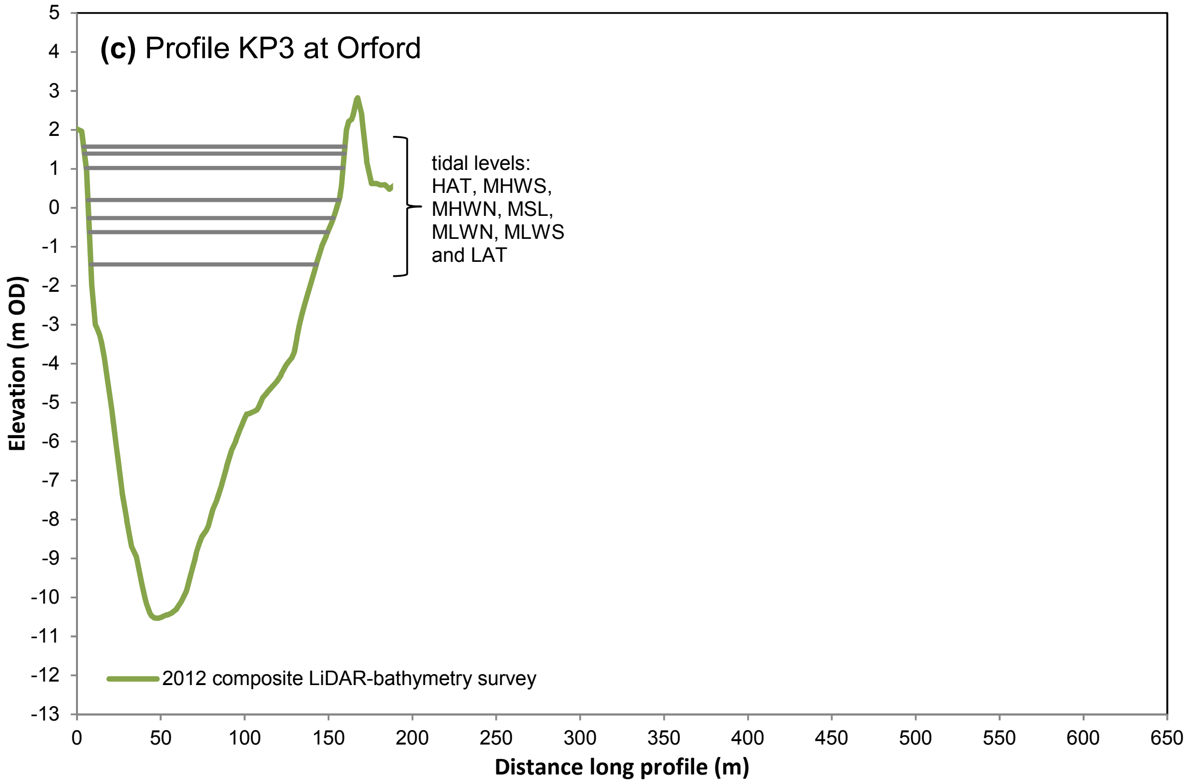
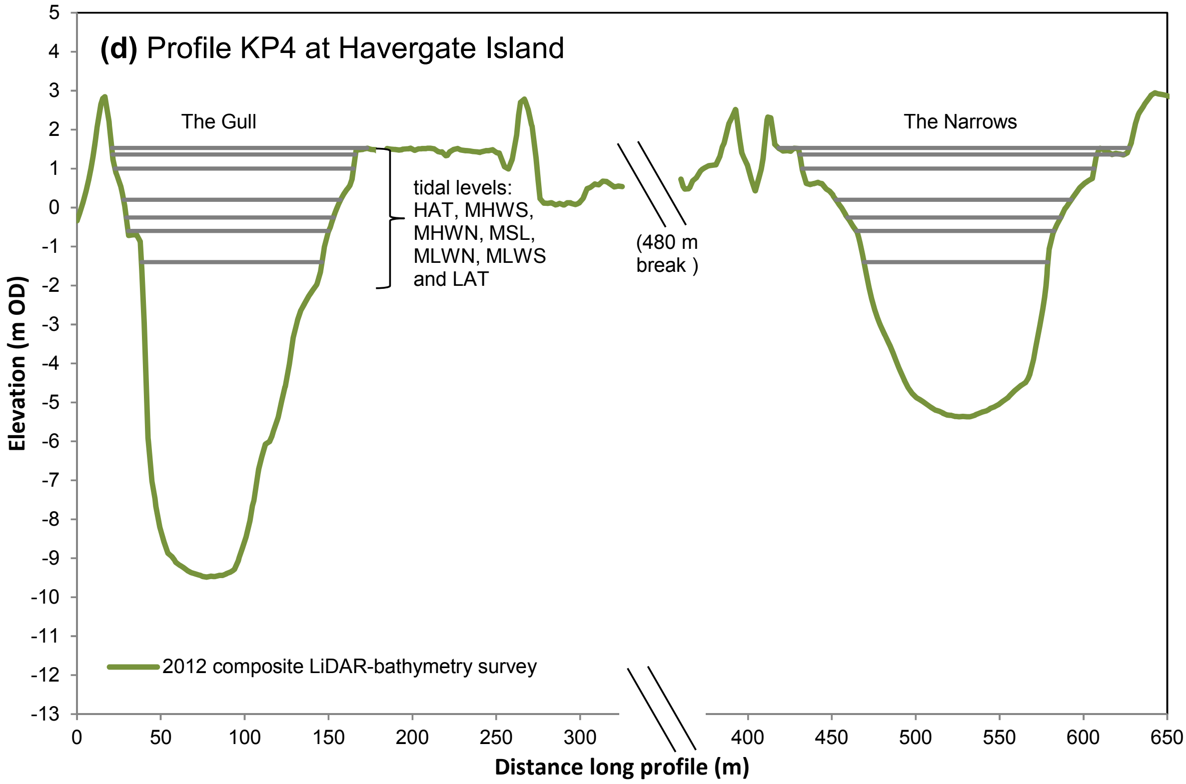


Figure 15. Cross-sections KP1, 2, 3 and 4, based on the 2012 composite LiDAR-bathymetry dataset and the April 2014 Trinity House survey of the estuary mouth. Marked shallowing at the KP 1 location is associated with northward movement of the river mouth bar between 2012 and 2014.





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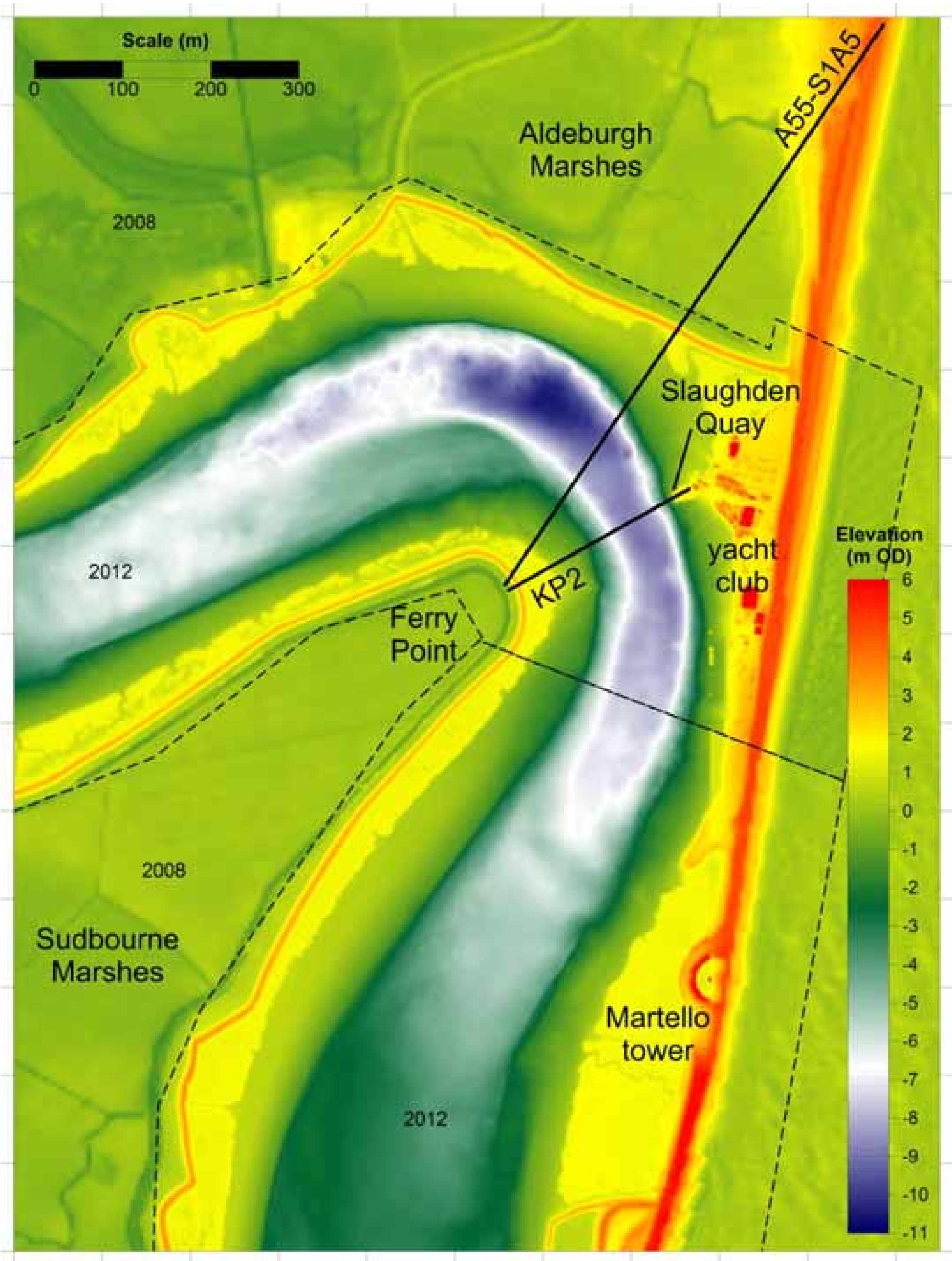


Figure 16. DEM of the Slaughden area, from composite LiDAR and bathymetric surveys dating from 2012 and 2008 (dashed line marks the boundary between datasets). Locations of cross-sections analysed in this study are also shown.

