Natural England Commissioned Report NECR250

Healthy Estuaries 2020: An Assessment of Estuary Morphological Equilibrium

Alde-Ore Estuary SSSI (SAC, SPA, Ramsar)
Deben Estuary SSSI (SPA, Ramsar)
Hamford Water SSSI (SPA, Ramsar)

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Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

Background

Coastal squeeze is an issue affecting many estuaries in England, particularly in the south and east of the country. To address coastal squeeze (the prevention by fixed sea defences of estuary 'roll-over' or migration of intertidal features in response to sea level rise) much work has been done with the Environment Agency. The evidence needs to inform this are complex and challenging, and the approach to replacing extent of lost habitat needed to be reviewed in the light of a greater focus on achieving a more sustainable estuary form. The original IPENS work (Healthy Estuaries 2020: Towards Addressing Coastal Squeeze in Estuaries) developed a method to enable the evaluation of estuary morphology in Natura 2000 sites and inform future planning for habitat creation.

Addressing the impacts of coastal squeeze is largely addressed through flood risk management, and Natural England require an evidence base to help give clear advice on the size, location, timing and type of habitat creation in estuary complexes affected by coastal squeeze. The outcomes of the work has the ability to inform condition assessments of designated sites and enable the condition threats to be more clearly identified.

The original Healthy Estuaries 2020 work considered the Humber and Chichester Harbour. To develop the tool and aid our appreciation of the outputs, three east coast estuaries were subject to modelling; Alde-Ore, Deben and Hamford Water.

The key audience for the work, which is of a technical nature, is the staff within the Environment Agency and Natural England.

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Natural England Project Manager – Nick Williams

Contractor – Royal Haskoning DHV

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An Assessment of Estuary Morphological Equilibrium

Alde-Ore Estuary, Deben Estuary and Hamford Water

HASKONINGDHV UK LTD.

Rightwell House
Rightwell East
Bretton
Peterborough
PE3 8DW
Industry & Buildings
VAT registration number: 792428892

+44 1733 334455 **T**
+44 1733 262243 **F**
email **E**
royalhaskoningdhv.com **W**

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Author(s): David Brew & Stuart Dawks

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Executive Summary

The Alde-Ore Estuary, Deben Estuary and Hamford Water are small estuary systems that support a variety of habitats designated within Sites of Special Scientific Interest (SSSI). These estuarine SSSIs are subject to a number of pressures including coastal squeeze and development, which could affect the whole-estuary condition. The challenge for this study was to characterise the landscape-scale functioning and degree of morphological equilibrium of the estuaries to support judgements about their condition (health), in accordance with Common Standards Monitoring (CSM) guidance of JNCC.

To define the condition of an estuary as favourable means that the special features of the designated areas are in a healthy state and are being conserved for the future by appropriate management. In order for this condition to be maintained over the long term, there must be confidence that the estuary can sustain adequate habitat of the appropriate quality, within an overall morphological equilibrium.

Morphological equilibrium in the Alde-Ore Estuary, Deben Estuary and Hamford Water was analysed using Regime Theory, which defines empirical relationships between estuary tidal prism and cross-sectional area. Equilibrium in these estuaries is seen as a dynamic state in which constant adjustments take place to their overall morphology so they are able to function effectively. The observed form of the estuary was compared to the predicted equilibrium form to determine how far from equilibrium each estuary is. Integration of natural (geological) and human-induced constraints then allowed an appraisal of reasons for disequilibrium.

The critical data upon which the Regime Theory method used in this project relies are bathymetry and tidal datum elevations. In this study, bathymetry datasets were used covering different parts of the estuaries; LiDAR across the intertidal areas and multibeam echosounder and single beam echosounder across subtidal areas. These datasets were evaluated and those that were considered to best represent the current bathymetry were integrated and used in the analyses. The data was quality assured to check for gaps and inconsistencies which were filled and rectified as appropriate.

The results for each of the estuaries are different. The whole of Hamford Water is under-sized compared to its predicted form; the observed channels are narrower than predicted for the present-day tidal regimes. In the Alde-Ore Estuary, the long (15km) north-northeast to south-southwest oriented reach behind Orford Ness from Slaughden to the mouth is under-sized, whereas in the Deben, only the downstream 3km (Felixstowe Marshes and Bawdsey Marshes) is undersized. This means that to obtain an equilibrium form in these reaches they have to widen from their current forms. They should erode by loss of intertidal habitat because in all the estuaries the high water mark is constrained by flood embankments which do not allow it to migrate landwards.

By contrast, most of the Deben Estuary is tending towards equilibrium or is marginally over-sized, whereby the observed and predicted widths are similar. Only a short stretch of the Alde-Ore Estuary (2km upstream from Slaughden) is near-equilibrium with an over-sized segment (3km long) upstream from that. All of the Butley Estuary is near-equilibrium. In the over-sized parts of the estuaries the observed channels are wider than predicted for the present-day tidal regimes. Here, they should accrete and develop further intertidal habitat by natural processes. There are no over-sized or near-equilibrium reaches in Hamford Water.

1 Introduction

One of the core duties of Natural England is to ensure protection and management of Sites of Special Scientific Interest (SSSIs), which underpin England's Natura 2000 network. This network of designated sites includes the Alde-Ore Estuary, Deben Estuary and Hamford Water SSSIs, which form the geographical basis for this study. These estuarine systems support a variety of habitats including intertidal sandflats, mudflats and saltmarsh, tidal creeks, sand banks, vegetated shingle and saline lagoons which are also designated within Special Areas of Conservation (SAC), Special Protection Areas (SPA), Ramsar sites and National Nature Reserves (NNR).

These designated estuaries are subject to a number of pressures including coastal squeeze due to coastal erosion and/or sea-level rise and development such as coast protection, ports and marinas (land claim and/or dredging), which can affect the whole-estuary condition. Natural England assesses the condition of SSSIs using Common Standards Monitoring (CSM) guidance developed by the Joint Nature Conservation Committee (the United Kingdom government's wildlife adviser) and the UK statutory nature conservation bodies (JNCC, 2004). In England, SSSIs are divided into smaller, more practical monitoring areas called 'units'. Each SSSI unit will have one or more notified features, which have one or more measurable characteristics that can be used to determine its condition (e.g. habitat extent and structure, species composition). A list of special features, and the targets against which they are measured on a unit, are specified in a 'favourable condition table' for each SSSI. After the assessment, the information gathered is used to determine if the unit meets all the required levels to assign it to one of the following condition categories:

- Favourable: this means that special features are in a healthy state and are being conserved for the future by appropriate management.
- Unfavourable recovering: this means that all necessary management measures are in place to address the reasons for unfavourable condition and if these measures are sustained, the site will recover over time.
- Unfavourable–no change or Unfavourable–declining: these terms are used to describe sites where the special features are not being adequately conserved, or are being lost. If appropriate management measures are not put in place, and damaging impacts are not addressed, these sites will never reach a favourable or recovering condition.
- Part destroyed or Destroyed: these terms describe a very small number of sites where there has been fundamental and lasting damage. The special features have been lost permanently and favourable condition cannot be achieved.

The assessment of SSSIs is also used in reporting on the status of features within Natura 2000 sites. Assessment of condition is a requirement in order to ensure that factors affecting condition and the remedies to achieve improvements in condition are put in place, both by individual landowners or public bodies.

The rationale behind this assessment is that the condition of the interest features and attributes of an estuary need to take account of the relationship between its broad-scale physical form and function. Local measurements of physical parameters, such as signs of erosion or accretion, aid the condition assessment of each feature attribute, but they should be viewed within the context of the broader-scale estuary processes that are contributing to change. This is particularly so for the Alde-Ore Estuary, Deben Estuary and Hamford Water, which are relatively small dynamic systems, potentially subject to longer-term fluctuations in morphology, reflecting estuary evolution processes as well as responses to past or present human interventions.

1.1 Aim and Objectives

The aim of this study is to apply the Healthy Estuaries 2020 toolbox software and methodology already developed (Natural England, 2015) at the Alde-Ore Estuary, Deben Estuary and Hamford Water SSSIs to provide information on the 'health' of these systems to support condition assessments. The aim is to determine how far each estuary is from favourable condition with regard to one of its morphological equilibrium attributes (tidal prism/cross-sectional area relationship) in accordance with Common Standards Monitoring (CSM) guidance (JNCC, 2004) (Table 1.1). The results support Natural England's advice to the Environment Agency on intertidal habitat creation that will be needed by 2020 to restore estuaries affected by coastal squeeze to favourable condition. To support this aim, the objectives are:

- investigate the equilibrium state of each estuary through comparison of its observed and predicted form (how far is each estuary from its 'ideal' morphological equilibrium);
- define the physical limitations to establishing morphological equilibrium including hard geology and developments; and
- identify potential locations on a broad scale where intertidal habitat creation could be implemented to encourage the estuary to evolve towards morphological equilibrium and move the parts of the SSSI in unfavourable condition towards favourable condition.

Table 1.1. Description of the tidal prism/cross-sectional area morphological equilibrium attribute (JNCC, 2004)

Attribute	Measure	Target	Comment	Method
Morphological Equilibrium	Tidal prism/cross-sectional area (T_p/C_s) relationship	No significant deviation from the intra- and inter-estuarine T_p/C_s relationship.	The relationship between T_p and C_s provides a measure of the equilibrium of an estuary which is fundamental to the way it adjusts to tidal energy and is reflected in rates of deposition and erosion. Substantial changes in this relationship may indicate that human-induced factors are taking effect and this would trigger more detailed evaluation of potential problems	Bathymetric survey every 12 years, or sooner if saltmarsh boundary measurements indicate a deviation away from standard limits of natural variation

1.2 Methods

This study uses existing data to characterise the functioning of the Alde-Ore Estuary, Deben Estuary and Hamford Water SSSIs in terms of their morphological equilibrium. This attribute was analysed using Regime Theory which uses empirical relationships between tidal prism and cross-sectional area (O'Brien, (1931; Coastal Geomorphology Partnership, 1999). Details of the Regime Theory are provided in Appendix A.

Crucial to the philosophy of Regime Theory is that the morphology will evolve to achieve equilibrium between the forcing of the waves and currents transporting sediment and the resulting form of the estuary created by that transport. Over time, an estuary will have had its dynamic equilibrium morphology changed in some way by human interference and different parts of its form are likely to be at different stages of adjustment to natural process inputs. Hence, an estuary will seek to reach a steady state over the long term by oscillating around theoretical equilibrium morphologies over the short term to medium term. The width and depth of the estuary will therefore change over time towards a state of dynamic equilibrium or 'most probable state'.

Regime Theory predicts the equilibrium width of an estuary, which when compared with its observed width can be used to determine how far an estuary is from an equilibrium form, which can then be used to define the condition of this attribute. The main stages of this study in support of an assessment of morphological equilibrium in the Alde-Ore Estuary, Deben Estuary and Hamford Water were:

- collate the essential bathymetry data up to the foot of flood embankments or mean high water spring (MHWS) if no defences are present;
- define the mean high water spring, mean high water neap (MHWN) and mean low water spring (MLWS) tidal datums;
- develop a series of cross sections from the tidal limit(s) to the estuary mouth and measure the current form and predict the equilibrium form of the estuary at each section;
- identify any natural (geological) and human-induced constraints to estuary form; and
- provide a preliminary assessment of the condition of the morphological equilibrium attribute, in accordance with Common Standards Monitoring (CSM) guidance (JNCC, 2004).

1.2.1 Bathymetry and Tidal Regime Data

Data to support the assessment was imported into an existing GIS that was developed for the Healthy Estuaries 2020 project (Natural England, 2015). The critical data upon which the Healthy Estuaries 2020 tool relies are recent bathymetry and tidal datum elevations. The regime relationship is between spring tidal prism (the volume of water that enters and leaves the estuary during a spring tide) and the cross-sectional area at MHWN tide at the mouth. Given this relationship, all the observed estuary morphological parameters were calculated using the bathymetric data set relative to the elevation of MHWN tide, whereas the observed tidal prism is calculated using a combination of the MHWS tide datum, MLWS tide datum, and the bathymetry.

Bathymetry

Digital bathymetries for each estuary were compiled from various sources, collected using several different methods. The best available bathymetry data for each estuary was compiled, as far as possible (described in Sections 2.2, 3.2 and 4.2 for the Alde-Ore Estuary, Deben Estuary and Hamford Water, respectively). The bathymetry data covers all intertidal and subtidal areas up to the seaward face of the front-line defences or up to the MHWS datum where the coastal plain rises naturally into the hinterland, and stretches from as close to the upstream tidal limit(s) as possible to the defined downstream boundaries. The bathymetries in all three systems have been composited from two or more surveys that cover different parts of the estuaries. The bathymetry data was quality assured to check for gaps and inconsistencies which have been filled and rectified, accordingly.

Tidal Regime

Although there are several methods available to determine the tidal regime in an estuary, the simple use of the predicted tidal levels published in the 2017 UK Admiralty Tide Tables is opted for here, in line with the Healthy Estuaries 2020 approach (Natural England, 2015). The tidal datums were used as a characterisation tool in their own right, but were also used along with bathymetry to calculate tidal prism and cross-sectional area for the morphological equilibrium analysis. The critical tidal datums for the estuary equilibrium analysis are MHWS, MHWN and MLWS.

1.2.2 Development of Sections and Observed and Predicted Estuary Forms

The basis of Regime Theory is that a downstream increase in tidal prism will be matched by an increase in the cross-sectional area of successive channel profiles. This provides a measure of the equilibrium morphology of an estuary along its length and is a tool to assess equilibrium by determining how the tidal prism / channel cross-sectional area relationship changes with distance along the estuary. Given this relationship, the observed cross-sectional area (at MHWN) and tidal prism (at MHWS) were calculated using the bathymetric datasets relative to the tidal elevations at specific sections along each of the estuaries. The sections stretch between MHWS tide on either side of the estuary and were perpendicular (as far as possible) to a line along the centre of the low-water channel. They transect the SSSI boundary where it is within the area affected by water movements.

In order to provide a preliminary assessment of the condition of the morphological equilibrium attribute, the observed planforms of the estuaries were compared to the equilibrium planforms predicted using a set of calculations at each of the sections originally defined in the measurement of observed form. The prediction of the equilibrium forms was carried out in four main stages using the methodology developed for Healthy Estuaries 2020:

- distribute throughout the estuary the total observed tidal prism at the mouth to predict the tidal prism upstream of each section;
- calculate equilibrium cross-sectional areas from the upstream tidal prisms at each section;
- calculate mean depths and equilibrium widths at each section; and
- compare the predicted widths with the observed widths.

The predicted forms and observed forms at each section were compared to gauge how far from equilibrium the estuary is. In this way, reaches of the observed estuary which are narrower or wider than their predicted form were mapped.

1.2.3 Constraints to Estuary Equilibrium Form

The reaches of the estuary that have observed widths which are narrower than the predicted widths are considered to be pressure points in the estuary (and may be subject to coastal squeeze). This means that at these locations the estuary form should be wider than it actually is and to obtain equilibrium the estuary has to widen from its current form (i.e. it should erode resulting in loss of intertidal habitat if the high water mark is unable to migrate landwards). Future sea-level rise will exacerbate this trend for erosion. However, it may not be possible for the estuary to widen because of constraints such as geology, essential infrastructure or other land uses. Therefore, the pressure points were mapped against physical constraints in the estuary.

The underlying geology of the estuary is important because it potentially constrains the channel from widening and/or deepening. If the geology is sufficiently hard so that the bed and banks are resistant to physical processes then it is likely that the estuary will not conform to the regime relationship. Also, the location of existing essential infrastructure or buildings such as flood and coastal defences, towns and harbours provide major constraints in estuaries.

1.2.4 Preliminary Assessment of the Morphological Equilibrium Attribute

The results of the morphological equilibrium analysis in combination with the results of the constraints analysis were used to determine how far each estuary is from favourable condition with regard to its morphological equilibrium attribute. The observed forms of the estuaries compare with the predicted equilibrium forms in one of three ways:

- observed form is under-sized compared to predicted form (i.e. the observed channel is narrower than predicted for the present-day tidal regime). The most likely cause for this type of disequilibrium is coastal squeeze caused by the inability of the intertidal system to migrate landwards due to flood embankments;

- observed and predicted forms are similar, suggesting that their observed forms are close to equilibrium; and
- observed form is over-sized compared to its predicted form (i.e. the observed channel is wider than predicted for the present-day tidal regime). In these cases, the estuary exceeds its predicted equilibrium width and over the long term there may be development of intertidal habitat by natural processes.

Along under-sized reaches, estuarine processes should be attempting to widen the channel to establish an equilibrium form. In order to allow a wider channel to develop in keeping with the equilibrium width may necessitate realignment of the flood embankments to restore former land-claimed intertidal areas to tidal processes. Future sea-level rise will exacerbate this trend for erosion. These locations were assessed (taking account of physical limitations such as hard geology or developments) to determine whether they provide opportunities for intertidal habitat creation to move the estuary towards morphological equilibrium and the SSSI towards favourable condition.

2 Alde-Ore Estuary SSSI

The estuary of the River Alde-Ore stretches from the normal tidal limit at Snape to the mouth at Shingle Street. Between Snape and the cliffs at Iken, the southerly course of the Alde Estuary channel is fixed by a series of abandoned embankments. From Iken Cliffs to Barber's Point the intertidal area widens to around 1km with a narrow, meandering low water channel which is largely unrestricted. At Barber's Point the low water channel reaches its maximum width. Intertidal mudflats bordered by narrow saltmarsh dominate this area. Between Barber's Point and Slaughden the estuary narrows and forms several tight meanders, confined by both defences and natural high ground, before turning sharply south at Slaughden. At Slaughden, the estuary approaches to within 50m of the North Sea.

From Slaughden to Shingle Street the estuary is confined between embankments (restricting any tendency for lateral movement) and flows parallel to the coast confined by Orford Spit. This spit stretches 6km south from Aldeburgh to Orford Ness and then southwest a further 9km to North Weir Point. Near Orford, the estuary bifurcates around Havergate Island where the Butley Estuary joins the inner reach at the south end of the island. The tidal limit of the Butley Estuary is at Butley Mills. The two channels converge again downstream of Havergate Island. Downstream of Havergate Island to its mouth, the regime becomes influenced by coastal processes, which exhibit considerable variability.

Over the past several thousand years the development of the Alde-Ore Estuary has been intimately linked to the development of Orford Spit and the land-claim of saltmarsh formed in the shelter of the spit. Before embanking and land-claim, saltmarsh was much more extensive in the estuary. The main enclosure of saltmarsh took place in two phases, between the 11th and 13th centuries and in the 16th and 17th centuries. The remaining active saltmarshes form a narrow fringe in front of the flood embankments along much of the estuary with more extensive active marshes near Iken.

2.1 Extent of Study Area and SSSI Designation

The Alde-Ore Estuary and Butley Estuary are covered by several designations including the Alde-Ore Estuary SSSI, Alde, Ore and Butley Estuaries SAC, Orfordness-Shingle Street SAC, Alde-Ore Estuary SPA and Alde-Ore Estuary Ramsar site. The SSSI is coincident with the SPA and Ramsar site. Part of the SSSI overlaps with the shingle and saline lagoon habitats that comprise the Orfordness-Shingle Street SAC and part overlaps with the estuary habitats that comprise the Alde, Ore and Butley Estuaries SAC. The Alde-Estuary SSSI has an area of 25.34km^2 (2,534ha) (Figure 2.1) and contains 35 units with features in various condition (Appendix B). The conservation interests are diverse, containing coastal formations and estuarine features including mudflats, saltmarsh, vegetated shingle and coastal lagoons which are of special botanical, ornithological and geological value. The overall condition of the estuary is described in Table 2.1.

Figure 2.1. Extent of the Alde-Ore Estuary SSSI

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Table 2.1. Overall unit condition assessment in the Alde-Ore Estuary SSSI

Size	Favourable	Unfavourable-Recovering	Unfavourable-No Change	Unfavourable-Declining
Area (km^2)	13.10	8.76	3.48	0.00
Percentage	51.68	34.58	13.74	0.00

2.2 Bathymetry

Digital bathymetries for the Alde-Ore Estuary and Butley Estuary were downloaded from the Environment Agency's Survey Open Data site (http://environment.data.gov.uk/ds/survey/index.jsp#/survey) and uploaded to the GIS:

- LiDAR (Alde-Ore Estuary and Butley Estuary) at 2m resolution captured in various years (combined dataset which uses the best data from a range of years) for areas not covered by water at that time (Figure 2.2); and
- Multibeam echosounder (Alde-Ore Estuary only) captured in 2013 for areas covered by water at that time (Figure 2.3). For these areas, the LiDAR data did not capture the bed of the estuary because of the water coverage. The LiDAR therefore recorded the water surface.

Both datasets required processing and manipulation before being 'stitched' together to create the final bathymetry. The LiDAR data, in Ordnance Datum (OD), was processed from single ASCII files into a mosaicked dataset covering the shallower parts of the Alde-Ore Estuary SSSI (Figure 2.2). The multibeam echosounder data was processed and added into the GIS. If the landward part of the multibeam echosounder data overlapped the seaward part of the LiDAR data, then the echosounder data was used to avoid errors associated with the water surface. Where there was a gap between the LiDAR data and the echosounder data, a linear interpolation was completed to stitch the LiDAR data to the shallowest parts of the echosounder data.

These two datasets were quality assured to check for gaps and inconsistencies. In this respect, the absence of multibeam echosounder data in the Butley Estuary, required artificial generation of bathymetry along the low water channel. This was completed by predicting the depths of the thalweg at the seaward end (from multibeam echosounder data in the adjacent Alde-Ore Estuary) and landward end (from Lidar) and interpolating along and across the channel to the adjacent bathymetries. The results of this interpolation are shown in Figure 2.4.

All the data were merged together (Figure 2.5) to create the overall bathymetry for the Alde-Ore Estuary SSSI used in the analysis. The bathymetry data covers all intertidal and subtidal areas up to the seaward face of the front-line defences or up to the MHWS datum where the coastal plain rises naturally into the hinterland, and stretches from as close to the upstream tidal limits as possible to the defined downstream boundaries.

