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Geomorphic evolution of the Great Yarmouth coastal system: spit sediment dynamics and forcing mechanisms

Geomorphic evolution of the Great Yarmouth coastal system: spit sediment dynamics and forcing mechanisms

The Crown Estate-Caird Research Fellowship

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i. Executive Summary

The potential for offshore sandbank systems to support resources such as wind farm developments, marine aggregates and sensitive habitats has triggered the need for an understanding of their geomorphic evolution. Such is the case for offshore sandbanks in the region of Great Yarmouth, Norfolk which have experienced a recent spate of investigation. However, despite the likelihood of sediment links, the interaction of these banks with adjacent coastal features has been largely overlooked. An understanding of coastal geomorphology is also central to the management of onshore resources such as buildings, infrastructure, scenic landscapes and sensitive habitats. This is especially pertinent in areas such as the Great Yarmouth region of Norfolk where the coastal geomorphology (the Great Yarmouth spit) protects low-lying land from extensive flooding.

Despite this strategic role in protecting and maintaining offshore and onshore resources, the role of coastal geomorphological features as sediment sinks is often neglected from studies of coastal sediment dynamics. For example, little is known of the volume of sediment held within the Great Yarmouth spit or its short-term fluctuations in sediment storage capacity. Such gaps in coastal sediment budgets mean that the effects of predicted future increases in relative sea level (RSL) and storminess are difficult to forecast. The current study will address this by examining the late-Holocene geomorphic evolution of the Great Yarmouth spit, providing a value for the volume of sediment stored within the feature and placing current morphological changes within an historical context. The specific aims of this research are to investigate: (1) spit volume, (2) spit morphological change (3) potential forcings for this change and (4) likely future morphological trends. Findings disseminated within this report result from the Crown Estate-Caird Research Fellowship, under the joint scheme between The Crown Estate and the National Maritime Museum.

Mathematical modelling of the pre-Holocene topography of the Great Yarmouth area highlights the existence of a wide palaeo-valley cutting the modern coastline between Caister-on-Sea in the North and Gorleston-on-Sea to the South. The Great Yarmouth spit lies across this feature and appears to be grounded against topographic highs contained within the channel. An early form (pre-1613AD) of the Great Yarmouth spit, lying across this estuary and extending southwards to Gunton, contained approximately $213 \times 10^6 m^3$ of sediment. The current feature holds approximately $190 \times 10^6 m^3$ and provides a significant sink for sediment within the Great Yarmouth coastal system.

Short-term fluctuations in the Great Yarmouth spit's sediment storage capacity were identified by investigating morphological changes within the feature's coastal zone from map and aerial photograph evidence. These fluctuations appear to be site-specific across the Great Yarmouth spit and adjacent areas. Indeed, between 1800 and 2007 Winterton-on-Sea experienced accretion whilst coastline retreat followed by a period of relative stability typified trends at Caister-on-Sea. North Denes shows sea-ward advance of the coastline but this occurs after a phase of erosion prior to 1890.

Great Yarmouth Pleasure Beach and Gorleston-on-Sea have remained relatively stable after a similar phase of pre-1890 erosion. All sites investigated are currently (2008 data) displaying either maintenance of or an increase in sediment storage capacity within the stable spit area (that above normal tidal conditions) with the exception of Caister Point which is undergoing erosion.

RSL change of +1.5mmyr^{-1} from 1000yrBP to present may account for a general landward migration of the coast planform. However, shorter term perturbations appear better related to individual storm events and coastal engineering works. The most significant event in terms of morphological change was the harbour engineering works of 1613AD which caused a reduction in spit volume of 11% through disruption of littoral drift patterns. The degree of morphological change caused by individual storm events is dependent upon antecedent beach levels, the combination of meteorological and tidal conditions and the state of the coastal defences. Predicted regional changes in sea-level and storminess are likely to cause landward retreat of the coastal planform and reduction in stable spit area. Along defended sections of the Great Yarmouth coast, narrowing of the inter-tidal zone may be expected.

ii. Glossary

Barrier beach
An elongate ridge composed of varying proportions of sand and gravel which lies parallel to the coastline, is joined to the mainland at either end and is not completely submerged at high tide.

Chart Datum (CD)
The level to which elevations on bathymetric charts are referred.

Digital Surface Model
Digital representation of ground surface topography where data points are assigned X, Y and Z values.

Fractal Effect
The variation in dimensions of a measured feature according to the scale at which the measurement is undertaken.

Georeferencing
The process of defining the existence of a spatial dataset (for example digital maps and aerial photographs) in physical space. Ground control points (readily identifiable features such as buildings, infrastructure and/or landscape elements) are used to assign real-world coordinates to specific locations on the spatial dataset.

Holocene
The most recent subdivision of geological time, ranging from the present to c.10,000yrBP.

Inter-tidal
The area of land which is subaerial at low tide and subaqueous at high tide.

Last Glacial Maximum
Maximum extent of ice sheets during the last glacial period, approximately 19,000yrBP

Little Ice Age
Period of relative climatic cooling within the Northern Hemisphere between 1400 and 1850AD.

Littoral Drift
The approximately coast-parallel movement of sediment in the inter-tidal and sub-tidal zones.

Marine Transgression
Landward movement of the coastline as sea-level rises relative to the land.

Medieval Warm Period
Period of relative climatic warming in the North Atlantic region between 800 and 1300AD.

Natural Neighbour Analysis
Method of surface interpolation where individual cells are assigned values using the value of and distance to nearby data points.

Ordnance Datum (OD)
The level to which elevations on topographic maps are referred. For the United Kingdom this is defined as mean sea-level measured at Newlyn in Cornwall between 1915 and 1921AD.

Palaeotopography
Ground surface elevations during specific historic periods.

Spit
An elongate ridge composed of varying proportions of sand and gravel which is connected to the coast at one end and is not completely submerged at high tide.

Sub-tidal
The area of land immediately marginal to and below the low tide level.

Supra-tidal
The area of land immediately marginal to and above the high tide level.

Years Before Present (yrBP)
Dating unit where present equals 1st January 1950.

1. Introduction

The potential for offshore sandbank systems to support resources such as wind farm developments, marine aggregates and sensitive habitats has triggered the need for an understanding of their geomorphic evolution. Such is the case for offshore sandbanks in the region of Great Yarmouth, Norfolk which have experienced a recent spate of investigation (Reeve, Horrillo-Caraballo & Magar, 2008; Centre for Environment, Fisheries and Aquaculture Science, 2006; Cooper, Townend & Balson, 2008; Horrillo-Caraballo & Reeve, 2008). However, the interaction of these banks with adjacent coastal features such as the Great Yarmouth spit and onshore promontories or ‘nesses’ (Figure 1) has been largely neglected. This is surprising given that each of these is likely to be linked and maintained through the exchange of sediment (Department for Environment, Food and Rural Affairs, 2002; HR Wallingford, 2002; Halcrow, 2006; North Norfolk District Council, 2007; Cooper, Townend & Balson, 2008; Berthot & Pattiaratchi, 2006; Park & Vincent, 2007; Reeve, Horrillo-Caraballo & Magar, 2008; Balson, 2008). Any study of offshore banks without consideration of the interactions with adjacent coastal geomorphology is liable to be incomplete and the resulting resource management decisions compromised.

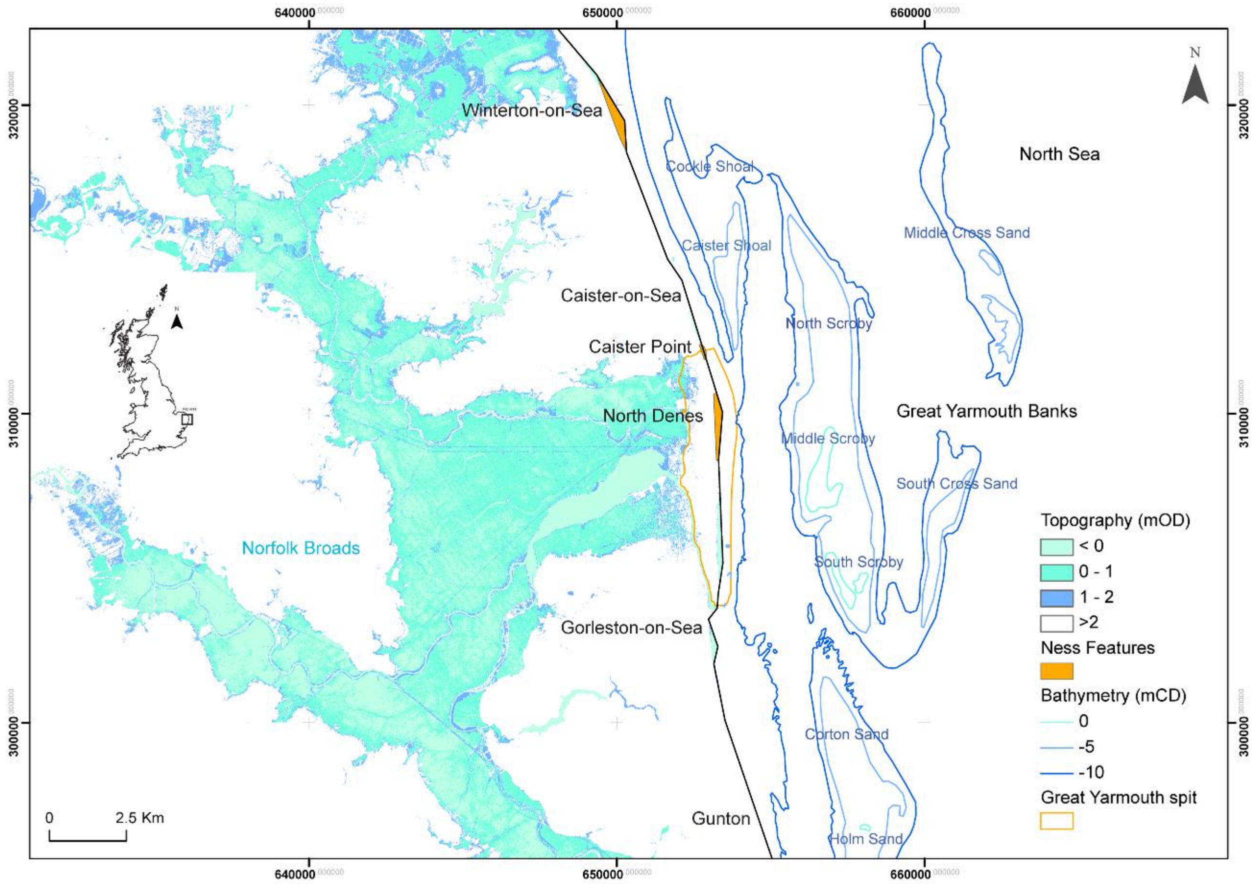

Figure 1 The Great Yarmouth coastal system, including: the Great Yarmouth Banks, Great Yarmouth spit, ness features and proximity to the Norfolk Broads. NEXTMap Britain elevation data from Intermap Technologies. Bathymetry after United Kingdom Hydrographic Office (2009a and b).

An understanding of coastal geomorphology is also central to the management of onshore resources, including: buildings, infrastructure, scenic landscapes and sensitive habitats. This is especially pertinent in areas such as the Great Yarmouth region of Norfolk where the coastal geomorphology protects adjacent low-lying land (the Norfolk Broads) from extensive flooding (Figure 2). Indeed, the development of the Norfolk Broads is closely tied to the dynamics of the Great Yarmouth coast, with periods of marine inundation interspersed by the re-establishment of terrestrial conditions having been identified in the region throughout the Holocene epoch (Ward, 1922; Jardine, 1979; Coles & Funnell, 1981; Cameron *et al*., 1992; Arthurton *et al*., 1994; Brew *et al*., 2000). Whilst global sea level rise following the Last Glacial Maximum is viewed as largely responsible for the marine inundations, renewal of terrestrial conditions is attributed to protection through the development of coastal barriers such as nearshore banks, barrier beaches and spits (Hydrographic Department, 1897; Chatwin, 1961; Ashwin & Davison, 2005).

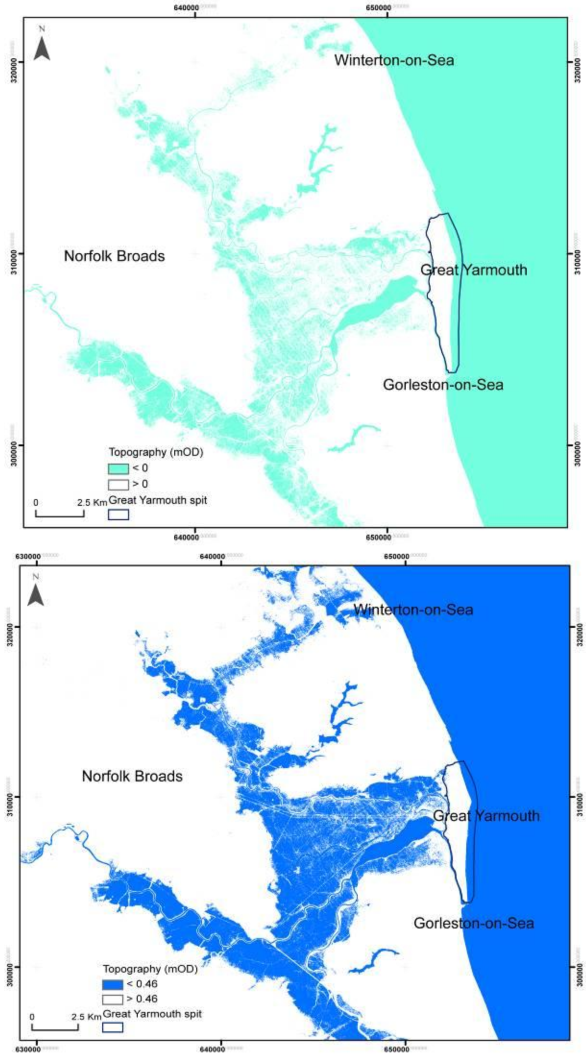

Figure 2 Potential coastline position in the absence of the Great Yarmouth spit. Shaded areas equal to: (Top) land below current mean sea-level and (Bottom) land below predicted mean sea-level in 2095. Note that wave action and tidal range are not accounted for making these coastline positions conservative estimates. Future sea-level prediction derived from Lowe *et al*. (2009) high emission scenario, central estimate for London in 2095.