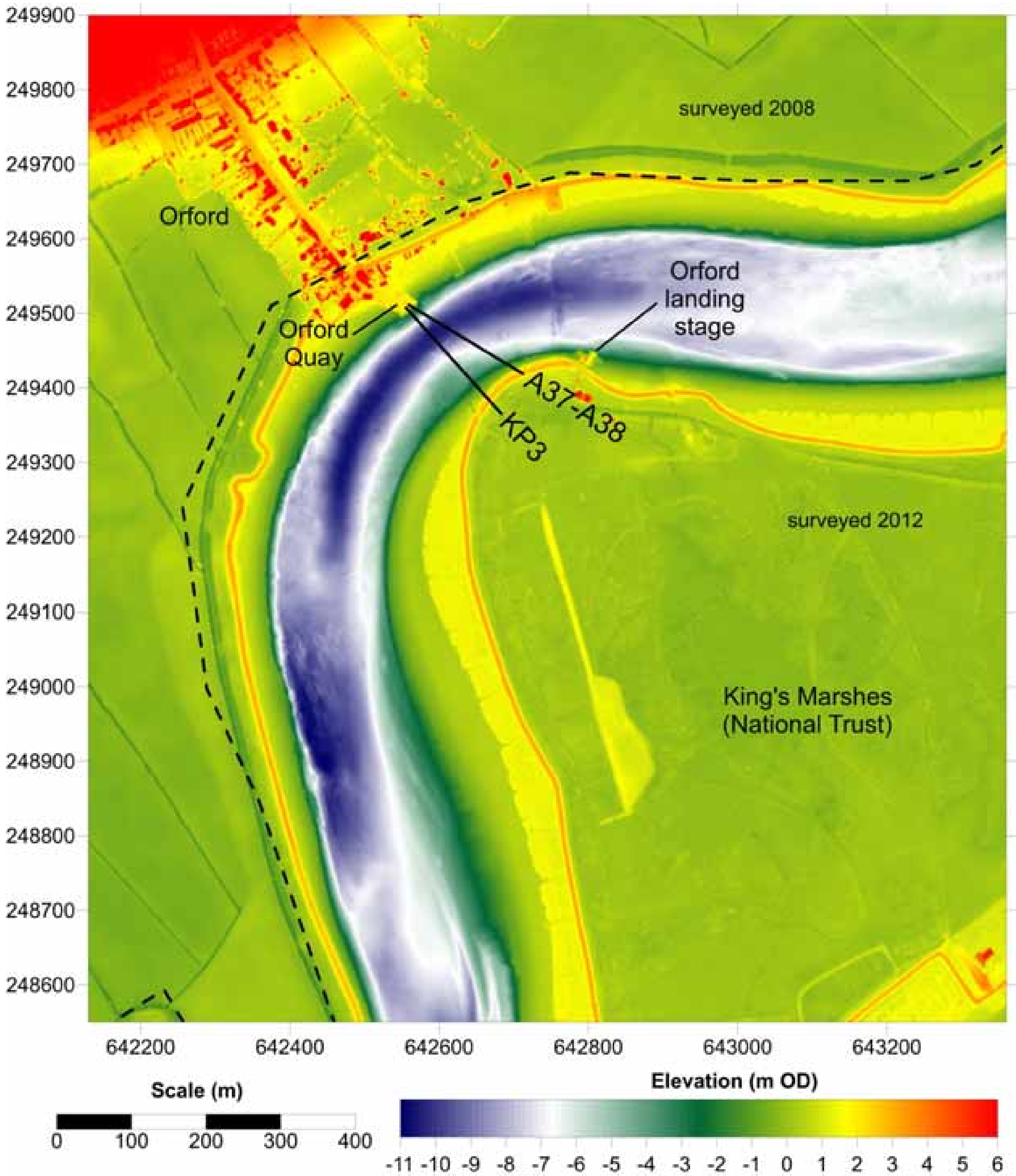


Figure 17. DEM of the Orford Quay area, from composite LiDAR and bathymetric surveys dating from 2012 and 2008 (dashed line marks the boundary between datasets), showing positions of profiles A37-A38 and KP3

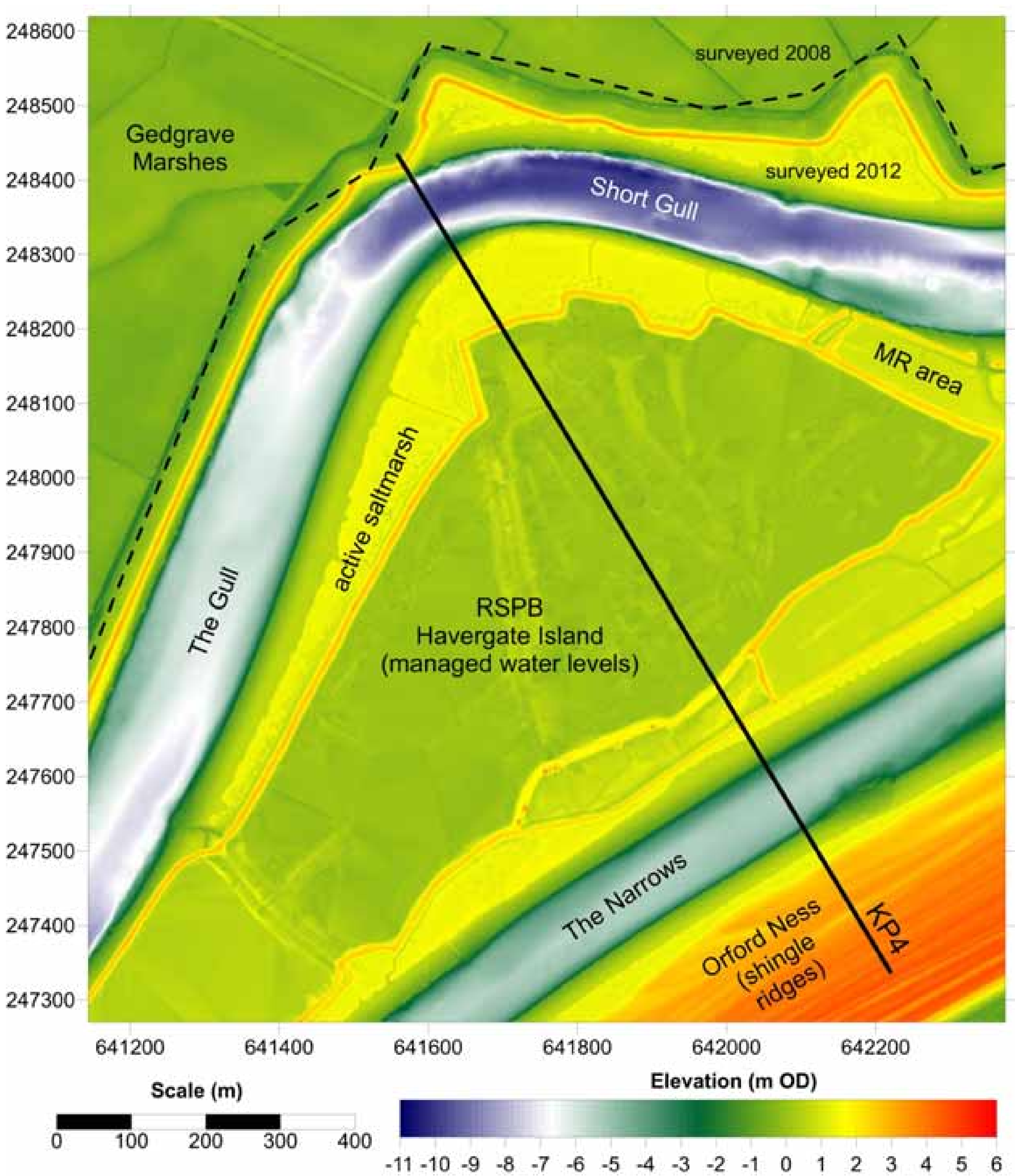
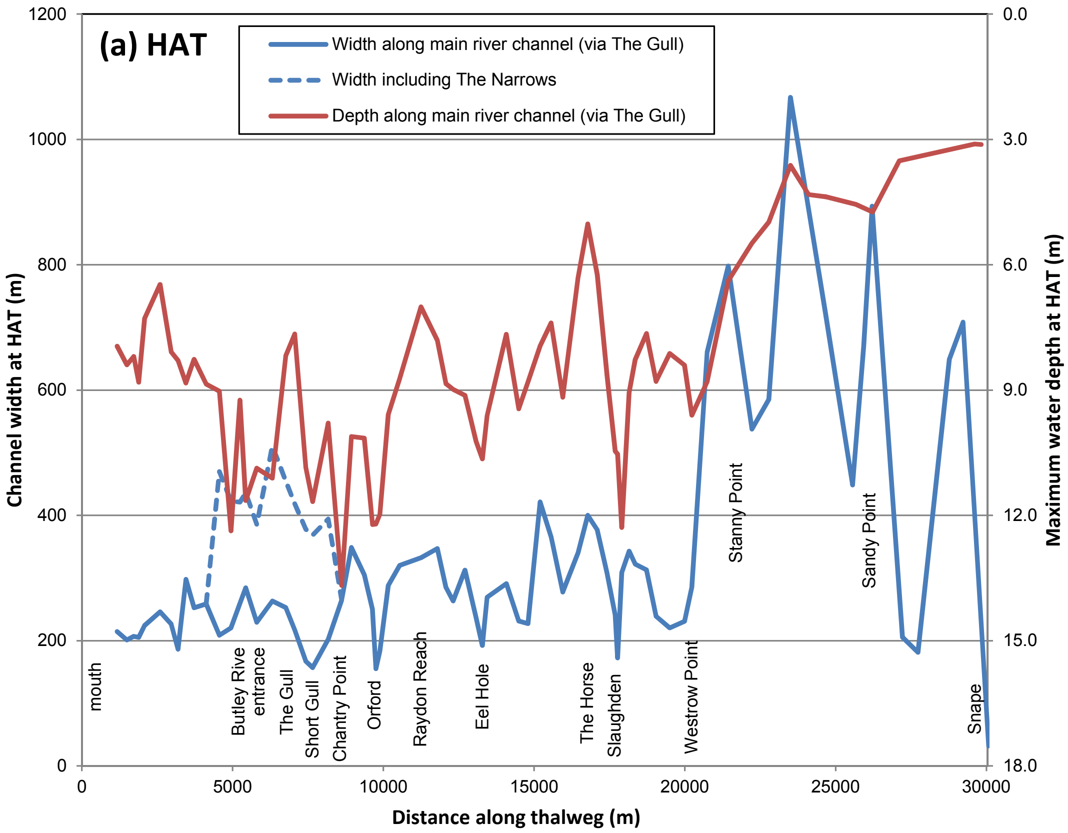


Figure 18. DEM of part of Havergate Island, The Gull and The Narrows, from composite LiDAR and bathymetric surveys dating from 2012 and 2008 (dashed line marks the boundary between datasets). Profile KP4 crosses the narrowest point of the river between the mouth and the upper estuary basin