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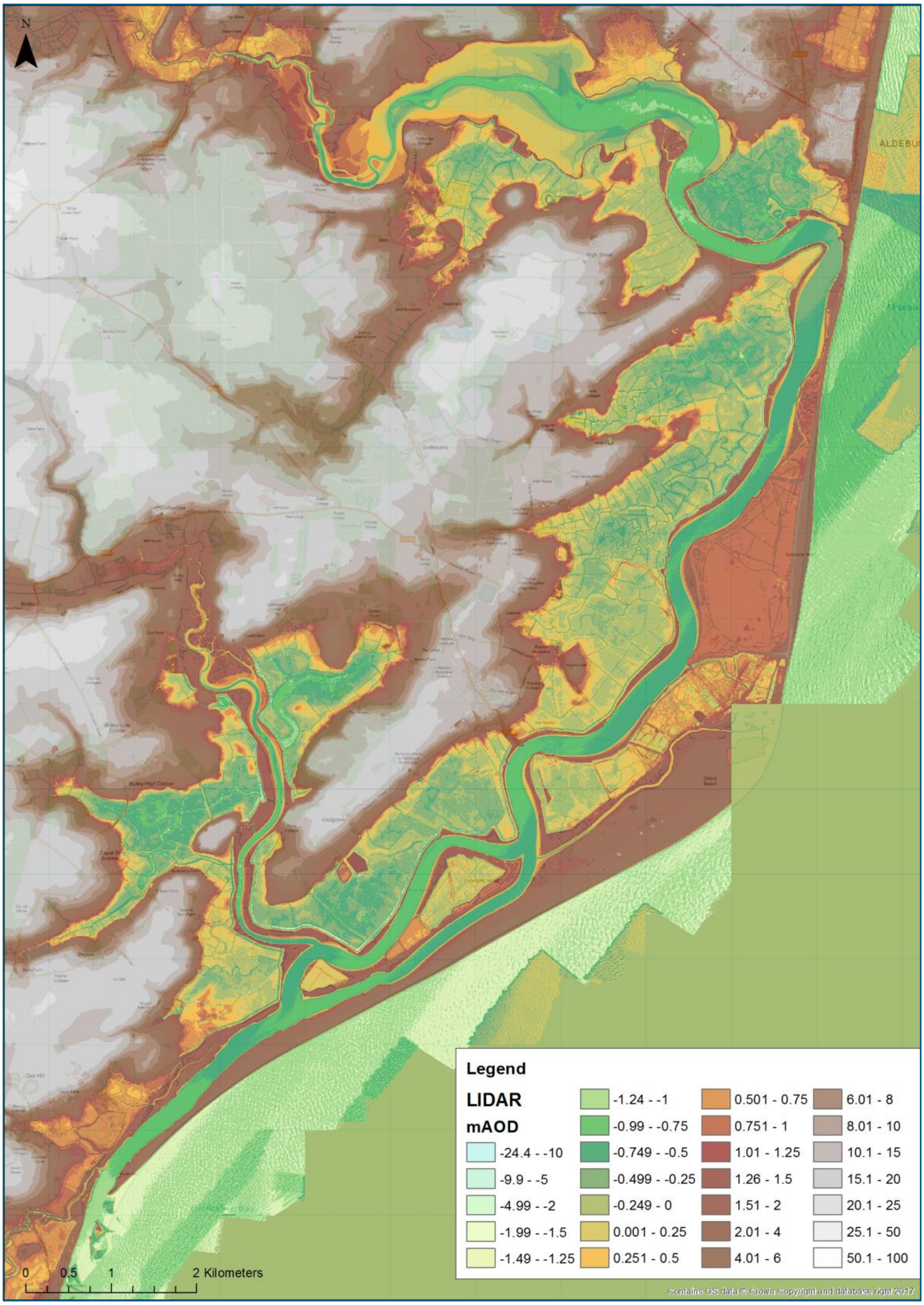

Figure 2.2. Environment Agency LiDAR data in the Alde-Ore Estuary and Butley Estuary (http://environment.data.gov.uk/ds/survey/index.jsp#/survey)

Figure 2.3. Environment Agency multibeam bathymetry data in the Alde-Ore Estuary (http://environment.data.gov.uk/ds/survey/index.jsp#/survey)

Figure 2.4. Interpolated bathymetry in the Butley Estuary

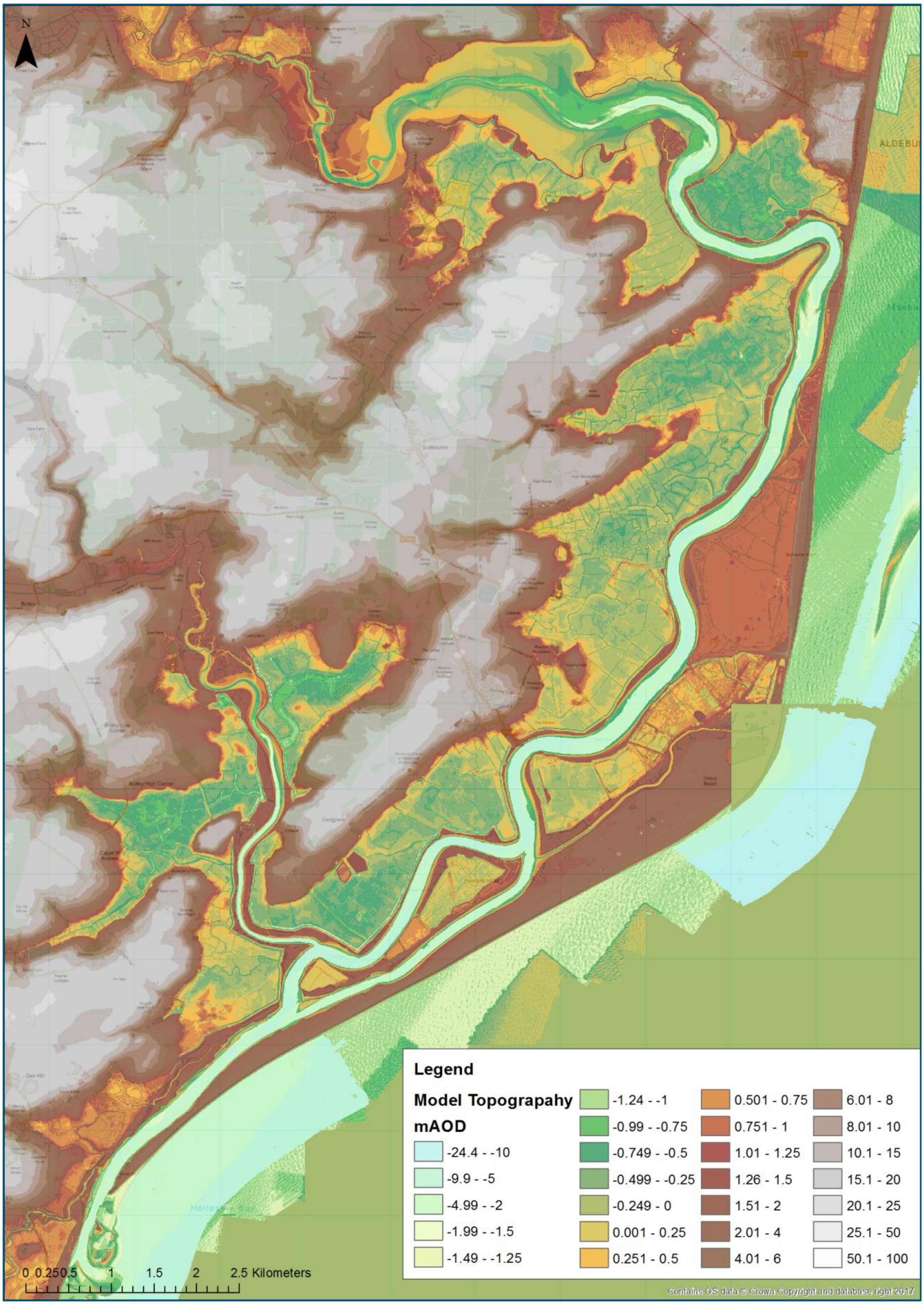

Figure 2.5. Combined LiDAR, multibeam echosounder and interpolated bathymetry in the Alde-Ore Estuary and Butley Estuary

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2.3 Tidal Regime

In order to calculate the spring tidal prism and cross-sectional area of the Alde-Ore Estuary and Butley Estuary it is necessary to know the elevations of tidal datums. Table 2.2 presents the MHWS, MHWN and MLWS tidal datum elevations at tidal stations along the Alde Ore Estuary. The elevations of the datums change with distance upstream and to create a surface that represents them along the estuary, the individual datum heights at each tidal station were linearly interpolated. Figure 2.6 shows the tidal datum surfaces transposed on to the bathymetry of the Alde-Ore Estuary and Butley Estuary.

Table 2.2. Tidal datums in the Alde-Ore Estuary relative to Ordnance Datum (OD) (2017 Admiralty Tide Tables)

Tidal Station	Coordinates		Mean High Water Spring Tide (m OD)	Mean High Water Neap Tide (m OD)	Mean Low Water Neap Tide (m OD)	Mean Low Water Spring Tide (m OD)
	Longitude	Latitude				
Orford Haven Bar	1.4667	52.0333	1.54	0.94	-0.66	-1.26
Orford Quay	1.5333	52.0833	1.20	0.70	-0.50	-1.00
Slaughden Quay	1.6	52.1333	1.30	1.00	-0.60	-1.00
Iken Cliffs	1.5167	52.15	1.30	0.80	-0.50	-1.00

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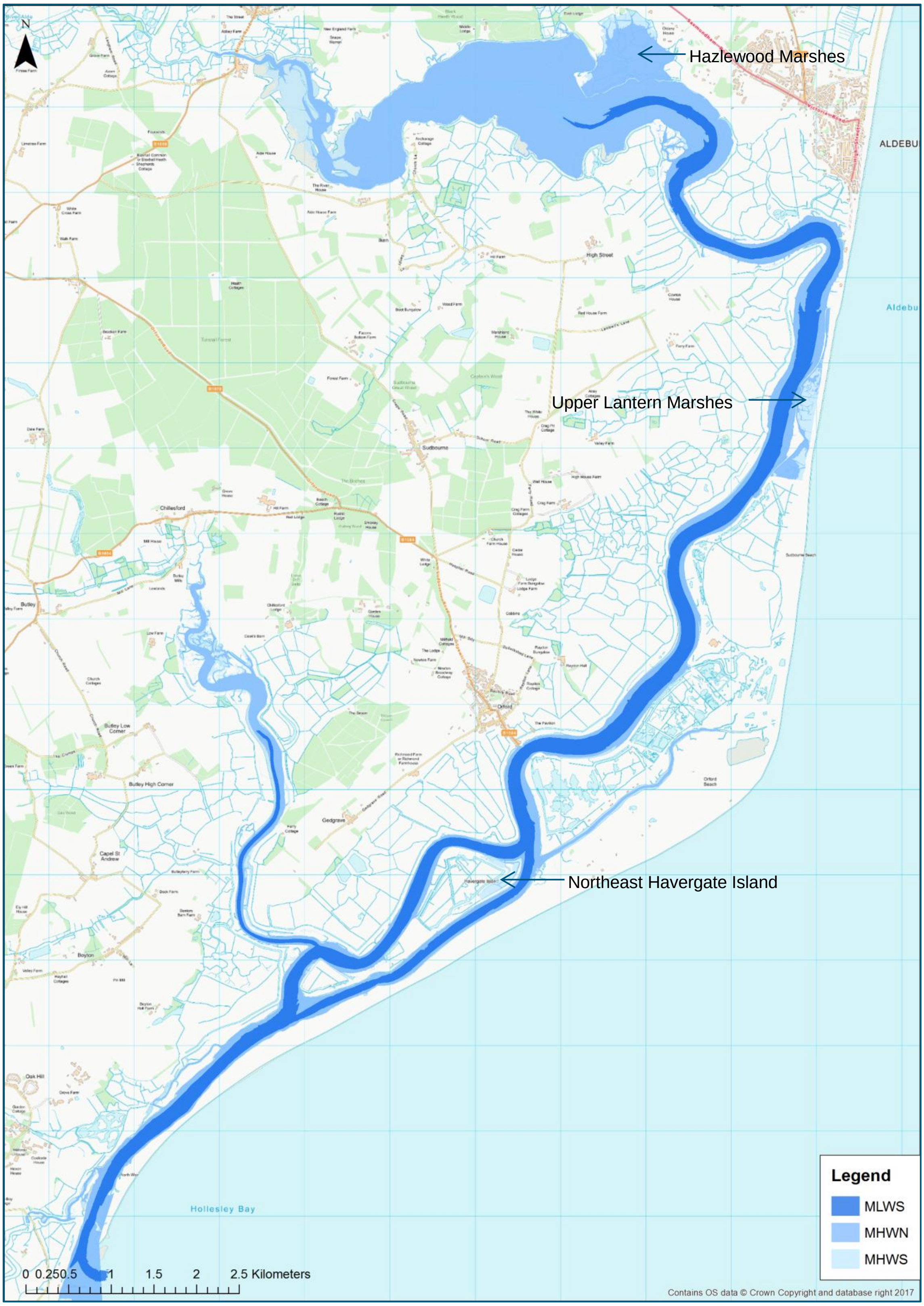

Figure 2.6. Tidal datums in the Alde-Ore Estuary and Butley Estuary

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2.4 Morphological Equilibrium

2.4.1 Observed Estuary Form

Using the bathymetry and tidal datums in the GIS, each of the following parameters were measured at sections spaced about 200m apart along the estuaries to quantify their observed forms:

- cross-sectional area beneath MHWN;
- width at MHWN;
- mean depth beneath MHWN; and
- spring tidal prism upstream of each section.

The locations of the sections where the observed form was measured are shown in Figure 2.7 and the data at each section is presented in Appendix C.

The observed estuary form includes three areas where inundation of previous land-claim has occurred through breaching of the flood embankment (i.e. their tidal prisms are taken into account). These are (Figure 2.6):

- Hazlewood Marshes on the north side of the estuary opposite Iken Marshes: damage to the front-line flood embankment took place during storms in 2013 resulting in a breach that allowed tidal inundation of the low-lying land behind. The embankment was not repaired and the site is now fully intertidal.
- Upper Lantern Marshes on the east side of the estuary behind the northern part of Orford Spit: a permanent breach of the embankment was established here in the mid-1980s and has remained open. The low-lying area is fully intertidal south to the American Wall (which was damaged in 2013 and then repaired with sluices).
- Northeast Havergate Island: a managed realignment of the flood embankment in 2000 allowing tidal waters to fully inundate and drain the northeast part of Havergate Island.

2.4.2 Predicted Estuary Form

The regime relationship that was used to predict estuary form is between spring tidal prism and the cross-sectional area at MHWN tide at each of the sections defined in the assessment of observed form (in line with Healthy Estuaries 2020, Natural England, 2015) (Appendix A). Two steps developed in Healthy Estuaries 2020 were followed to determine morphological equilibrium. Details of these steps are provided in Appendix A and they are only briefly summarised here.

The first step was to predict cross-sectional area from the re-distributed tidal prism. The regime equation that encapsulates all United Kingdom estuaries was used.

$$CSA = 0.024.P^{0.71} \ (r^2 = 0.75)$$

where:

CSA = cross-sectional area (MHWN); and
P = upstream spring tidal prism.

The second step was to calculate planform width from cross-sectional area. Several different methods were tested in Healthy Estuaries 2020 to develop a robust way of estimating planform width from cross-sectional area. It was concluded that the most reliable was the ‘constant evolution’ method (Appendix A), and this was adopted here. Using these two steps, the equilibrium width of the Alde-Ore Estuary / Butley Estuary system was predicted at each section, presented in Appendix D.

Figure 2.7. Location of sections in the Alde-Ore Estuary and Butley Estuary

2.4.3 Comparison of Predicted Equilibrium Widths with Observed Widths

The results were interrogated using the GIS to compare the predicted equilibrium widths (Appendix D) with the observed widths (Appendix C) at each section. The comparison for the Alde-Ore Estuary / Butley Estuary system is shown in Figure 2.8 and Figure 2.9. The observed widths compare with the predicted equilibrium widths in the Alde-Ore Estuary in one of three ways:

- The estuary downstream of Slaughden to the mouth at Shingle Street is under-sized compared to its predicted form (i.e. the observed channel is narrower than predicted for the present-day tidal regime). The magnitude of the disequilibrium increases in a downstream direction. Between Slaughden and Lantern Marshes the under-sizing is relatively small, increasing between Lantern Marshes and Havergate Island, before the largest relative under-sizing between Havergate Island and Shingle Street. The observed estuary between the tidal limit at Snape and Iken Cliffs is also under-sized compared to its predicted form. Larger scale maps showing the under-sized portions of the Alde-Ore Estuary are presented in Appendix E.
- Between Iken Cliffs and Iken Marshes, the estuary is over-sized compared to its predicted form (i.e. the observed channel is wider than predicted for the present-day tidal regime).
- The estuary between Iken Marshes and Slaughden has observed and predicted widths which are similar, suggesting that along this short stretch the observed form is close to equilibrium. The whole of the Butley Estuary is also predicted to be in near-equilibrium.

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Figure 2.8. Comparison of predicted equilibrium widths with observed widths in the Alde-Ore Estuary (map background)

Figure 2.9. Comparison of predicted equilibrium widths with observed widths in the Alde-Ore Estuary (aerial photograph background)

2.5 Physical Constraints to Morphological Equilibrium

The three distinct predicted equilibrium states of the Alde-Ore Estuary suggest that different parts are at different stages of adjustment to natural process inputs.

2.5.1 Under-sized Reaches

Downstream of Slaughden to the mouth at Shingle Street is predicted as under-sized and processes will be attempting to widen the channel to establish an equilibrium width. However, it is not possible for the estuary to widen here because of flood embankment constraints. The shores of the Alde-Ore Estuary downstream of Slaughden are dominated by intertidal mudflats with a narrow fringe of active saltmarsh behind which are former floodplains protected from inundation at high water by flood embankments.

2.5.2 Reaches in Near-equilibrium

The Alde-Ore Estuary between Iken Marshes and Slaughden and all of the Butley Estuary appear to be in a state of near-equilibrium. The short stretch (about 2km) between Iken Marshes and Slaughden is the transition between the over-sized upstream reach and the downstream under-sized reach. In the Butley Estuary, it appears that a balance between erosion and accretion has been established over the long term (although adjustments may be taking place over the short term and medium term to maintain this form). The channel of the Butley Estuary is relatively broad and unconstrained, with some width for expansion and limited pressure on the intertidal areas.

2.5.3 Over-sized Reaches

In the predicted over-sized part of the estuary between Iken Cliffs and Iken Marshes, the flood embankments were breached and abandoned in the 1960s allowing the former land-claim to be flooded. The remains of the defences provide some control to the channel at low tide. Water has filled the accommodation space created by subsidence after land-claim behind the former embankment, and so the channel is artificially wide. The newly flooded area is now a potential sink for sediment and should accrete over time to move towards its equilibrium width.

2.5.4 Overall Condition of the Morphological Equilibrium Attribute

The results of Regime Theory in the Alde-Ore Estuary SSSI show that only the Butley Estuary and a short stretch of the Alde-Ore Estuary at Iken / Slaughden are close to morphological equilibrium. The long reach downstream of Slaughden has developed into a more confined shape than would be expected if it was in morphological equilibrium. However, the reach upstream of Iken Marshes is wider than its predicted equilibrium width.

The Natural England condition assessments are compared to the morphological equilibrium attribute in Table 2.3. The condition assessments indicate that throughout the estuary the units (predominantly defined as littoral sediment) are either favourable or unfavourable-recovering, regardless of morphological equilibrium. However, the condition risk threat for all units (apart from the Butley Estuary) is high, related to the threat of coastal squeeze into the future.

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Table 2.3. Condition assessment and morphological equilibrium in the Alde-Ore Estuary SSSI

Reach	Units	Predicted Morphological Equilibrium	Overall Condition	Condition Threat Risk
Snape to Iken Cliffs	1-4	Under-sized	Favourable	High
Iken Cliffs to Iken Marshes	5-9	Over-sized	Unfavourable-recovering	High
Iken Marshes to Slaughden	10	Near-equilibrium	Unfavourable-recovering	High
Slaughden to Shingle Street	11-12, 19, 23-25, 31	Under-sized	Favourable	High
Butley Estuary	28-29, 42-43	Near-equilibrium	Favourable (upstream) to Unfavourable-recovering (downstream)	Low (upstream) to Medium-High (downstream)

The presence or absence of flood embankments controls the equilibrium in the Alde-Ore Estuary. The under-sized reaches (Snape to Iken Cliffs and downstream of Slaughden to the mouth at Shingle Street) are pressure points in the estuary. This means that here the estuary form should be wider than it actually is and to obtain equilibrium it has to widen from its current form (i.e. it should erode, resulting in loss of intertidal habitat if the high water mark is unable to migrate landwards).

Boyes and Thomson (2011) analysed saltmarsh change in the Alde-Ore Estuary and Butley Estuary between 2000 and 2007. Data describing changes in saltmarsh area over the past 10 years is not available. In the under-sized reach downstream of Slaughden (units 11-12, 19, 23-25 and 31), they showed an overall gain of saltmarsh of 4.26ha. The data is skewed towards a relatively large gain due to increases of 3.19ha and 1.14ha in units 12 and 25, respectively. These gains comprise new saltmarsh formation across Upper Lantern Marshes (due to the flood embankment breach and realignment south to the American Wall) and managed realignment of the flood embankment at northeast Havergate Island. If these managed realignment gains are removed, then there is a small overall loss of 0.07ha within the under-sized unit between 2000 and 2007. In the under-sized reach between Snape and Iken Cliffs (units 1-4) the estuary described a small overall loss in saltmarsh of 0.09ha.

Along the Alde-Ore Estuary reach in near-equilibrium (only unit 10), there was an overall very small loss in saltmarsh of 0.04ha (Boyes and Thomson, 2011). In the near-equilibrium Butley Estuary, the lower reaches (units 28-29) gained 1.39ha of saltmarsh and the upper reaches (units 42-43) were stable (no overall loss of gain of saltmarsh).

Where the channel is over-sized (Iken Cliffs to Iken Marshes), it exceeds its predicted equilibrium width and over the long term there should be a tendency for development of intertidal habitat by natural processes. Boyes and Thomson (2011) showed that along this over-sized reach (units 5-9) there was an overall gain of 0.25ha of saltmarsh between 2000 and 2007. The analysis was undertaken prior to the breach at Hazlewood Marshes in 2013.

2.6 Morphological Equilibrium and the Alde-Ore Estuary Plan

The preferred policy option of the Alde-Ore Estuary Plan (Alde and Ore Estuary Partnership, 2016) is to hold the existing defences in place (i.e. retain the flood embankments *in situ*). The plan advocates a resilience approach to management of the Alde-Ore Estuary and Butley Estuary in the medium term (20-50 years). This means management of flood embankments throughout the estuary, accepting that they may be overtopped on large surges, but reducing the risk of a breach through catastrophic damage. Under this approach, Alde and Ore Estuary Partnership (2016) suggested that most of the embankments could be maintained for the next few decades.

The resilience approach recognises that coastal squeeze is taking place in the estuary, but there is uncertainty around the timing and degree of coastal squeeze effects. Alde and Ore Estuary Partnership (2016) suggested that the vertical accretion of existing saltmarshes could potentially keep pace with projected sea-level rise. They also indicated that intertidal habitat has been developing at Hazlewood Marshes following the unplanned breach of the flood embankment in 2013, and should contribute to offsetting the potential coastal squeeze impacts of the resilience approach. In addition, ongoing and planned saltmarsh restoration work would contribute to mitigating coastal squeeze impacts. However, Alde and Ore Estuary Partnership (2016) do recommend monitoring and review of the estuary on a 5-yearly basis. If this identifies net loss of key features, then it is acknowledged that replacement habitat will have to be provided.

Currently, there are several potential options for managed realignment being discussed in the Alde-Ore Estuary and being investigated to determine if they could work alongside the proposals set out in the Alde-Ore Estuary Plan. These are potential managed realignment at Iken Marshes, Gedgrave Marshes and Boyton Marshes. The Gedgrave Marshes and Boyton Marshes locations are supported by this analysis of morphological equilibrium, as they are both located along the under-sized part of the estuary with the greatest difference between the observed and predicted widths. The Iken Marshes site is located adjacent to a part of the estuary that is predicted to be in near-morphological equilibrium, and is a less obvious candidate for managed realignment with respect to this attribute.

3 Deben Estuary SSSI

The Deben Estuary extends for over 12km in a generally south-southeasterly direction from its normal tidal limit at Bromeswell to its mouth at Felixstowe Ferry. From Bromeswell to Martlesham Creek the estuary is confined to a narrow channel by embankments and gently meanders through fringing mudflats and saltmarsh. Between Martlesham Creek and Ramsholt the channel meanders within the limits of a relatively wide intertidal area which is bounded by either natural high ground or defended land-claim. At Ramsholt, the estuary narrows and continues to its mouth at Felixstowe Ferry confined on both sides by embankments with large areas of low-lying land-claim on either side. The mouth of the estuary is unusual in that it narrows before entering the North Sea. A ridge of higher land to the east at Bawdsey constricts the estuary mouth between it and a low ridge of shingle at Felixstowe Ferry on the opposite bank.

Interaction between tidal estuary processes and open coast processes has led to the development of a series of shifting shingle bars at the mouth of the estuary known as The Knolls. Here, the topography is in continuous motion due to processes driven predominantly by waves and modified by tidal currents into and out of the estuary. On the flood, secondary flows exist through swatchways in The Knolls, causing the main current to be deflected onto the western bank of the channel. During the ebb, the main flow is down the eastern bank of the channel, with secondary flows re-defining swatchways in The Knolls.

Between the 11th and 17th centuries the Deben Estuary underwent periods of land-claim, most of which took place along the lower part of the estuary downstream of Martlesham Creek. The marshes at Bawdsey, Ramsholt, Falkenham and Felixstowe Ferry were frequently flooded prior to land-claim. The development of saltmarsh in the Deben Estuary has been strongly influenced by the control of tidal flooding by embanking adjacent agricultural areas. Narrow strips of saltmarsh or mudflat exist in front of flood defence embankments. Saltmarsh is currently being lost, through erosion of the front edge and through processes of creek widening within the marsh.

3.1 Extent of Study Area and Designations

The Deben Estuary is covered by several designations including the Deben Estuary SSSI, Deben Estuary SPA and Deben Estuary Ramsar site. The entire SSSI lies within the Ramsar site. The Deben Estuary SSSI has an area of 9.81km^2 (981ha) (Figure 3.1) and contains 22 units (Appendix B) with features either in favourable condition (23%, 2.3km^2) or favourable-declining condition (77%, 7.5km^2) (Table 3.1). It is important for its extensive and diverse saltmarsh communities. Much of the intertidal area is occupied by mudflats with more sandy deposits occurring where exposed Red Crag erodes from cliffs. Other key habitats are the saltmarsh and saline transitions into swamp/reed bed at a number of locations.