Despite this vital protective function, the role of coastal barriers as sediment sinks is often neglected from studies of coastal sediment dynamics. Indeed, whilst some aspects of the Great Yarmouth coastal system are well studied (Figure 3), little is known of the volume of sediment held within the Great Yarmouth spit in its current form or in the larger feature documented prior to 1613AD. Short-term fluctuations in sediment storage capacity of the Great Yarmouth spit are also relatively unknown. Such gaps in coastal sediment budgets mean that the effects of predicted future increases in relative sea level (RSL) and storminess (Lowe *et al*., 2009) are difficult to forecast. The current study will address this by examining the late-Holocene geomorphic evolution of the Great Yarmouth spit, providing an estimate for the volume of sediment stored within the feature and placing current morphological changes within an historical context. The specific aims of this research are to investigate (1) spit volume, (2) spit morphological change, (3) potential forcings for this change and (4) likely future morphological trends. Findings disseminated within this report result from the Crown Estate-Caird Research Fellowship.

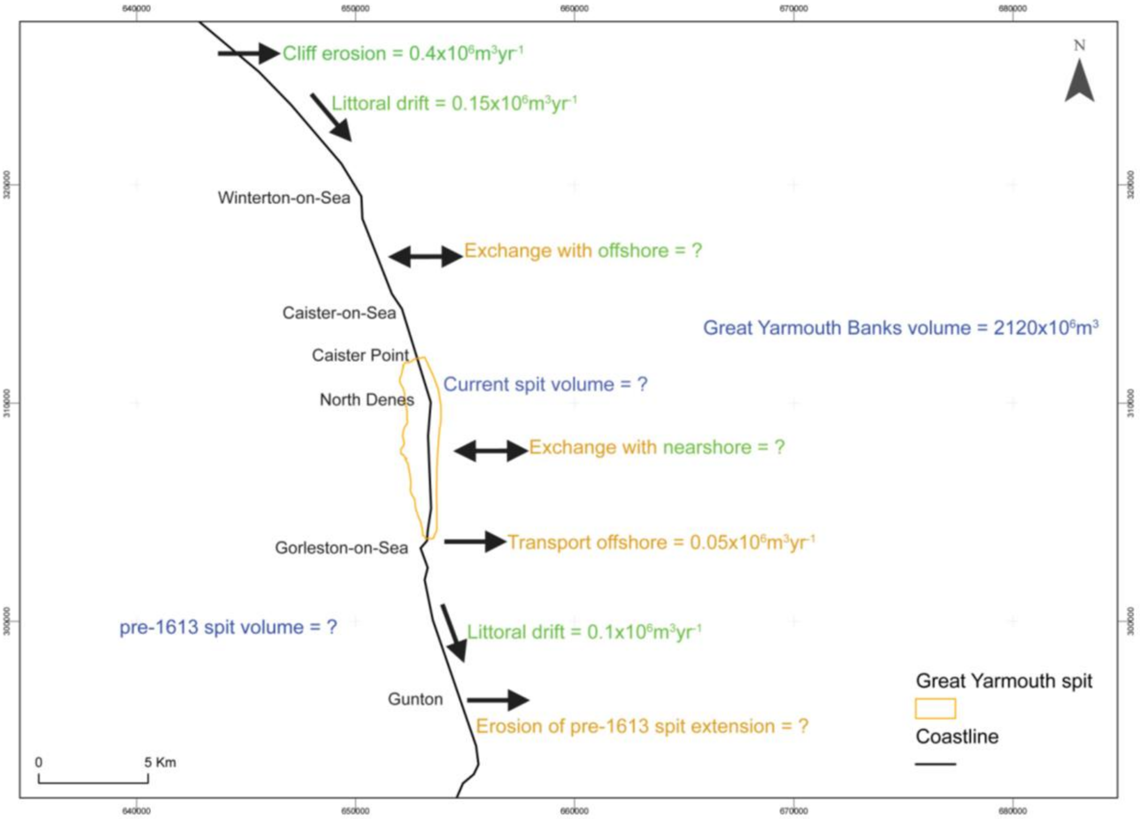

Figure 3 The existing state of knowledge of the Great Yarmouth coastal system sediment budget. Blue labels denote sediment sinks; orange labels represent sediment losses from the coastal system and green labels equal sediment inputs. Question marks highlight data gaps. The cliff erosion value equates to erosion of cliffs to the north of the study area. The Great Yarmouth banks include the Inner Great Yarmouth Banks (detailed in Figure 1) and the Outer Great Yarmouth Banks which lie further offshore (Smith's Knoll, Hewett Ridge, Hearty Knoll, Winterton Ridge, Hammond Knoll and Haisborough Sand). The Great Yarmouth Banks volume is a conservative estimate based upon assumed base surfaces for the banks. Values from McCave & Balson (1990) and Cooper, Townend & Balson (2008).

2. Methodology

2.1 Calculation of spit sediment volume

For the purposes of this study, spit volume is defined as spit area multiplied by spit deposit thickness. Spit deposit thickness, in turn, corresponds to the elevation difference between the spit deposit top and base surfaces.

2.1.1 Current spit volume

In accordance with Arthurton et al (1994), the Great Yarmouth spit is characterised by deposits of the North Denes Formation. The current spit area was, therefore, defined by digitising these deposits in ESRI ArcMap 9.2 from the 1:50,000 Geological Map Sheet 162 (Solid and Drift) (British Geological Survey, 1994). The conditions outlined in Table 1 were followed.

Margin	Defined Limit	Justification
Northern	Northern edge of North Denes Formation continued to coast at Caister-on-Sea	Characteristic spit deposits
Eastern	Centre line of offshore sand unit	Published North Denes Formation seaward limit is arbitrary extent (Arthurton et al, 1994). Offshore unit suffix indicates shoreface and beach deposits, potentially corresponding to North Denes Formation. Centre line position chosen to prevent inclusion of nearby sheet and tabular deposits which represent a different depositional environment
Southern	Yarmouth Haven North Pier	The Yare mouth and associated defence works truncate the spit, limiting transfer of sediment to the south
Western	Western edge of North Denes Formation	Characteristic spit deposits. The actual extent of the North Denes Formation may advance westwards at depth due to intercalation with the Breydon Formation (Steve Booth, British Geological Survey, pers. comm, 2009). However, current borehole coverage is insufficient to map this accurately.

Table 1 Definition criteria for the current spit area.

As intercalation of the North Denes Formation with the underlying Breydon Formation is likely at depth (Steve Booth, British Geological Survey, pers. comm., 2009), the current spit base surface was taken as equal to that of the Breydon Formation, i.e. the base of Holocene deposits. Breydon Formation elevation and thickness data were extracted from borehole records held within the British Geological Survey (BGS) Single Onshore Borehole Index. 44,060 records were examined and divided into those proving the base of the Breydon Formation (Base Proven-BP), those with Breydon Formation at borehole termination depth (Termination Depth-TD) and those terminating before the Breydon Formation was reached (Terminating Before-TB). Alternative methods for determining the elevations of geological units, such as trail pitting and Ground Penetrating Radar analyses (van Heteren *et al*., 1996;

Dickson *et al*., 2009), were precluded by the great depths at which the Breydon Formation is present.

Mathematical modelling of the spit base surface was undertaken in order to provide an absolute spit volume rather than relative changes as is often the case in coastal morphological studies (Arens, 1997; Hapke & Richmond, 2000; Lapinskis, 2005; Shrestha *et al*., 2005). The edge of the Breydon Formation was digitised from BGS 1:50,000 Geological Map Sheet 162 (Solid and Drift) (British Geological Survey, 1994) within ESRI ArcMap 9.2. These points form the onshore limit of the spit base surface model and were ascribed a deposit thickness of 1m (deposits thinner than 1m are not detailed on BGS maps). Elevation data was achieved by subtracting this thickness from NEXTMap Digital Surface Model (DSM) data.

The model's offshore limits were derived by digitising the meeting point of the Crag and Breydon Formation deposits from 1:50,000 Geological Map Sheet 162 (Solid and Drift) (British Geological Survey, 1994). Breydon Formation thickness is here equal to 1m. As Crag is stratigraphically lower than the Breydon Formation this represents the true edge of the Holocene deposits: in other areas, the presence of stratigraphically higher units may mask a continuation of the Breydon Formation at depth. 9 vibrocores collected under the East Coast Regional Environmental Characterisation Study (Centre for Environment, Fisheries and Aquaculture Science, in preparation) were also examined for Breydon Formation deposits, further constraining the offshore limits. The onshore and offshore constraint data were added to the model as additional base proven (BP) points. Dating is currently being undertaken to ascertain if these represent Holocene or pre-Holocene sea-level fluctuations: the latter being the case for similar deposits identified by Wessex Archaeology (Wessex Archaeology, 2008).

Natural Neighbour analysis was performed on the base proven (BP) data in order to interpolate a spit base surface. The resulting grid was refined by ensuring that minimum Breydon Formation depths identified in borehole records with Breydon Formation at termination depth (TD) were adhered to. In areas where boreholes proving the base of the Breydon Formation are limited, the spit base surface may appear shallower than seabed level. As this is stratigraphically incorrect in areas with mapped Holocene seabed sediments, the model was forced to seabed level.

The current spit top surface was created by digitising bathymetry from United Kingdom Hydrographic Office Admiralty Chart 1534 (United Kingdom Hydrographic Office, 2009a) georeferenced in ESRI ArcMap 9.2 using the Admiralty Raster Chart Service (ARCS) for GIS 1.8. This data was interpolated to form a surface using natural neighbour analysis and merged with NEXTMap DSM data for the onshore areas. The spit top and base surfaces were then examined in cross-section using Geological Surveying and Investigation in 3D (GSI3D) and Subsurface Viewer software. Next, the spit top surface, spit base surface and spit area data were imported into Mapinfo 8.0 where Vertical Mapper 3.1 allowed calculation of deposit thickness and spit volume. Mapinfo was used in preference to ESRI ArcMap at this stage as a value for volume is automatically generated.

The NEXTMap DSM data used in the spit top surface calculations includes infrastructure and anthropogenic deposits (Dowman *et al*., 2003). As a result, the contribution of artificial ground to the above volume calculation was assessed using data provided by Norfolk Landscape Archaeology. Specifically, 142 Dando Terrier borehole records were provided in which the deposits were categorised into 7 archaeological units- Modern (1950-2008), Post-Medieval (1650-1950), Late-Medieval (1350-1650), Early-Medieval (1050-1350), Aeolian (pre-1050), Marine (pre-1050) and Pre-Marine (pre-1050)- for a test area of the current Great Yarmouth spit. Interpolation of this data in the current study using natural neighbour analysis in ESRI ArcMap 9.2 led to the production of 7 surfaces or ‘palaeotopographies’ (Ken Hamilton, Norfolk Landscape Archaeology, pers. comm., 2009). These represent ground surface elevations at the end of each archaeological unit identified above.

In order to separate the natural and anthropogenic contributions to spit volume, 7 further volume calculations were performed in Mapinfo 8.0 (with Vertical Mapper 3.1) using the base of Holocene model as spit base surface but alternating each of the palaeotopographies as the spit top surface. A final analysis was performed for the test area with NEXTMap DSM data as the spit top surface. Calculations using Aeolian, Marine and Pre-Marine palaeotopographies represent purely natural spit sediment volumes whilst those with NEXTMap, Modern, Post-Medieval, Late-Medieval and Early-Medieval data possess an artificial component.

2.1.2 Pre-1613 spit volume

Since 1346, the mouth of the River Yare has occupied seven different positions along the Great Yarmouth coast (Swinden, 1772, Parkin, 1776; Rennie, 1819; Manship, 1845; Palmer, 1853; Hedges, 1959; Meeres, 2007). Prior to the cutting of the current exit at Gorleston-on-Sea (the 7th Haven), the Great Yarmouth spit extended as far south as the Corton/ Gunton area (Swindon, 1772; Parkin, 1776; Press, 1956; Hedges, 1959; Arthurton *et al*., 1994). However, the exact date for the completion of this engineering work is ambiguous with estimates ranging from 1560 to 1613 (Crisp, 1871; Press, 1956; Arthurton *et al*., 1994; Skempton, 2002; HR Wallingford, 2002; Cooper, Townend & Balson, 2008). For the purposes of this study the pre-7th Haven spit will, therefore, be referred to as the pre-1613 form.