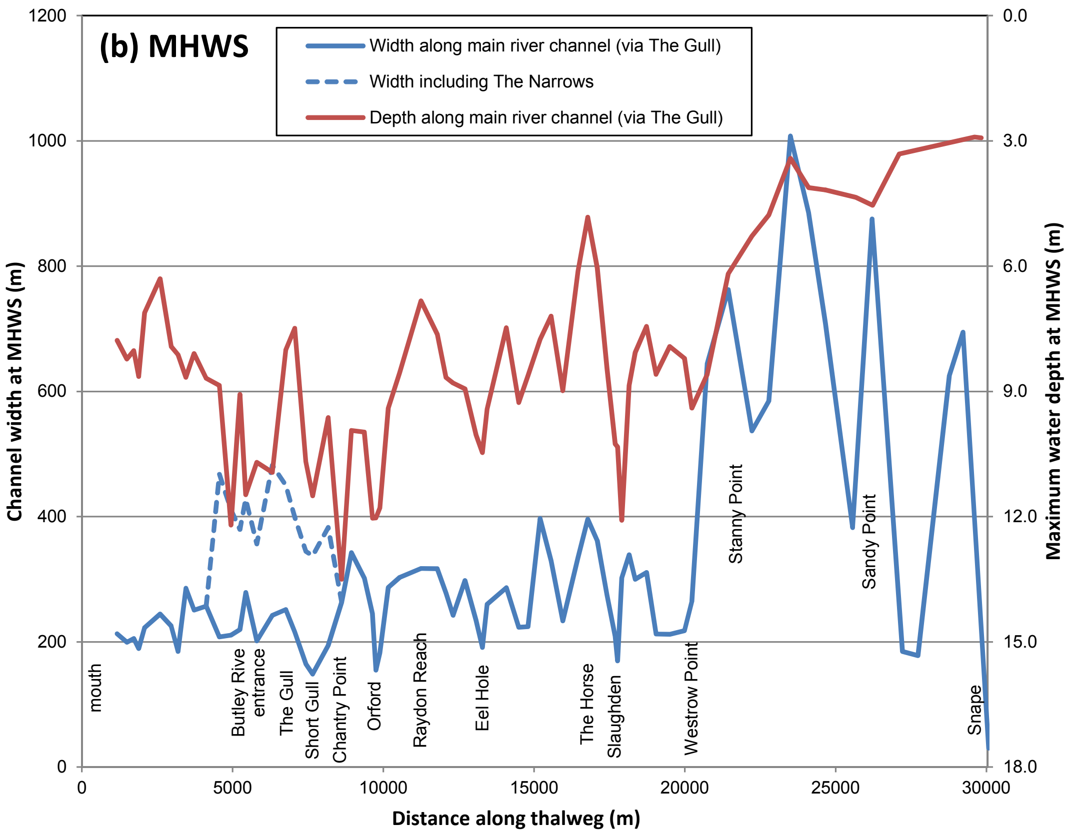
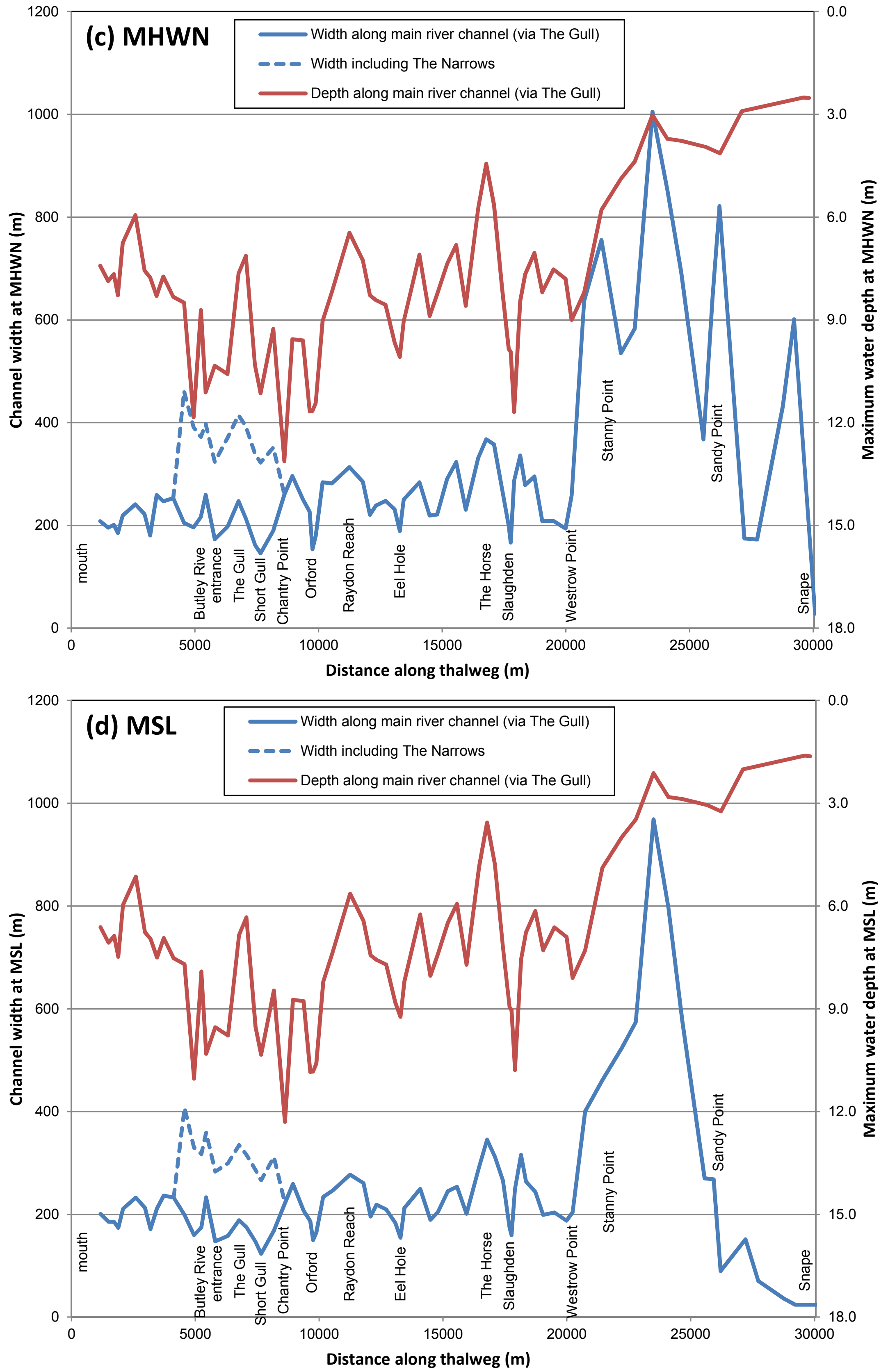


Figure 19. Width and depth of the river channel at different tidal levels, measured at 73 locations along the thalweg of the Alde-Ore from the 2012 combined LiDAR-bathymetry dataset.



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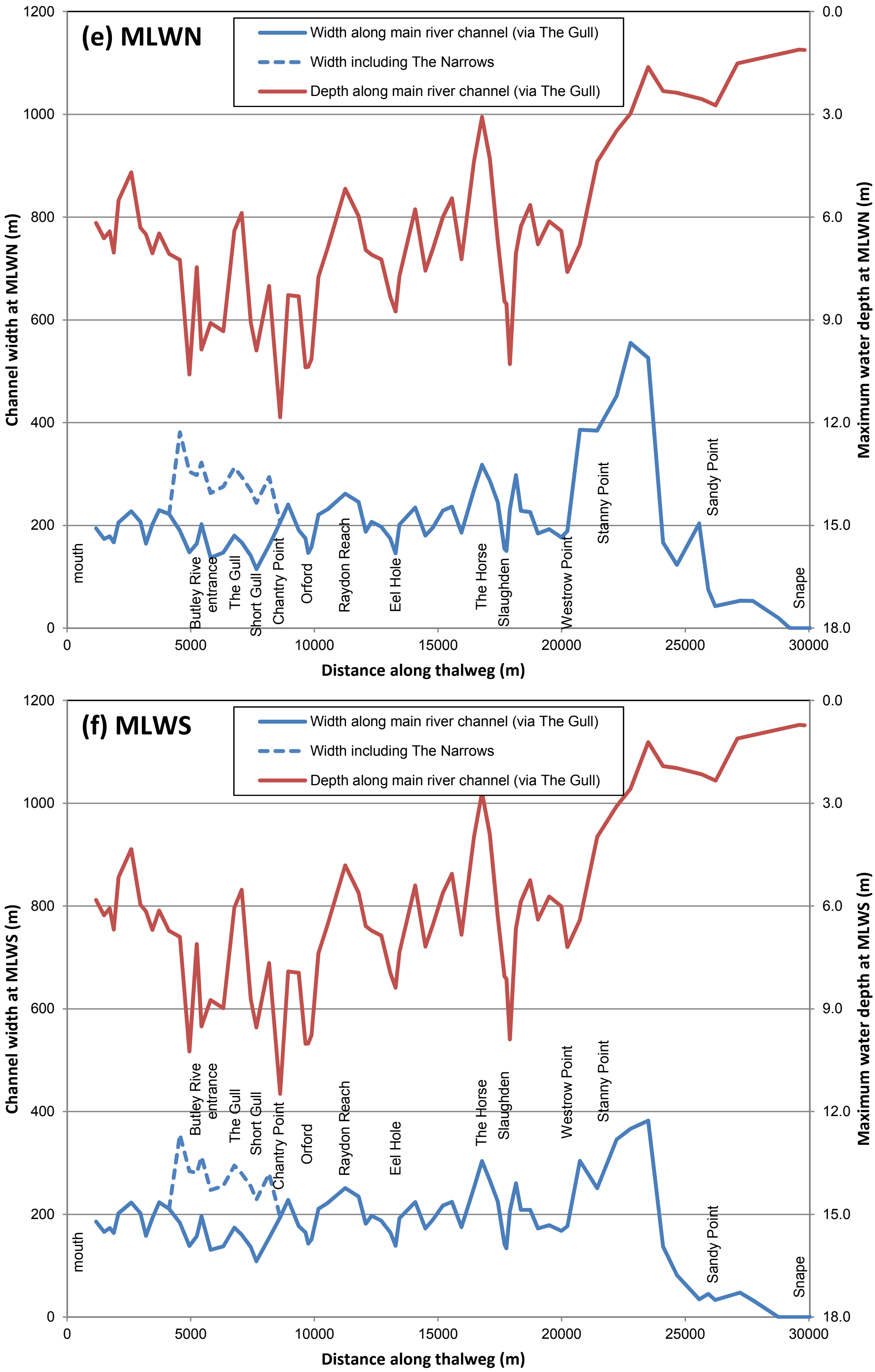

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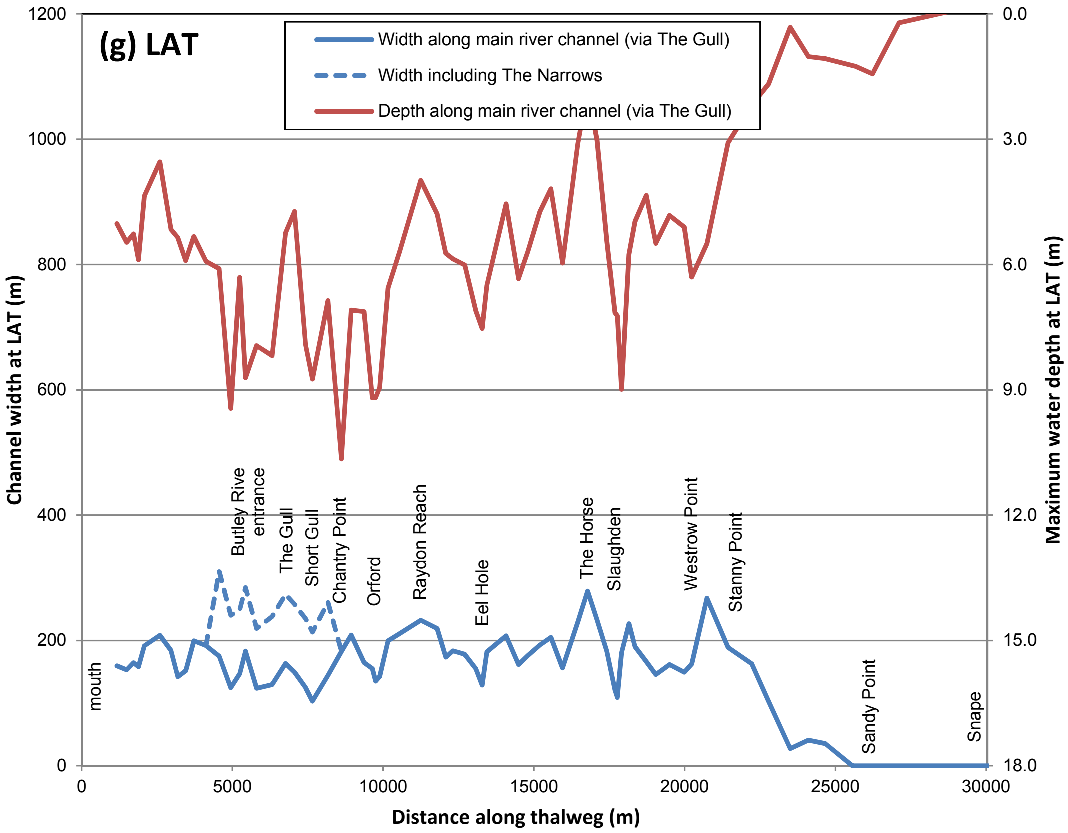