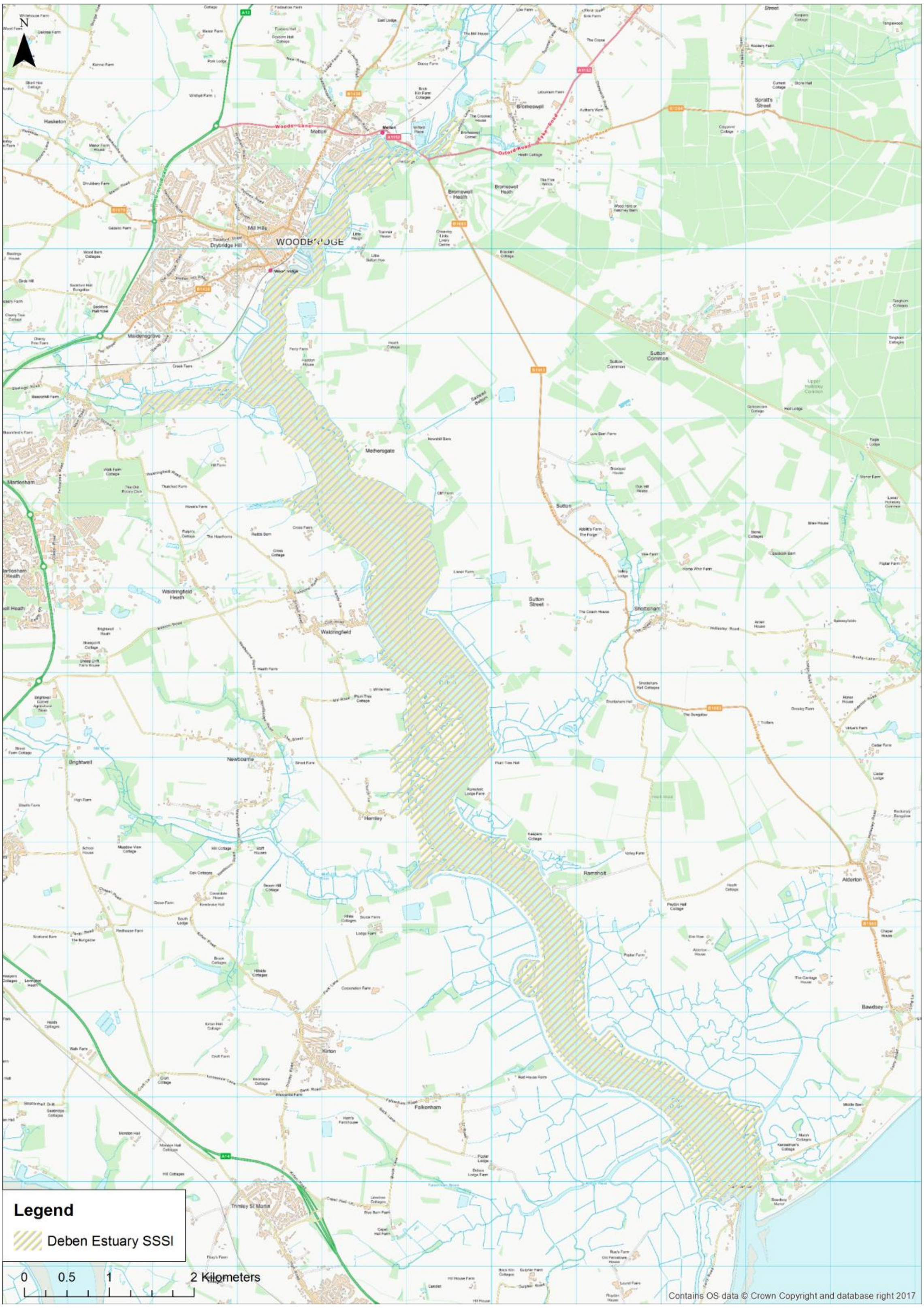

Figure 3.1. Extent of the Deben Estuary SSSI

Table 3.1. Overall unit condition assessment in the Deben Estuary SSSI

Size	Favourable	Unfavourable-Recovering	Unfavourable-No Change	Unfavourable-Declining
Area (km^2)	2.27	0.00	0.00	7.54
Percentage	23.16	0.00	0.00	76.84

3.2 Bathymetry

The bathymetric surface in the Deben Estuary was created using a variety of datasets and the artificial creation of a channel based on expert geomorphological assessment where no data existed. Open source LiDAR data from the Environment Agency (at 2m resolution captured in various years, combined dataset which uses the best data from a range of years) for areas not covered by water at that time was used for areas above elevations -1m OD (Figure 3.2). Below this elevation, the LiDAR data did not capture the bed of the estuary because it was covered by water. The LiDAR therefore recorded the water surface. Hence, in areas below -1m OD (mainly the low water channel), open source multibeam echosounder data from the Environment Agency recorded in 2013 was used (Figure 3.3). If the landward part of the multibeam echosounder data overlapped the seaward part of the LiDAR data, then the echosounder data was used to avoid errors associated with the water surface. Where there was a gap between the LiDAR data and the echosounder data, a linear interpolation was completed to stitch the -1m OD contour of the LiDAR data to the shallowest parts of the echosounder data.

At the mouth of the estuary a small sand bank in its centre was not captured correctly by either the LiDAR or multibeam echosounder data. Here, a single beam echosounder dataset recovered by UKHO (2004-2007) was used (Figure 3.4). This dataset also captured the morphology of The Knolls. Bathymetry data between the points was created by interpolation.

The multibeam echosounder data was terminated at a point downstream of Woodbridge and only LiDAR data was available from this point upstream. This meant that the low water channel was not captured in the upper reach of the estuary to the tidal limit. In the reach between the upstream extent of the echosounder data and the tidal limit, an artificial low water channel was created. The thalweg of the channel at the upstream end of the echosounder data was at -1.55m OD, and the water surface (as recorded by the LiDAR) at the tidal limit was at 1m OD. Hence, an artificial channel was created by defining a 10m-wide thalweg starting at -1.55m OD at its seaward end (to tie into the echosounder data) rising to 1m OD at the tidal limit. The 10m-wide thalweg was then stitched to the Lidar data to either side.

All the data were merged together (Figure 3.5) to create the overall bathymetry for the Deben Estuary SSSI used in the analysis. The bathymetry data covers all intertidal and subtidal areas up to the seaward face of the front-line defences or up to the MHWS datum where the coastal plain rises naturally into the hinterland, and stretches from as close to the upstream tidal limits as possible to the defined downstream boundaries.

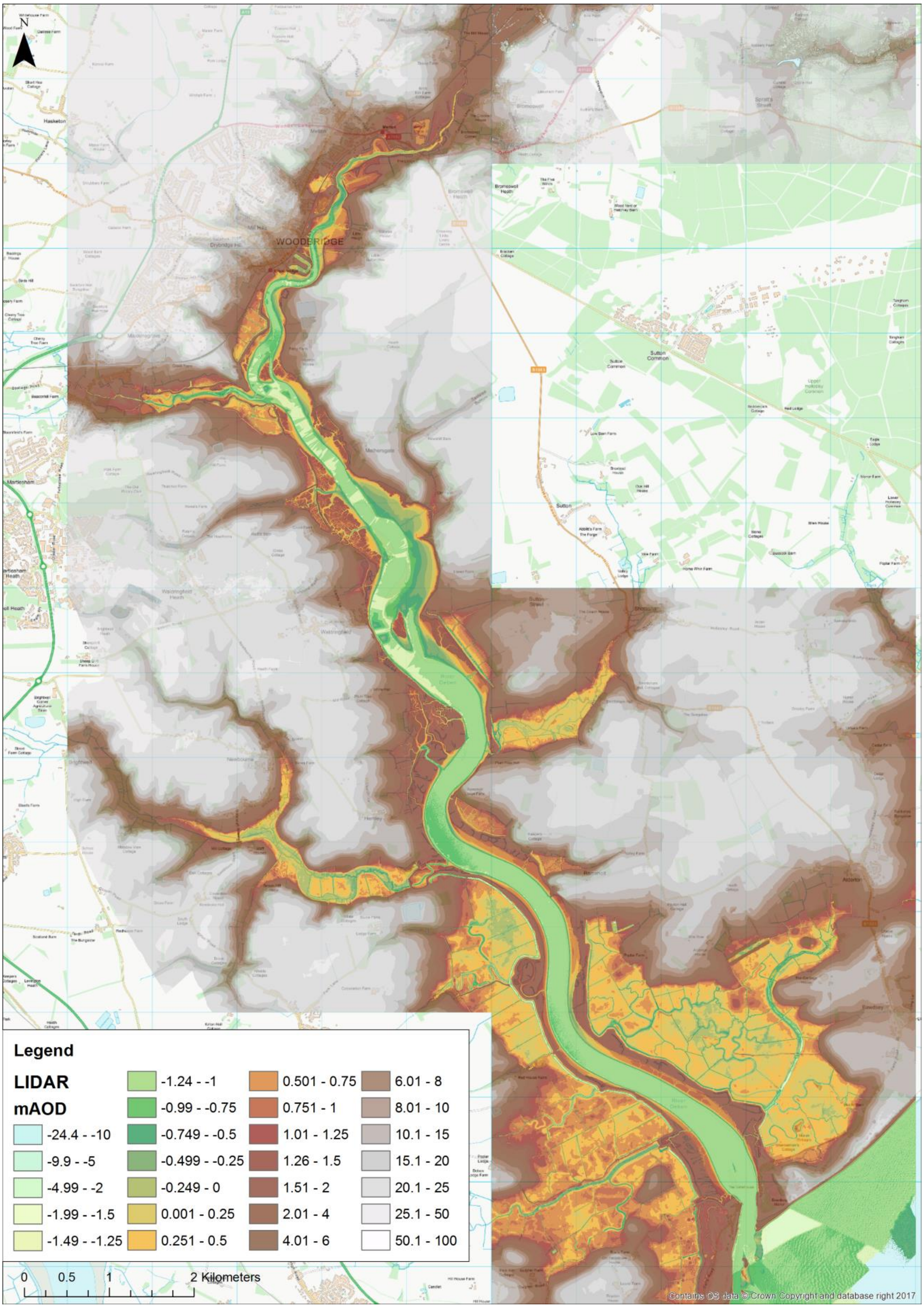

Figure 3.2. Environment Agency LiDAR data in the Deben Estuary (http://environment.data.gov.uk/ds/survey/index.jsp#/survey)

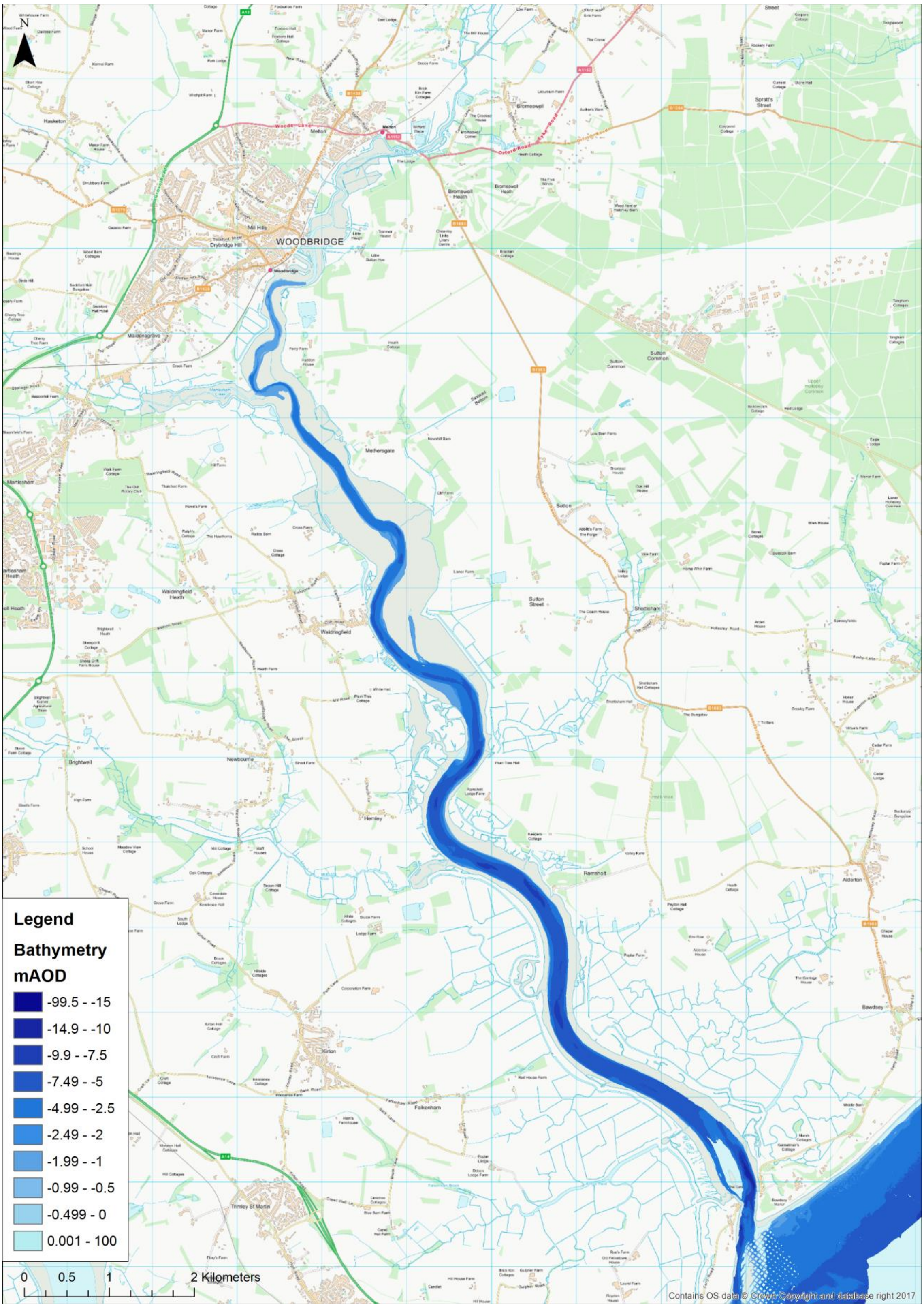

Figure 3.3. Environment Agency multibeam bathymetry data in the Deben Estuary (http://environment.data.gov.uk/ds/survey/index.jsp#/survey)

Figure 3.4. UKHO bathymetry data in the Deben Estuary (http://aws2.caris.com/ukho/mapViewer/map.action)

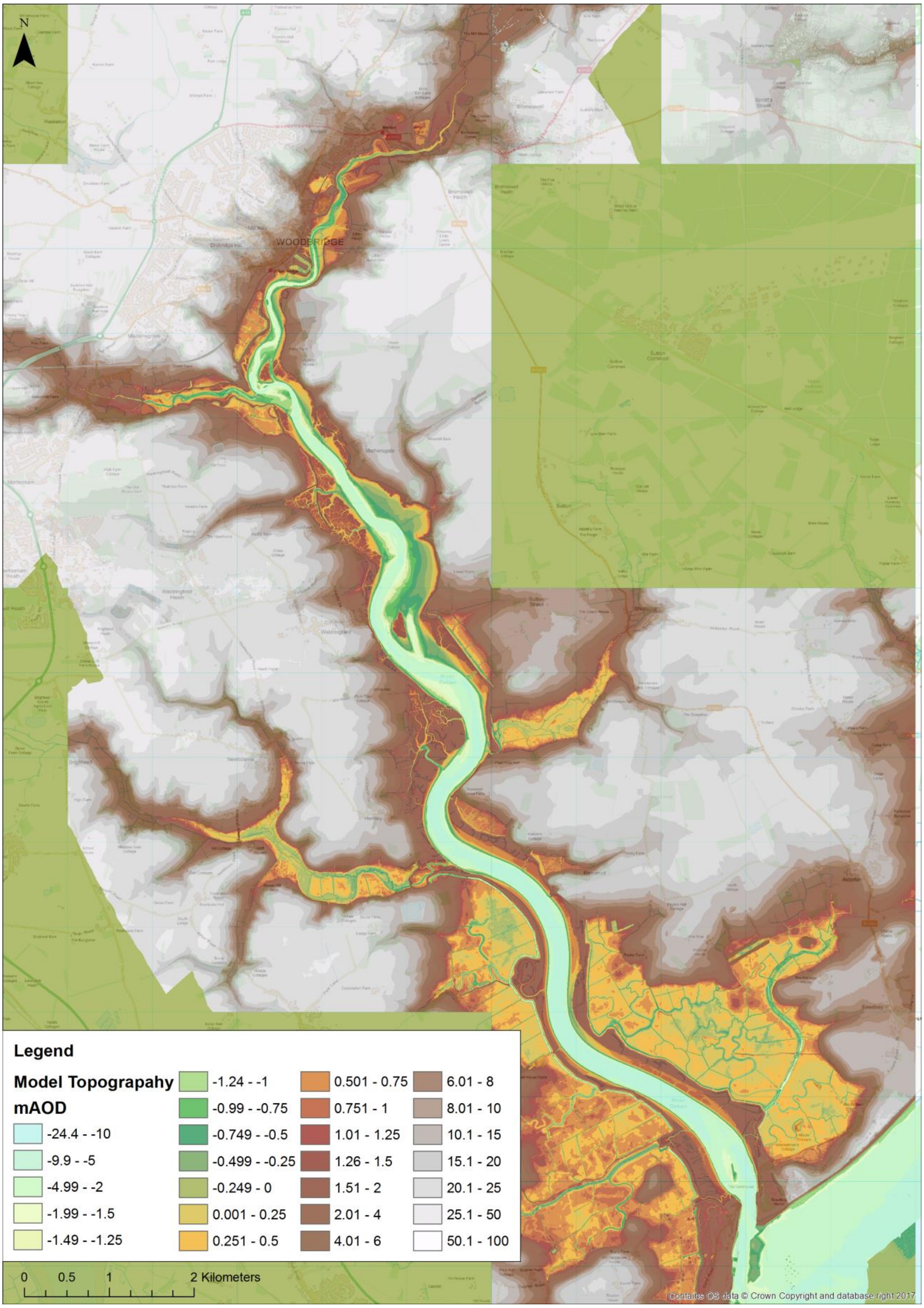

Figure 3.5. Combined LiDAR, multibeam echosounder and interpolated bathymetry in the Deben Estuary

3.3 Tidal Regime

In order to calculate the spring tidal prism and cross-sectional area of the Deben Estuary it is necessary to know the elevations of tidal datums. Table 3.2 presents the MHWS, MHWN and MLWS tidal datum elevations at tidal stations along the Deben Estuary. Figure 3.6 shows the tidal datum surfaces transposed on to the bathymetry of the Deben Estuary.

Table 3.2. Tidal datums in the Deben Estuary relative to Ordnance Datum (OD) (2017 Admiralty Tide Tables)

Tidal Station	Coordinates		Mean High Water Spring Tide (m OD)	Mean High Water Neap Tide (m OD)	Mean Low Water Neap Tide (m OD)	Mean Low Water Spring Tide (m OD)
	Longitude	Latitude				
Woodbridge Haven	1.4	51.9833	1.77	0.97	-0.93	-1.43
Woodbridge	1.3167	52.0833	2.07	1.17	-1.03	-1.53

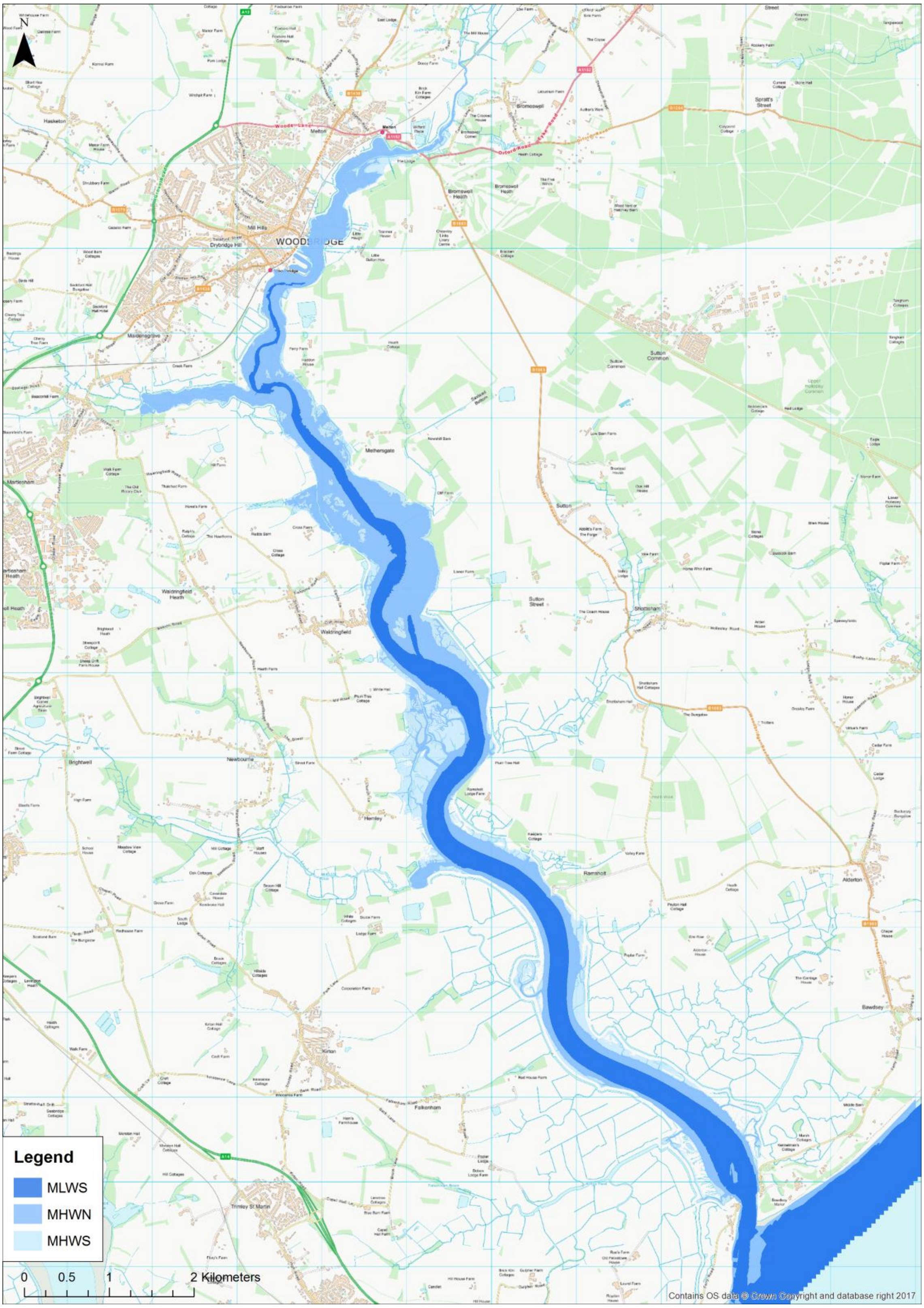

Figure 3.6. Tidal datums in the Deben Estuary

3.4 Morphological Equilibrium

3.4.1 Observed Estuary Form

Using the bathymetry and tidal datums in a GIS, the observed estuary parameters at sections spaced 200m apart were measured along the estuary in a similar way to the Alde-Ore Estuary analysis. The locations of the sections in the Deben Estuary where the observed form is measured are shown in Figure 3.7 and the data at each section is presented in Appendix F.

3.4.2 Predicted Estuary Form

The same method used to predict estuary form in the Alde-Ore Estuary (Section 2.4.2) is used in the Deben Estuary and is not repeated here. Using this method, the predicted form of the Deben Estuary at each section is presented in Appendix G.

3.4.3 Comparison of Predicted Equilibrium Widths with Observed Widths

The results were interrogated using the GIS to compare the predicted equilibrium widths (Appendix G) with the observed widths (Appendix F) at each section. The comparison for the Deben Estuary is shown in Figure 3.8 and Figure 3.9. The observed widths compare with the predicted equilibrium widths in the Alde-Ore Estuary in one of three ways:

- From the tidal limit at Bromeswell to just downstream of Martlesham Creek, and from Shottisham Creek to Ramsholt, the estuary is near to equilibrium with predicted widths similar to observed widths.
- From just downstream of Martlesham Creek to Shottisham Creek, the estuary is marginally over-sized. However, the difference between predicted and observed width is so small, it could be argued that the estuary is near equilibrium. If the latter is accepted, then the Deben Estuary from its tidal limit to Ramsholt is close to its equilibrium width.
- Downstream of Ramsholt, the Deben Estuary is under-sized compared to its predicted form (i.e. the observed channel is narrower than predicted for the present-day tidal regime). A larger scale map showing the under-sized portion of the Deben Estuary is presented in Appendix H.

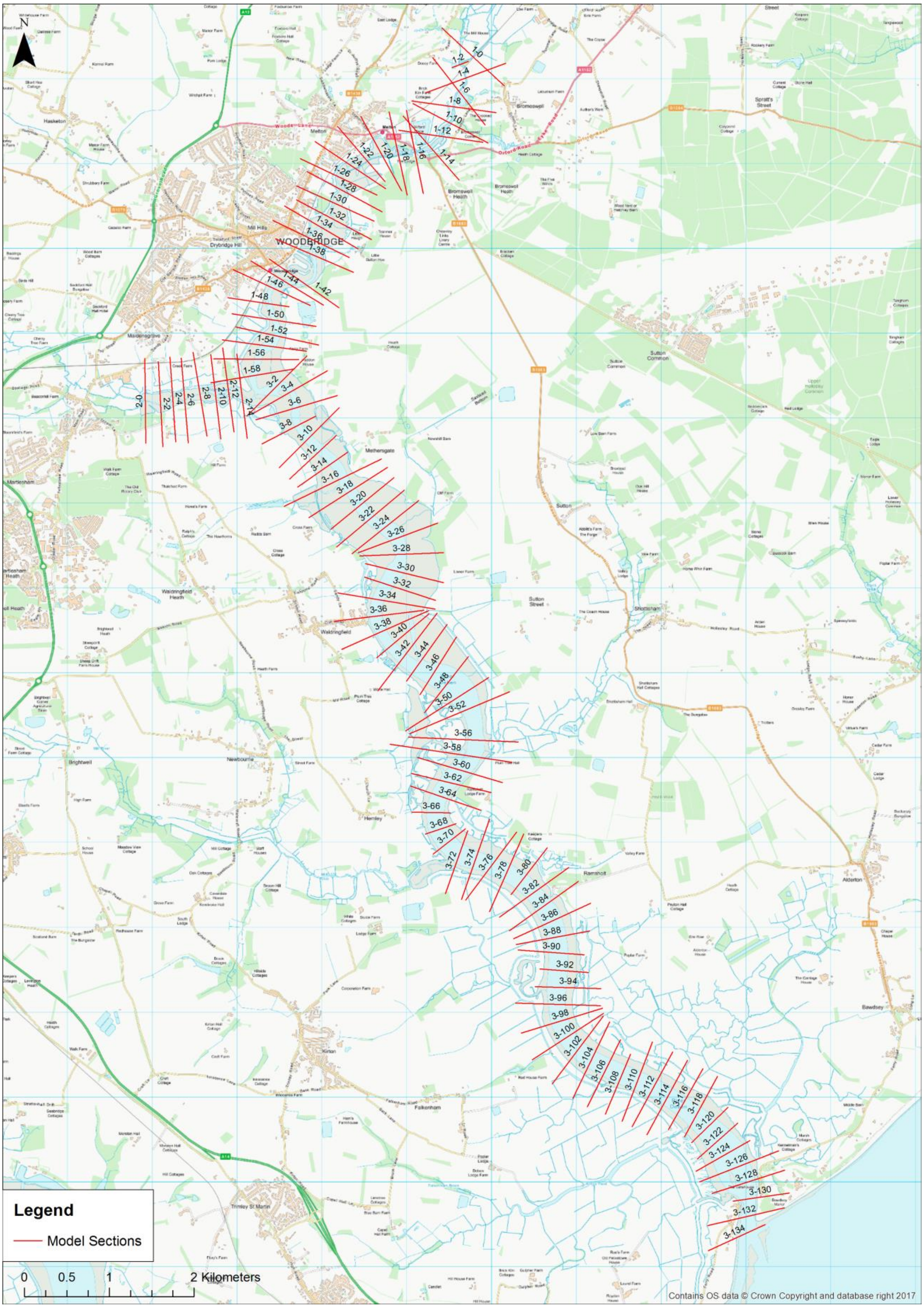

Figure 3.7. Location of sections in the Deben Estuary

Figure 3.8. Comparison of predicted equilibrium widths with observed widths in the Deben Estuary (map background)

Figure 3.9. Comparison of predicted equilibrium widths with observed widths in the Deben Estuary (aerial photograph background)

3.5 Physical Constraints to Morphological Equilibrium

The three distinct predicted equilibrium states of the Deben Estuary suggest that different parts are at different stages of adjustment to natural process inputs.