The volume of the pre-1613 Gorleston-on-Sea to Gunton spit extension was calculated in order to estimate the storage potential of the pre-1613 feature and the amount of sediment that was transferred to the coastal system following cutting. An ESRI ArcMap 9.2 polygon was digitised according to the criteria in Table 2 to define the area of the pre-1613 spit extension.

Post-1613 marine erosion has removed Holocene deposits from this area and, as such, the base of the Breydon Formation cannot be directly determined for use as the spit base. Instead, Crag underlies the spit extension area and the top surface of this unit was used as a proxy for the base of the Breydon Formation. Bathymetry data was digitised from United Kingdom Hydrographic Office Admiralty Charts 1534 and 1535 (United Kingdom Hydrographic Office, 2009a and b) georeferenced in ESRI ArcMap 9.2 using ARCs for GIS 1.8. The resulting point data was interpolated to a grid surface using natural neighbour analysis. The potential effects of marine erosion upon the Crag mean that the bathymetry data may represent a minimum elevation for the base surface. The volume calculation for the spit extension is, therefore, likely to be a maximum estimate.

Margin	**Defined Limit**	**Justification**
Northern	Southern limit of current spit	A continuous feature existed between Caister-on-Sea and Gunton (Ward, 1922; Swindon, 1772; Parkin, 1776; Hedges, 1959)
Eastern	Continuation of current spit eastern limit.	A continuous feature existed between Caister-on-Sea and Gunton (Ward, 1922; Swindon, 1772; Parkin, 1776; Hedges, 1959)
Southern	Gunton	A continuous feature existed between Caister-on-Sea and Gunton (Ward, 1922; Swindon, 1772; Parkin, 1776; Hedges, 1959)
Western	8m seaward of current coast.	This buffer between the pre-1613 spit and the current coast represents a continuation of the River Yare with mean river width equal to current mean river width in the area (Ordnance Survey, 2007).

Table 2 Definition criteria for the pre-1613 spit extension area.

The top surface for the pre-1613 extension was derived by digitising points running along 4 coast-parallel lines in ESRI ArcMap 9.2. Elevation values attributed to these points were based upon the assumptions in table 3 and natural neighbour analysis was performed to interpolate a grid surface. The use of elevations similar to those for the current spit relies upon minimal roll-back of this feature having taken place since 1613. The top and base surfaces were clipped to the extension area and imported into Mapinfo 8.0 where Vertical Mapper 3.1 was used to calculate deposit thickness and volume.

Line	**Elevation (mOD)**	**Justification**
1. Western	0	The limit would have been bounded by the pre-1613 River Yare. Assuming minimal change in sea level since 1613, elevations would have approached 0mOD.
2. West-central	6 decreasing southwards to 4	Continue elevation trends seen within current spit which are likely to have changed little since the 11th Century (Arthurton *et al.*, 1994).
3. East-central	0	This limit would have been bounded by the pre-1613 coastline. Assuming minimal change in sea level since 1613, elevations would have approached 0mOD.
4. Eastern	-7.5	Equal to current bathymetry. Given the minimal elevation difference between the current spit top and base surfaces along the current spit eastern limit, a meeting of the pre-1613 top and base spit surfaces is reasonable.

Table 3 Top-surface elevations for the pre-1613 spit extension.

2.2 Examination of morphological change

2.2.1 Long-term morphological change

Over 25 maps of the Great Yarmouth coast were examined, ranging from the 2007 OS map to the 'Hutch Map' which purports to show an 11th Century view of the region (Ives, 1803). A comprehensive list of maps consulted and their metadata is given in Appendix 1. These maps were scanned in high resolution (300dpi) by the National Maritime Museum and British Library (with the exception of the 'Hutch map' which was provided digitally by the Norfolk Record Office). Raster images (TIFF format) were georeferenced within ESRI ArcMap 9.2 to the Cartesian British National Grid (OSGB36) coordinate system using available ground control points (for example, churches and roads). The degree of error in the rectification process typically increased with map age and, in limited cases, varied within the same map. For example, settlements named upon the 'Hutch Map' accord relatively well with those on the 2007 OS topographic map in some areas but diverge increasingly (up to approximately 5000m) towards the east and west (Figure 4). These errors will be taken into account.

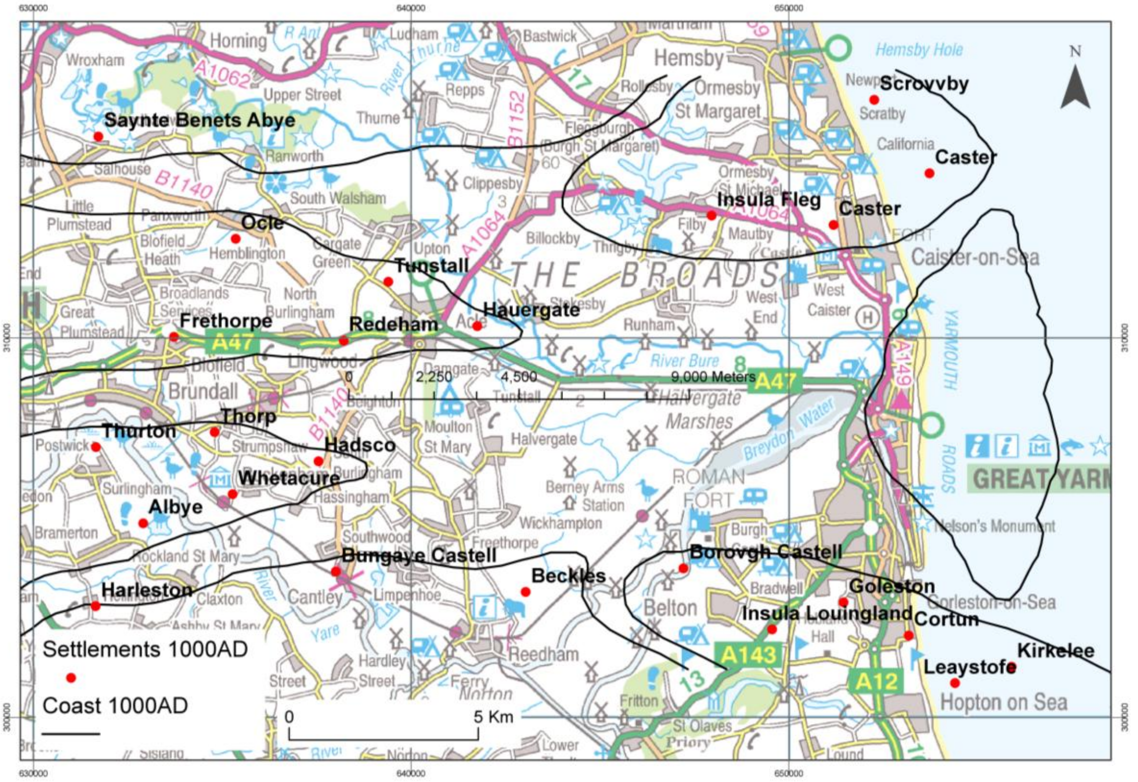

Figure 4 Coastline and settlement positions within the Great Yarmouth area in 1000 and 2007. Features dating to 1000AD are digitised from the 'Hutch Map', georeferenced to the Cartesian British National Grid (OSGB36) coordinate system.

In order to examine long-term (1000 year) morphological trends within the Great Yarmouth spit's coastal zone and place short-term changes in context, coastline positions were digitised from the maps at a scale of 1:2,500. Coastline change can also provide a useful proxy for volume change (Farris &

List, 2007). As the coastline may be defined as the land-water interface, one of the most readily identifiable proxies is water level, i.e. the intersection of the tidal datum with the coastal profile (Boak & Turner, 2005). Consequently, mean high water mark position was captured from the above maps. However, many of the older maps neglected to show tidal limits, instead displaying a single contour. As Great Yarmouth is micro-tidal, with a vertical tidal range of approximately 2m (Horrillo-Caraballo & Reeve, 2008; Reeve, Horrillo-Caraballo & Magar, 2008), the error incurred by digitising different tidal stages is likely to fall within that of the georectification process. Coast planform changes were then quantified by determining the distance of the digitised coast to an arbitrary, unchanging point at five locations along the Great Yarmouth coast for each of the map dates.

2.2.2 Short-term morphological change

Large sections of the Great Yarmouth spit have been protected in recent times by man-made coastal defences. However, morphological change seaward of these structures is possible (Halcrow, 2006; North Norfolk District Council, 2007). 153 aerial photographs of the Great Yarmouth coast flown by the Royal Air Force, Ordnance Survey and Environment Agency were collated for the years 1940-2008. Photographs were selected to give coverage at approximately 5 year intervals across this 68 year period: specifically, 1940, 1945, 1951, 1955, 1965, 1978, 1981, 1988, 1992, 1997, 2001, 2005 and 2008. Photographs were supplied as high resolution scans (300dpi) in TIFF format. A comprehensive list of images consulted and their metadata is given in Appendix 2. These were georeferenced in ESRI ArcMap 9.2 to the Cartesian British National Grid (OSGB36) coordinate system. In all cases a minimum rectification accuracy of 5m was achieved.

As the level of image overlap available was often less than that recommended for Digital Terrain Model or orthophotograph creation (60% according to Hapke & Richmond, 2000), coast planforms were, instead, investigated. Water level in the above images was digitised in ESRI ArcMap 9.2 at a scale of 1:750 in order to identify a continuous contour along the Great Yarmouth spit’s coastal zone. Changes in the contour’s cross-shore location represent changes in beach elevation and, thus, morphology. The point of wave breaking rather than maximum wave run-up was captured so as to minimise the possible effect of variable wind conditions and the 7th wave phenomenon (Podgórski *et al*., 2000). The digitised water levels are dependent upon the tide conditions at the time of photograph acquisition; these were unobtainable for the older photographs due to a lack of date and/or time information for these images. As such, recognition of the same planform moving east-west across the beach may merely indicate a change in the state of the tide whilst a changing planform in a north-south direction reflects altered morphology.

ESRI ArcMap 9.2 polygons, bounded to the east by the seaward beach vegetation limit and to the west by an arbitrary line inland of the 2008 coastal defences, were digitised from the aerial photographs at a scale of 1:750. The spit within these polygons is regarded as morphologically stable during normal tidal conditions. Changes in the area of these polygons represent fluctuations in sediment storage capacity with an increased stable spit area reflecting seaward extension of the stable polygon. It should be noted that these polygons provide a measure of the stable spit area and not the stable spit surface area. Two polygons with the same area can, therefore, provide different sediment storage capacities depending on spit elevation. However, for the purposes of this study it is assumed that an increased stable spit area represents an increased sediment storage capacity as supra-tidal elevations are likely to be similar at the same location throughout the study period.

2.3 Investigation of potential forcings

Relative sea-level (RSL) observation and prediction data for the East Anglian region were provided by Ian Shennan (University of Durham). Methodological details can be found in Shennan *et al*. (2006) and Shennan, Milne & Bradley (2009) with model updates in Bradley *et al*. (2009) and Bradley *et al*. (2010). RSL rates and trends were calculated for the last 1,000 years in order to identify potential forcings for coastal morphological change. As only one sea-level index point and two model values are available for this period, data from 3000yrBP to present were used for rate calculations. Historic references and existing scientific literature were also reviewed in order to determine further potential forcing mechanisms including, storm events and coastal engineering works.

3. Results and discussion

3.1 Calculation of spit sediment volume

3.1.1 Current spit volume

Mathematical modelling of the current spit base surface (Figure 5) highlights the existence of a wide trough within the pre-Holocene deposits. This feature cuts the modern coastline between Caister-on-Sea in the North and Gorleston-on-Sea to the South and corresponds with the location of the proposed ‘Great Estuary’ (Manship, 1845; Walcott, 1861; Coles & Funnell, 1981; Arthurton *et al*., 1994). As the current study focuses upon the area of the Great Yarmouth coast, extensive interrogation of borehole data to the west of the region was beyond the study’s remit. As such, the trough’s western limit is only loosely defined in Figure 5 and the feature is best regarded as a palaeo-valley rather than an embayment.

A general deepening seawards and towards the centre of the valley is evident, with the exception of topographic highs present around grid references $^{6}52100$, $^{3}08433$ and $^{6}52325$, $^{3}09637$. The current spit lies across the palaeo-valley and appears to be grounded against these highs. As marine transgression during the Holocene has previously been demonstrated for this area (Coles & Funnell, 1981; Cameron *et al*., 1992; Arthurton *et al*., 1994; Brew *et al*., 2000) and retreat of coastal barriers (barrier islands, barrier beaches and spits) is typical in the face of such transgression (Hails, 1975; Rampino & San, 1980; Andrews *et al*., 2000; Massey & Taylor, 2007), the spit currently at Great Yarmouth is likely to have migrated landwards to its current position. Intercalation of Breydon Formation and North Denes Formation deposits along the current spit’s western limit, identified from borehole records, may result from such migration.