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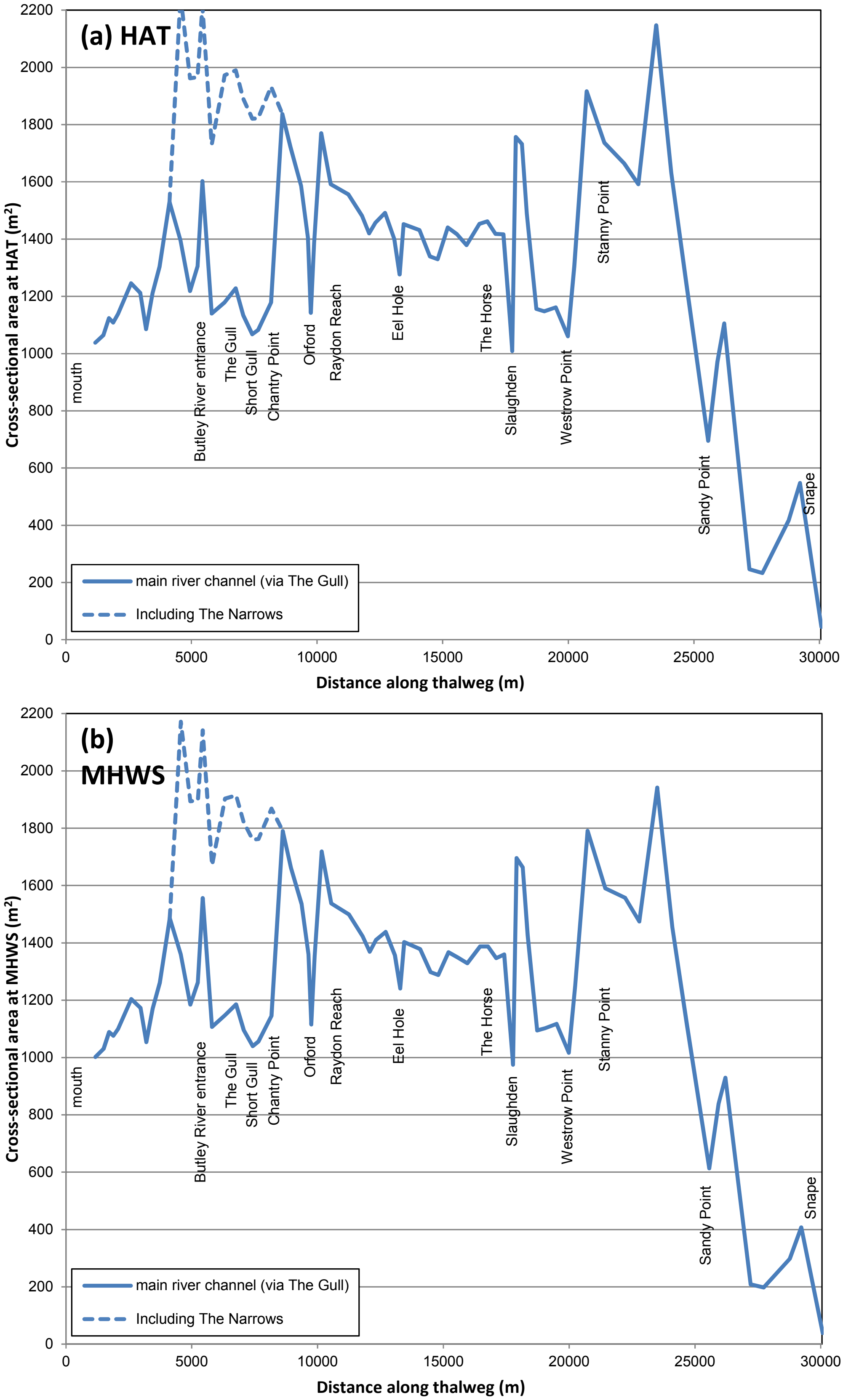
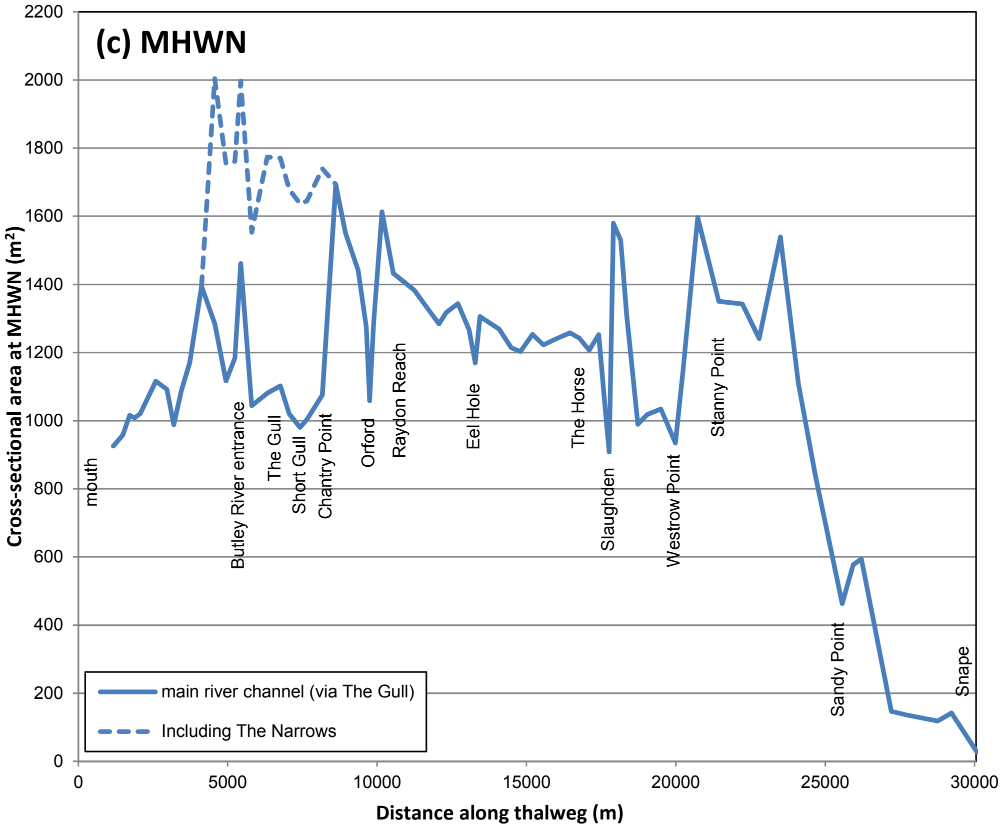
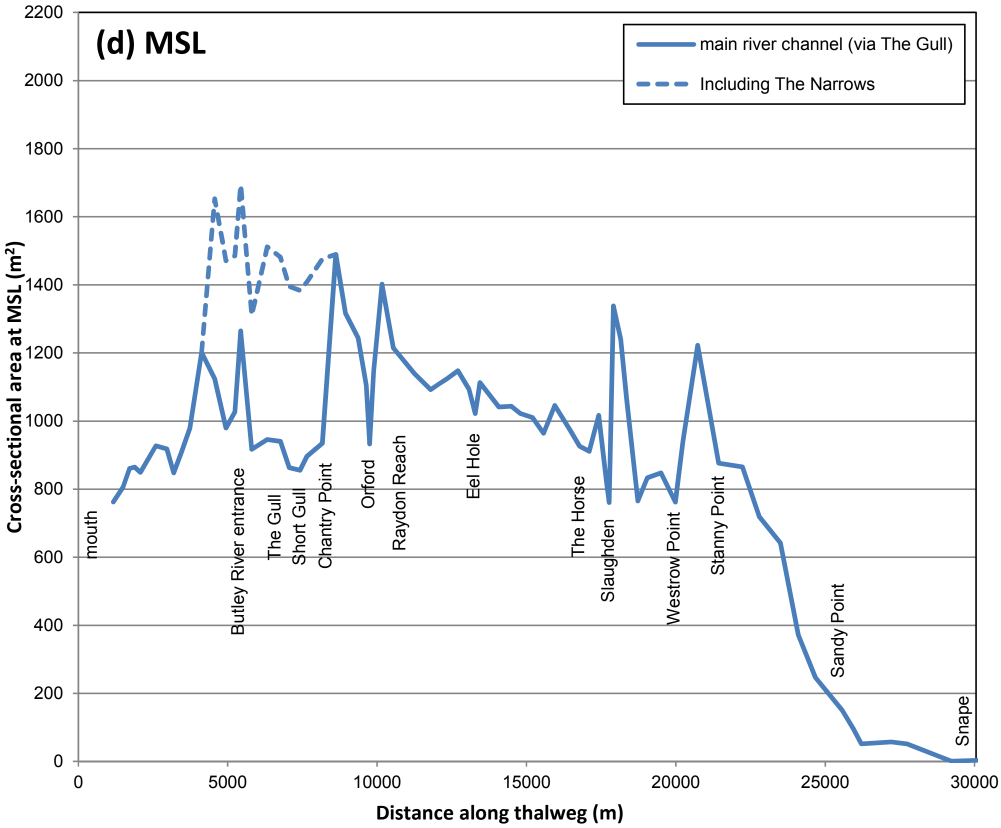


Figure 20. Cross-sectional area of the river channel at different tidal levels, measured at 73 locations along the thalweg of the Alde-Ore from the 2012 combined LiDAR-bathymetry dataset.





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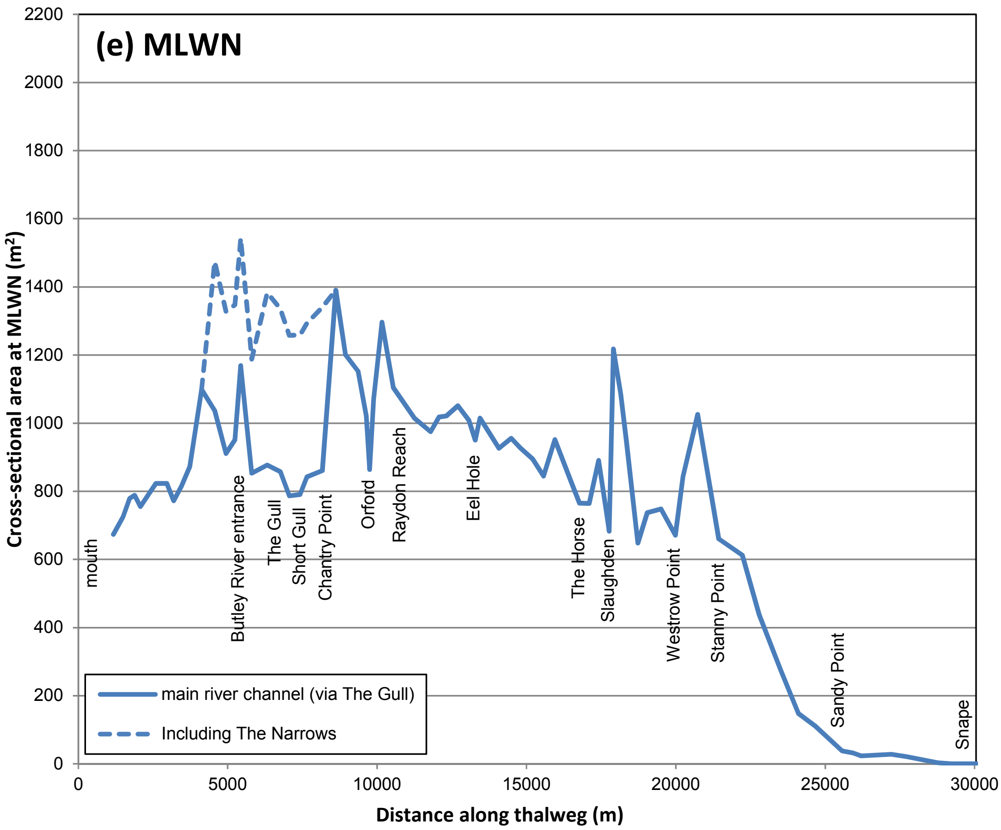