3.5.1 Under-sized Reaches

Downstream of Ramsholt to the mouth at Felixstowe Ferry the estuary is predicted as under-sized and processes will be attempting to widen the channel to establish an equilibrium width. However, there are several constraints along this reach that are not allowing the widening to take place. The meandering of the channel that occurs upstream of Ramsholt becomes more constricted downstream because of the continuous flood embankments and areas of higher ground. The flood embankments protect large areas of low-lying land-claim at Felixstowe Marshes (southwest of the channel) and Bawdsey Marshes (northeast of the channel). At the mouth of the estuary, the width is constrained by coastal defences at Felixstowe Ferry on the southwest side and coastal defences and cliffs at Bawdsey on the northeast side.

3.5.2 Reaches in Near-equilibrium

Two reaches of the Deben Estuary are predicted to be near to equilibrium, with predicted widths similar to observed widths; from the tidal limit at Bromeswell to just downstream of Martlesham Creek, and from Shottisham Creek to Ramsholt. Upstream of Martlesham Creek, the estuary is bounded by high ground to the east (including Ferry Cliff, Sutton SSSI) and the coastal defences of Woodbridge to the west. Although these features bound the channel, it appears to have enough space to allow the estuary form to adapt and equilibrate to the driving processes. The low-water channel is relatively narrow compared to the width of the adjacent intertidal areas, and upstream of Woodbridge almost completely dries out at low water. The relatively short stretch (about 3km) between Shottisham Creek and Ramsholt is the transition between the marginally over-sized upstream reach and the downstream under-sized reach. The northern end of this reach contains Ramsholt Cliff SSSI, but this appears to be only a local constraint and does not affect equilibrium.

3.5.3 Marginally Over-sized Reaches

From just downstream of Martlesham Creek to Shottisham Creek, the estuary is marginally over-sized. Along this reach, the estuary widens and the meanders lengthen compared to upstream and downstream. This reach contains relatively large areas of intertidal mudflat and saltmarsh with the flood embankments set back from the low-water channel. Recent breaches of the embankments in this marginally over-sized reach (and the upstream near equilibrium reach) have led to an increase in saltmarsh area. This has allowed a more natural cross-section/width to become established consistent with the driving forces.

3.5.4 Overall Condition of the Morphological Equilibrium Attribute

A combination of flood embankments and geological constraints control the downstream under-sizing of the Deben Estuary from Ramsholt to Felixstowe Ferry. The geological constraints, such as Bawdsey Cliff, are permanent and cannot be changed (Figure 3.10). Further upstream, the estuary is healthier with respect to morphological equilibrium with the entire reach upstream from Ramsholt either near-equilibrium or marginally over-sized.

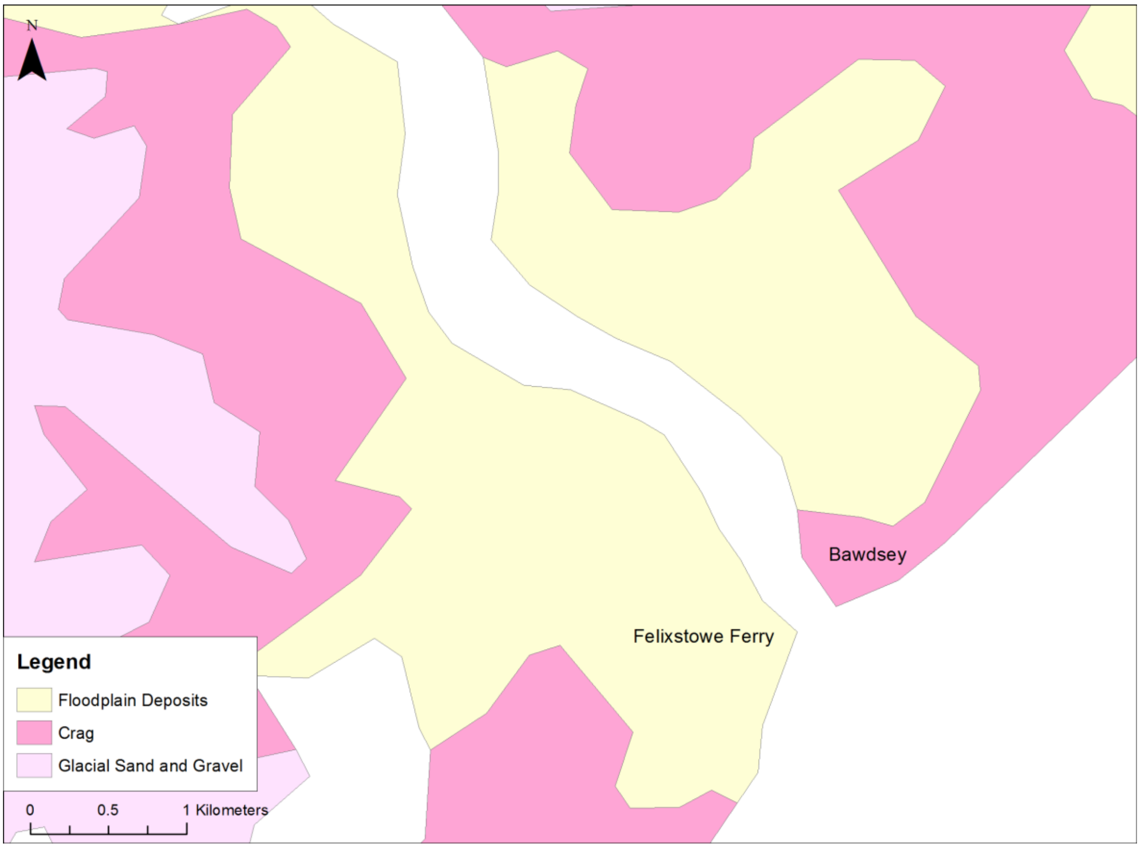

Figure 3.10. Geological constraints at Bawdsey at the mouth of the Deben Estuary. Map is based on 1:625,000 scale data from the British Geological Survey

Table 3.3 compares the Natural England condition assessments with the morphological equilibrium attribute. The condition assessments indicate that throughout the estuary the units (predominantly defined as littoral sediment) are mainly unfavourable-declining with some favourable, regardless of morphological equilibrium. Very few condition threat risks have been undertaken.

Table 3.3. Condition assessment and morphological equilibrium in the Deben Estuary SSSI

Reach	Units	Predicted Morphological Equilibrium	Overall Condition	Condition Threat Risk
Bromeswell to just downstream of Martlesham Creek	1-8	Near-equilibrium	Unfavourable-declining	Low / No assessment
Just downstream of Martlesham Creek to Shottisham Creek	9-12	Marginally Over-sized	Unfavourable-declining	None / No assessment
Shottisham Creek to Ramsholt	13-18	Near-equilibrium	Favourable (upstream) to Unfavourable-declining (downstream)	No assessment
Ramsholt to Felixstowe Ferry	19-22	Under-sized	Unfavourable-declining	No assessment

The presence or absence of flood embankments controls the equilibrium in the Deben Estuary. The under-sized reach from Ramsholt to Felixstowe Ferry is a pressure point in the estuary. This means that here the estuary form should be wider than it actually is and to obtain equilibrium it has to widen from its current form (i.e. it should erode resulting in loss of intertidal habitat if the high water mark is unable to migrate landwards).

Boyes and Thomson (2011) analysed saltmarsh change in the Deben Estuary between 2000 and 2007, and show that all units (apart from units 1 and 21) described a loss. The magnitude of this loss varied across the reaches with predicted different levels of equilibrium:

- The near-equilibrium reach from Bromeswell to just downstream of Martlesham Creek (units 1-8) showed an overall loss of 5.84ha of saltmarsh.
- The marginally over-sized reach from just downstream of Martlesham Creek to Shottisham Creek (units 9-12) showed an overall loss of 6.07ha of saltmarsh.
- The near-equilibrium reach from Shottisham Creek to Ramsholt (units 13-18) showed an overall loss of 1.53ha of saltmarsh.
- The under-sized reach from Ramsholt to Felixstowe Ferry (units 19-22) showed an overall loss of 0.63ha of saltmarsh.

The losses along the near-equilibrium and marginally over-sized reaches are counter-intuitive to what would be expected. Along these reaches, the equilibrium attribute suggests that the saltmarsh should be stable or marginally accreting.

3.6 Morphological Equilibrium and the Deben Estuary Plan

In the Deben Estuary Plan (Deben Estuary Partnership, 2015), the preferred option for the estuary downstream of Shottisham Creek is to maintain the existing defences (Hold the Line). The rationale for this policy is:

- If the defences fail at Felixstowe Ferry it is likely that the estuary channel would widen and deepen with an attendant effect on the level of erosion on the Felixstowe Ferry shore followed by an unquantifiable alteration in the behaviour of The Knolls.
- The loss of the flood embankments at either Bawdsey Marshes or Felixstowe Marshes would lead to an increase in the tidal prism and, in turn, an increase in the tidal velocities at the mouth of the estuary. This could exacerbate erosion, increasing the width and depth of the estuary mouth and placing the coastal defences at Felixstowe Ferry at increased risk.
- If the flood embankments failed at Bawdsey Marshes and Felixstowe Marshes, there would be an initial decrease in water levels within the estuary as tidal waters inundate a greater area. However, over time, the widening of the estuary mouth, combined with sea-level rise, would lead to an estuary wide increase in water levels placing low-lying areas from Woodbridge to Felixstowe Ferry at risk.

Deben Estuary Partnership (2015) advocate a management strategy that ensures the flood embankments can survive storm surge events without breaching. The proposed policy is one of ‘controlled overtopping’, which allows temporary flooding of the areas behind the flood embankment. This approach would focus on securing survivable estuary defences which are resilient to future tidal flooding. However, Deben Estuary Partnership (2015) acknowledges that, in the long term, there may be some land-claimed areas where the need may arise to consider different options, such as flood embankment realignment. This is particularly so where the current protection afforded by a fringing saltmarsh might fail in the future.

4 Hamford Water SSSI

Walton Backwaters is a tidal inlet 5km south of Harwich, covering an area of about 24km^2 comprising intertidal mudflats, saltmarsh, and numerous islands interspersed with ancient land-claims and embankments. The entrance is about 1.5km wide with a single channel through Pye Sand, known as Hamford Water. From the entrance, Hamford Water channel (north of Horsey Island) divides into various secondary channels with a dendritic pattern. One of these is Kirby Creek, between Horsey Island and Skipper's Island. A further secondary channel (Walton Channel) extends from the entrance along the eastern side of Horsey Island. At Hedge End Island, it curves to the west where is becomes Twizzle Creek.

Walton Backwaters has large areas of saltmarsh with some degree of fragmentation and highly dissected areas. Over 10km^2 of saltmarsh has been land-claimed within Walton Backwaters in the past, although many of the enclosing embankments have been breached to allow the enclosed areas to revert back to saltmarsh.

4.1 Extent of Study Area and Designations

Hamford Water is designated for its many features of conservation interest, covered by SSSI, NNR, SAC, SPA and Ramsar. Parts are also managed nature reserves within the site. The Hamford Water SSSI has an area of 21.89km^2 (2,189ha) (Figure 4.1) and contains 28 units (Appendix B) with features in either favourable condition (28%, 6km^2) or unfavourable-recovering condition (72%, 16km^2) (Table 4.1). The conservation objectives state that, subject to natural change, the listed habitats (intertidal mudflats and sandflats, shell, sand and gravel shores, and saltmarsh communities) should be maintained in favourable condition.

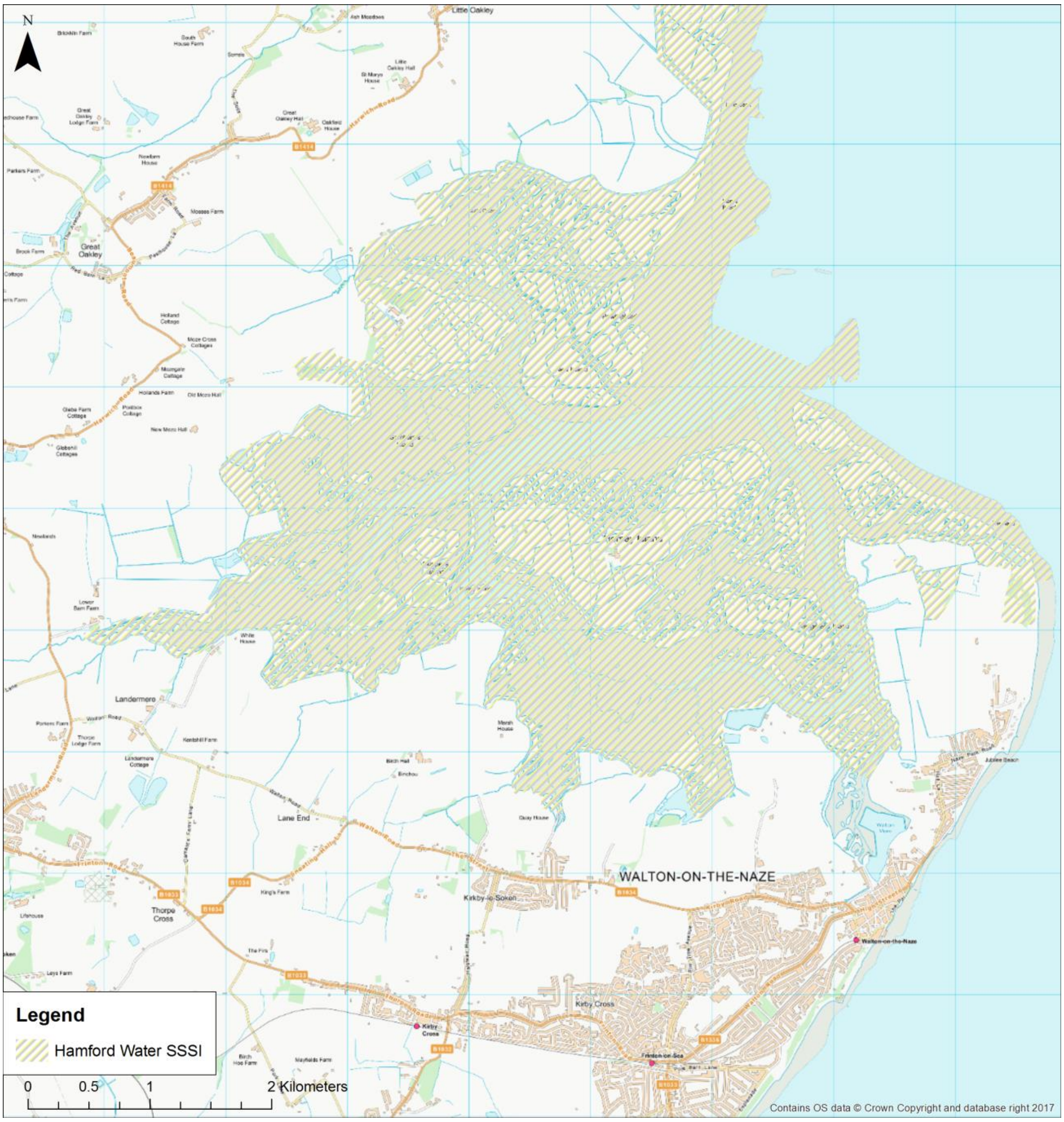

Figure 4.1. Extent of the Hamford Water SSSI

Table 4.1. Overall unit condition assessment in the Hamford Water SSSI

Size	Favourable	Unfavourable-Recovering	Unfavourable-No Change	Unfavourable-Declining
Area (km^2)	6.10	15.78	0.00	0.00
Percentage	27.89	72.11	0.00	0.00

4.2 Bathymetry

The bathymetric surface in Hamford Water was created using a variety of datasets and the artificial creation of several channels based on expert geomorphological assessment where no data existed. The same methods as those applied to the Deben Estuary were applied to Hamford Water, including open source LiDAR data from the Environment Agency (Figure 4.2), open source multibeam echosounder data from the Environment Agency recorded in 2013 (Figure 4.3), and single beam echosounder dataset recovered by UKHO (2004-2007) (Figure 4.4).

Some intertidal areas of Hamford Water that are included in the assessment but are not immediately obvious include (Figure 4.5):

- Small intertidal area behind the seawall at Skipper's Island which is fed with water through a sluice in the seawall that has been stuck open. At low tide some water does remain within the old borrow dyke behind the seawall, so the estimated tidal exchange is about 80-90%;
- Tidal exchange to a small area behind the seawall at Horsey Island, with water entering and exiting through a pipe in the seawall. At low tide some water does remain behind the seawall, so the estimated tidal exchange is about 90-95%; and
- Managed realignment at Devereux Farm with the site inundated through the 50m-wide Rigdons breach. There is a pipe through the Rigdons closure bank, which has created an area of intertidal habitat to the south of the bank.

All the data were merged together (Figure 4.6) to create the overall bathymetry for Hamford Water SSSI used in the analysis. The bathymetry data covers all intertidal and subtidal areas up to the seaward face of the front-line defences or up to the MHWS datum where the coastal plain rises naturally into the hinterland, and stretches from as close to the upstream tidal limits as possible to the defined downstream boundaries.

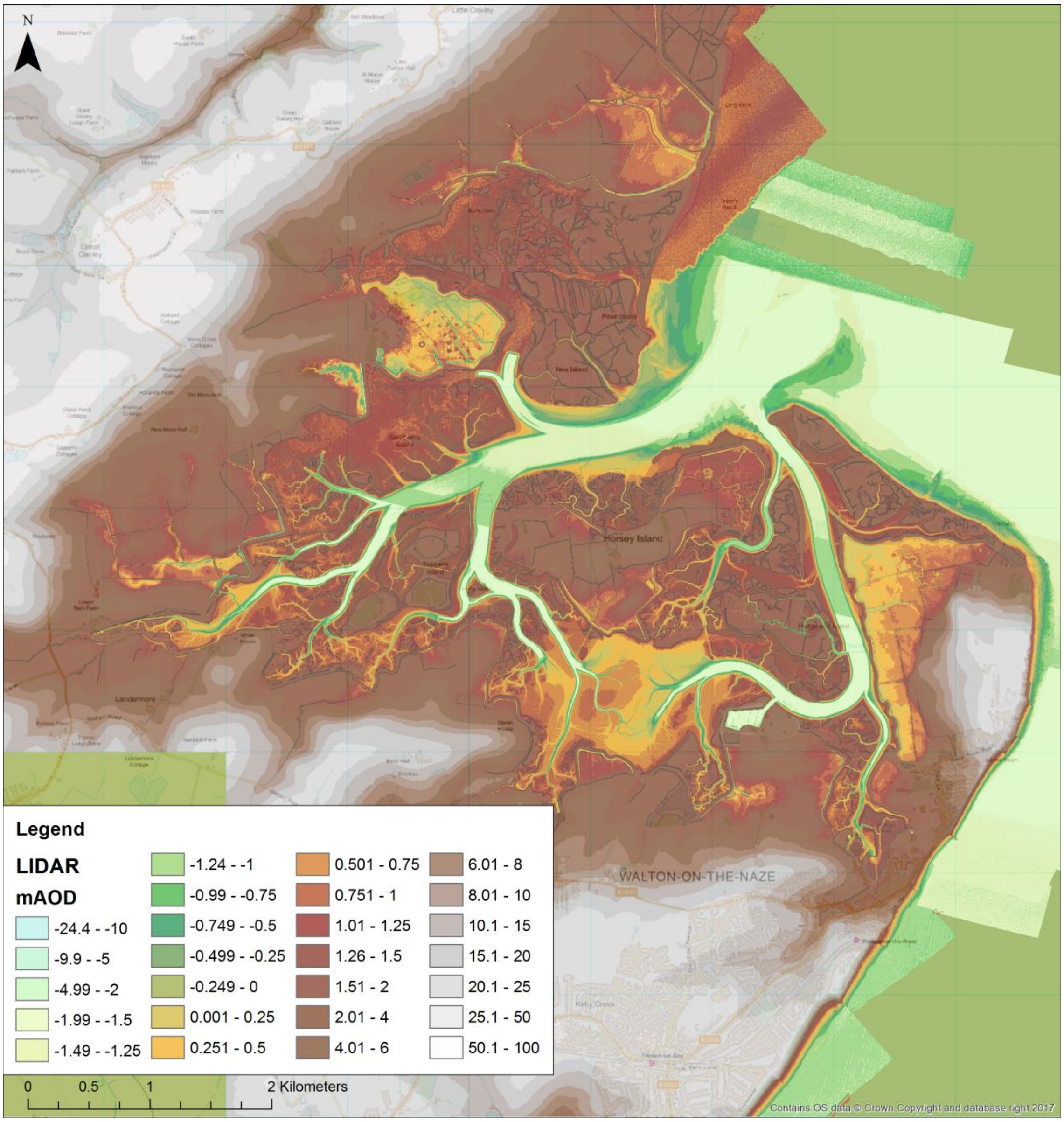

Figure 4.2. Environment Agency LiDAR data in Hamford Water (http://environment.data.gov.uk/ds/survey/index.jsp#/survey)

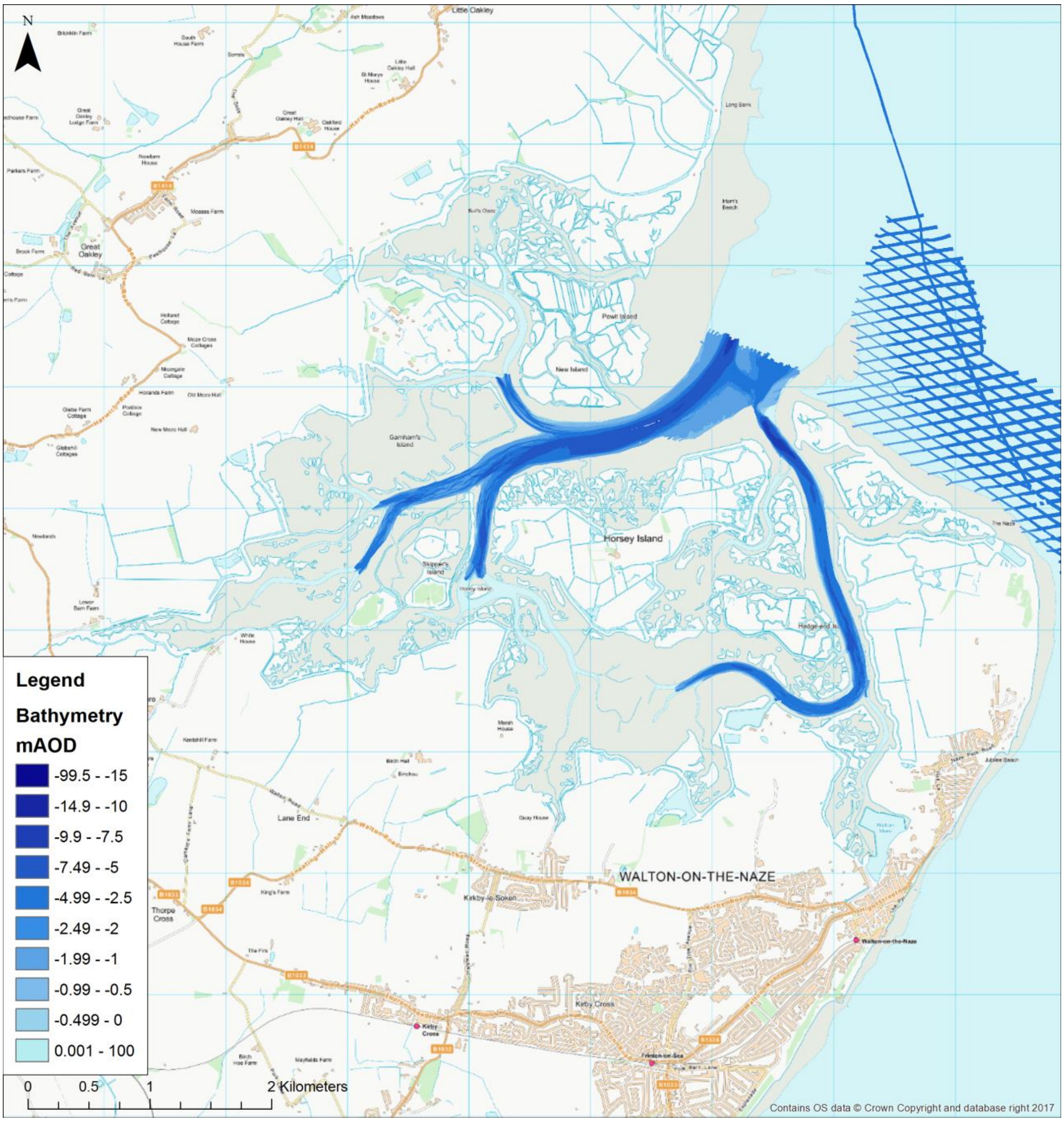

Figure 4.3. Environment Agency multibeam echosounder data in Hamford Water (http://environment.data.gov.uk/ds/survey/index.jsp#/survey)