Significant topographic lows are also evident from the spit base surface. That at $^{6}52537$, $^{3}10653$ approximates to the location of Grubb’s Haven: an historic mouth of the River Yare (Swinden, 1772; Druery, 1826; Crisp, 1871; Ward, 1922; Lewis, 1980). A more localised feature at $^{6}53140$, $^{3}05363$, in turn, corresponds with the mouth of the River Yare between approximately 1392 and 1407 and 1548 and 1549, Great Yarmouth’s 2nd and 6th Havens (Swinden, 1772; Crisp, 1871; Press, 1956). The similar depths achieved by these features suggest that both experienced a comparable degree of fluvial erosion. Reports of a barrier lying within the estuary mouth during the Holocene (Swinden, 1772; Ives, 1803; Arthurton et al., 1994), suggest that these topographic lows could originally have been contemporaneous, forming the northern and southern limits of this barrier. In this case, the relatively short-lived 2nd and 6th Havens would have re-used the original southern channel. The different spatial extent achieved by these features may reflect fluctuations in the location of this barrier, greater fluctuations being experienced along its northern margin. Further boreholes are required before the offshore portions of these proposed channels can be characterised in detail.

Modelling of the current spit top surface reveals a step in elevation between the onshore and offshore portions (Figure 6). This can be attributed to erosion via wave action and tidal scouring following formation of the spit. Calculation of the sediment volume held within the current spit provides a value of $190 \times 10^6 m^3$. The use of conservative eastern and western limits for the spit area means that this value is a minimum estimate. Less than 25% of this volume is exposed above current sea level.

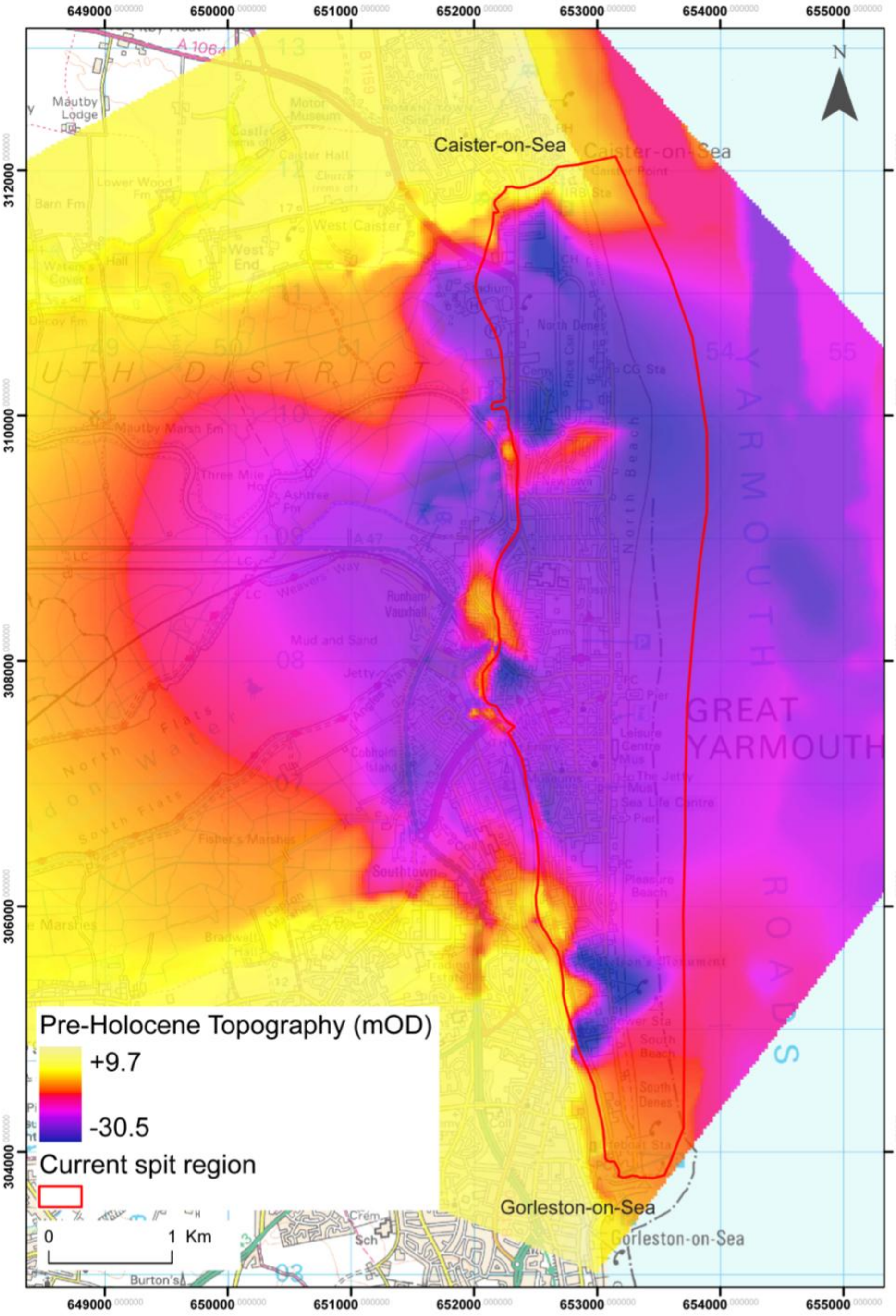

Figure 5 Pre-Holocene topography of the Great Yarmouth area derived from mathematical modelling. The current Great Yarmouth spit (outlined) appears to be banked against topographic highs existing with the palaeo-valley. Significant topographic lows are also evident, lying near the northern and southern limits of the current spit.

Figure 6 The three-dimensional morphology of the Great Yarmouth spit revealed from east-west cross-sections through the spit deposits (North Denes Formation and Breydon Formation). 15x vertical exaggeration. Section positions are denoted by orange lines. Note the step in elevation between the onshore and offshore portion of the spit. The marked undulation in spit base surface immediately north of Newtown corresponds with the southernmost topographic high seen in Figure 5.

The contribution of artificial ground to the current spit volume within the test area is presented in Table 4. When NEXTMap DSM data is used to represent the spit top surface, 17.6% of the sediment volume may be derived from artificial sources, namely buildings, infrastructure, landscaping and rubbish disposal (Rogerson, 1976; Davies, in preparation). This corresponds to a masking of the natural topography by as much as 6m of artificial deposits (Figure 7). Intermixing of natural and artificial deposits within the Early-Medieval period (Rogerson, 1976; Ken Hamilton, Norfolk Landscape Archaeology, pers. comm., 2009) means that this artificial sediment contribution represents a maximum estimate.

After the development of the town walls in 1262 (Crisp, 1871) incursion of natural windblown sand deposits into the test area will have been reduced. Successive increases in sediment accumulation rate through time (1050-1350, 0.6x10^{-3}myr^{-1}; 1350-1650, 1.0x10^{-3}myr^{-1} and 1650-2008, 1.7x10^{-3}myr^{-1}) are, therefore, attributed to increased deposition of artificial sediments in line with increased population of the area. Reported short-term depopulation during 1350 to 1380 (Saul, 1982) appears to have had little effect on average sedimentation rates. The degree of erosion of each palaeotopography is impossible to quantify and, as such, the calculated sedimentation rates may be lower than actual. The Aeolian, Marine and Pre-Marine deposits have not been included in this analysis due to a lack of dating evidence prior to 1050.

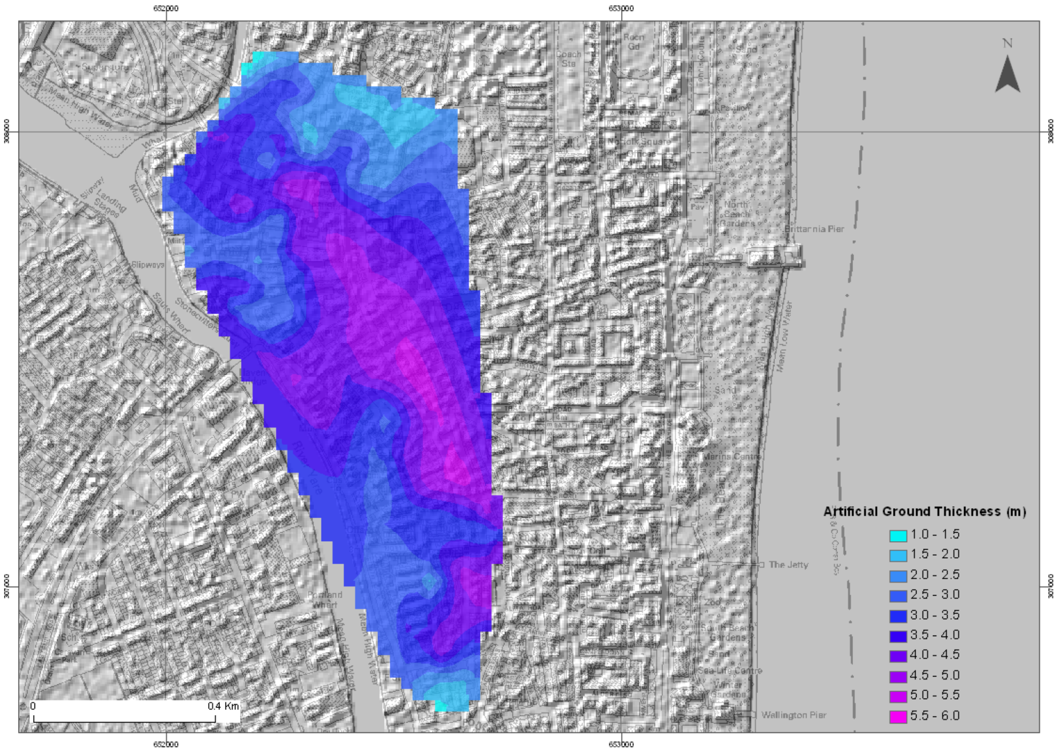

Figure 7 Artificial deposit thickness within the Great Yarmouth test area. The greatest thickness is centred upon Fuller's Hill, generally accepted as the site of first occupation within Great Yarmouth. Underlying NEXTMap Britain elevation data from Intermap Technologies.

As the test area selected for the artificial deposit contribution possesses the longest occupation history in the Great Yarmouth area (Swinden, 1772; Chambers, 1829; Crisp, 1871; Rogerson, 1976; Lewis, 1980; Ashwin & Davison, 2005), anthropogenic activity and artificial deposit thicknesses across the remainder of the current spit are expected to be lower. 1.8% of the test area volume (calculated using NEXTMap DSM data as the spit-top surface) is attributable to the presence of modern infrastructure. Again this figure is likely to be reduced in other regions of the current spit as the vertical accuracy of NEXTMap data improves towards an optimum of ±0.5m with lower infrastructure density (Dowman *et al*., 2003). As such NEXTMap DSM data provides a viable proxy for the current spit top surface.

Archaeological Unit	**Sediment Source**	**Cumulative Volume ($10^6 m^3$)**	**Difference from volume derived using NEXTMap DSM as spit top surface (%)**
Pre-Marine	**Natural**	5.4	22.4
Marine	**Natural**	5.6	19.4
Aeolian	**Natural**	5.7	**17.6**
Early-Medieval	Natural & Artificial	5.9	15.2
Late-Medieval	Artificial	6.2	10.4
Post-Medieval	Artificial	6.7	3.8
Modern	Artificial	6.8	**1.8**

Table 4 Artificial ground contribution to current spit volume within the test area.

3.1.2 Pre-1613 spit volume

Calculation of the sediment volume held within the pre-1613 spit extension provides a value of 23x10^{6}m^{3}. The current spit, therefore, contains 11% less sediment than its earlier form. Examination of the Great Yarmouth spit (pre- and post-1613 forms) and published results for the individual Great Yarmouth Banks suggests that these features contain comparable sediment volumes (Table 5). It is important to note, however, that the values for the Great Yarmouth banks are based upon assumed feature base surfaces which often do not consider the bank volume lying below the modern seabed level. Therefore, whilst the current spit represents a significant sediment sink within the Great Yarmouth coastal system, the volume of the other features in Table 5 are conservative estimates.

Feature	Volume (10^{6}m^{3})	Feature base surface	References
Haisborough Sand	530	Average elevation of surrounding seabed	Cooper, Townend & Balson (2008).
Smiths Knoll	390	Average elevation of surrounding seabed	Cooper, Townend & Balson (2008).
Pre-1613 spit	**213**	**Base of Holocene deposits**	**This study**
Post-1613 spit	**190**	**Base of Holocene deposits**	**This study**
Hewett Ridge	190	Average elevation of surrounding seabed	Cooper, Townend & Balson (2008).
Hearty Knoll	120	Average elevation of surrounding seabed	Cooper, Townend & Balson (2008).
Winterton Ridge	105	Average elevation of surrounding seabed	Cooper, Townend & Balson (2008).
Hammond Knoll	99	Average elevation of surrounding seabed	Cooper, Townend & Balson (2008).
Scroby Sands	32.1	5m below CD	Horrillo-Caraballo & Reeve, 2008.
Holm Sand	12.2	5m below CD	Horrillo-Caraballo & Reeve, 2008.

Table 5 Sediment volumes for the Great Yarmouth spit and Great Yarmouth Banks.

3.2 Examination of morphological change

3.2.1 Long-term morphological change

Water levels digitised from 27 maps reveal coastal morphological change throughout the last 1000 years. Whilst more recent maps show the existence of a spit within the Great Yarmouth area, the oldest 2 maps portray a large estuary cutting the modern coastline between Caister-on-Sea in the North and Gorleston-on-Sea to the South. The mapped location of this estuary mouth ties well with that of the base of Holocene palaeo-valley. The width of the estuary mouth can be seen to shrink gradually from the 1000 to 1588 map and is eventually enclosed by a spit depicted upon a 1661 edition. However, radiocarbon dating of the top surface of Holocene estuarine sediments suggests that the most-recent Holocene marine transgression terminated circa 1500yrBP (Coles & Funnell, 1981; Brew *et al.*, 2000). As such, it is likely that the maps misrepresent the date of the most-recent estuary closure by about 1000 years.