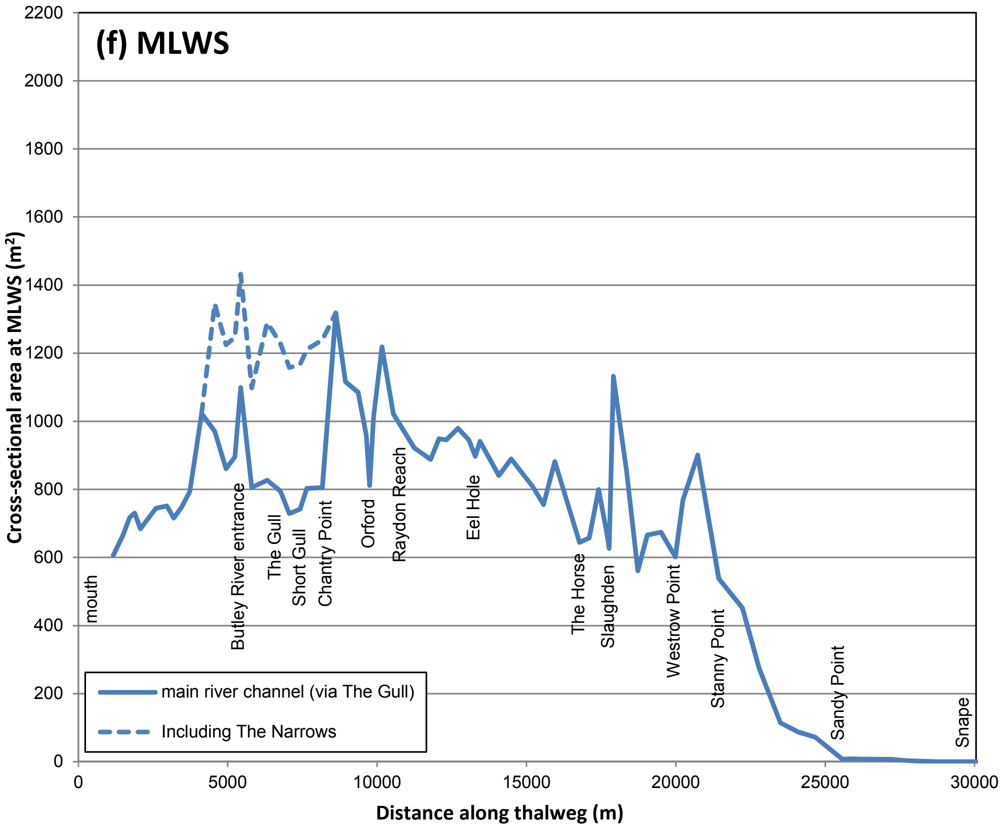

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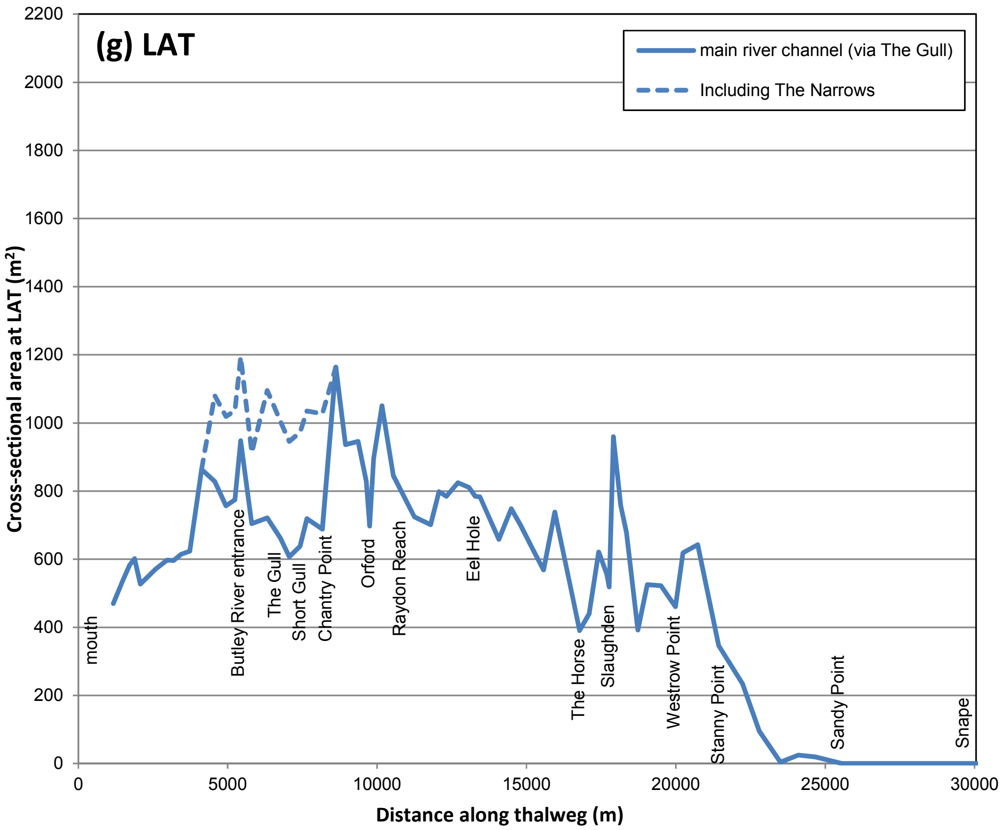

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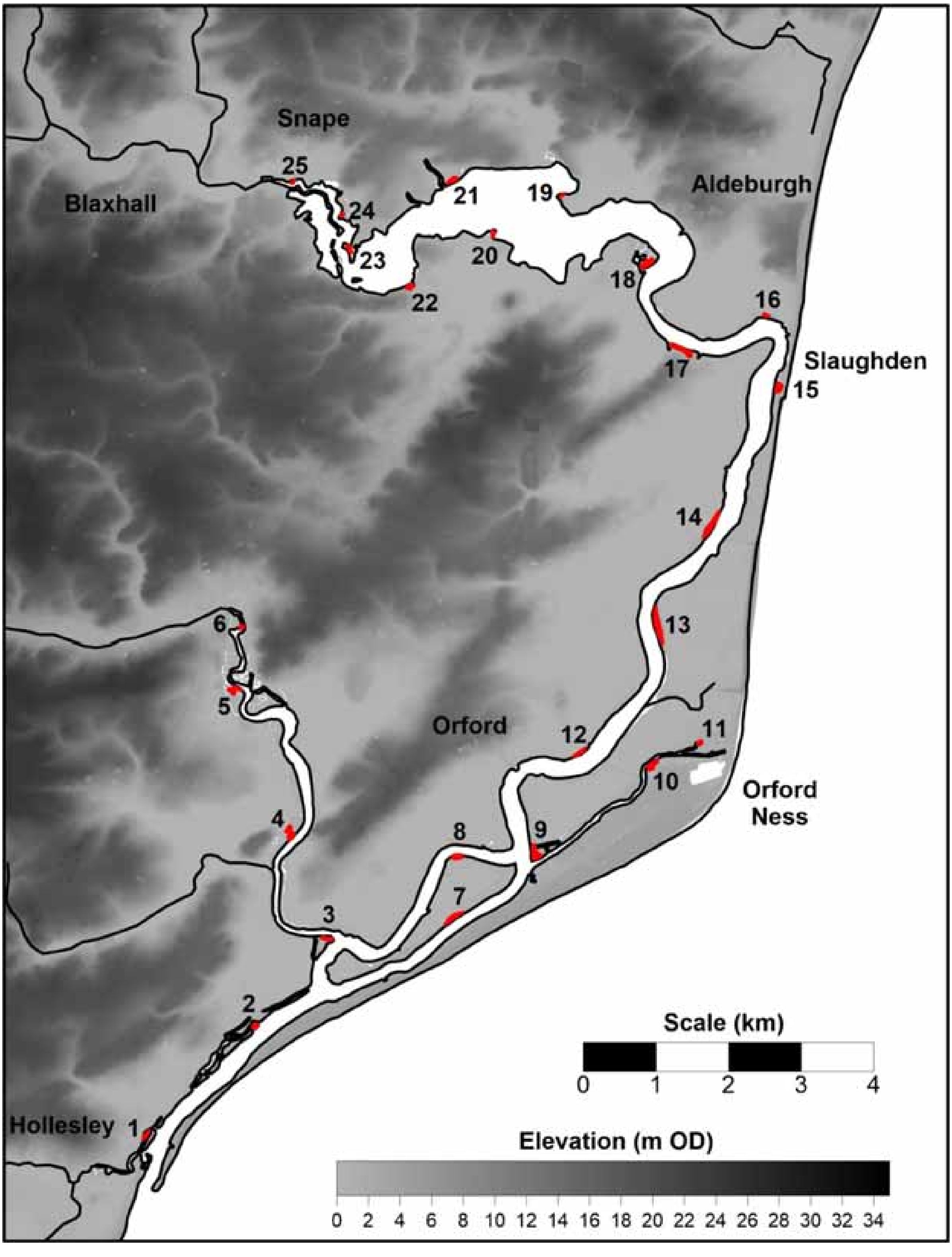


Figure 21. Map showing locations where marsh elevations were determined by analysis of 2012 and 2008 LiDAR data.

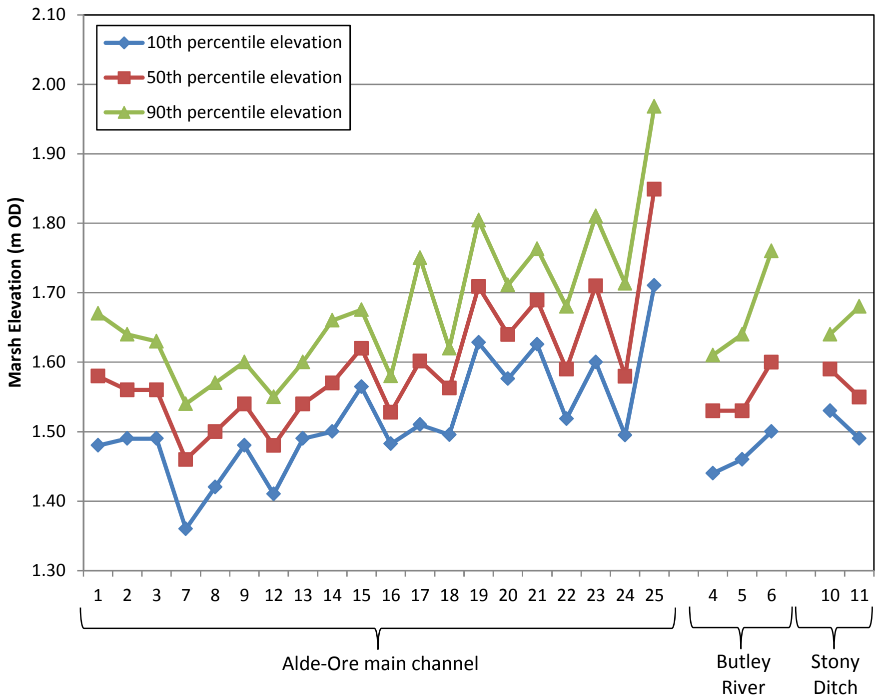


Figure 22. Active saltmarsh elevations at locations shown in Figure 11, based on 2008 and 2012 LiDAR surveys

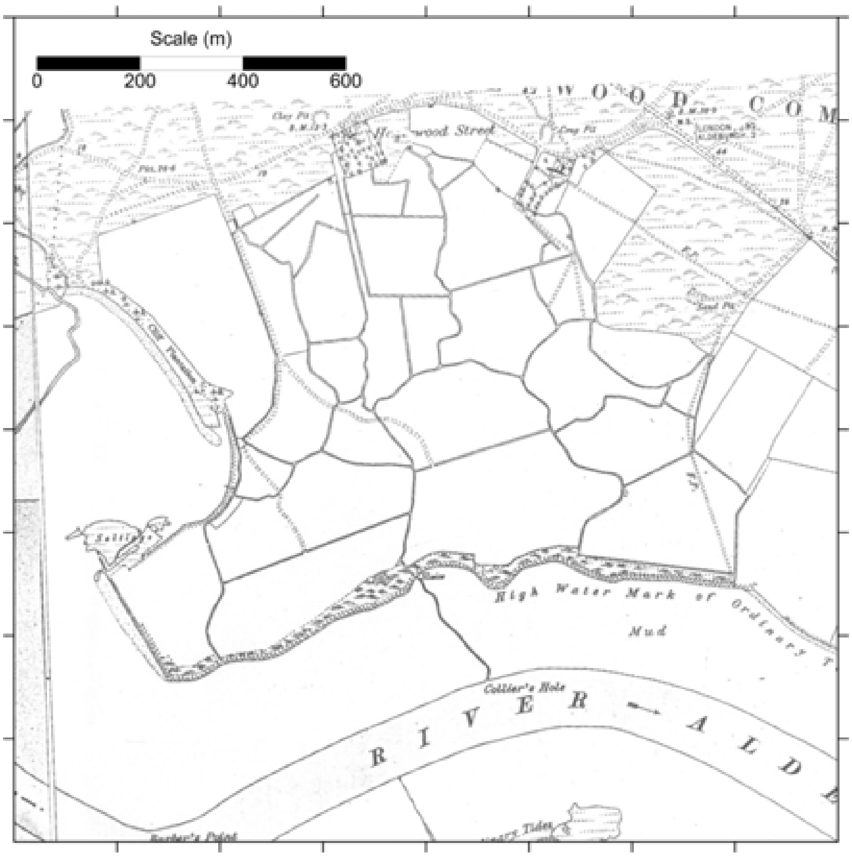


Figure 23. Six-Inch Ordnance Survey map of Hazlewood Marshes, published in 1890.