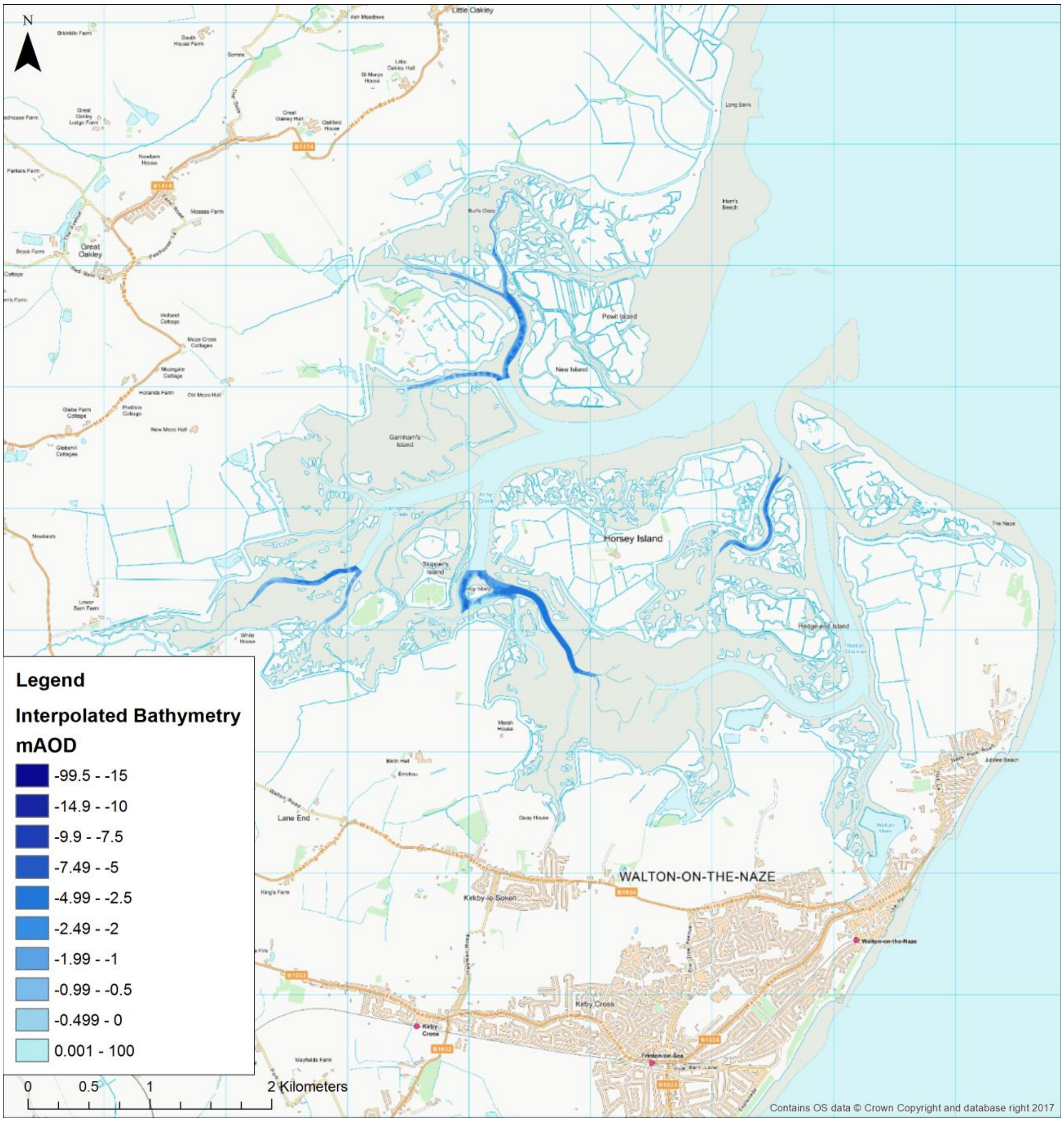

Figure 4.4. UKHO bathymetry data in Hamford Water (http://aws2.caris.com/ukho/mapViewer/map.action)

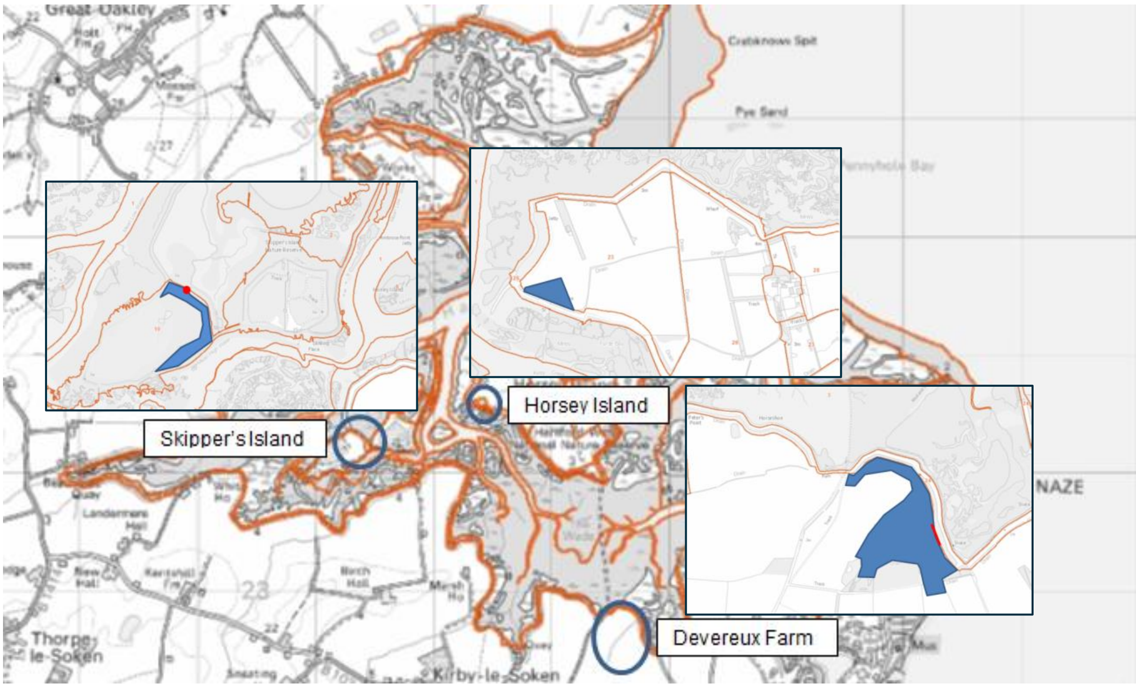

Figure 4.5. Locations of intertidal areas not immediately obvious in the bathymetric data. Red shows the locations of a sluice (Skipper's Island), pipe (Horsey Island) and breach (Rigdons breach at Devereux Farm)

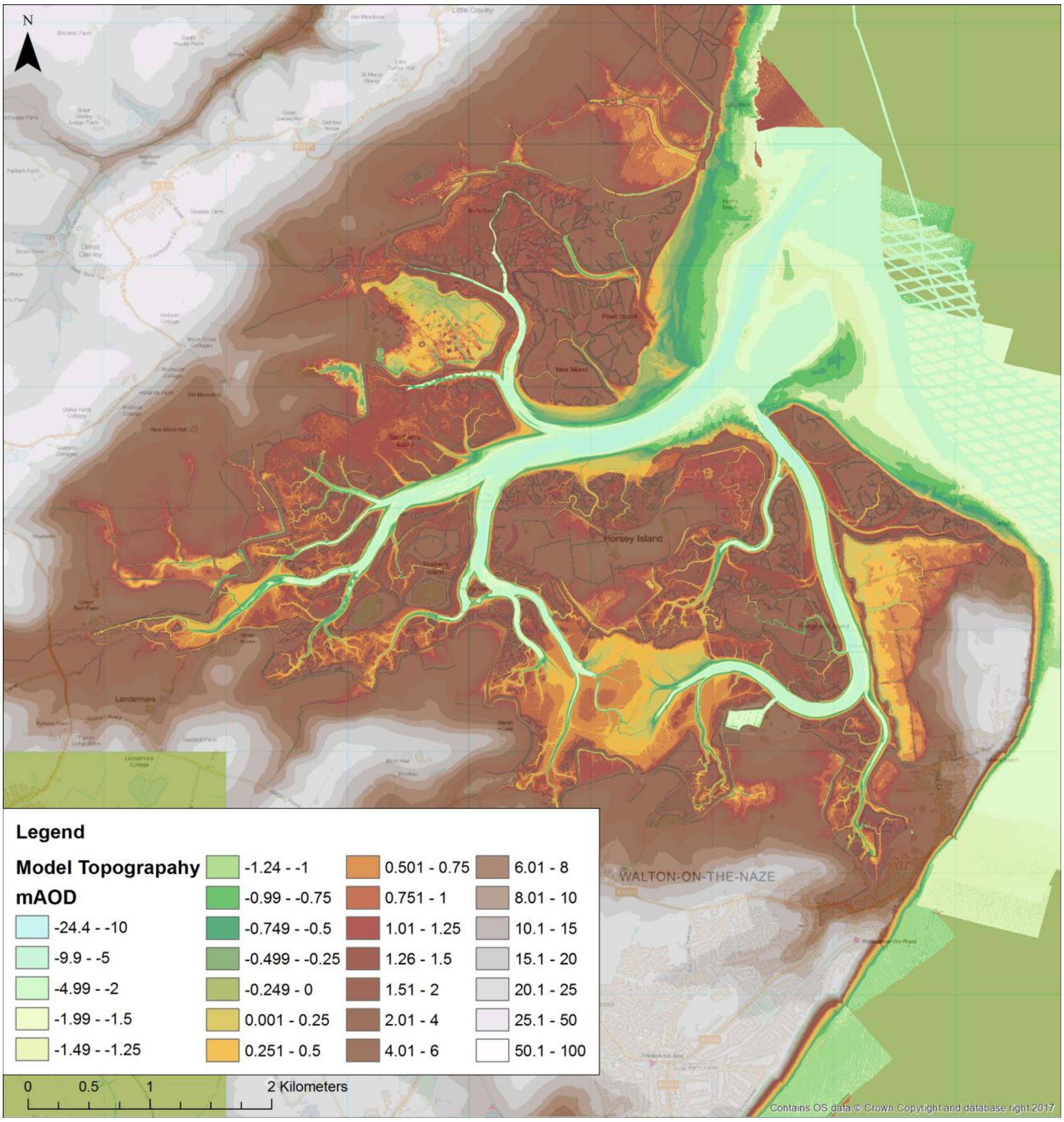

Figure 4.6. Combined LiDAR, multibeam echosounder and single beam echosounder data in Hamford Water

4.3 Tidal Regime

In order to calculate the spring tidal prism and cross-sectional area of Hamford Water it is necessary to know the elevations of tidal datums. Table 4.2 presents the MHWS, MHWN and MLWS tidal datum elevations at tidal stations along Hamford Water. Figure 4.7 shows the tidal datum surfaces transposed on to the bathymetry of Hamford Water.

Table 4.2. Tidal datums in Hamford Water relative to Ordnance Datum (OD) (2017 Admiralty Tide Tables)

Tidal Station	Coordinates		Mean High Water Spring Tide (m OD)	Mean High Water Neap Tide (m OD)	Mean Low Water Neap Tide (m OD)	Mean Low Water Spring Tide (m OD)
	Longitude	Latitude				
Bramble Creek	1.2333	51.8833	2.40	1.60	-0.70	-1.40

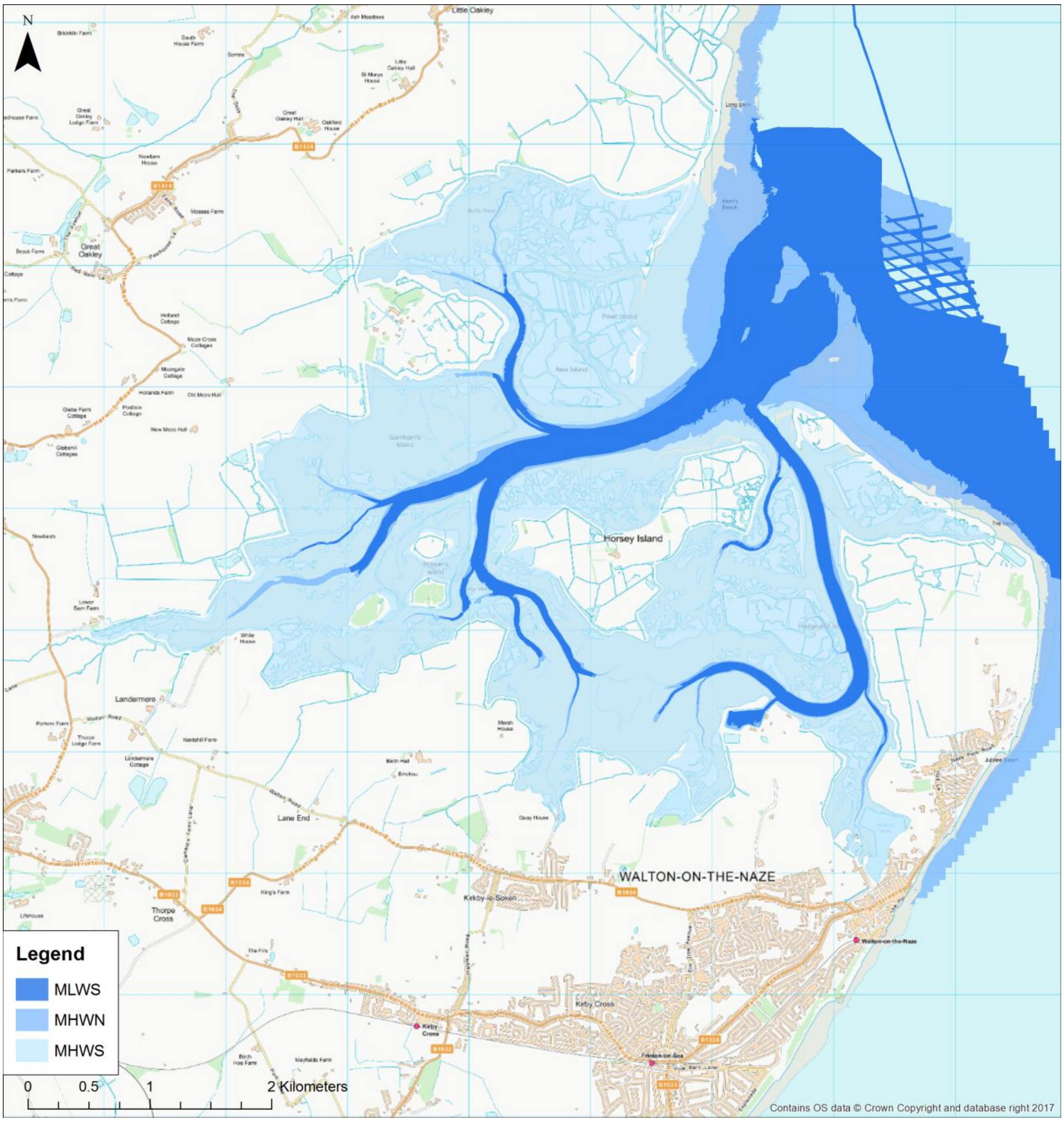

Figure 4.7. Tidal datums in Hamford Water

4.4 Morphological Equilibrium

4.4.1 Observed Estuary Form

Using the bathymetry and tidal datums in a GIS, the observed estuary parameters at sections spaced 200m apart were measured along the tidal inlet in a similar way to the Alde-Ore Estuary and Deben Estuary analyses. The main difference between Hamford Water tidal inlet and the estuaries is the larger number of channels draining the inlet and their separation by areas of saltmarsh at or below the elevation of MHWS. This presents difficulties in compartmentalisation of the inlet in order for the spring tidal prism to be split logically to drive the equilibrium profiles of the neap channels. The difficulty was that between channels, the saltmarsh areas are flooded on spring tides, and so the tidal prism that floods and drains these areas has to be attributed to both of the tidal channels to either side of it. The key was to place the 'tidal watersheds' at locations across the saltmarsh so that the tidal prism is shared appropriately between each channel.

The locations of the sections in Hamford Water where the observed form is measured and the locations of the tidal watersheds are shown in Figure 4.8 and the data at each section is presented in Appendix I.

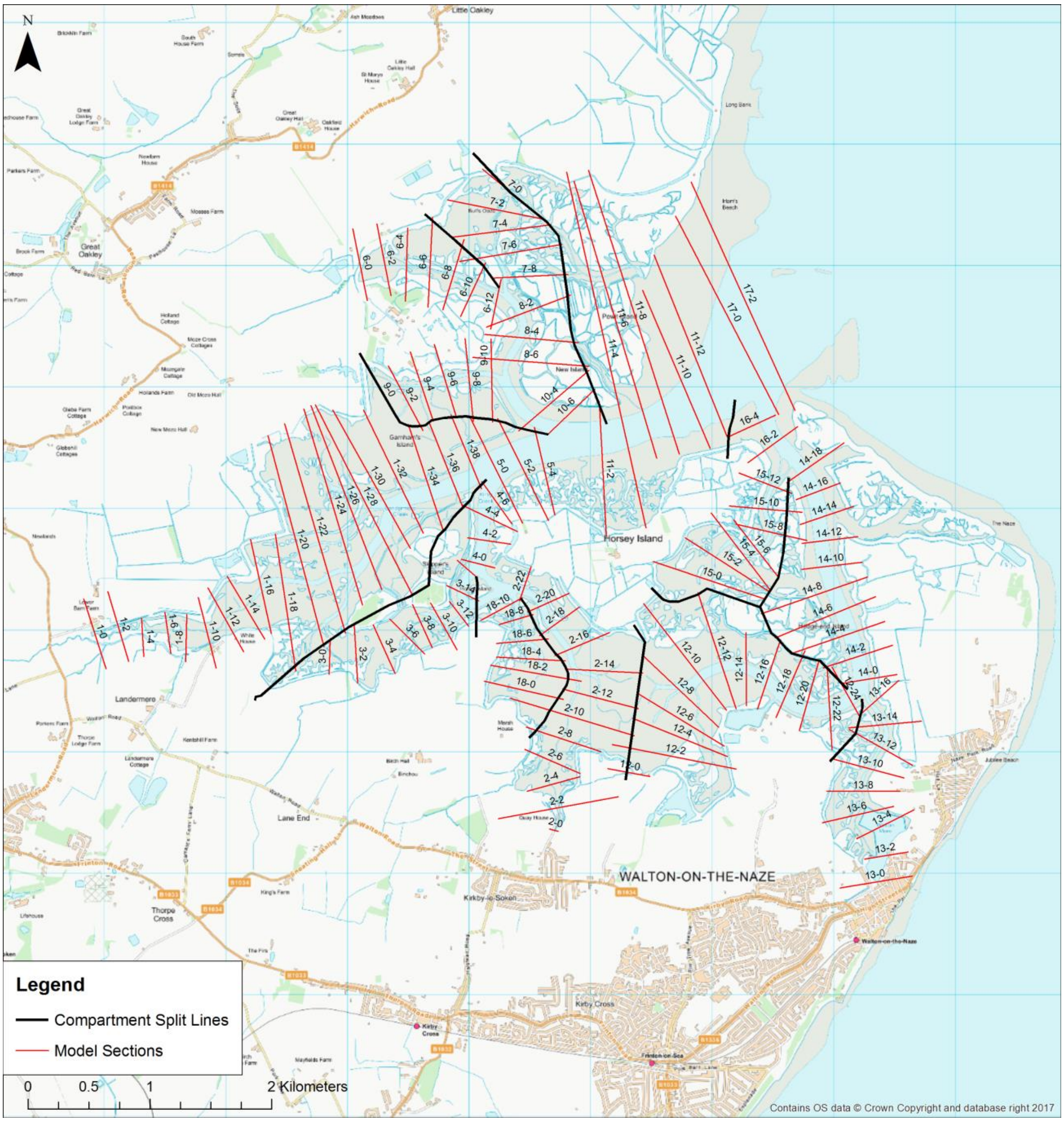

Figure 4.8. Location of sections in Hamford Water. The black lines are the locations of the 'tidal watersheds' driving the tidal prism along the adjacent channels

4.4.2 Predicted Estuary Form

The same method used to predict estuary forms in the Alde-Ore Estuary and Deben Estuary (Sections 2.4.2 and 3.4.2) is used in Hamford Water and is not repeated here. Using this method, the predicted form of Hamford Water at each section is presented in Appendix J.

4.4.3 Comparison of Predicted Equilibrium Widths with Observed Widths

The results were interrogated using the GIS to compare the predicted equilibrium widths (Appendix J) with the observed widths (Appendix I) at each section. In this way, reaches of the observed estuary which are narrower or wider than their predicted form were mapped. The comparison for Hamford is shown in Figure 4.9 and Figure 4.10. Along all the main and secondary channels the estuary is under-sized compared to its predicted form (i.e. the observed channel is narrower than predicted for the present-day tidal regime).

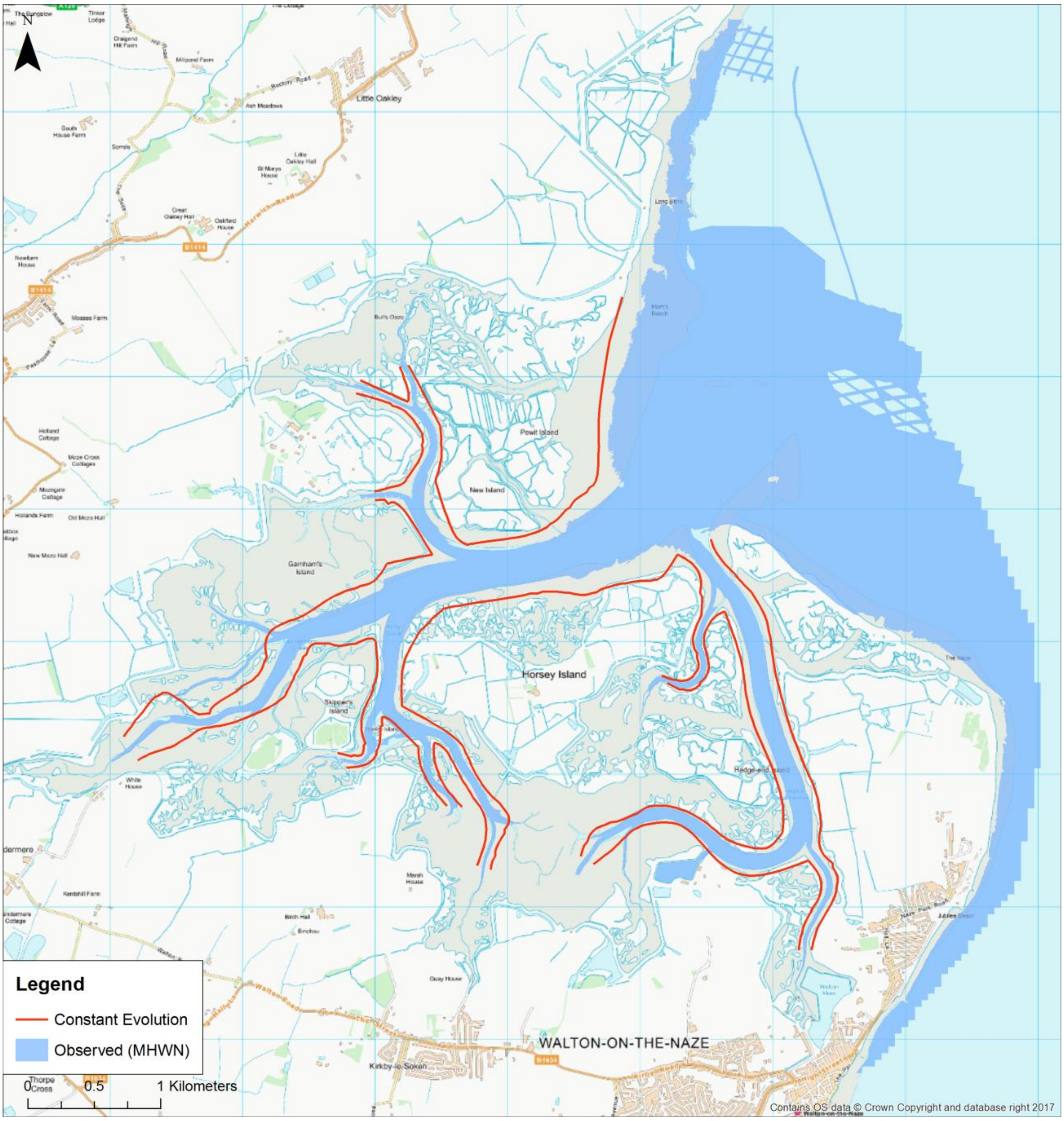

Figure 4.9. Comparison of predicted equilibrium widths with observed widths in Hamford Water (map background)

Figure 4.10. Comparison of predicted equilibrium widths with observed widths in Hamford Water (aerial photograph background)

4.5 Physical Constraints to Morphological Equilibrium

The single distinct equilibrium state of Hamford Water suggests that the entire system is at a similar stage of adjustment to natural process inputs. The entire tidal inlet is predicted as under-sized and processes will be attempting to widen it to establish an equilibrium width. However, it is not possible for the channels to widen because of flood embankment constraints. The shores of Hamford Water are dominated by wide areas of active saltmarsh behind which are former floodplains, which are protected from inundation at high water by flood embankments. The flood embankments currently artificially constrain the natural widening of the system.