Morphological change is also evident once the Great Yarmouth spit has formed. Indeed, digitised planforms reveal that the coast in the vicinity of Winterton-on-Sea, Caister Point and North Denes, each of which forms a sand promontory or 'ness', appears highly dynamic. Representation of these nesses is varied with some earlier maps appearing more schematic. However, several maps mark the formation of a shore-attached bar at North Denes, with remarkable consistency in its location: is this a stage of ness formation? The coast at Great Yarmouth Pleasure Beach and Gorleston-on-Sea is also subject to significant cross-shore fluctuation in planform. Planform changes were quantified at Winterton-on-Sea, Caister-on-Sea, North Denes, Great Yarmouth Pleasure Beach and Gorleston-on-Sea by calculating the distance between the coastline and a specified unchanging point. The earliest map (1000AD) was excluded from this analysis because of the approximately 600 year interval between the date of mapping and date of the coastline represented.

Error Source	**Likely Effect**	**Error Value**
Original mapping inaccuracies	Misplacement/ misrepresentation of the coastline	Variable
Coastline definition	Suitable water levels for defining the coastline (for example, mean high water mark, mean low water springs, highest astronomical tide) occur in different positions across the beach profile. Use of different water levels will result in varying planforms.	Maximum 2m vertical error, horizontal error depends upon beach gradient.
Re-use of previous data	Wrong date attached to planform	Variable
Mapping purpose	Variable accuracy of mapping across the same map with focus upon particular areas and/or features.	Variable
Mapping scale	Fractal effect causing neglect of smaller scale features	Variable
Mapping projection	Lack of information hindering georeferencing	Variable
Map condition	Poor condition may obscure detail	Variable

Table 6 Potential sources of mapping inaccuracy.

Significant variations in coastal planform are evident prior to 1800 with, for example, cross-shore position varying by $35myr^{-1}$ between 1588 and 1685 at Winterton-on-Sea and Caister-on-Sea and by $10myr^{-1}$ at North Denes, Great Yarmouth Pleasure Beach and Gorleston-on-Sea (Figure 8). Whilst these may reflect actual morphological trends and, thus, a period of increased activity, the variation in coastline position by as much as 2500m between two maps published in 1700 suggests a significant contribution from mapping errors. Limitations to accuracy in early maps may arise from a number of factors, the majority of which produce unquantifiable errors (Table 6). Mapping accuracy is said to have improved vastly in the late 18th and early 19th Centuries (Boak & Turner, 2005) and, as such, the older maps may prove more useful for their general trends rather than specific values. In the case of the pre-1800 Great Yarmouth maps, a general trend of landward retreat of the coast planform is evident since the late 17th Century. Prior to this the coastline appears to have advanced seawards.

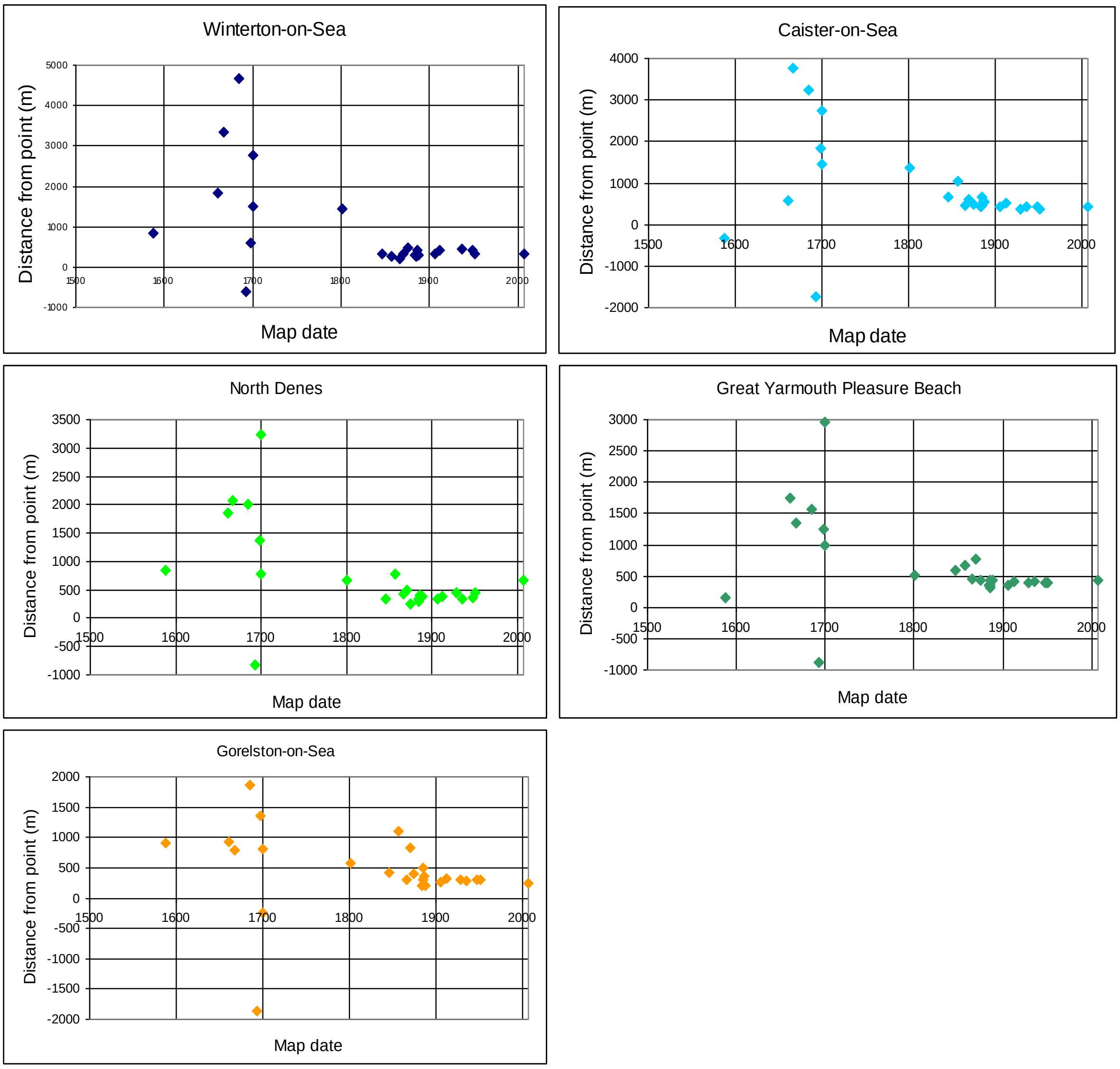

Figure 8 Pre-1800 coast planform changes at Winterton-on-Sea, Caister-on-Sea, North Denes, Great Yarmouth Pleasure Beach and Gorleston-on-Sea derived from distance to point calculations. Note the great variation in coastline position between the two maps published in 1700. Relative study site locations can be seen in Figure 1 (Great Yarmouth Pleasure Beach lies south of North Denes at approximately ^{6}53266, ^{3}06689).

Coast planform trends revealed from later maps (post-1880) were checked against those seen in Ordnance Survey editions. As Ordnance Survey maps are generally produced to a consistent standard, errors arising from coastline definition, mapping purpose, mapping scale, mapping projection and map condition are reduced. Investigation of Ordnance Survey maps revealed similar trends to those identified from non-Ordnance Survey editions and, as such, the post-1800 maps can be seen to be relatively accurate. Indeed, coast planform position at Winterton-on-Sea has remained relatively stable, within a range of 30m; initial seaward advance having been replaced by a very slight retreat of the coastline. Caister-on-Sea has undergone a slight landward retreat followed by an advance back to the 1884 position. North Denes displays marked accretion throughout the 123 year period. Great Yarmouth Pleasure Beach coast planform has also advanced but at a reduced rate, whilst an initial advance at Gorleston-on-Sea appears to have stabilised.

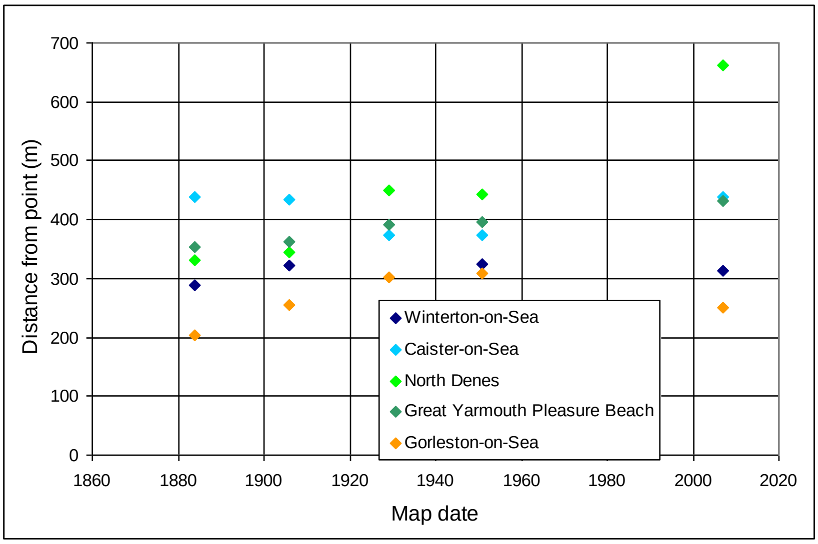

Figure 9 Coast planform changes at Winterton-on-Sea, Caister-on-Sea, North Denes, Great Yarmouth Pleasure Beach and Gorleston-on-Sea for the period 1884 to 2007 derived from Ordnance Survey maps.

The near identical water levels seen in 1929 and 1951 at North Denes (Figure 10) and also Caister-on-Sea, Great Yarmouth Pleasure Beach and Gorleston-on-Sea may result from incomplete revision between map series and re-use of the previous edition's coastline. It is important to note that the Ordnance Survey use water levels averaged over a period of time from measured values (Lesley Flood, Ordnance Survey, pers. comm., 2009). This may mask perturbation of the coast planform by some individual events where recovery is rapid.

3.2.2 Short-term morphological change

Water levels digitised from aerial photographs were investigated in order to identify short-term morphological changes along the Great Yarmouth coast. Results from Caister-on-Sea, North Denes, Great Yarmouth Pleasure Beach and Gorleston-on-Sea are presented in detail here to allow comparison with the long-term morphological trends noted above. Caister Point provides a fifth site, chosen to aid examination of expected changes in the vicinity of Caister Ness (Clayton, McCave & Vincent, 1983; Halcrow, 1988; HR Wallingford. 2002).

Water levels at Caister-on-Sea suggest a period of relative stability in coast planform from 1940 to 2001, with accretion evident in the vicinity of the rock islands implemented in 1995. Apparent accretion at Caister Point may be an artefact of differing tide conditions at the time of aerial photograph acquisition.

However, the near-perfect chronological sequence displayed by the seaward advances in planform suggests some accretion throughout the 68 year period. Along-shore migration of the promontory at Caister Point is also evident with northerly movement between 1965 and 1988 in the order of 269m and southerly movement of a less pronounced form between 2001 and 2008 of 360m. Southerly migration of a coast planform is also seen at North Denes, where along-shore movement of the ness corresponds with seaward advance. Great Yarmouth Pleasure Beach and Gorleston-on-Sea display a consistent coast planform throughout the study period, with any planform changes identified within the magnitude of tidal changes.

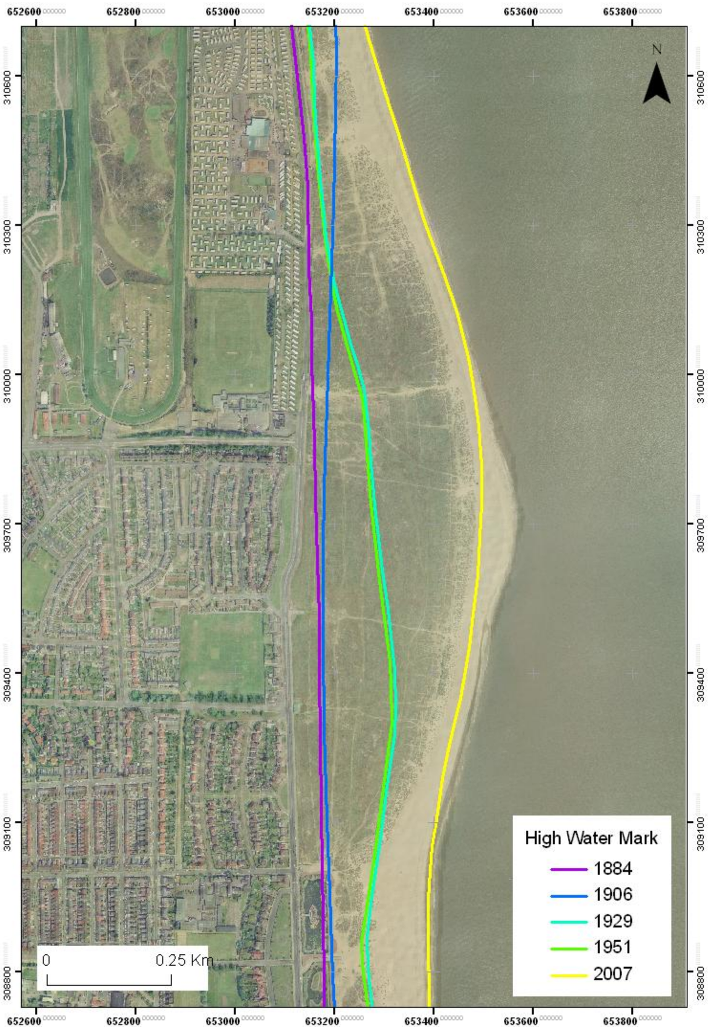

Figure 10 Mean high water positions at North Denes, Great Yarmouth. These levels, digitised from Ordnance Survey topographic maps, reveal significant coastline accretion throughout the last 125 years. The near identical water levels seen in 1929 and 1951 may result from incomplete revision of topographic data between map series.