Figure 24. Aerial photograph of Hazlewood Marshes, flown 15th July 2011.

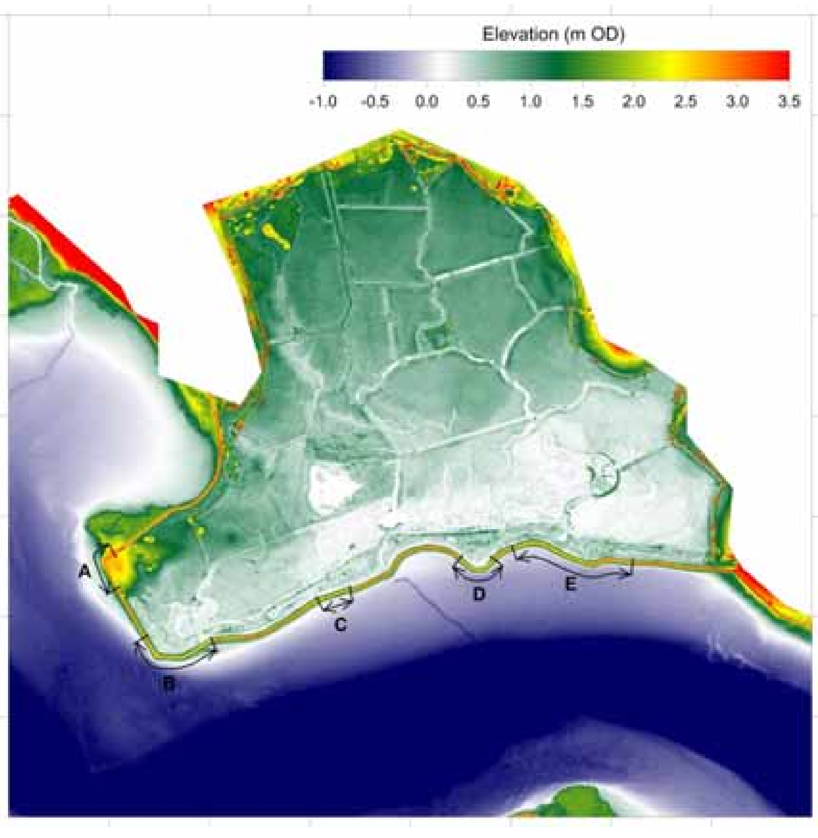


Figure 25. Composite LiDAR / swath bathymetry DEM of Hazlewood Marshes showing embankment lengths A to E where the crest level was substantially below 3.0 m OD before the surge tide of 6th December 2013

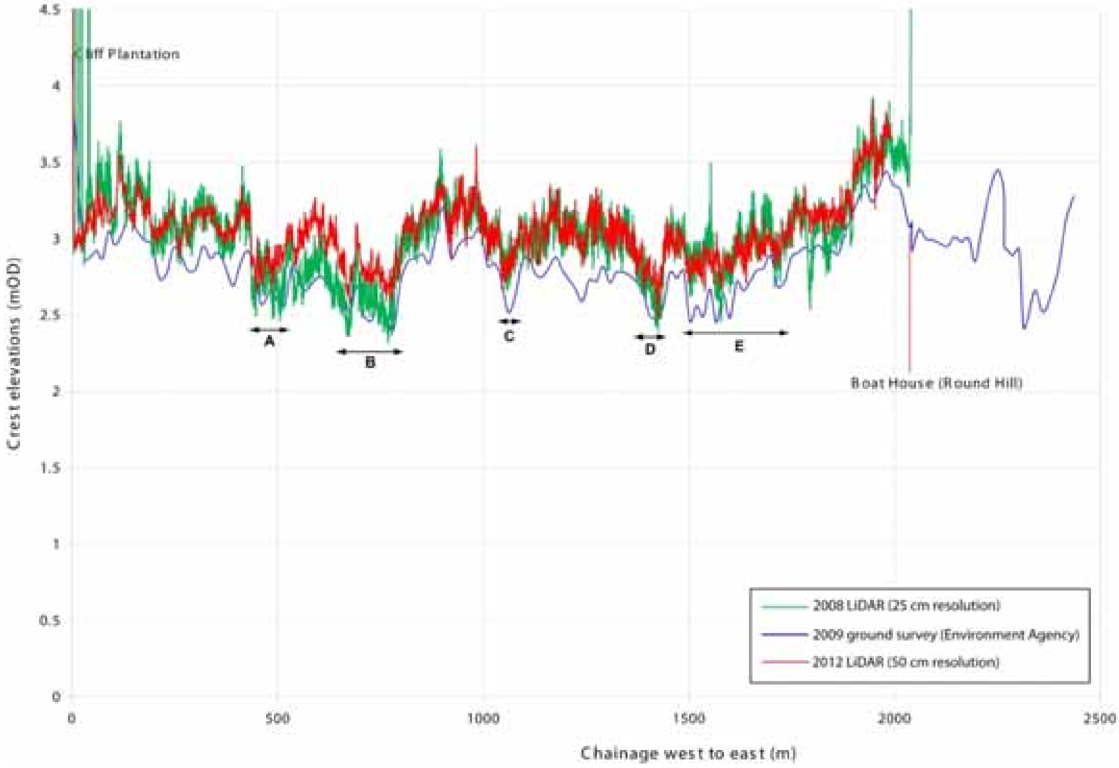


Figure 26. Crest levels along the river wall at Hazlewood marshes, from EA 2009 ground survey and airborne LiDAR surveys in 2008 and 2010. Sections where the crest level was substantially below 3.0 m OD are indicated by letters A to E

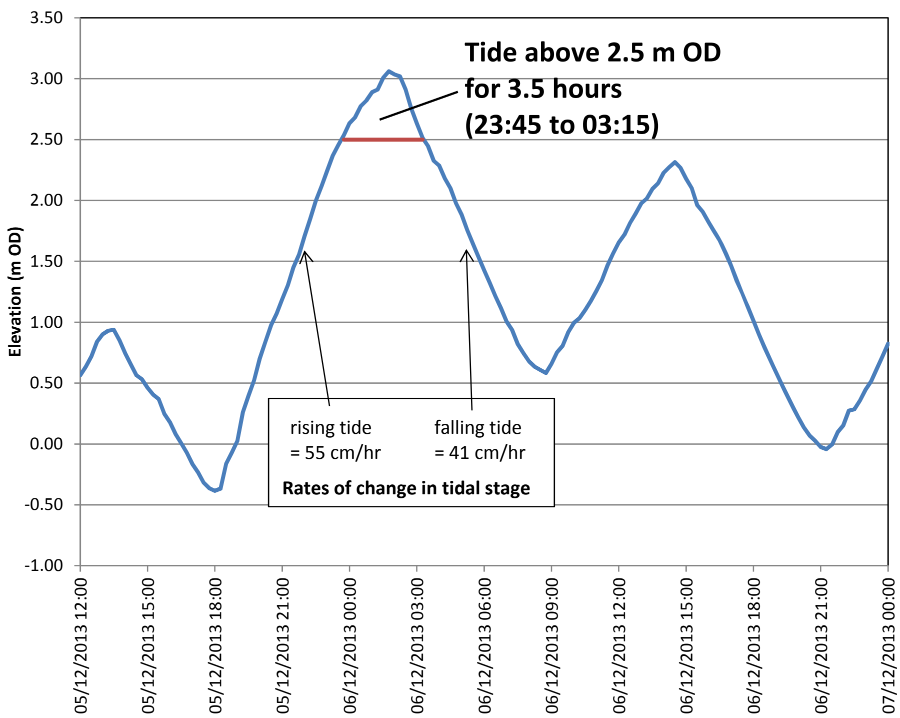


Figure 27. Tidal curve recorded at Orford Quay during the storm surge tide on 5th - 7th December 2013

Figure 28. Two breaches in the river wall at Hazelwood Marshes created on 6th December 2013; photograph taken 3rd March 2014

Figure 29. View landward through the eastern breach at Hazelwood Marshes, photograph taken 3rd March 2014

Figure 30. The landward edge of Hazlewood Marshes, photograph taken 3rd March 2014

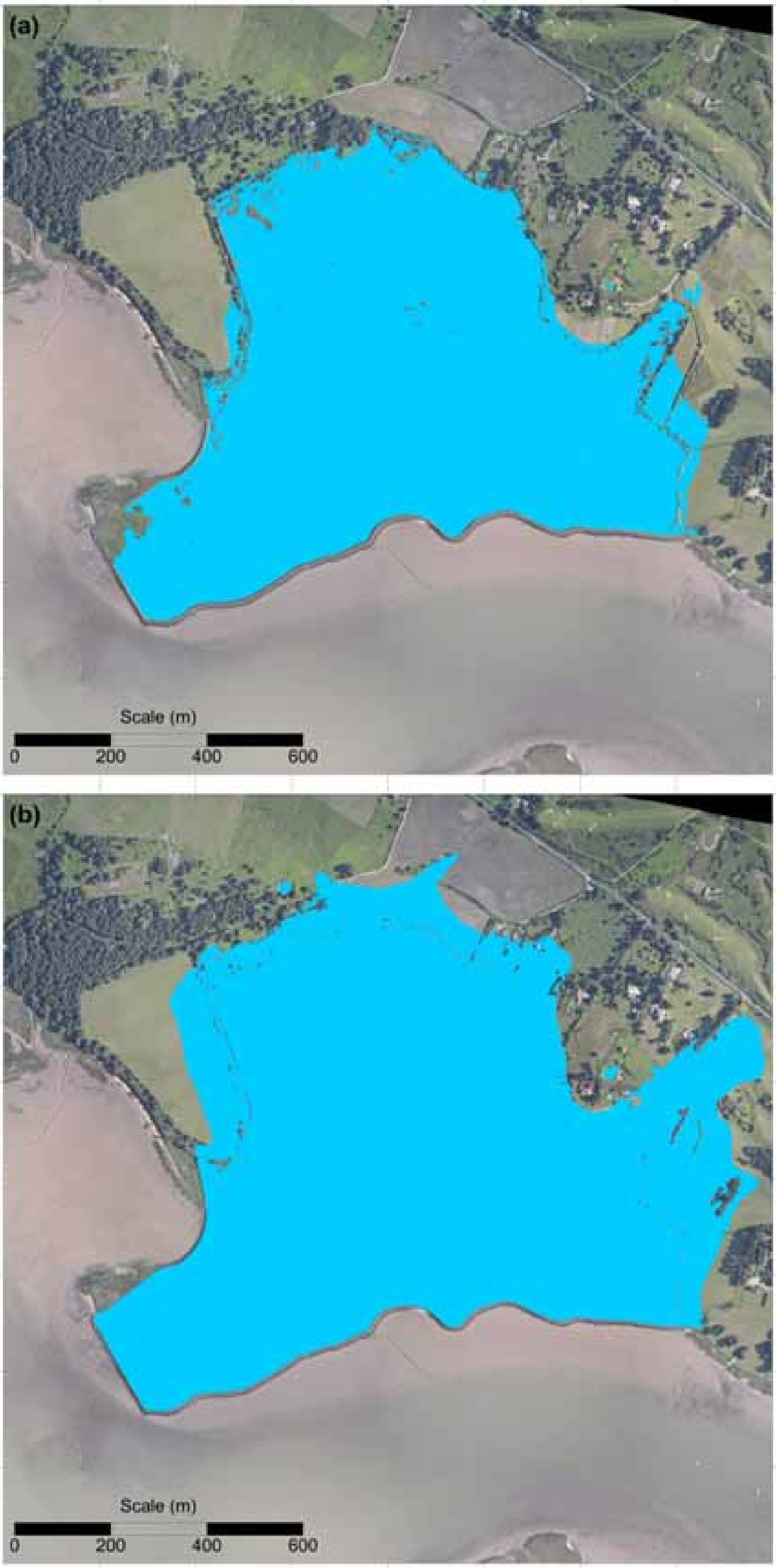
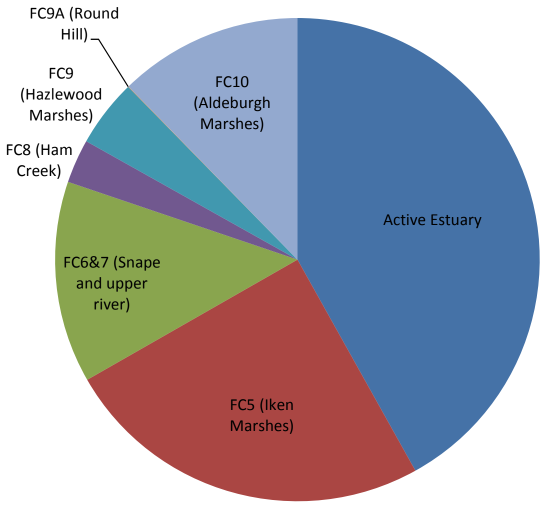