4.5.1 Overall Condition of the Morphological Equilibrium Attribute

A continuous line of flood embankments around the periphery of Walton Backwaters and Horsey Island control the equilibrium throughout the system. In order to allow wider channels to develop in keeping with the equilibrium form may necessitate realignment of the embankments to restore former land-claimed intertidal areas to tidal processes. English Nature (2006) analysed saltmarsh change in Hamford Water SPA between 1988 and 1998. They showed that in 1988, the estimated area of saltmarsh in Hamford Water was 758.5ha. In 1998, 144.2ha had been lost (20%) to leave 614.3ha, equating to an average rate of loss of 14.42 ha/year over the ten year period. Conversely, Thomson et al. (2011) showed that in 1997, there was 694.8ha of saltmarsh present in the Hamford Water SSSI. By 2008, a total of 30.8ha had been lost due to erosion throughout the SSSI, with 34.1ha gained through accretion. This resulted in a net gain of 3.3ha by 2008 (0.30ha/year), representing 0.5% of the total area in 1997. This was a different outcome compared to the loss of 14.42ha/year recorded by English Nature (2006).

The Natural England condition assessments compared to the morphological equilibrium attribute are shown in Table 4.3. The condition assessments indicate that throughout the estuary the conditions of the units (predominantly defined as littoral sediment) are predominantly unfavourable-recovering with medium condition risk threat.

Table 4.3. Condition assessment and morphological equilibrium in Hamford Water SSSI

Reach	Units	Predicted Morphological Equilibrium	Overall Condition	Condition Threat Risk
Hamford Water	1-9	Under-sized	Unfavourable-recovering	Medium

Currently, the Shoreline Management Plan (Royal Haskoning, 2010) is dominated by hold the line policies but does contain several managed realignment policies for some reaches of the tidal inlet that could act as drivers to move the system towards morphological equilibrium (Table 4.4 and Figure 4.11). The Shoreline Management Plan policies are to maintain flood defence to the majority of the defended land, including properties and infrastructure at risk of flooding, whilst also allowing coastal and estuarine processes to act in a less constrained manner by realigning flood embankments that are under pressure.

Table 4.4. Potential managed realignment sites in Hamford Water (Royal Haskoning, 2010)

Coastal Stretch	Management Unit	Epoch 1	Epoch 2	Epoch 3
South Dovercourt	B1	HTL	HTL	HTL
Little Oakley	B2	HTL	**MR**	HTL
Oakley Creek to Kirby-le-Soken	B3	HTL	HTL	HTL
Horsey Island	B3a	HTL	HTL	**MR**

Kirby-le-Soken to Coles Creek	B4a	**MR**	HTL	HTL
Coles Creek to the Martello Tower	B4b	HTL	HTL	HTL
Walton Channel	B5	HTL	HTL	**MR**

Figure 4.11. Shoreline Management Plan policies for Hamford Water (Royal Haskoning, 2010). Green is hold the line and yellow is managed realignment

The defences that are under pressure from coastal change are at Little Oakley, Horsey Island, Devereux Farm and Walton Channel (Management Units B2, B3a, B4a and B5) and a landward realignment would create a more sustainable situation by reducing the pressure from the channels on the defences and moving towards a more natural estuary with increase of tidal prism and intertidal area. The realignment for Devereux Farm (B4a) was proposed in 2010 for Epoch 1 and has now been implemented. Realignment is proposed for Epoch 2 (possibly Epoch 1) for Little Oakley (B2), and Epoch 3 for Horsey Island (B3a), and Walton Channel (B5).

5 Conclusions

An understanding of how the Alde-Ore Estuary, Deben Estuary and Hamford Water function is essential to ensure sustainable human uses of them into the future. This work was based on the assumption that the 'health' or condition of these estuaries is founded on the relationship between their physical forms (geometry) and the forces driving their forms (function/process) in line with the Regime Theory concepts and approaches developed by the Healthy Estuaries 2020 project (Natural England, 2015).

To support habitat in favourable condition, the estuary morphologies need to be in equilibrium with natural wave, tidal and sediment transport processes. Over time, these three estuaries have had their dynamic equilibrium morphologies changed in some way by human interference and different parts of their forms are at different stages of adjustment to natural process inputs. Hence, into the future all the estuaries will seek to reach a steady state over the long term and their widths and depths will change over time towards a state of dynamic equilibrium or 'most probable state'.

Regime Theory has been used in the Alde-Ore Estuary, Deben Estuary and Hamford Water to predict their equilibrium widths, which have been compared with their observed widths to determine, at a high level, how far they are from equilibrium forms. How close each estuary is to morphological equilibrium defines the condition of this attribute. The method has been combined with known natural and human constraints on morphology, where adjustment of the estuary form may not be possible due to hard geology or essential infrastructure. The method also supports identification of potential locations to restore intertidal habitat in such a way that a more sustainable estuary form is produced.

6 References

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Appendix A: Regime Theory and its Application

General Principles of Regime Theory

Regime Theory is based on empirical relationships between estuary properties that reflect their size and shape. The most widely used of these regime relationships is between channel cross-sectional area and upstream tidal prism (or discharge). This relationship, first proposed by O'Brien (1931), is between the spring tidal prism (the volume of water that enters and leaves the estuary during a spring tide) and the cross-sectional area at mean sea (tide) level at the mouth. This equation takes the form:

$$CSA = a.P^{b}$$

where:

CSA = cross-sectional area (mean sea level);
P = upstream spring tidal prism;
a = constant coefficient; and
b = constant exponent.

In the regime equation adopted in the Alde-Ore Estuary, Deben Estuary and Hamford Water SSSIs, the cross-sectional area at MHWN tide is used instead of mean sea level. This is because MHWN tide is deemed to be the boundary of the active estuarine channel geomorphology, because when the water level is at this datum, maximum discharge takes place (immediately before inundation of the saltmarsh). Areas higher than MHWN tide within the tidal environment will have tidal current velocities that approach zero.

Applying Regime Theory to Inter-estuary Analysis

When the regime relationship is applied to a number of estuaries it is found to be linear when both datasets are transformed into their log values. The best-fit regression line that is constructed through a log-log plot represents the theoretical equilibrium morphology for those estuaries in general. This theoretical equilibrium has been applied successfully across a range of estuaries in the United Kingdom. Townend et al. (2000) described an empirical regime relationship for 66 estuaries around the United Kingdom coast (Figure A.1). The regression (regime) equation for the whole dataset is:

$$CSA = 0.024.P^{0.71} \ (r^2 = 0.75)$$

This is the regression equation that was used in the Alde-Ore Estuary, Deben Estuary and Hamford Water SSSIs.

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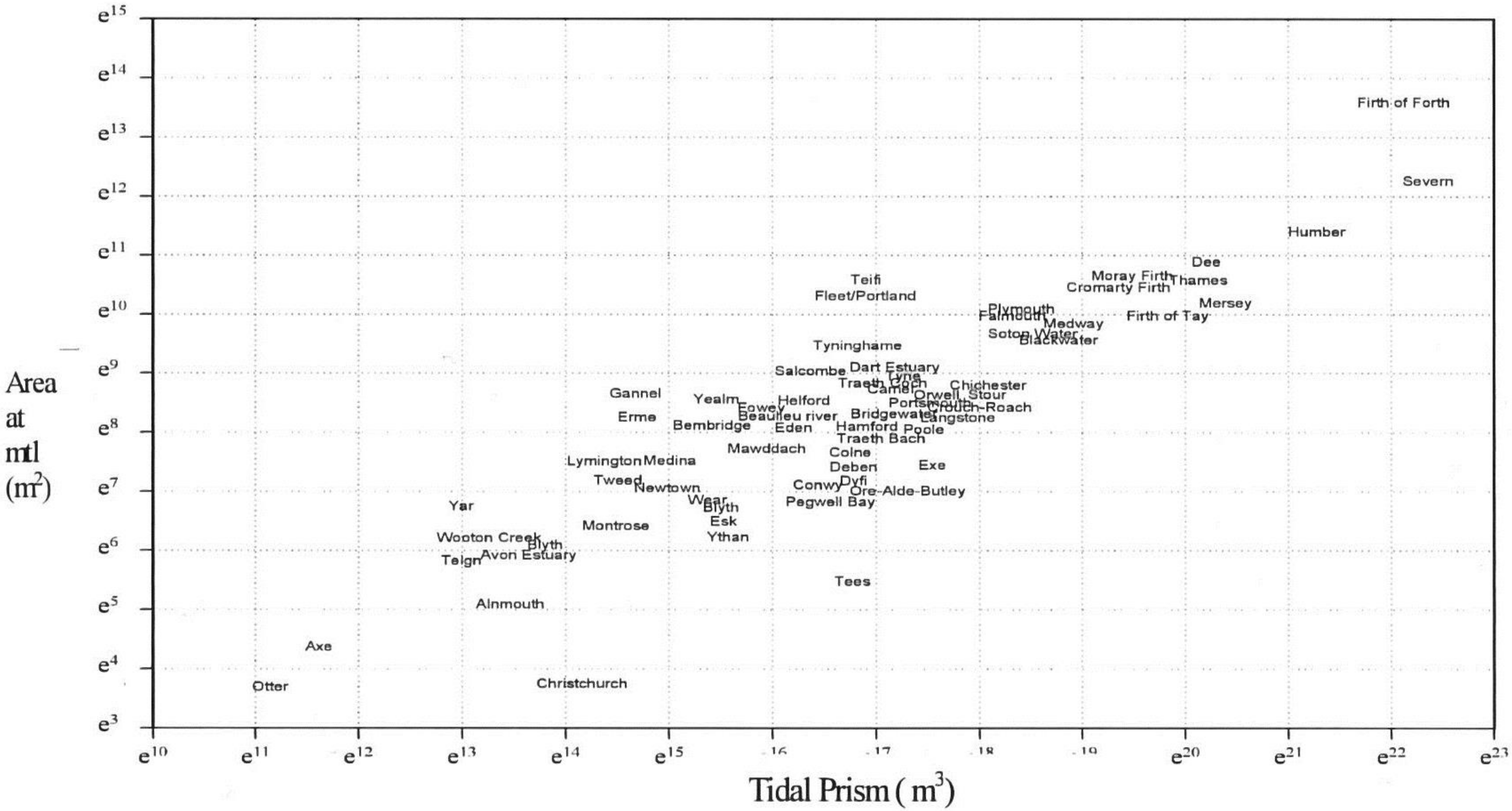

Figure A.1. Tidal prism – cross-sectional area relationship for 66 estuaries around the United Kingdom coast (from Townend et al., 2000)

Figure A.1 shows that although individual estuaries may depart from the ideal relationship between flow (tidal prism) and form (cross-section) (i.e. a linear regression line through the data) due to, for example human intervention or natural constraints such as geology, these departures will form a random scatter around the fundamental relationship that can be expressed as the best-fit regression to the data. The relationship is in this way, a useful tool to describe the overall condition of a given estuary compared to others in a regional group (but see uncertainties below).

Applying Regime Theory to Intra-estuary Analysis

As well as being applicable between estuaries, the relationship can equally be applied within a single estuary. Thus a downstream increase in tidal prism in a given estuary will be matched by an increase in the cross-sectional area of successive channel profiles. This provides a measure of the equilibrium morphology of an estuary along its length and a tool to assess condition by determining how the tidal prism / channel cross-sectional area relationship changes with distance along the estuary.

Uncertainties with Regime Theory

The Regime Theory only requires geometric and water level information to be used as inputs. This is so the method is simple to apply. HR Wallingford et al. (2007) showed that the use of only bathymetry as input to the method is an oversimplification because it does not take into account other important mechanisms controlling estuary evolution. These may include the effects of waves, fluvial discharge, longshore sediment transport and geology.

The potential weakness of the method related to these parameters is acknowledged, but it is beyond the scope of this study to include what are more complicated mathematical formulae (which are still not fully understood and to date haven't been applied successfully). It is understood that the level of uncertainty in the regime equation is important for understanding the uncertainty in the corresponding equilibrium predictions arising from its use.

Methods used to Predict Estuary Equilibrium Form in the Alde-Ore Estuary, Deben Estuary and Hamford Water

The two main parts to the analysis in the Alde-Ore Estuary, Deben Estuary and Hamford Water are:

1 Measure the observed forms; and

2 Predict the equilibrium forms.

These two forms are then compared to see how close the estuaries are to morphological equilibrium.

Development of Sections and Observed Estuary Form

The observed (present-day) cross-sectional area and tidal prism have been calculated in each estuary using the bathymetric datasets relative to the tidal elevations at specific sections along each of the estuaries. The number of sections is typically determined by the size of the estuary. Given the relatively small scales of the three estuaries, the spacing's of the sections are approximately 200m in each. The sections stretch between MHWS tide on either side of the estuary and are perpendicular (as far as possible) to a line along the centre of the channel. It is then possible to create a table in GIS with values for each estuary parameter calculated at each section. This data is defined as the observed morphology of the estuary (Appendices C, E and G).

Morphological Equilibrium based on the Predicted Estuary Form

In order to provide a preliminary assessment of the condition of the morphological equilibrium attribute, the observed forms of the estuaries are compared to the equilibrium forms predicted using a set of calculations at each of the sections originally defined in the measurement of observed form. The prediction of the equilibrium forms was carried out in three main stages using the methodology developed for Healthy Estuaries 2020 (Natural England, 2015):

- distribute throughout the estuary the total observed tidal prism at the mouth to predict the tidal prism upstream of each section;
- calculate equilibrium cross-sectional areas from the upstream tidal prisms at each section; and
- calculate mean depths and equilibrium widths at each section.

The calculations of predicted form are automated in the Excel tool and the outputs defined as the predicted morphology of the estuary (Appendices D, F and H). The results obtained are then interrogated using GIS to compare the predicted form with the observed form at each section to gauge how far from equilibrium the estuary is.

Distributing the Observed Tidal Prism at the Mouth throughout the Estuary

One result of the measurement of observed form using GIS is the spring tidal prism of the entire estuary (i.e. the tidal prism observed at the estuary mouth). In order to predict the equilibrium form of the estuary at each section this total tidal prism has to be distributed throughout the estuary from its mouth to its head. The tidal prism at each section is calculated using an equal distribution model with the following equation:

$$P_x = e^{[-3.(x/l)]}.P_{tot}$$

where:

P_x = tidal prism at each section (m^3);
x = distance to section from estuary mouth (m);
l = total estuary length from mouth to head (m); and
P_{tot} = total tidal prism (observed) (m^3).

This equation distributes the total tidal prism along the estuary according to distance from the mouth. The calculation of tidal prism upstream of a particular section from the mouth is based on a cubic exponent, which is multiplied by the ratio of the distance to the section from the mouth (x) and the total length of the estuary (l). The ratio x/l is a non-dimensional distance along the estuary axis; i.e. it varies from 0 at the mouth to 1 at the head. The use of an exponential set at 3 has been verified by empirical calibration using United Kingdom estuaries (unpublished).

The calculation of P_x is straightforward in an estuary with a single channel. However, an estuary typically has a main channel with one or more smaller channels joining it, which makes the designation of x and l in the equation complicated. For example, all the estuaries have major channels with smaller channels joining at points along their lengths. In this situation, the equal distribution equation is first applied to each joining channel; the tidal prism is apportioned based on the observed tidal prism at the channel mouths with l as the total channel length. The equation is then applied to the main channel only, but the observed tidal prism at the mouth is reduced by the sum of the observed tidal prisms at the mouths of the joining channels. The sum of the tidal prisms of the joining channels is then added back on to the predicted tidal prism at each section of the main channel. The calculation of tidal prism at each section is automated in the Excel tool from files imported directly from GIS.

Calculating Equilibrium Cross-sectional Areas

The calculation of equilibrium cross-sectional area from predicted tidal prism at each section is based on the regime equation for all United Kingdom estuaries:

$$CSA = 0.024.P^{0.71} \; (r^2 = 0.75)$$

Predicting Estuary Width using the 'Constant Evolution' Method

Using the regime equation the equilibrium cross-sectional area at each section is predicted. However, the crucial parameter in the assessment is regime width (planform). In order to predict the regime width from the equilibrium cross-sectional area, it is necessary to predict the equilibrium mean depth. In this study, the 'constant evolution' method is used as described in Healthy Estuaries 2020 (Natural England, 2015).

One of the main difficulties with Regime Theory is that in most cases, an estuary system does not conform to a smooth relationship of the type:

$$CSA = a.P^{b}$$

Instead an estuary presents considerable scatter around a best fit relationship of that form. Adopting the best fit relationship and implementing the regime equation to derive the equilibrium cross-sectional area of an estuary may provide results that are driven mainly by the scatter in the data and the uncertainty inherent in the method (Spearman, 1995, 2001; HR Wallingford et al., 2007).

To overcome this problem, Spearman (2001) suggested that the discrepancies between the observed estuary cross-sectional area and the equilibrium cross-sectional area given by the regime equation at each section are held to be constant throughout the evolution. In this way the observed cross-sectional area at each section is assumed to be in regime (for reasons that are not fully understand) and is adjusted in proportion to the relative change between its form and the equilibrium form (HR Wallingford et al., 2007).

Using this methodology it is possible to predict mean depths and equilibrium widths based on the relationship between the observed and predicted cross-sectional areas at each section. Equilibrium width is predicted using the observed mean depth to width ratio at each section and applying the same ratio to the predicted cross-sectional area:

$$W_E = (CSA_E.W_O/D_O)^{0.5}$$

where:

W_E = equilibrium width (m);
CSA_E = equilibrium cross-sectional area (m^2);
W_O = observed width (m); and
D_O = observed mean depth (m).

The same principle can be applied to calculate equilibrium mean depth:

$$D_E = (CSA_E/[W_O/D_O])^{0.5}$$

where:

D_E = equilibrium mean depth (m).

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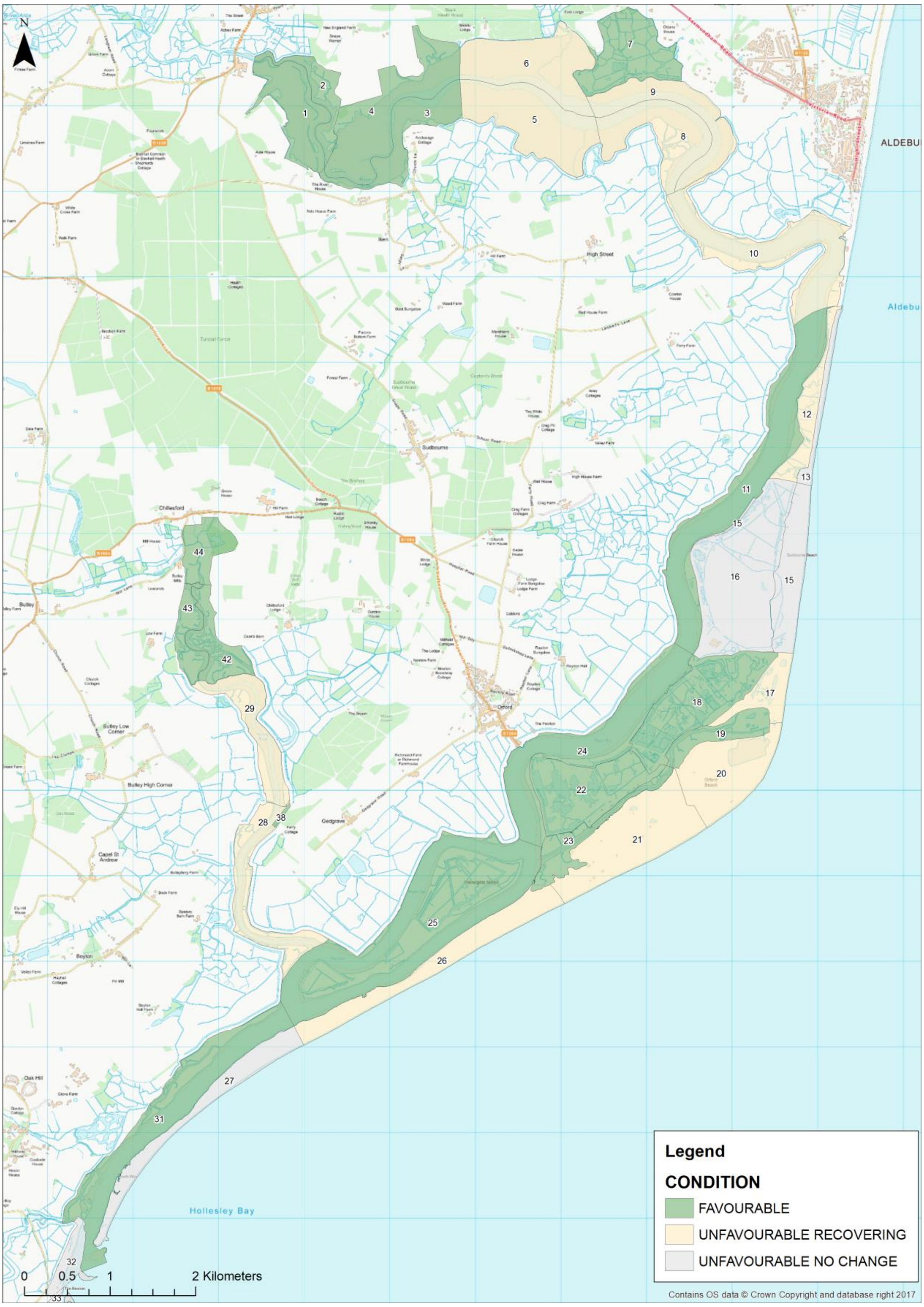
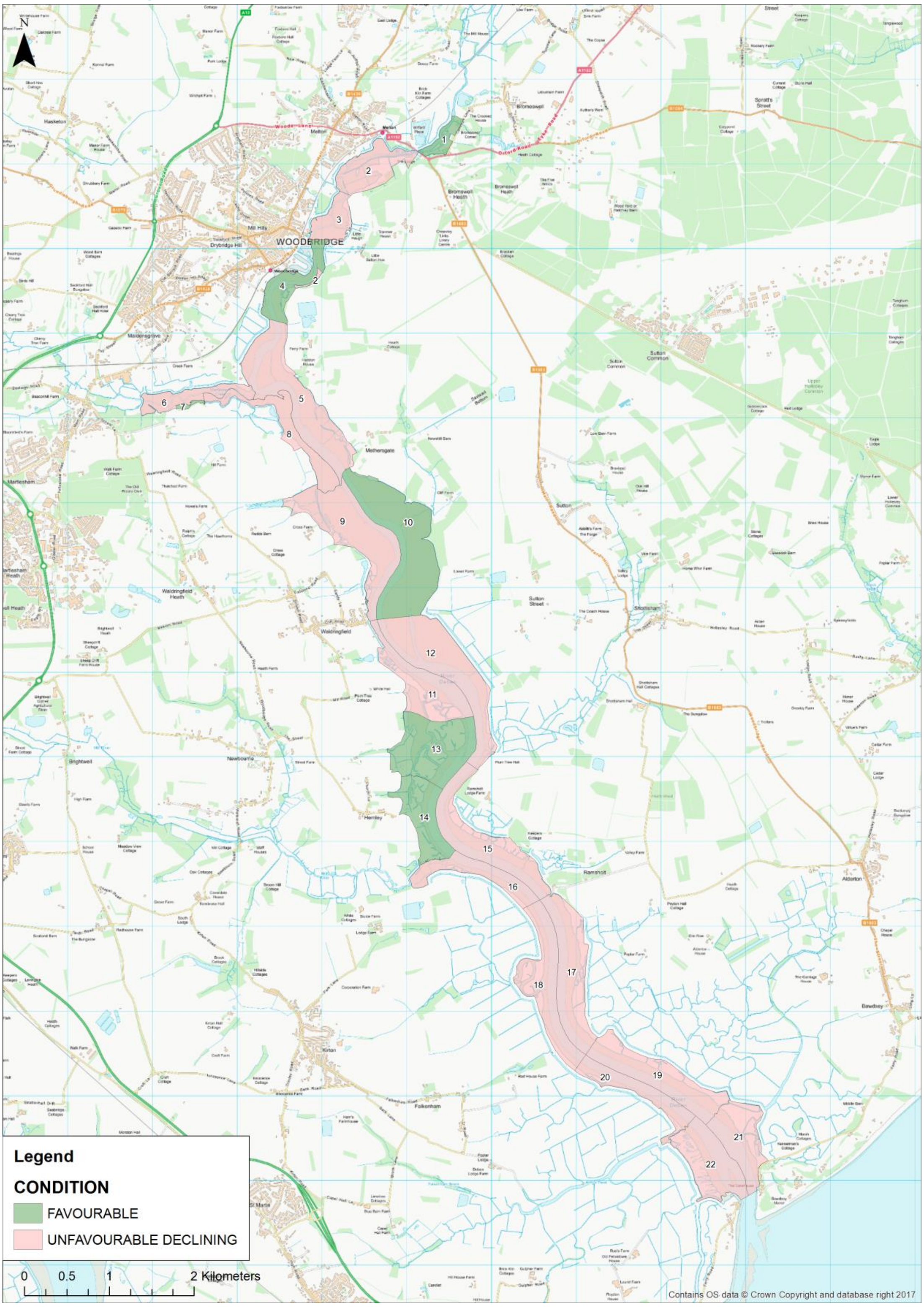
Appendix B: Unit Condition Assesments in the Alde-Estuary SSSI, Deben Estuary SSSI and Hamford Water SSSI