Calculation of stable spit area (that unaffected by wave action during normal tidal conditions and low magnitude storm events) at five points within the Great Yarmouth spit's coastal zone reveals spatial variation in morphological trends (Figure 11). Caister-on-Sea has experienced two periods of relative stability, between 1940 and 1965 and 1988 and 1997. These are interspersed with a slight decrease in stable area between 1978 and 1988 and two periods of stable area increase in 1965 to 1978 and 1997 to 2008. This latter period of stable area increase may be tied to the development of rock islands in 1995. This suggests a slight (~2 year) time-lag between the installation of coastal defences in the area and beach morphological response. Caister Point, meanwhile, demonstrates a slight increase in stable area prior to 1999, followed by a marked increase between 1988 and 1992. The recent trend of stable spit area reduction has continued since 1992. As of 2008, the stable spit area value had returned to that of the 1978 level.

In contrast to, and perhaps latterly as a result of, reduction at Caister Point (Alan Brampton, HR Wallingford, pers. comm., 2009) North Denes has displayed a steady increase in and, thus, seaward growth of the stable spit area since 1945. This progradation can also be seen in records dating back to the 1930s (Clayton, McCave & Vincent, 1983) and corresponds with a period of elongation of Caister Shoal (the sandbank immediately offshore from this area) southwards towards North Denes (Anna Bakare, University College London, pers. comm., 2010). This supports Berthot & Pattiaratchi's (2006) suggestion of a strong relationship between headland growth and the location of headland-associated linear sandbanks. Any future changes in the location of North Denes may be associated with changes in morphology of the Great Yarmouth Banks.

The Great Yarmouth Pleasure Beach has, meanwhile, displayed a gradual decrease in stable spit area between 1945 and 1992. This agrees with the decreasing beach gradient identified by Aranuvachupun & Johnson (1979) between 1966 and 1974. Post-1992 this trend has reversed and stable spit area is increasing. Finally, the Gorleston-on-Sea frontage appears to have been remarkably stable since 1992. The apparent landward shift in stable spit area in 1997 is likely to result from distortion of the aerial photograph used in stable spit area calculation rather than actual landward regression of the coast planform. Clayton, McCave & Vincent (1983) suggest a similar period of stability from 1976 to 1983 for this area.

Interestingly, Caister-on-Sea, Caister Point, North Denes and Great Yarmouth Pleasure Beach all experienced loss of stable spit area between 1940/45 and 1955. In each case, this represented erosion to the lowest level achieved for the 68 year period. Post-1955 recovery was rapid (maximum 10 years) and at all sites, excepting the Great Yarmouth Pleasure Beach, to greater than pre-1955 levels. Gorleston-on-Sea was excluded from this analysis due to a lack of aerial photographs for the relevant period.

A general agreement between coast planform and stable spit area trends for the five Great Yarmouth study sites can be seen from the above discussion. This raises the validity of using water levels, digitised where knowledge of tide conditions at the time of aerial photograph collection is absent, to identify morphological change. Indeed, although some of the more detailed fluctuations, noted from the stable spit area calculations, are overlooked the overall trends are well represented. It is, therefore, possible to be confident in the planform tendencies identified for the Great Yarmouth coast, including those from areas lying outside of the stable spit area calculations. It is important to note, however, that digitised water levels may not provide such a reliable proxy for coastal morphological change in areas where marked narrowing of the inter-tidal area is occurring.

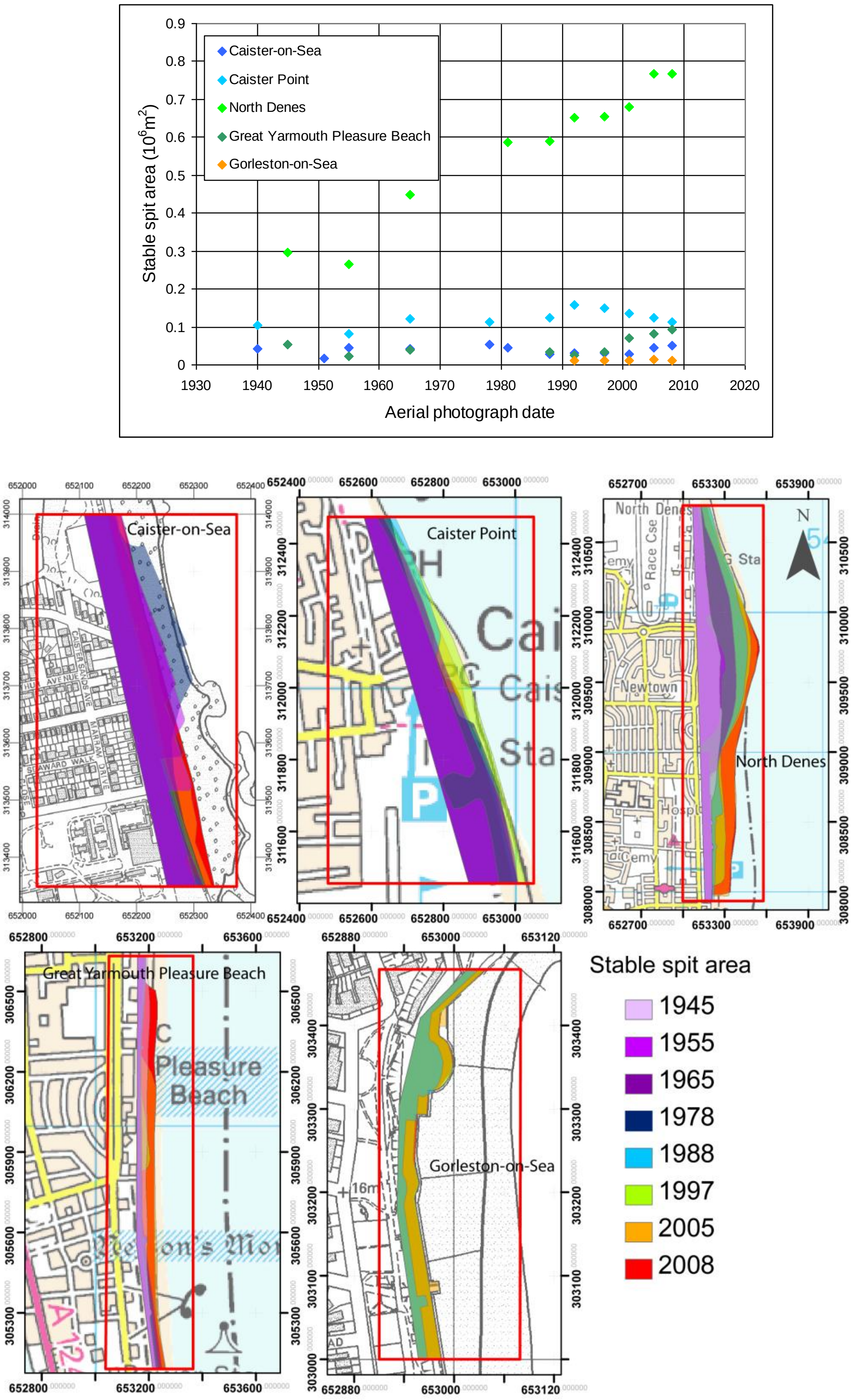

Figure 11 Changes in stable spit area at Caister-on-Sea, Caister Point, North Denes, Great Yarmouth Pleasure Beach and Gorleston-on-Sea derived from aerial photographs.

3.3 Investigation of potential forcings

Calculation of RSL change for the East Anglian region from 3000yrBP to present (where present equals 1950AD) reveals an average value of +1.5mmyr^{-1} when using both observed and modelled data (Figure 12). Whilst this may account for the general landward migration of the coast planform seen in distance from point calculations, the existence of only a few observed and modelled RSL values for the period of interest (1000yrBP to 0yrBP) means that correlation with short-term coastal changes is limited. Indeed, the data appear to show no evidence of relatively short-term fluctuations as seen in Coles & Funnell (1981) or of recent major climatic episodes, the Medieval Warm Period, Little Ice Age and 20th/21st Century warming (Department for Environment, Food and Rural Affairs, 2002; Cronin *et al*., 2003; Esper *et al*., 2005) which may drive such changes. The identification of sea-level index points from new field sites is required before this can be addressed further. In addition, the observed data was collected from sites across the East Anglian region, with distances from the Great Yarmouth area ranging up to 35m. Whilst, this provides a reliable regional picture of RSL, more site-specific changes may be overlooked.

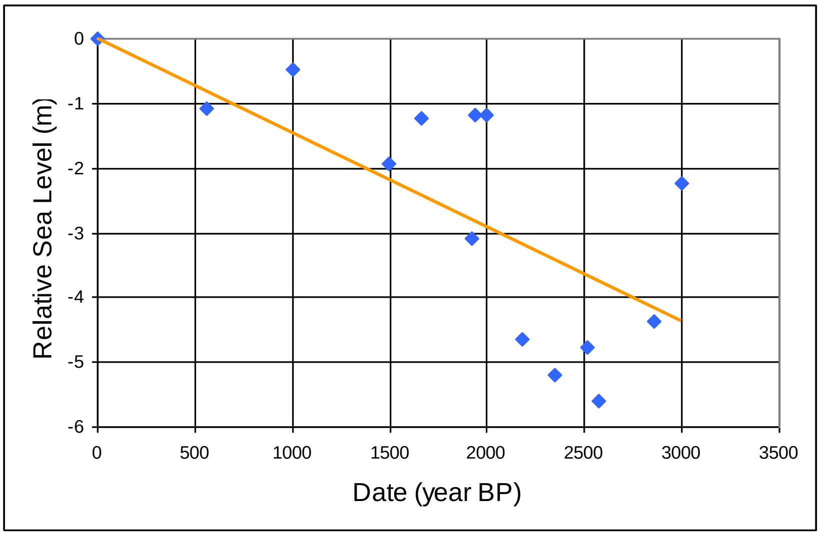

Figure 12 Relative sea-level observations and model predictions for East Anglia between 3000yrBP and present with linear trendline. Model parameters are detailed in Shennan, Milne & Bradley (2009) and Bradley *et al*. (2009).

Further potential forcings for coastal morphological change, including storm events and coastal engineering works, are summarised in Table 7. Correlation of the observed changes in coastline position and stable spit area with potential forcings reveals that the apparent landward retreat of coastline position between 1685 and 1693 may be due to a phase of increased windiness from 1588 to 1698. Prior to 1661, however, this appears to have had little effect as coast planform advanced seawards. Between 1801 and 1846 coastline retreat was seen at all sites, excepting Great Yarmouth Pleasure Beach, and may be attributed to the effect of the 1816, 1825 and 1845 storm events. A significant retreat is also evident between 1857 and 1866, possibly resulting from erosion during the 1861 and 1862 storms.

Coastline retreat at Caister Point, North Denes and Great Yarmouth Pleasure Beach between 1888 and 1906 may tie in with the 1895, 1897 and 1905 storms. Loss of stable spit area evident at Caister Point, North Denes and Great Yarmouth Pleasure Beach between 1940/45 and 1955 may be attributed to the 1953 storm event. Caister-on-Sea, however, appears to have suffered more significantly from the 1949 than 1953 storm, as evidenced by a reduced stable spit area in 1951. The installation of coastal defences at Caister-on-Sea in 1949 may also have contributed through disruption of the seaward vegetation edge during engineering works and, thus, apparent reduction in stable spit area; or alteration of the beach profile and water level. Post storm recovery was rapid at all sites excepting the Great Yarmouth Pleasure Beach.

Interestingly, the 1607 and 1695 storms correspond with a time of seaward advance of the coastline. This may result from transfer of sediment from the nearshore zone to the beach during the storm events or a change in sediment supply to the system outweighing erosional effects. The 1938 storm appears to have had limited morphological effect, with landward retreat of the coastline evident only at Caister-on-Sea. Elsewhere, the coastline planform remained stable. The 1983 and 1987 storms also only affected Caister-on-Sea, causing stable spit area decrease at this site. The 1949 storm event only affected the stable spit area of Caister-on-Sea and Caister Point, leaving the other study sites apparently unaffected. The 1989 storm, meanwhile, only affected the Great Yarmouth Pleasure Beach. The 1978 storm appears to have left no impact upon the study areas.