Figure 31. Areas on Hazlewood Marshes potentially flooded at levels of (a) 1.4 m OD and (b) 3.5 m OD

Figure 32. The potential saltmarsh elevation 'window' (between 0.9 and 1.7 m OD), highlighted in red, on Hazlewood Marshes



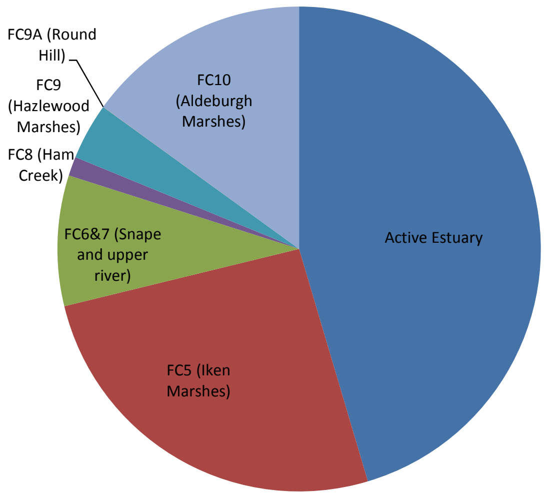


Figure 33. Pie charts showing the relative tidal volumes, calculated above 0 m OD and below 3.5 m OD (left) and above 0 m OD but below 1.5 m OD (right), in the active estuary and different flood cells in the estuary above Slaughden

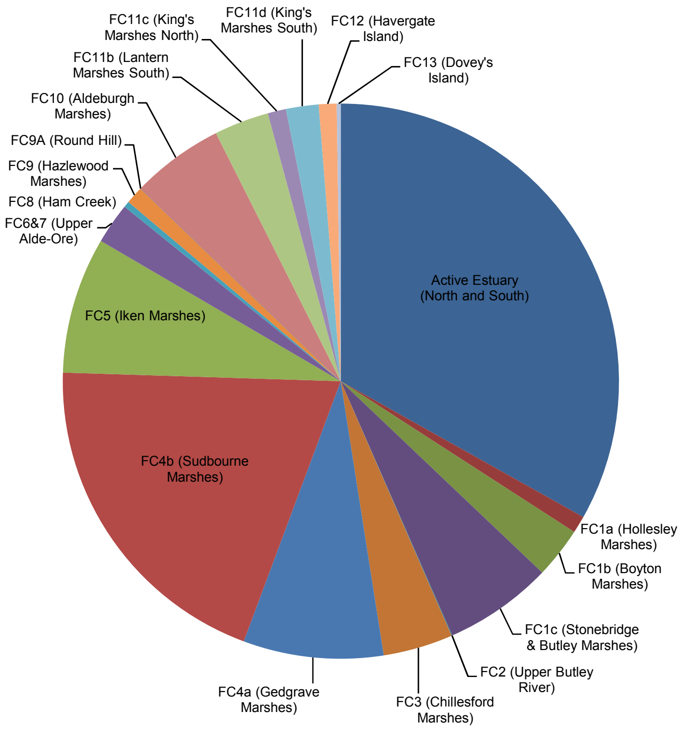


Figure 34. Relative potential tidal volumes within the entire active estuary and different flood cells throughout the estuary for a MHWS tide reaching 1.5 m OD at Hazlewood Marshes

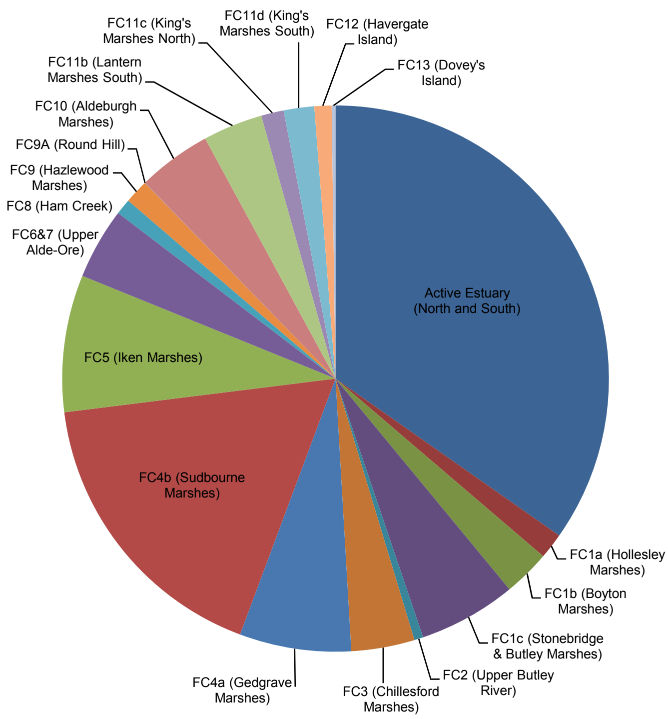


Figure 35. Relative potential tidal volumes in the entire active estuary and different flood cells throughout the estuary for a large storm surge tide reaching 3.5 m OD at Hazlewood Marshes

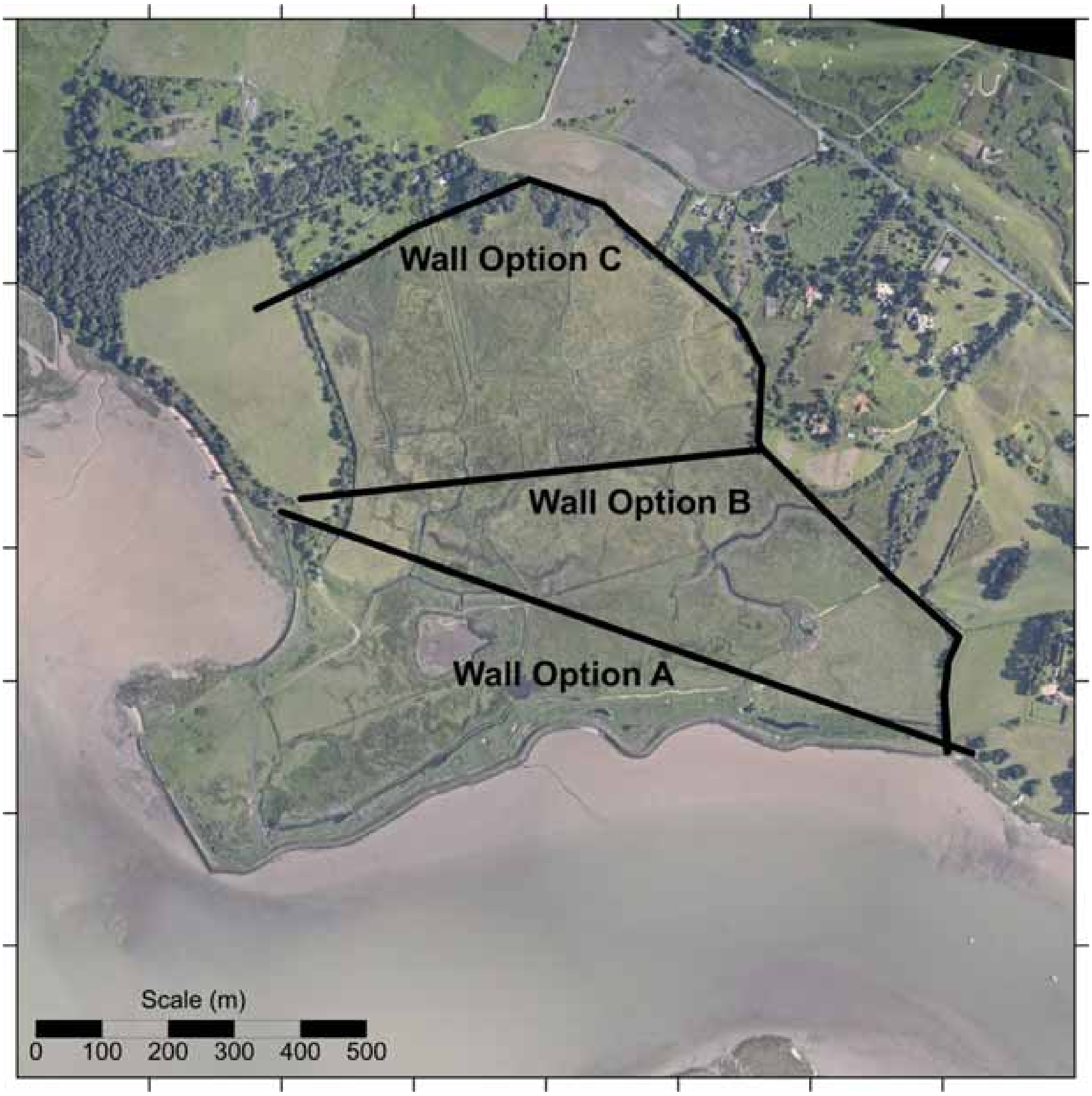


Figure 36. Management options including possible set-back of walls on Hazlewood Marshes.