Alde-Ore Estuary SSSI



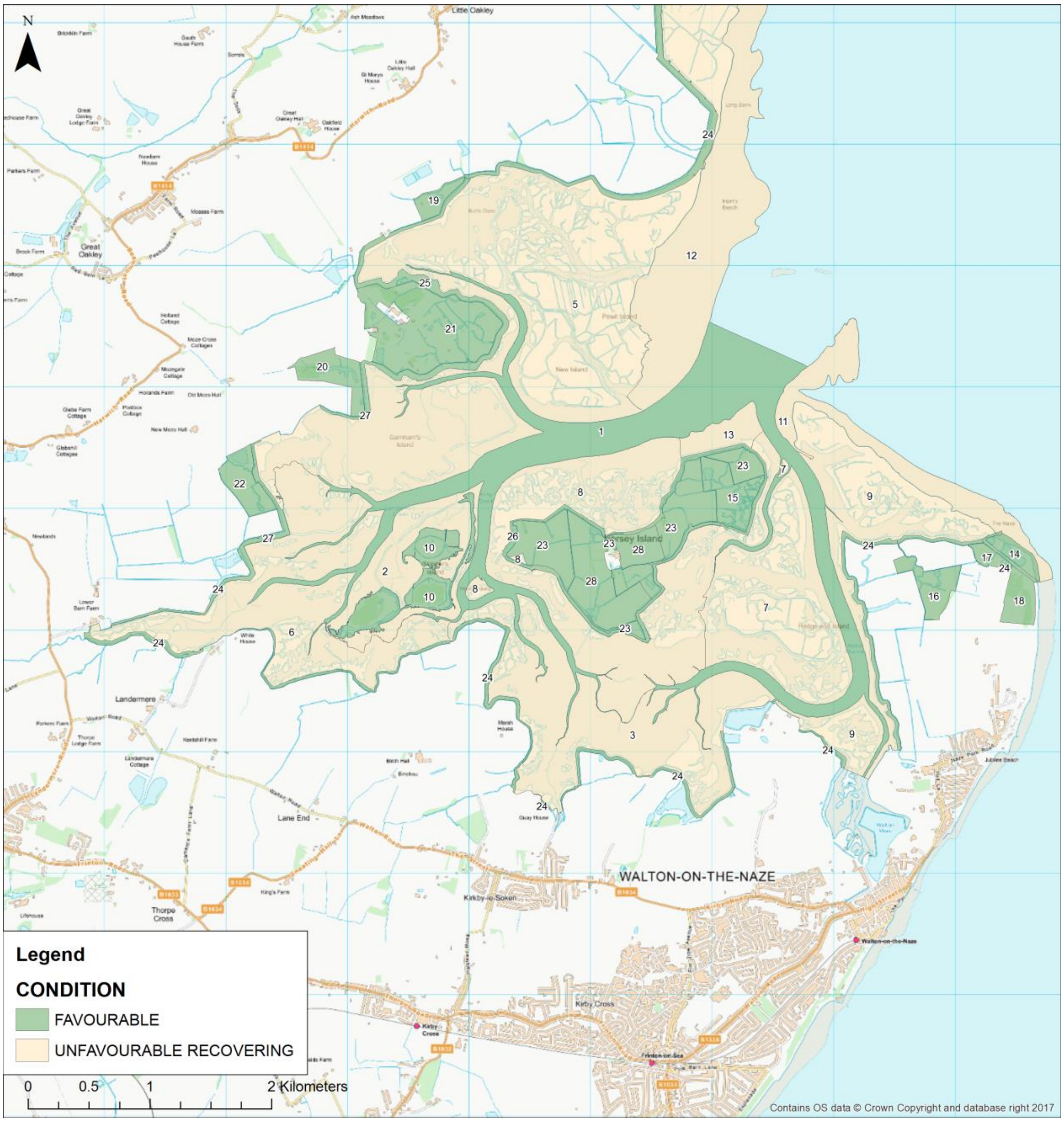
Unit	Condition	Date	Habitat	Area (ha)	Area (km^2)
1	Favourable	29/09/2009	Littoral Sediment	59.87	0.60
2	Favourable	30/09/2009	Littoral Sediment	29.38	0.29
3	Favourable	28/09/2009	Littoral Sediment	51.84	0.52
4	Favourable	11/01/2010	Littoral Sediment	101.94	1.02
5	Unfavourable Recovering	10/11/2010	Littoral Sediment	97.60	0.98
6	Unfavourable Recovering	08/11/2010	Littoral Sediment	93.13	0.93
7	Favourable	23/10/2013	Neutral Grassland-Lowland	71.94	0.72
8	Unfavourable Recovering	16/11/2010	Littoral Sediment	71.36	0.71
9	Unfavourable Recovering	21/05/2010	Littoral Sediment	63.32	0.63
10	Unfavourable Recovering	21/05/2010	Littoral Sediment	108.71	1.09
11	Favourable	01/10/2009	Littoral Sediment	146.51	1.47
12	Unfavourable Recovering	30/09/2013	Littoral Sediment	33.17	0.33
13	Unfavourable No change	26/08/2010	Supralittoral Sediment	14.86	0.15
15	Unfavourable No change	03/10/2013	Supralittoral Sediment	58.27	0.58
16	Unfavourable No change	03/10/2013	Neutral Grassland-Lowland	156.92	1.57
17	Unfavourable Recovering	03/10/2013	Supralittoral Sediment	29.91	0.30
18	Favourable	23/10/2013	Neutral Grassland-Lowland	99.70	1.00
19	Favourable	21/05/2010	Littoral Sediment	31.58	0.32
20	Unfavourable Recovering	30/09/2013	Supralittoral Sediment	81.61	0.82
21	Unfavourable Recovering	03/10/2013	Supralittoral Sediment	112.43	1.12
22	Favourable	27/10/2009	Neutral Grassland-Lowland	86.50	0.86
23	Favourable	21/05/2010	Littoral Sediment	35.03	0.35
24	Favourable	21/05/2010	Littoral Sediment	117.32	1.17
25	Favourable	21/06/2012	Littoral Sediment	252.11	2.52
26	Unfavourable Recovering	30/09/2013	Supralittoral Sediment	79.03	0.79
27	Unfavourable No change	30/09/2013	Supralittoral Sediment	57.72	0.58
28	Unfavourable Recovering	15/10/2009	Littoral Sediment	57.24	0.57
29	Unfavourable Recovering	21/05/2010	Littoral Sediment	48.63	0.49
31	Favourable	25/09/2009	Littoral Sediment	131.02	1.31
32	Unfavourable No change	30/09/2013	Supralittoral Sediment	19.96	0.20
33	Unfavourable No change	03/10/2013	Supralittoral Sediment	40.42	0.40
38	Favourable	18/03/2014	Earth Heritage	1.29	0.01
42	Favourable	25/09/2009	Littoral Sediment	36.24	0.36
43	Favourable	14/10/2009	Littoral Sediment	25.27	0.25
44	Favourable	18/11/2010	Fen, Marsh and Swamp-Lowland	32.13	0.32
Total				2533.95	25.34

Deben Estuary SSSI



Unit	Condition	Date	Habitat	Area (ha)	Area (km^2)
1	Favourable	04/05/2010	Fen, Marsh and Swamp-Lowland	9.08	0.09
2	Unfavourable-Declining	13/11/2009	Littoral Sediment	33.54	0.34
3	Unfavourable-Declining	13/11/2009	Littoral Sediment	18.15	0.18
4	Favourable	13/11/2009	Littoral Sediment	24.98	0.25
5	Unfavourable-Declining	18/11/2009	Littoral Sediment	78.75	0.79
6	Unfavourable-Declining	03/11/2009	Littoral Sediment	20.35	0.20
7	Favourable	04/05/2010	Fen, Marsh and Swamp-Lowland	1.34	0.01
8	Unfavourable-Declining	03/11/2009	Littoral Sediment	29.73	0.30
9	Unfavourable-Declining	11/11/2009	Littoral Sediment	74.33	0.74
10	Favourable	18/11/2009	Littoral Sediment	91.78	0.92
11	Unfavourable-Declining	10/08/2011	Littoral Sediment	47.24	0.47
12	Unfavourable-Declining	08/10/2009	Littoral Sediment	76.97	0.77
13	Favourable	10/08/2011	Littoral Sediment	62.79	0.63
14	Favourable	30/06/2011	Littoral Sediment	37.26	0.37
15	Unfavourable-Declining	08/10/2009	Littoral Sediment	57.82	0.58
16	Unfavourable-Declining	11/11/2009	Littoral Sediment	29.84	0.30
17	Unfavourable-Declining	12/11/2009	Littoral Sediment	58.99	0.59
18	Unfavourable-Declining	30/06/2011	Littoral Sediment	54.26	0.54
19	Unfavourable-Declining	30/06/2011	Littoral Sediment	55.71	0.56
20	Unfavourable-Declining	30/06/2011	Littoral Sediment	30.10	0.30
21	Unfavourable-Declining	30/06/2011	Littoral Sediment	40.62	0.41
22	Unfavourable-Declining	30/06/2011	Littoral Sediment	47.43	0.47
Total				981.08	9.81

Hamford Water SSSI



Unit	Condition	Date	Habitat	Area (ha)	Area (km^2)
1	Favourable	11/12/2008	Littoral Sediment	225.07	2.25
2	Unfavourable-Recovering	25/06/2010	Littoral Sediment	55.98	0.56
3	Unfavourable-Recovering	25/06/2010	Littoral Sediment	168.71	1.69
4	Unfavourable-Recovering	25/06/2010	Littoral Sediment	19.55	0.20
5	Unfavourable-Recovering	25/06/2010	Littoral Sediment	488.67	4.89
6	Unfavourable-Recovering	25/06/2010	Littoral Sediment	168.84	1.69
7	Unfavourable-Recovering	25/06/2010	Littoral Sediment	134.51	1.35
8	Unfavourable-Recovering	25/06/2010	Littoral Sediment	202.29	2.02
9	Unfavourable-Recovering	25/06/2010	Littoral Sediment	119.24	1.19
10	Favourable	11/12/2008	Broadleaved, Mixed and Yew Woodland - Lowland	34.16	0.34
11	Unfavourable-Recovering	25/06/2010	Supralittoral Sediment	55.35	0.55
12	Unfavourable-Recovering	25/06/2010	Supralittoral Sediment	150.14	1.50
13	Unfavourable-Recovering	16/02/2016	Supralittoral Sediment	14.92	0.15
14	Favourable	21/10/2011	Inshore Sublittoral Sediment - CL	6.57	0.07
15	Favourable	29/03/2012	Neutral Grassland-Lowland	17.16	0.17
16	Favourable	21/10/2011	Neutral Grassland-Lowland	15.25	0.15
17	Favourable	21/10/2011	Neutral Grassland-Lowland	4.01	0.04
18	Favourable	21/10/2011	Neutral Grassland-Lowland	10.20	0.10
19	Favourable	29/03/2012	Neutral Grassland-Lowland	6.03	0.06
20	Favourable	26/03/2012	Neutral Grassland-Lowland	14.59	0.15
21	Favourable	29/03/2012	Neutral Grassland-Lowland	59.90	0.60
22	Favourable	26/03/2012	Neutral Grassland-Lowland	13.58	0.14
23	Favourable	29/03/2012	Neutral Grassland-Lowland	57.30	0.57
24	Favourable	26/03/2012	Neutral Grassland-Lowland	59.21	0.59
25	Favourable	26/03/2012	Neutral Grassland-Lowland	20.84	0.21
26	Favourable	29/03/2012	Neutral Grassland-Lowland	18.57	0.19
27	Favourable	26/03/2012	Neutral Grassland-Lowland	5.63	0.06
28	Favourable	29/03/2012	Arable and Horticulture	42.32	0.42
Total				2188.59	21.89

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Appendix C: Observed Form of the Alde-Ore Estuary and Butley Estuary at each Section

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
1-0	5,643	24	30	0.79
1-2	14,251	26	30	0.88
1-4	23,584	27	34	0.80
1-6	36,924	40	62	0.64
1-8	65,887	45	155	0.29
1-10	94,288	41	68	0.60
1-12	102,858	46	63	0.72
1-14	112,366	56	84	0.67
1-16	161,586	110	218	0.50
1-20	231,852	133	196	0.68
1-22	275,561	98	88	1.10
1-24	314,868	120	160	0.75
1-28	390,707	120	162	0.75
1-34	558,357	245	718	0.34
1-38	759,695	337	722	0.47
1-40	871,365	350	410	0.85
1-42	970,986	355	388	0.92
1-44	1,059,443	369	433	0.85
1-46	1,162,865	421	477	0.90
1-48	1,298,390	489	605	0.81
1-50	1,452,755	570	693	0.82
1-52	1,621,436	666	789	0.84
1-54	1,840,940	801	964	0.83
1-56	2,092,001	876	895	0.98
1-58	2,335,765	1,002	1,018	0.98
1-60	2,629,971	1,146	1,145	1.00
1-62	2,974,727	1,446	1,336	1.08
1-64	3,382,648	1,729	1,477	1.17
1-66	3,787,412	1,152	905	1.27
1-68	4,162,956	980	642	1.53
1-70	4,412,772	1,067	699	1.53
1-72	4,673,606	995	541	1.84
1-76	5,527,329	970	468	2.07
1-78	5,697,764	928	514	1.81

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-82	6,040,867	944	492	1.91
1-84	6,200,892	979	643	1.55
1-88	6,564,131	1,255	464	2.70
1-90	6,733,300	1,269	373	3.39
1-92	6,856,370	873	246	3.55
1-94	6,949,939	684	192	3.56
1-96	7,033,332	685	196	3.49
1-98	7,119,117	783	210	3.73
1-100	7,213,509	713	215	3.30
1-102	7,304,172	726	209	3.47
1-104	7,393,775	758	213	3.57
1-106	7,489,306	735	248	2.96
1-108	7,592,448	849	264	3.21
1-110	7,696,899	967	263	3.68
1-112	7,813,956	1,117	305	3.66
1-114	7,943,187	1,269	288	4.41
1-116	8,043,425	738	203	3.63
1-118	8,131,816	915	263	3.48
1-120	8,243,529	902	300	3.00
1-122	8,366,556	796	363	2.19
1-124	8,514,094	695	364	1.90
1-126	8,662,653	793	368	2.15
1-128	8,805,455	865	336	2.57
1-130	8,937,716	824	318	2.59
1-132	9,049,374	1,053	244	4.31
1-134	9,147,635	898	284	3.15
1-136	9,370,549	796	322	2.47
1-138	9,488,159	899	313	2.86
1-140	9,598,449	889	287	3.10
1-142	9,711,688	885	298	2.97
1-144	9,811,189	897	222	4.02
1-146	9,903,708	930	241	3.86
1-148	9,994,966	859	216	3.98
1-150	10,092,834	870	262	3.31
1-152	10,202,786	868	291	2.98
1-154	10,306,962	983	258	3.80
1-156	10,404,551	1,010	247	4.09

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-158	10,501,058	1,090	228	4.78
1-160	10,578,616	1,006	214	4.68
1-162	10,662,550	1,045	236	4.43
1-164	10,753,500	1,010	246	4.09
1-166	10,850,669	955	262	3.65
1-168	10,948,550	969	237	4.09
1-170	11,044,481	966	217	4.43
1-172	11,139,981	931	268	3.47
1-174	11,251,964	903	266	3.38
1-176	11,365,687	829	300	2.76
1-178	11,486,917	887	306	2.90
1-180	11,608,045	862	312	2.75
1-182	11,732,233	888	323	2.74
1-184	11,846,838	876	267	3.28
1-186	11,960,844	1,039	261	3.97
1-188	12,062,959	1,130	254	4.43
1-190	12,165,313	1,226	243	5.05
1-192	12,255,483	1,016	174	5.84
1-194	12,325,123	871	199	4.35
1-196	12,404,763	1,061	225	4.71
1-198	12,492,856	1,121	257	4.36
1-200	12,589,394	1,167	291	4.01
1-202	12,700,335	1,042	291	3.58
1-204	12,805,912	1,330	258	5.13
1-206	12,900,675	1,339	346	3.87
2-6	656	#N/A	#N/A	#N/A
2-8	4,273	6	22	0.26
2-10	8,328	7	25	0.28
2-12	13,169	11	32	0.34
2-14	18,783	15	35	0.42
2-16	25,409	15	32	0.44
2-18	32,230	14	28	0.48
2-20	39,071	13	30	0.45
2-22	45,927	15	31	0.45
2-24	53,857	17	33	0.51
2-26	62,258	19	41	0.47
2-28	71,992	22	34	0.65

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
2-30	82,519	24	34	0.70
2-32	94,779	27	55	0.51
3-0	13,107,014	764	218	3.49
4-0	6,649,157	740	164	4.60
4-2	6,713,074	782	145	5.36
4-4	6,769,852	819	140	5.85
4-6	6,826,668	748	148	5.05
4-8	6,890,139	709	172	4.12
4-10	6,964,933	736	196	3.80
4-12	7,048,825	747	220	3.40
4-14	7,138,585	793	209	3.78
4-16	7,230,731	811	191	4.24
4-18	7,312,189	853	200	4.26
4-20	7,386,940	793	161	4.96
4-22	7,461,140	823	173	4.76
4-24	7,537,762	852	182	4.84
4-26	7,634,111	1,096	267	4.30
4-28	7,745,021	975	245	3.99
5-2	6,620,431	442	159	2.78
5-4	6,677,536	427	174	2.51
5-6	6,741,429	407	174	2.33
5-8	6,805,773	425	174	2.44
5-10	6,870,252	444	165	2.69
5-12	6,934,553	452	165	2.74
5-14	7,000,392	454	168	2.69
5-16	7,068,110	415	170	2.50
5-18	7,133,588	469	182	2.70
5-20	7,203,445	484	167	2.90
5-22	7,270,922	410	149	2.83
5-24	7,333,021	321	137	2.33
5-26	7,394,529	336	134	2.49
5-28	7,457,101	369	154	2.41
5-30	7,527,898	390	190	2.06
5-32	7,607,264	415	255	1.66
6-0	1,413	#N/A	#N/A	#N/A
6-2	5,005	#N/A	#N/A	#N/A
6-4	26,267	28	68	0.40

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
6-8	41,645	23	65	0.35
6-10	59,945	42	83	0.50
6-12	75,500	31	74	0.42
6-14	96,200	43	67	0.64
6-16	132,760	70	158	0.44
6-18	260,176	74	112	0.65
6-20	287,087	62	85	0.74
6-24	326,570	115	197	0.58
6-28	371,092	116	159	0.73
6-30	410,004	120	105	1.15
6-32	454,091	165	148	1.11
6-34	503,550	171	154	1.11
6-36	556,403	200	136	1.46
6-38	609,459	201	118	1.71
6-40	659,261	202	113	1.78
6-42	704,248	204	106	1.91
6-44	744,089	202	107	1.89
6-46	790,772	206	101	2.04
6-48	830,475	212	93	2.25
6-50	869,323	225	80	2.81
6-52	905,122	219	94	2.31
6-54	942,446	232	92	2.49
6-56	974,562	214	78	2.74
6-58	1,002,427	206	63	3.22
6-60	1,039,021	252	92	2.74
6-62	1,075,986	259	96	2.69
6-64	1,112,855	294	101	2.94
7-2	9,027,324	886	182	4.95
7-4	9,115,743	799	209	3.81
7-6	9,220,794	1,053	249	4.23
8-0	17,032,637	1,222	293	4.17
8-2	17,149,861	978	220	4.44
8-4	17,250,760	817	220	3.71
8-6	17,359,736	812	248	3.27
8-8	17,468,072	764	225	3.54
8-10	17,577,881	736	212	3.56
8-12	17,664,114	769	220	3.48

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
8-14	17,766,162	775	224	3.46
8-16	17,881,503	752	267	2.83
8-18	17,995,367	708	224	3.16
8-20	18,120,889	682	230	2.98
8-22	18,232,297	671	210	3.22
8-24	18,330,014	795	210	3.79
8-26	18,432,035	765	196	3.90
8-28	18,528,586	747	216	3.44
8-30	18,694,322	702	210	3.34
8-32	18,813,957	665	259	2.57
8-34	18,941,417	646	247	2.61
8-36	19,041,877	667	238	2.79
8-38	19,171,746	767	315	2.45

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Appendix D: Predicted Equilibrium Form of the Alde-Ore Estuary and Butley Estuary at each Section

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-0	642,287	319	110	2.89
1-2	661,269	326	106	3.06
1-4	680,813	332	119	2.80
1-6	700,934	339	181	1.87
1-8	721,650	346	431	0.80
1-10	742,978	354	200	1.77
1-12	764,936	361	177	2.04
1-14	787,543	369	215	1.71
1-16	810,819	376	403	0.93
1-20	859,454	392	338	1.16
1-22	884,855	400	179	2.23
1-24	911,006	409	296	1.38
1-28	965,650	426	303	1.40
1-34	1,053,824	453	975	0.47
1-38	1,117,035	472	854	0.55
1-40	1,150,048	482	481	1.00
1-42	1,184,037	492	457	1.08
1-44	1,219,031	503	504	1.00
1-46	1,255,059	513	523	0.98
1-48	1,292,152	524	627	0.84
1-50	1,330,341	535	672	0.80
1-52	1,369,658	546	714	0.76
1-54	1,410,138	557	804	0.69
1-56	1,451,814	569	722	0.79
1-58	1,494,721	581	775	0.75
1-60	1,538,897	593	824	0.72
1-62	1,584,379	605	864	0.70
1-64	1,631,204	618	883	0.70
1-66	1,679,414	631	670	0.94
1-68	1,729,048	644	521	1.24
1-70	1,780,149	658	548	1.20
1-72	1,832,760	671	445	1.51
1-76	1,942,694	700	398	1.76
1-78	2,000,110	714	450	1.59

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Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-82	2,120,081	745	438	1.70
1-84	2,182,739	760	561	1.36
1-88	2,313,665	792	369	2.15
1-90	2,382,045	809	298	2.71
1-92	2,452,445	826	239	3.45
1-94	2,524,926	843	213	3.96
1-96	2,599,549	861	220	3.92
1-98	2,676,377	879	222	3.95
1-100	2,755,476	897	242	3.71
1-102	2,836,913	916	235	3.90
1-104	2,920,757	935	236	3.96
1-106	3,007,078	954	283	3.38
1-108	3,095,951	974	283	3.44
1-110	3,187,450	995	267	3.73
1-112	3,281,654	1,015	291	3.49
1-114	3,378,642	1,037	260	3.98
1-116	3,478,496	1,058	243	4.35
1-118	3,581,301	1,080	286	3.78
1-120	3,687,145	1,103	332	3.32
1-122	3,796,117	1,126	432	2.61
1-124	3,908,309	1,150	469	2.45
1-126	4,023,817	1,174	448	2.62
1-128	4,142,739	1,198	396	3.02
1-130	4,265,176	1,223	388	3.16
1-132	4,391,231	1,249	266	4.70
1-134	4,521,012	1,275	339	3.76
1-136	4,654,629	1,301	412	3.16
1-138	4,792,194	1,329	381	3.48
1-140	4,933,825	1,356	354	3.83
1-142	5,079,642	1,385	373	3.72
1-144	5,229,768	1,414	279	5.06
1-146	5,384,332	1,443	300	4.81
1-148	5,543,463	1,473	283	5.21
1-150	5,707,298	1,504	345	4.35
1-152	5,875,974	1,536	387	3.97
1-154	6,049,636	1,568	327	4.80
1-156	6,228,430	1,600	311	5.15

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-158	6,412,508	1,634	279	5.86
1-160	6,602,027	1,668	276	6.04
1-162	6,797,147	1,703	301	5.66
1-164	6,998,033	1,738	324	5.37
1-166	7,204,857	1,775	357	4.97
1-168	7,417,793	1,812	324	5.59
1-170	7,637,022	1,850	301	6.14
1-172	7,862,731	1,888	382	4.95
1-174	8,095,110	1,928	390	4.95
1-176	8,334,357	1,968	462	4.26
1-178	8,580,675	2,009	460	4.37
1-180	8,834,273	2,051	482	4.25
1-182	9,095,366	2,094	497	4.21
1-184	9,364,175	2,138	417	5.13
1-186	9,640,929	2,182	379	5.75
1-188	9,925,862	2,228	357	6.23
1-190	10,219,216	2,275	331	6.87
1-192	10,521,240	2,322	263	8.83
1-194	10,832,191	2,371	330	7.19
1-196	11,152,331	2,420	340	7.12
1-198	11,481,933	2,471	381	6.48
1-200	11,821,276	2,522	428	5.90
1-202	12,170,648	2,575	457	5.63
1-204	12,530,346	2,629	364	7.23
1-206	12,900,675	2,684	490	5.48
2-6	8,282	15	#N/A	#N/A
2-8	9,990	17	38	0.44
2-10	12,050	19	41	0.46
2-12	14,535	22	45	0.48
2-14	17,532	25	46	0.54
2-16	21,148	28	45	0.62
2-18	25,509	32	44	0.74
2-20	30,770	37	49	0.75
2-22	37,116	42	54	0.78
2-24	44,770	48	56	0.85
2-26	54,003	55	69	0.79
2-28	65,140	63	57	1.10