The variable degree of morphological change caused by different storm events is unsurprising. Indeed, whilst all storm events have the potential to initiate change, as the landward limit of coastal morphological change is dependent on the maximum water level achieved (Roberts, Wang & Kraus, 2007); the exact magnitude of this change is dependent upon wind direction, wind strength, tide level, tide state and the relative timing of these factors. The antecedent conditions are also important, with water levels dependent on pre-existing beach elevations (Callaghan, *et al*., 2008). For example, a storm approaching Great Yarmouth from the east or northeast, timed to hit the coast at high water on a spring tide, when beach volumes are already low could be expected to cause the most change. As such, not all reported storm events can be expected to cause coastal morphological change. A natural bias in reporting tendencies toward the most destructive storms means the most morphologically significant events should fall within those listed in Table 7.

Examination of the characteristics of the morphologically significant and insignificant storm events detailed above suggests that there is little trend between wind direction and degree of coastal change. In addition, Aranuvachapun & Johnson (1979) have noted a lack of correlation between beach gradient and wind speed at Great Yarmouth for the period 1966-1976. Storm surge levels alone also appear to have little effect on the degree of erosion: events with surges 1.8m, 2.3m, 2.9m and 3.0m above predicted sea level caused morphological change, whilst those of 1.8m, 2.0m and 2.3m above predicted sea level did not. This suggests the importance of antecedent factors and the combination of, rather than individual, meteorological and tidal conditions in conditioning coastal change. The state of coastal defences is also likely to affect matters. Indeed, improvement of defence structures post-1953 is likely to reduce the landward extent of change and increase the surge level required for such change. This may account for the apparent lack of response to the proposed increase in storminess post-1950 (Lamb, 1991) with events such as the 1978, 1983, 1987 and 1989 storms causing little morphological change. Works to upgrade the coast defences after the 1953 storm may account for the reduced level of beach recovery seen at the Great Yarmouth Pleasure Beach.

The influence of coastal engineering works is also seen in the loss of the Gorleston-on-Sea to Gunton spit extension. This coincides with the building of the 7th Haven piers in 1613 and may be attributed to interruption and transferral further offshore of the sediment drift patterns by these structures. Indeed, recent littoral drift along the Great Yarmouth coast occurs in a general southerly direction (Clayton, McCave & Vincent, 1983; Shih-Chiao & Evans, 1992; HR Wallingford, 1998; HR Wallingford, 2002; Halcrow, 2006) and it has been suggested that this was also the case prior to 1613 (Whittaker, 1907). Loss of the pre-1613 spit extension, therefore, highlights the dominant influence of sediment sources to the north of the area in maintaining the spit (McCave, 1987; McCave and Balson, 1990; Cameron et al, 1992; Balson, 1999; Cooper, Townend & Balson, 2008). Indeed, Clayton, McCave & Vincent (1983) tie beach volume to the rate of littoral drift. Park & Vincent (2007) suggest that the Great Yarmouth Banks represent a sink for much of the sediment transferred offshore from the Great Yarmouth coast. If this was the case for the pre-1613 spit extension then the loss of $23 \times 10^6 m^3$ of sediment is equal to 45 years of sediment supply at the current coastal erosion rates (based on sediment supply of $5 \times 10^5 m^3 yr^{-1}$, Cooper, Townend & Balson, 2008).

Since 1890, the Gorleston-on-Sea area seems to have been relatively stable in planform, with maintenance of the post-1613 lower beach levels likely controlled by sediment movement between the nearshore and inter-tidal zone. Meanwhile, the lack of significant storm events between 1991 and 2008 may account for the maintenance of the stable spit area. The outer harbour engineering works, begun in 2007 have acted to alter water levels in their immediate vicinity. However, this represents the initial development of coastal defence structures rather than the resulting erosion or accretion of sediment. Stable spit area in the vicinity is, as yet, unaffected.

3.4 Likely future morphological trends

Clayton, McCave & Vincent (1983) suggest that the rate of sea level rise has a greater effect on erosion along the Great Yarmouth coast than engineering works. The above discussion demonstrates that this is certainly the case for the general trends seen in coastal morphology over the last 1000 years. Shorter term perturbations in coastal morphology are, however, better related to individual storm events and coastal engineering works. The most significant of these events remains the cutting of the 7th Haven which caused erosion of the Gorleston-on-Sea to Gunton spit extension and loss of 11% of the spit sediment volume.

All sites investigated are currently (2008 data) displaying either maintenance of or an increase in sediment storage capacity within the stable spit area with the exception of Caister Point which is undergoing erosion. Coast planform tendencies mirror those of the stable spit area. If RSL, average storm magnitude and frequency and anthropogenic activity remain as at present then these trends can be expected to continue in the short-term. As coastal morphology at Gorleston-on-Sea appears to be maintained by sediment exchange with the nearshore, the current Outer Harbour engineering works are likely to cause some erosion of the beach in this area by reducing the available sediment supply. This was recognised in the impact assessment report and maintenance of sediment supply to the area through intervention suggested as a means of offsetting erosion (HR Wallingford, 1998).

Proposed changes in coastal defence policy (Halcrow, 2006; North Norfolk District Council, 2007) are likely to alter these tendencies in the long-term. Indeed, managed realignment, planned for some areas in the future, will inevitably lead to landward migration of the coastal planform and stable spit area. As of 2008, 75% of the coast between Kelling and Lowestoft is defended by engineering structures (Environment Agency, 2008). Further protection of cliffs to the north of the area will result in a reduced sediment supply to the Great Yarmouth coastal system and likely retreat of the coastal planform and stable spit area. Clayton (1980) suggests that if this occurs, the entire system could face considerable decline.

Predicted regional RSL changes of +25.9cm (relative to 1990 level) in 2050 and +49.7cm in 2090 under the high emissions scenario (Lowe *et al*., 2009) are likely to cause landward retreat of the coastal planform and stable spit area. Along defended sections of the Great Yarmouth coast reduction in stable spit area and narrowing and steepening of the inter-tidal zone may be expected. Coastal steepening, in particular, is likely to increase overtopping of and damage to coastal defences and beach erosion (HR Wallingford, 1999). Steepening of the sub-tidal shoreface is also a possibility, causing deeper water to penetrate further inshore and increased tidal currents (HR Wallingford, 1999).

Meanwhile, the influence of storm events is likely to increase with projected future extreme water levels reaching a maximum of 2.7m above present-day highest astronomical tide by 2095 (50 year return period). The current equivalent is 2.1m (Lowe *et al*., 2009). This is likely to lead to landward retreat of the stable spit area although potential changes in storm tracks may alter the degree to which this effect is felt.

Variations in sediment supply trends are more difficult to ascertain. However, an increased RSL and storm magnitude may help increase sediment supply from coastal cliffs to the north of the area, assuming that these areas remain relatively undefended. However, sediment eroded from these cliffs is expected to take a maximum of 50 years to reach the Great Yarmouth area

(Clayton, McCave & Vincent, 1983) and so there is likely to be a lag time before the effect of changed erosion patterns are felt at the spit. Should this sediment eventually reach the spit, some of the predicted erosion along the Great Yarmouth coast may be offset.

As linkage of the Great Yarmouth spit and Great Yarmouth Banks is suggested via nesses at Winterton-on-Sea, North Denes and Gorleston-on-Sea (Reeve, Li & Thurston, 2001; Park & Vincent, 2007; Cooper, Townend & Balson, 2008), sediment eroded from the spit under increased RSL may be transferred to the banks. Future fluctuations in bank morphology are also likely to affect that at the coast as a result of changes in wave energy and/or tidal currents (Halcrow, 1988; HR Wallingford, 1998; Reeve, Horrillo-Caraballo & Magar, 2008). Whilst these fluctuations remain difficult to predict in the long-term, the offshore banks have been seen to respond to storm events: increased wind speeds correspond with lower sandbank heights (Anna Bakare, University College London, pers. comm., 2010). If the predicted increased storminess in the future (Lowe *et al*., 2009) manifests itself as increased wind speed then the sheltering effect of the offshore banks may be reduced.

Date	**Storm Event**	**Anthropogenic Activity**	**Reference**
1588-1698	Sand dune formation far inland in East Anglia suggesting wind of increased strengths relative to today.		12
1607	Breaching of sea defences at Great Yarmouth.		11
1613		Completion of the 7th Haven cut and piers, Great Yarmouth.	2; 7
22nd September 1695	North easterly gales recorded in Yarmouth, 140 ships driven ashore near Winterton Ness and formation of bar across the 7th Haven mouth.		2; 12
14th August 1737	Easterly gales in East Anglia and storm surge.		11; 12
1st, 21st and 22nd March 1791	Gales and storm surge with sea and river meeting across the Great Yarmouth spit at South Denes.		2; 12
1816	Storm surge on February 16th with sea and river meeting across the Great Yarmouth spit at South Denes.		2
1825	West-south-westerly becoming westerly, west-north-westerly and northerly gales with storm surge.		1
C.1840		Esplanade built, Great Yarmouth.	8
1845	Storm surge of 2.9m above predicted sea level.		5
1854		Wellington Pier built, Great Yarmouth	8
1858		Britannia Pier built, Great Yarmouth.	8
21st February 1861	Southerly and west-south-westerly gales in Great Yarmouth.		12
26 -27th December 1862	West-south-westerly gales. Village of Eccles lost to sea in 18th Century exposed by scouring action.		12
1880-1890 (exact date unknown)		Extension of 7th Haven piers, Great Yarmouth.	14
c.1890		Groynes installed, Gorleston-on-Sea; Railway sea wall built, Caister-on-Sea.	8
24th March 1895	North-westerly and westerly gale in Norfolk.		12
28-29th November 1897	North-westerly becoming northerly gale and storm surge of 3.0m above predicted sea level.		2; 5; 12
1905	In Yarmouth 'the rapid current of this unusual tide washed the Front with much violence, and at the south end of the parade the concrete sea wall was broken up…'		11; 12
c.1920		Sea wall and 17 groynes built, Great Yarmouth.	
c.1930		North Denes sea wall built; Sea wall built, Gorleston-on-Sea.	8
June 1938	Northerly gales with storm surge of 2.0m above predicted sea level and damage to the Front.		3; 5; 11

1949	West and south-westerly gales with storm surge of 1.8m above predicted sea level.		5; 12
1949		Sea wall and 15 groynes installed, Caister-on-Sea.	8
31st January 1953	Northerly gales and storm surge of 2.3m above predicted sea level with damage to the Front.		4; 5; 9; 11; 12
1953		Groynes built, Winterton-on-sea; Boundary revetment and groynes built, Caister-on-Sea and Great Yarmouth.	8
1960		Sea wall and 6 groynes built, Caister-on-Sea; Sea wall developed, Great Yarmouth; Harbour piers upgraded, Great Yarmouth.	8
1970-1971		Sea wall, revetment and 12 groynes installed, Gorleston-on-Sea.	8
12-13th November 1972	Gales in East Anglia.		12
2-3rd April 1973	Gales in East Anglia.		11
2-3rd January 1976	Gales in Norfolk.		12
11-12th January 1978	Northerly gales with storm surge of 2.3m above predicted sea level. Severe scouring at Winterton-on-Sea. Improved coastal defences prevented major flooding.		6; 10; 12
1st February 1983	Westerly and north-westerly gales with storm surge in East Anglia. Improved coastal defences prevented major flooding.		12
16th October 1987	South-south-westerly gales in East Anglia, 85 knots at Gorleston-on-Sea.		12
8th November 1989	South-westerly and Westerly gales, 78 Knots off Norfolk coast.		12
1995		Installation of rock islands at Caister-on-Sea.	13; 15; 16
8-9th November 2007	North to north-westerly gales and storm surge in East Anglia. Highest observed water level of 0.71m above Environment Agency alert level.		17; 18
2007		Outer Harbour development begun	19

Table 7 Potential forcing mechanisms for morphological change along the Great Yarmouth coast. 1= Druery, 1826; 2= Crisp, 1871; 3= Mosby, 1939; 4= Grove, 1953; 5= Farquharson, 1954; 6= Rossiter, 1954; 7= Press, 1956; 8= Craig-Smith, 1972; 9= Summers, 1978; 10= Steers *et al*., 1979; 11= Harland & Harland, 1980; 12= Lamb, 1991; 13= HR Wallingford, 1998; 14= HR Wallingford, 2002; 15= Halcrow, 2006; 16= Environment Agency, 2008; 17= Parker & Foden, 2009; 18= www.metoffice.gov.uk/corporate /verification/stormsurge.htm [Accessed 01/02/2010 11:49am]; 19= http://www.norfolk.gov.uk/consumption/ groups/public/documents/ committee_report/areacom261107item5pdf.pdf [Accessed 01/02/2010 09:50am].

4. Conclusions

Examination of the Holocene geomorphic evolution of the Great Yarmouth coastline has demonstrated that the Great Yarmouth spit was pre-dated by a wide estuary, cutting the present-day coastline between Caister and Gorleston-on-Sea. An early form of the Great Yarmouth spit, lying across this estuary and extending southwards to Gunton, contained approximately $213\text{x}10^6\text{m}^3$ of sediment. The current equivalent holds approximately $190\text{x}10^6\text{m}^3$ and provides a significant sink for sediment within the Great Yarmouth coastal system. An improved sediment budget for the area is presented in Figure 13.