Figure 37. First Edition Six-inch County Series Ordnance Survey map of Boyton Marshes, surveyed in 1880

Figure 38. Aerial photograph of Boyton Marshes, flown 15th July 2011

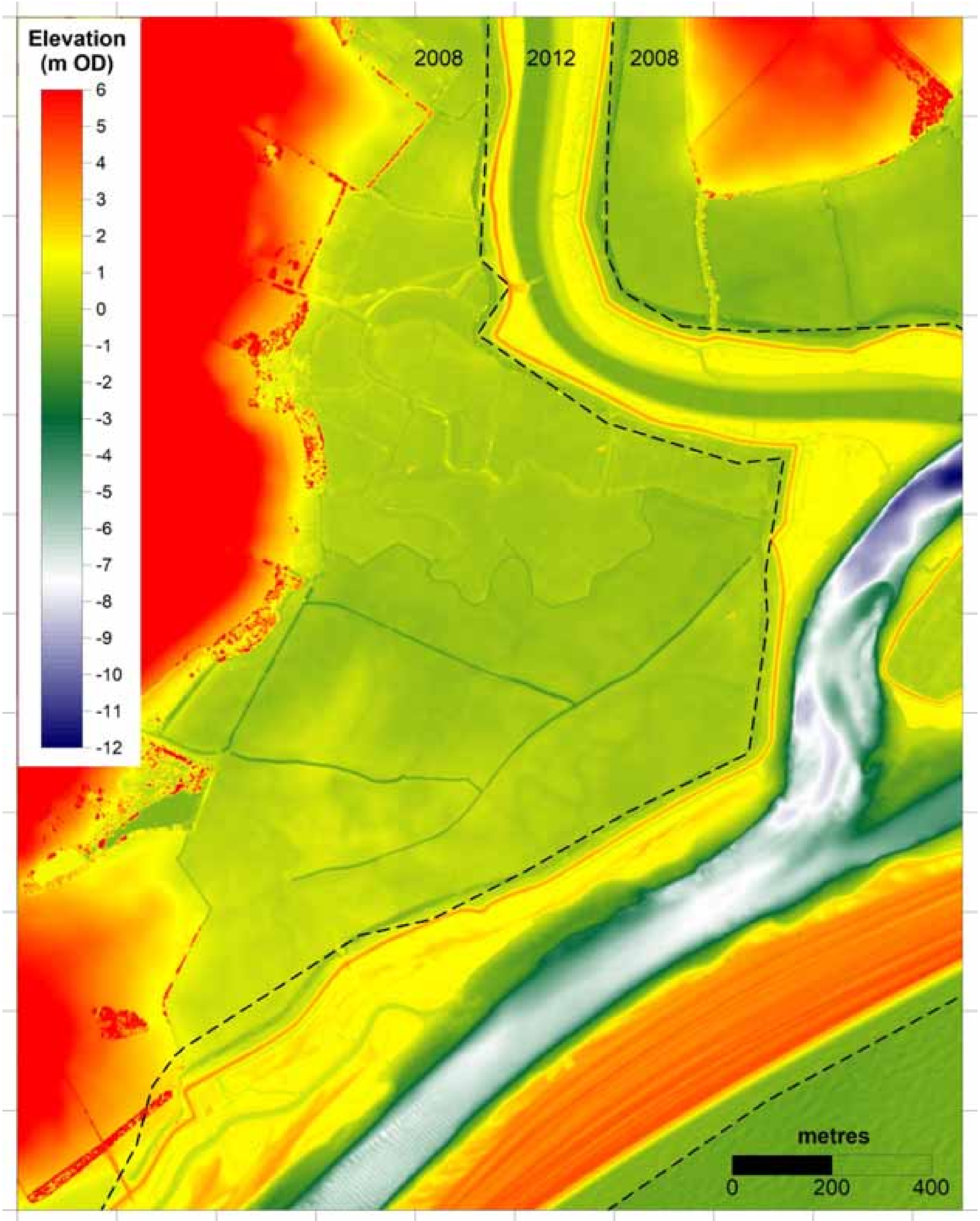


Figure 39. DEM of Boyton Marshes, from composite LiDAR and bathymetric surveys dating from 2012 and 2008 (dashed line marks the boundary between datasets)

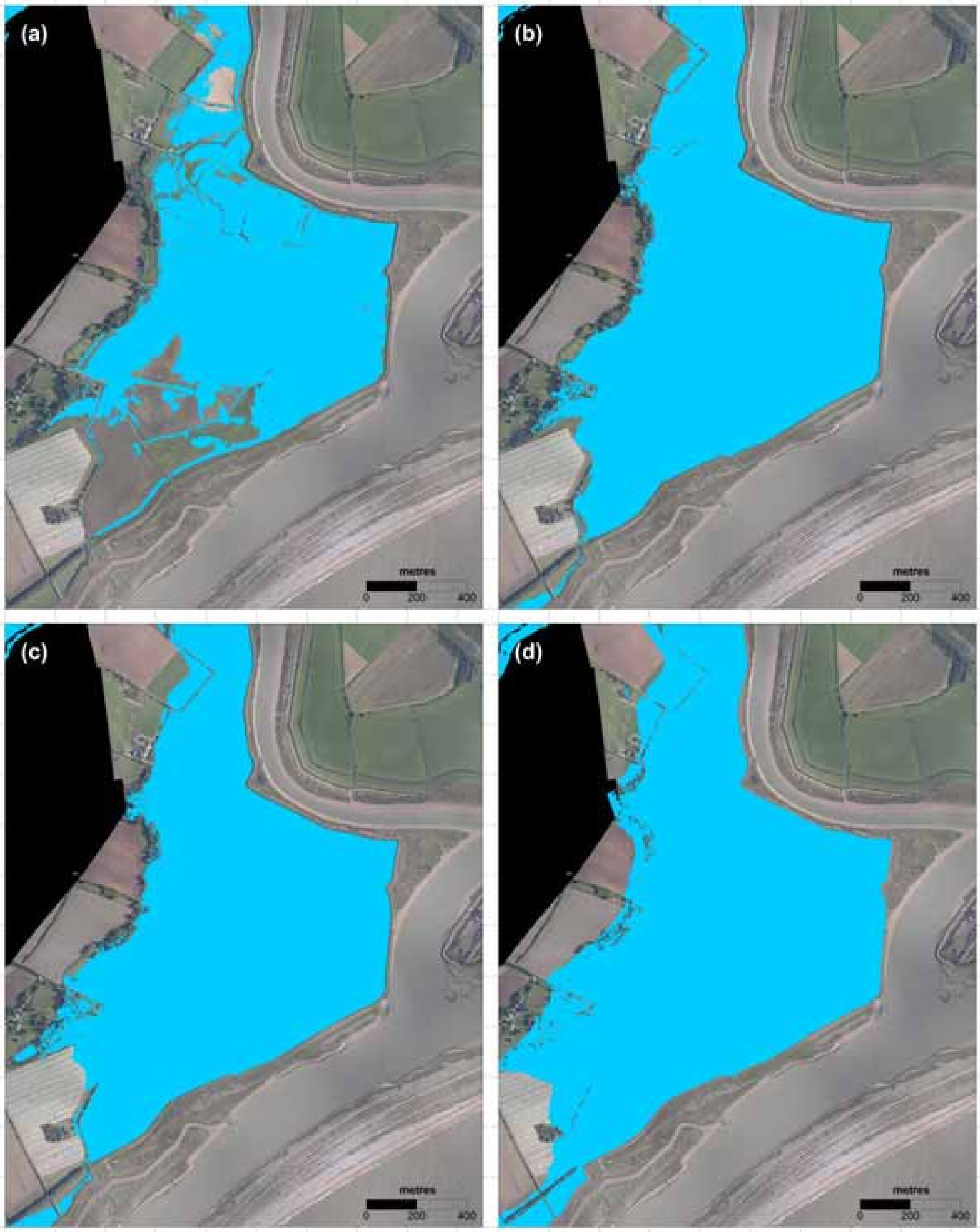


Figure 40. Potentially floodable areas on Boyton Marshes below (a) 0.2 m OD (MSL); (b) 1.0 m OD (MHWN); (c) 1.53 m OD (HAT); and (d) 3.13 m OD (equivalent to a 3.5 m OD tide in the upper estuary

Figure 41. The present saltmarsh elevation 'window' on Boyton Marshes area between 1.0 m OD (MHWN) and 1.53 m OD (HAT), highlighted in red

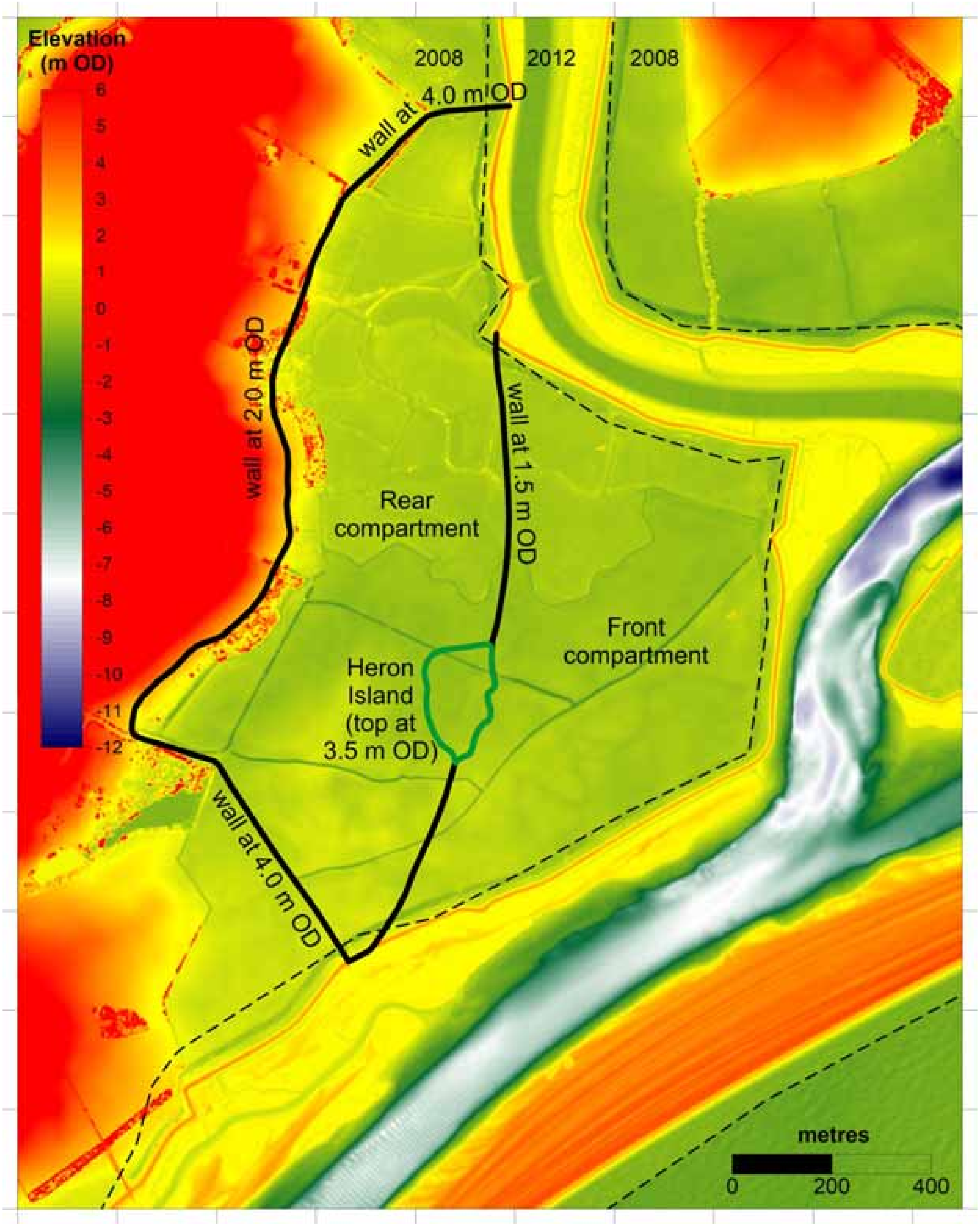


Figure 42. Digital elevation model of Boyton Marshes, from composite LiDAR and bathymetric surveys dating from 2012 and 2008 (dashed line marks the boundary between datasets). Also shown are the proposed management realignment works for the site.

Glossary

DEM	Digital elevation model
HAT	Highest Astronomical Tide level
LiDAR	Light Direction and Ranging
MHWN	Mean High Water of Neap tides level
MHWS	Mean High Water of Spring tides level
MLWN	Mean Low Water of Neap tides level
MLWS	Mean Low Water of Spring tides level
MSL	Mean Sea Level
Ordnance Datum	Datum at Newlyn used as the reference level for UK geodetic surveys
NTSLF	National Tidal and Sea Level Facility
PSMSL	Permanent Service for Mean Sea Level
SAC	Special Area of Conservation
SPA	Special Protection Area
SSSI	Site of Special Scientific Importance

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