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
2-30	78,574	72	59	1.21
2-32	94,779	82	95	0.87
3-0	13,107,014	2,714	412	6.59
4-0	6,612,829	1,670	244	6.84
4-2	6,627,006	1,672	213	7.85
4-4	6,644,570	1,676	200	8.36
4-6	6,666,332	1,679	221	7.58
4-8	6,693,294	1,684	265	6.35
4-10	6,726,700	1,690	295	5.72
4-12	6,768,089	1,698	331	5.13
4-14	6,819,370	1,707	308	5.55
4-16	6,882,905	1,718	278	6.19
4-18	6,961,623	1,732	285	6.08
4-20	7,059,153	1,749	238	7.35
4-22	7,179,991	1,770	253	6.98
4-24	7,329,706	1,796	260	6.91
4-26	7,515,199	1,829	337	5.43
4-28	7,745,021	1,868	338	5.52
5-2	6,616,790	1,671	309	5.41
5-4	6,629,841	1,673	340	4.92
5-6	6,645,583	1,676	354	4.73
5-8	6,664,572	1,679	346	4.86
5-10	6,687,477	1,683	321	5.24
5-12	6,715,106	1,688	318	5.30
5-14	6,748,432	1,694	326	5.20
5-16	6,788,632	1,701	340	5.00
5-18	6,837,122	1,710	340	5.04
5-20	6,895,612	1,720	315	5.47
5-22	6,966,164	1,733	302	5.74
5-24	7,051,267	1,748	321	5.45
5-26	7,153,920	1,766	308	5.72
5-28	7,277,743	1,787	338	5.29
5-30	7,427,102	1,813	409	4.43
5-32	7,607,264	1,845	532	3.47
6-0	55,406	56	#N/A	#N/A
6-2	60,851	60	#N/A	#N/A
6-4	66,832	64	104	0.61

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
6-8	80,615	73	116	0.63
6-10	88,538	78	114	0.69
6-12	97,240	83	122	0.68
6-14	106,797	89	97	0.92
6-16	117,294	95	184	0.52
6-18	128,822	102	132	0.77
6-20	141,484	109	112	0.97
6-24	170,662	124	205	0.61
6-28	205,858	142	176	0.81
6-30	226,090	152	118	1.29
6-32	248,312	162	147	1.10
6-34	272,717	174	155	1.12
6-36	299,521	186	132	1.41
6-38	328,959	198	117	1.69
6-40	361,291	212	116	1.83
6-42	396,801	227	112	2.02
6-44	435,800	242	117	2.07
6-46	478,633	259	113	2.29
6-48	525,676	277	107	2.58
6-50	577,342	296	92	3.22
6-52	634,086	316	114	2.78
6-54	696,407	338	112	3.02
6-56	764,854	361	101	3.57
6-58	840,027	386	87	4.43
6-60	922,590	412	118	3.50
6-62	1,013,266	441	125	3.52
6-64	1,112,855	471	127	3.71
7-2	8,906,992	2,063	275	7.50
7-4	8,991,386	2,077	338	6.15
7-6	9,220,794	2,114	353	6.00
8-0	16,944,744	3,257	478	6.81
8-2	16,964,702	3,260	402	8.12
8-4	16,988,074	3,263	440	7.42
8-6	17,015,443	3,267	497	6.57
8-8	17,047,494	3,271	456	7.18
8-10	17,085,027	3,276	442	7.42
8-12	17,128,980	3,282	456	7.20

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Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
8-14	17,180,450	3,289	461	7.13
8-16	17,240,724	3,297	559	5.90
8-18	17,311,308	3,307	484	6.83
8-20	17,393,964	3,318	506	6.56
8-22	17,490,759	3,331	466	7.15
8-24	17,604,109	3,347	431	7.77
8-26	17,736,847	3,364	411	8.19
8-28	17,892,289	3,385	461	7.34
8-30	18,074,318	3,410	463	7.37
8-32	18,287,482	3,438	588	5.84
8-34	18,537,106	3,472	574	6.05
8-36	18,829,426	3,510	548	6.41
8-38	19,171,746	3,556	676	5.26

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Appendix E: Under-sized Reaches of the Alde-Ore Estuary

Slaughden to Havergate Island (map background)

Slaughden to Havergate Island (aerial photograph background)

Havergate Island to Shingle Street (map background)

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Havergate Island to Shingle Street (aerial photograph background)

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Appendix F: Observed Form of the Deben Estuary at each Section

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
1-2	2,207	8	24	0.32
1-4	6,299	2	8	0.20
1-6	10,940	8	18	0.47
1-8	16,728	10	20	0.51
1-10	25,594	14	23	0.58
1-12	37,066	22	32	0.68
1-14	54,494	35	52	0.68
1-16	68,294	33	39	0.88
1-18	89,811	70	82	0.87
1-20	133,604	113	203	0.56
1-22	185,271	87	139	0.62
1-24	252,618	158	354	0.45
1-26	344,154	219	344	0.64
1-28	399,365	201	150	1.34
1-30	447,507	172	132	1.30
1-32	528,609	279	281	0.99
1-34	638,113	334	422	0.79
1-36	730,530	260	196	1.33
1-38	809,904	306	280	1.19
1-42	1,004,920	435	312	1.39
1-44	1,094,569	500	273	1.84
1-46	1,175,842	326	225	1.57
1-48	1,272,955	351	200	1.75
1-50	1,383,801	394	200	1.97
1-52	1,484,541	429	260	1.66
1-54	1,596,253	637	329	1.94
1-56	1,760,739	689	442	1.68
1-58	1,939,243	599	399	1.57
2-0	12,982	108	238	0.45
2-2	73,018	199	212	1.01
2-4	128,439	202	148	1.35
2-6	169,623	170	157	1.08
2-8	224,081	135	134	1.00
2-10	274,392	129	161	1.03

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
2-12	329,730	156	159	1.16
2-14	378,155	208	159	1.30
3-2	2,636,127	1,054	518	2.03
3-4	2,813,975	891	430	2.07
3-6	3,027,878	755	384	1.97
3-8	3,220,180	729	388	1.93
3-10	3,416,312	744	436	2.19
3-12	3,613,300	805	354	2.37
3-14	3,818,689	801	407	2.15
3-16	4,043,187	922	666	1.61
3-18	4,334,181	1,071	633	1.80
3-20	4,663,570	1,157	697	1.90
3-22	5,008,910	1,415	855	1.72
3-24	5,353,047	1,598	881	1.94
3-26	5,776,473	1,591	893	1.84
3-28	6,159,117	1,498	795	1.96
3-30	6,603,004	1,618	703	2.30
3-32	6,986,033	1,599	680	2.35
3-34	7,323,466	1,609	665	2.42
3-36	7,581,038	1,604	659	2.46
3-38	7,808,932	1,350	499	2.71
3-40	8,029,578	1,386	521	2.65
3-42	8,318,209	1,595	652	2.45
3-44	8,659,954	1,503	539	2.78
3-46	9,001,191	1,713	556	3.07
3-48	9,368,000	1,725	563	3.06
3-50	9,795,725	1,638	693	2.63
3-52	10,097,134	1,393	418	3.33
3-56	10,506,990	1,229	292	4.21
3-58	10,774,682	1,565	493	3.17
3-60	11,061,498	1,551	392	3.97
3-62	11,283,238	1,561	364	4.29
3-64	11,467,404	1,482	319	4.65
3-66	11,670,267	1,466	316	4.64
3-68	11,880,752	1,422	356	4.00
3-70	12,082,844	1,499	398	3.77
3-72	12,398,796	1,556	436	3.57

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
3-74	12,635,720	1,514	424	3.57
3-76	12,858,481	1,625	399	4.07
3-78	13,060,145	1,604	389	4.12
3-80	13,273,440	1,637	460	3.55
3-82	13,472,567	1,628	357	4.56
3-84	13,664,105	1,631	379	4.31
3-86	13,879,663	1,611	405	3.98
3-88	14,101,919	1,668	381	4.38
3-90	14,313,082	1,673	429	3.90
3-92	14,538,692	1,680	431	3.90
3-94	14,758,427	1,681	378	4.45
3-96	15,005,653	1,718	344	4.99
3-98	15,208,825	1,740	372	4.68
3-100	15,413,913	1,767	378	4.67
3-102	15,622,934	1,782	419	4.25
3-104	15,841,209	1,769	420	4.22
3-106	16,057,608	1,751	378	4.63
3-108	16,268,575	1,715	397	4.32
3-110	16,470,615	1,732	362	4.77
3-112	16,675,348	1,770	385	4.60
3-114	16,881,300	1,808	402	4.50
3-116	17,099,848	1,849	456	4.05
3-118	17,360,937	1,929	522	3.69
3-120	17,624,022	1,850	533	3.48
3-122	17,913,991	1,931	556	3.47
3-124	18,543,539	2,068	595	3.48
3-128	18,851,907	2,053	445	4.61
3-130	19,076,980	1,415	234	6.05
3-132	19,202,058	1,057	228	4.63
3-134	19,341,638	1,486	345	4.31

Appendix G: Predicted Equilibrium Form of the Deben Estuary at each Section

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
1-2	107,072	89	81	1.10
1-4	118,742	96	63	1.53
1-6	131,683	104	63	1.66
1-8	146,035	111	66	1.68
1-10	161,951	120	69	1.74
1-12	179,602	129	78	1.65
1-14	199,176	139	103	1.35
1-16	220,884	149	81	1.84
1-18	244,958	161	123	1.30
1-20	271,656	173	251	0.69
1-22	301,263	186	205	0.91
1-24	334,097	201	398	0.50
1-26	370,510	216	341	0.63
1-28	410,891	232	161	1.44
1-30	455,674	250	159	1.57
1-32	505,337	269	276	0.98
1-34	560,413	290	393	0.74
1-36	621,491	312	214	1.45
1-38	689,227	335	281	1.19
1-42	847,649	388	295	1.32
1-44	940,033	418	249	1.68
1-46	1,042,486	450	254	1.77
1-48	1,156,104	484	235	2.06
1-50	1,282,106	521	230	2.26
1-52	1,421,841	561	296	1.89
1-54	1,576,805	603	320	1.88
1-56	1,748,659	649	413	1.57
1-58	1,939,243	699	421	1.66
2-0	18,827	26	117	0.22
2-2	28,901	35	86	0.41
2-4	44,365	48	72	0.66
2-6	68,103	65	97	0.67
2-8	104,542	88	108	0.81
2-10	160,479	119	137	0.87

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
2-12	246,345	162	149	1.08
2-14	378,155	219	164	1.34
3-2	3,203,799	998	505	1.98
3-4	3,244,391	1,007	458	2.20
3-6	3,286,841	1,017	446	2.28
3-8	3,331,235	1,026	454	2.26
3-10	3,377,663	1,036	454	2.28
3-12	3,426,216	1,047	395	2.65
3-14	3,476,993	1,058	447	2.37
3-16	3,530,095	1,069	666	1.61
3-18	3,585,629	1,081	617	1.75
3-20	3,643,706	1,094	634	1.73
3-22	3,704,443	1,107	742	1.49
3-24	3,767,961	1,120	712	1.57
3-26	3,834,387	1,134	742	1.53
3-28	3,903,856	1,149	683	1.68
3-30	3,976,506	1,164	596	1.95
3-32	4,052,482	1,179	584	2.02
3-34	4,131,938	1,196	573	2.09
3-36	4,215,033	1,213	569	2.13
3-38	4,301,933	1,231	476	2.59
3-40	4,392,812	1,249	495	2.52
3-42	4,487,853	1,268	581	2.18
3-44	4,587,246	1,288	500	2.58
3-46	4,691,190	1,309	487	2.69
3-48	4,799,895	1,330	494	2.69
3-50	4,913,578	1,352	598	2.26
3-52	5,032,467	1,376	416	3.31
3-56	5,286,826	1,425	315	4.53
3-58	5,422,808	1,450	475	3.05
3-60	5,565,016	1,477	382	3.86
3-62	5,713,736	1,505	357	4.21
3-64	5,869,267	1,534	325	4.73
3-66	6,031,920	1,564	326	4.79
3-68	6,202,022	1,596	377	4.23
3-70	6,379,913	1,628	415	3.93
3-72	6,565,951	1,661	451	3.69

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Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
3-74	6,760,508	1,696	449	3.78
3-76	6,963,974	1,732	412	4.21
3-78	7,176,758	1,770	409	4.33
3-80	7,399,286	1,809	484	3.73
3-82	7,632,005	1,849	381	4.86
3-84	7,875,381	1,890	407	4.64
3-86	8,129,901	1,934	444	4.36
3-88	8,396,077	1,978	415	4.77
3-90	8,674,442	2,025	472	4.29
3-92	8,965,555	2,073	479	4.33
3-94	9,269,999	2,122	425	5.00
3-96	9,588,384	2,174	387	5.62
3-98	9,921,349	2,227	421	5.29
3-100	10,269,562	2,283	429	5.31
3-102	10,633,721	2,340	480	4.87
3-104	11,014,557	2,399	488	4.91
3-106	11,412,832	2,460	448	5.49
3-108	11,829,345	2,524	482	5.24
3-110	12,264,933	2,589	443	5.84
3-112	12,720,467	2,657	472	5.63
3-114	13,196,862	2,727	494	5.52
3-116	13,695,073	2,800	561	4.99
3-118	14,216,099	2,875	637	4.51
3-120	14,760,984	2,953	673	4.39
3-122	15,330,822	3,034	697	4.35
3-124	15,926,755	3,117	730	4.27
3-128	17,201,741	3,292	564	5.84
3-130	17,883,350	3,384	362	9.34
3-132	18,596,172	3,479	414	8.41
3-134	19,341,638	3,578	535	6.69

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Appendix H: Under-sized Reach of the Deben Estuary

Ramsholt to Felixstowe Ferry (map background)

Ramsholt to Felixstowe Ferry (aerial photograph background)

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Appendix I: Observed Form of Hamford Water at each Section

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
1-0	1,606	#N/A	#N/A	#N/A
1-2	14,858	#N/A	#N/A	#N/A
1-4	33,980	#N/A	#N/A	#N/A
1-6	73,631	#N/A	#N/A	#N/A
1-8	148,108	#N/A	#N/A	#N/A
1-10	230,388	#N/A	#N/A	#N/A
1-12	312,838	#N/A	#N/A	#N/A
1-14	455,755	10	36	0.27
1-16	601,029	10	56	0.18
1-18	880,416	7	52	0.13
1-20	1,249,926	80	54	1.52
1-22	1,664,524	98	79	1.26
1-24	2,095,418	115	111	1.05
1-26	2,386,700	260	167	1.56
1-28	2,697,182	213	212	1.01
1-30	3,036,493	304	213	1.43
1-32	3,340,832	376	148	2.54
1-34	3,764,500	272	187	1.45
1-36	4,035,149	250	189	1.33
1-38	4,300,631	336	192	1.75
2-0	82	#N/A	#N/A	#N/A
2-2	5,897	#N/A	#N/A	#N/A
2-4	57,298	#N/A	#N/A	#N/A
2-6	197,785	#N/A	#N/A	#N/A
2-8	309,092	#N/A	#N/A	#N/A
2-10	581,284	8	21	0.37
2-12	852,491	13	23	0.60
2-14	1,128,078	167	133	1.25
2-16	1,489,975	125	68	1.84
2-18	1,660,149	137	62	2.21
2-20	1,761,710	167	67	2.53
2-22	1,871,464	171	62	2.71
3-0	71,254	#N/A	#N/A	#N/A
3-2	160,160	#N/A	#N/A	#N/A

Section	Tidal Prism (m^3)	Cross-Sectional Area (m^2)	Width (m)	Mean Depth (m)
3-4	308,921	#N/A	#N/A	#N/A
3-6	410,236	#N/A	#N/A	#N/A
3-8	498,622	#N/A	#N/A	#N/A
3-10	573,578	11	34	0.36
3-12	628,484	26	29	0.89
3-14	710,893	102	99	1.04
3-16	788,057	59	60	0.97
4-0	3,641,431	361	147	2.44
4-2	3,764,548	366	112	3.26
4-4	3,959,164	326	140	2.33
4-6	4,099,209	319	194	1.64
5-0	8,698,670	789	358	2.21
5-2	9,037,932	789	284	2.79
5-4	9,322,683	812	263	3.10
6-0	3,501	#N/A	#N/A	#N/A
6-2	62,243	#N/A	#N/A	#N/A
6-4	126,425	#N/A	#N/A	#N/A
6-6	215,936	#N/A	#N/A	#N/A
6-8	309,041	11	31	0.35
6-10	379,049	14	22	0.66
6-12	425,274	20	22	0.90
7-2	132,883	#N/A	#N/A	#N/A
7-4	287,154	#N/A	#N/A	#N/A
7-6	423,738	43	33	1.32
7-8	556,473	32	34	0.94
8-2	1,155,519	69	58	1.19
8-4	1,296,085	84	62	1.34
8-6	1,428,028	114	98	1.16
9-0	2,983	#N/A	#N/A	#N/A
9-2	90,559	#N/A	#N/A	#N/A
9-4	162,072	#N/A	#N/A	#N/A
9-6	258,696	#N/A	#N/A	#N/A
9-8	353,226	31	30	1.05
9-10	448,582	11	34	0.32
10-4	2,350,967	147	100	1.50
10-6	2,534,671	167	121	1.38
11-2	12,760,444	1,029	279	3.69

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
11-4	13,618,469	1,002	286	3.49
11-6	14,233,383	966	367	2.63
11-8	14,780,683	1,032	432	2.39
11-10	15,635,711	1,063	505	2.11
11-12	16,411,959	1,190	784	1.51
12-0	14	#N/A	#N/A	#N/A
12-2	261,163	#N/A	#N/A	#N/A
12-4	466,735	#N/A	#N/A	#N/A
12-6	670,033	22	37	0.60
12-8	987,374	48	93	0.53
12-10	1,378,277	95	64	1.48
12-12	1,819,935	193	99	1.95
12-14	2,084,553	234	92	2.54
12-16	2,262,478	266	106	2.51
12-18	2,583,367	295	124	2.39
12-20	2,724,531	232	125	1.87
12-22	2,883,218	271	114	2.36
12-24	3,043,828	262	136	1.94
13-0	15	#N/A	#N/A	#N/A
13-2	26,052	#N/A	#N/A	#N/A
13-4	131,615	#N/A	#N/A	#N/A
13-6	247,024	#N/A	#N/A	#N/A
13-8	367,370	6	22	0.28
13-10	459,385	15	33	0.45
13-12	547,371	22	35	0.64
13-14	628,629	33	46	0.71
13-16	700,743	28	36	0.79
14-0	3,895,748	361	166	2.17
14-2	4,046,640	359	152	2.36
14-4	4,234,059	415	143	2.88
14-6	4,436,475	387	135	2.89
14-8	4,715,222	374	138	2.69
14-10	4,949,987	362	143	2.57
14-12	5,117,233	385	132	2.92
14-14	5,549,269	392	134	2.95
14-16	5,745,250	403	144	2.78
14-18	5,926,134	422	129	3.27

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
15-0	123,813	#N/A	#N/A	#N/A
15-2	267,907	#N/A	#N/A	#N/A
15-4	421,443	56	59	0.97
15-6	502,413	26	45	0.68
15-8	575,561	52	44	1.18
15-10	638,401	57	41	1.43
15-12	694,450	72	41	1.80
16-2	6,916,699	655	118	5.55
16-4	7,085,539	456	140	3.26
17-0	25,657,378	2,267	1,364	1.66
17-2	26,847,635	2,629	1,635	1.61
18-0	134,176	#N/A	#N/A	#N/A
18-2	288,188	19	28	0.68
18-4	400,277	17	50	0.34
18-6	503,045	58	66	0.87
18-8	578,231	53	56	0.94
18-10	630,847	48	52	0.92

Appendix J: Predicted Equilibrium Form of Hamford Water at each Section

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
1-0	214,116	146	#N/A	#N/A
1-2	250,739	164	#N/A	#N/A
1-4	293,626	183	#N/A	#N/A
1-6	343,848	205	#N/A	#N/A
1-8	402,661	229	#N/A	#N/A
1-10	471,534	256	#N/A	#N/A
1-12	552,186	286	#N/A	#N/A
1-14	646,634	320	209	1.54
1-16	757,236	358	330	1.09
1-18	886,756	401	398	1.01
1-20	1,038,429	449	126	3.56
1-22	1,216,045	502	177	2.83
1-24	1,424,041	561	243	2.31
1-26	1,667,613	628	260	2.42
1-28	1,952,846	702	384	1.83
1-30	2,286,867	786	342	2.30
1-32	2,678,019	879	227	3.88
1-34	3,136,076	983	356	2.76
1-36	3,672,479	1,100	395	2.78
1-38	4,300,631	1,230	367	3.35
2-0	93,175	81	#N/A	#N/A
2-2	122,389	98	#N/A	#N/A
2-4	160,763	119	#N/A	#N/A
2-6	211,169	145	#N/A	#N/A
2-8	277,379	176	#N/A	#N/A
2-10	364,349	213	109	1.95
2-12	478,588	259	99	2.61
2-14	628,645	314	183	1.72
2-16	825,752	381	119	3.20
2-18	1,084,660	463	114	4.07
2-20	1,424,746	562	122	4.62
2-22	1,871,464	681	125	5.45
3-0	39,235	44	#N/A	#N/A
3-2	57,087	57	#N/A	#N/A

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
3-4	83,061	75	#N/A	#N/A
3-6	120,852	97	#N/A	#N/A
3-8	175,839	127	#N/A	#N/A
3-10	255,845	166	126	1.31
3-12	372,252	217	84	2.56
3-14	541,623	283	164	1.72
3-16	788,057	369	152	2.43
4-0	3,330,638	1,026	249	4.12
4-2	3,399,833	1,041	189	5.51
4-4	3,587,924	1,082	256	4.23
4-6	4,099,209	1,189	376	3.17
5-0	8,445,785	1,987	567	3.51
5-2	8,605,754	2,013	453	4.45
5-4	9,322,683	2,131	425	5.01
6-0	21,173	28	#N/A	#N/A
6-2	34,909	40	#N/A	#N/A
6-4	57,555	58	#N/A	#N/A
6-6	94,891	82	#N/A	#N/A
6-8	156,449	117	103	1.14
6-10	257,942	167	75	2.23
6-12	425,274	238	77	3.09
7-2	58,652	58	#N/A	#N/A
7-4	124,166	99	#N/A	#N/A
7-6	262,859	169	65	2.61
7-8	556,473	288	102	2.82
8-2	1,042,145	450	148	3.05
8-4	1,145,924	481	150	3.22
8-6	1,428,028	562	218	2.58
9-0	22,334	29	#N/A	#N/A
9-2	40,694	45	#N/A	#N/A
9-4	74,150	69	#N/A	#N/A
9-6	135,110	105	#N/A	#N/A
9-8	246,187	161	68	2.37
9-10	448,582	247	161	1.54
10-4	2,118,697	744	223	3.34
10-6	2,534,671	845	272	3.10
11-2	12,231,218	2,584	442	5.85

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
11-4	12,473,752	2,620	464	5.65
11-6	12,873,623	2,680	612	4.38
11-8	13,532,899	2,777	709	3.92
11-10	14,619,861	2,933	839	3.50
11-12	16,411,959	3,184	1,284	2.48
12-0	151,543	114	#N/A	#N/A
12-2	194,585	137	#N/A	#N/A
12-4	249,853	163	#N/A	#N/A
12-6	320,817	195	111	1.76
12-8	411,937	233	202	1.15
12-10	528,938	278	110	2.53
12-12	679,170	332	130	2.56
12-14	872,071	396	120	3.31
12-16	1,119,762	473	141	3.36
12-18	1,437,802	565	171	3.30
12-20	1,846,175	675	212	3.18
12-22	2,370,535	806	198	4.08
12-24	3,043,828	963	260	3.71
13-0	34,888	40	#N/A	#N/A
13-2	50,762	53	#N/A	#N/A
13-4	73,858	69	#N/A	#N/A
13-6	107,462	90	#N/A	#N/A
13-8	156,357	117	96	1.22
13-10	227,498	153	105	1.45
13-12	331,008	199	104	1.91
13-14	481,613	260	130	2.00
13-16	700,743	339	124	2.75
14-0	3,853,185	1,138	295	3.86
14-2	3,896,154	1,147	272	4.22
14-4	3,956,121	1,160	240	4.83
14-6	4,039,813	1,177	234	5.02
14-8	4,156,615	1,201	248	4.83
14-10	4,319,625	1,234	262	4.72
14-12	4,547,123	1,280	241	5.31
14-14	4,864,623	1,343	247	5.44
14-16	5,307,729	1,429	272	5.25
14-18	5,926,134	1,545	246	6.27

Section	Tidal Prism (m³)	Cross-Sectional Area (m²)	Width (m)	Mean Depth (m)
15-0	34,575	40	#N/A	#N/A
15-2	57,004	57	#N/A	#N/A
15-4	93,984	81	70	1.16
15-6	154,953	116	87	1.33
15-8	255,474	166	79	2.11
15-10	421,205	236	82	2.88
15-12	694,450	337	87	3.86
16-2	6,724,329	1,690	189	8.93
16-4	7,085,539	1,754	275	6.38
17-0	23,664,291	4,129	1,841	2.24
17-2	26,847,635	4,516	2,140	2.11
18-0	31,408	37	#N/A	#N/A
18-2	57,229	57	49	1.17
18-4	104,278	88	113	0.78
18-6	190,008	134	101	1.33
18-8	346,216	206	111	1.85
18-10	630,847	315	134	2.35