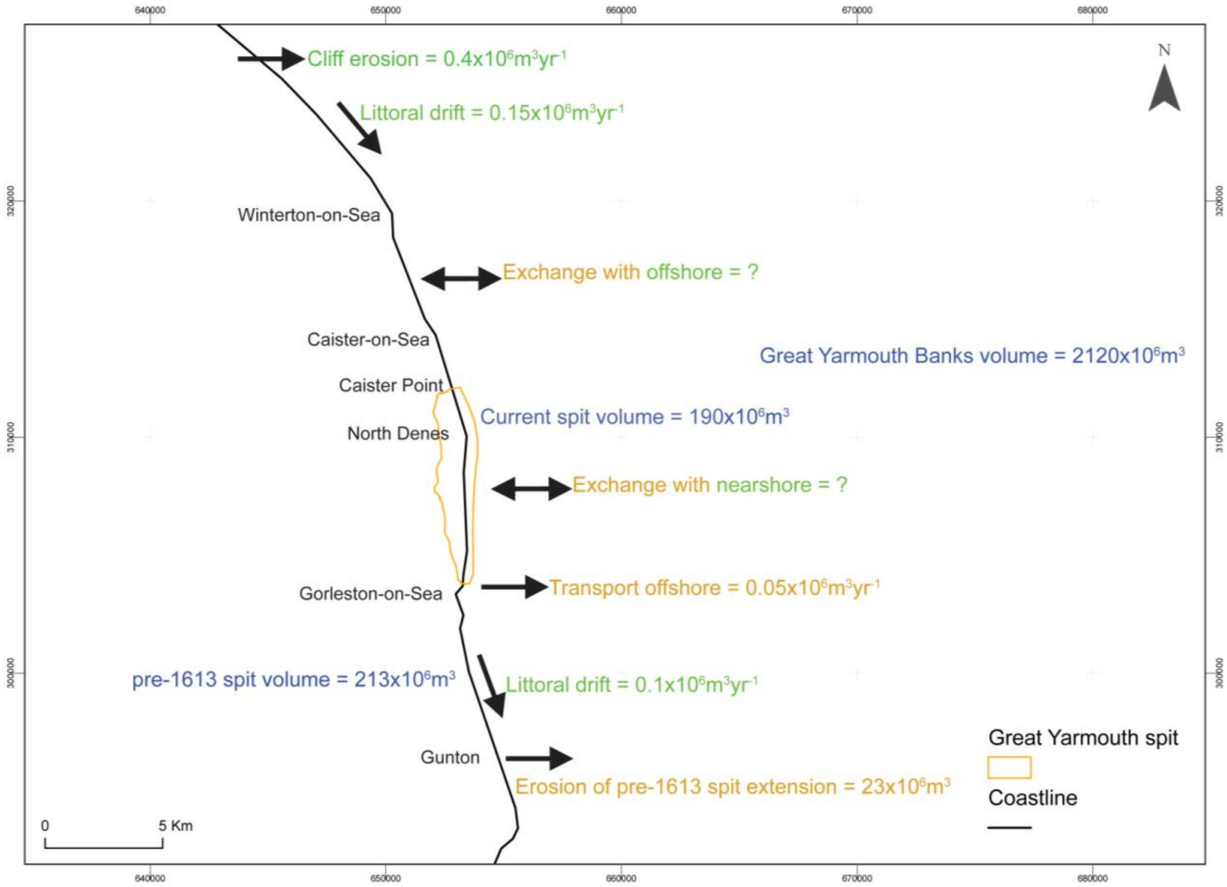

Figure 13 An improved sediment budget for the Great Yarmouth coastal system. Blue labels denote sediment sinks; orange labels represent sediment losses from the coastal system and green labels equal sediment inputs. Question marks highlight remaining data gaps. The cliff erosion value equates to erosion of cliffs to the north of the study area. The Great Yarmouth banks include the Inner Great Yarmouth Banks (detailed in Figure 1) and the Outer Great Yarmouth Banks which lie further offshore (Smith's Knoll, Hewett Ridge, Hearty Knoll, Winterton Ridge, Hammond Knoll and Haisborough Sand). The Great Yarmouth Banks volume is a conservative estimate based upon assumed base surfaces for the banks. Values from McCave & Balson (1990); Cooper, Townend & Balson (2008) and this study.

Short-term fluctuations in the spit's sediment storage capacity were identified by investigating morphological changes within the Great Yarmouth coastal zone. Whilst a general trend of landward retreat of the coastline is identified prior to 1800, improvements in mapping accuracy post-1800 suggest that the spit morphology actually varies temporally and spatially. Indeed, between 1800 and

2007 Winterton-on-Sea experienced accretion whilst coastline retreat followed by a period of relative stability typified trends at Caister-on-Sea. North Denes shows sea-ward advance of the coastline but this occurs after a phase of erosion prior to 1890. Great Yarmouth Pleasure Beach and Gorleston-on-Sea have remained relatively stable after a similar phase of pre-1890 erosion. Aerial photograph analysis, meanwhile, demonstrates that all sites investigated are currently (2008 data) displaying either maintenance of or an increase in sediment storage capacity within the stable spit area with the exception of Caister Point which is undergoing erosion.

Although the RSL change of +1.5mmyr^{-1} from 1000yrBP to present may account for a general landward migration of the coast planform, shorter term perturbations appear better related to individual storm events and coastal engineering works. The most significant event in terms of morphological change was the harbour engineering works of 1613 which caused a reduction in spit volume of 11% through disruption of littoral drift patterns. The degree of morphological change caused by individual storm events is dependent upon antecedent beach levels, the combination of meteorological and tidal conditions and the state of the coastal defences. Predicted regional changes in sea-level and storminess are likely to cause landward retreat of the coastal planform and reduction in stable spit area. Along defended sections of the Great Yarmouth coast, narrowing of the inter-tidal zone may be expected. Examination of the remaining gaps in the sediment budget, specifically the interaction of the spit with the nearshore zone and offshore banks, is required before these future trends can be fully characterised.

5. References

Andrews, J. E., Boomer, I., Bailiff, I., Balson, P., Bristow, C., Chroston, P. N., Funnell, B. M., Harwood, G. M., Jones, R., Maher, B. A. and Shimmield, G. B. 2000. Sedimentary evolution of the north Norfolk barrier coastline in the context of Holocene sea-level change. *Geological Society, London, Special Publications*, 166, 219-251.

Aranuvachupun, S. and Johnson, J. A. 1979. Beach profiles at Gorleston and Great Yarmouth. *Coastal Engineering*, 2, 201-213.

Arens, S. M. 1997. Transport rates and volume changes in a coastal foredune on a Dutch Wadden island. *Journal of Coastal Conservation*, 3, 49-56.

Arthurton, R. S., Booth, S. J., Morigi, A. N., Abbott, M. A. W. and Wood, C. J. 1994. Geology of the country around Great Yarmouth. *Memoir of the British Geological Survey sheet 162 (England & Wales)*. HMSO, London.

Ashwin, T. and Davison, A. 2005. *An historical atlas of Norfolk*. Phillimore & Co. Ltd, Chichester.

Balson, P. S. 1999. The Holocene coastal evolution of eastern England: evidence from the offshore Southern North Sea. *Proceedings of the 4th International Symposium on Engineering Science of Coastal Sediments*, 1284-1294.

Balson, P. S. 2008. Behaviour of Sandbanks: Long-term and wide-scale morphological changes in sandbanks- state of current knowledge. *British Geological Survey Commissioned Report CR/08/033*.

Berthot, A. and Pattiaratchi, C. 2006. Mechanisms for the formation of headland-associated linear sandbanks. *Continental Shelf Research*, 26, 987-1004.

Boak, E. H. and Turner, I. L. 2005. Shoreline Definition and Detection: A Review. *Journal of Coastal Research*, 21 (4), 688-703.

Bradley, S. L., Milne, G. A., Teferle, F. N., Bingley, R. M. and Orliac, E. J. 2009. Glacial isostatic readjustment of the British Isles: new constrains from GPS measurements of crustal motion. *Geophysical Journal International*, 178, 14-22.

Bradley, S. L., Milne, G. G., Shennan, I., Edwards, R. J., Zong, Y., Horton, B. and Teferle, F. N. 2010. An improved Glacial Isostatic Adjustment Model for the British Isles and Ireland. In: Woodroffe, S. A., Long, A. J., Shennan, I. and Roberts, D. H. (Editors). 2010. Sea-level Changes: the Science of a Changing World. *Quaternary Research Association Annual Discussion Meeting: Abstract Volume*. Durham University, Durham.

Brew, D. S., Holt, T., Pye, K. and Newsham, R. 2000. Holocene sedimentary evolution and palaeocoastlines of the Fenland embayment, eastern England. In: Shennan, I. and Andrews, J. (eds.) *Holocene Land-Ocean Interactions and Environmental Change around the North Sea*. Geological Society, London, Special Publications, 166, 253-273.

British Geological Survey. 1994 Geological Map Sheet 162 (Great Yarmouth) Solid and Drift. *1:50,000 Geology Series*. Keyworth, Nottingham.

Callaghan, D. P., Nielsen, P., Short, A. and Ranasinghe, R. 2008. Statistical simulation of wave climate and extreme beach erosion. *Coastal Engineering*, 55, 375-390.

Cameron, T. D. J., Crosby, A., Balson, P. S., Jeffery, D. H., Lott, G. K., Bulat, J. and Harrison, D. J., 1992. The geology of the Southern North Sea. *British Geological Survey UK Offshore Regional Report*. HMSO, London.

Centre for Environment, Fisheries and Aquaculture Science. 2006. *Scroby Sands Offshore Wind Farm- Coastal Process Monitoring: Final Report, Contract AE0262*.

Centre for Environment, Fisheries and Aquaculture Science. In preparation. *Marine Environment Protection Fund, East Coast Regional Environmental Characterisation Cruise Report, CEND 09/09*.

Chambers, J. 1829. *A general history of the county of Norfolk intended to convey all the information of a Norfolk Tour with the more extended details of antiquarian, statistical, pictorial, architectural and miscellaneous information including biographical notices, original and selected: Volume I*. John Stacy, Norwich.

Chatwin, C. P. 1961. *British Regional Geology: East Anglia and adjoining areas*. Institute of Geological Sciences. HMSO, London.

Clayton, K. M. 1980. Coastal protection along the East Anglian coast, UK. *Zeitschrift Für Geomorphologie Supplementary Issue*, 34, 165-172.

Clayton, K. M., McCave, I. N. and Vincent, C. E. 1983. The establishment of a sand budget for the East Anglian coast and its implications for coastal stability. In: Institute of Civil Engineers. *Shoreline Protection: Proceedings of a conference organised by the Institute of Civil Engineers, University of Southampton*. Thomas Telford Ltd, London, 91-96.

Coles, B. P. L. and Funnell, B. M. 1981. Holocene palaeoenvironments of Broadland, England. *Special Publication of the International Association of Sedimentologists*, 5, 123-131.

Cooper, W. S., Townend, I. H. and Balson, P. S. 2008. A synthesis of Current Knowledge on the Genesis of the Great Yarmouth and Norfolk Banks Systems. The Crown Estate. 69 pages. ISBN: 978-0-9553427-8-3

Craig-Smith, S. J. 1972. East Anglian Coastal Study report 3: *The changing system*. Great Yarmouth B. C., Lothingland R. D.C and Lowestoft B. C.

Crisp, W. F. 1871. *Chronological retrospect of the history of Great Yarmouth containing nearly two thousand local events etc. from the year of our Lord 46 to 1870*. Great Yarmouth.

Cronin, T. M., Dwyer, G. S., Kamiya, T., Schwede, S. and Willard, D. A. 2003. Medieval Warm Period, Little Ice Age and 20th Century temperature variability from Chesapeake Bay. *Global and Planetary Change*, 36, 17-29.

Davies, D. In preparation. *Building houses on shifting sand: an archaeological micro-history of the area to the west of Fuller's Hill, Great Yarmouth*.

Department for Environment, Food and Rural Affairs. 2002. *Prediction of Future Coastal Evolution for SMP Review (FUTURECOAST), Project FD2002*.

Dickson, M. E., Bristow, C. S., Hicks, D. M., Jol, H., Stapleton, J. and Todd, D. 2009. Beach volume on an eroding sand-gravel coast determined using Ground Penetrating Radar. *Journal of Coastal Research*, 25 (5), 1149-1159.

Dowman, I., Balan, P., Renner, K. and Fisher, P. 2003*. An Evaluation of NEXTMap Terrain Data in the Context of UK National Datasets for Getmapping*. University College London, London.

Druery, J. H. 1826. *Historical and topographical notices of Great Yarmouth in Norfolk and its environs including the parishes and hamlets of the half hundred of Lothingland in Suffolk*. Nichols & Son, London.

Environment Agency. 2008. *Anglian Coastal Monitoring Programme Coastal Trends Analysis: Northeast Norfolk and North Suffolk, Subcell 3b-Kelling to Lowestoft*. Environment Agency, Peterborough.

Esper, J., Wilson, R. J. S., Frank, D. C., Moberg, A., Wanner, H. and Luterbacher, J. 2005. Climate: past ranges and future changes. *Quaternary Science Reviews*, 24, 2164-2166.

Farquharson, W. I. 1954. Storm surges o the East Coast of England. In: *Conference on the North Sea Floods of 31st January/ 1st February, 1953: A collection of papers presented at the Institution in December 1953*. Institution of Civil Engineers, London, 14-27.

Farris, A. S. and List, J. H. 2007. Shoreline change as a proxy for subaerial beach volume change. *Journal of Coastal Research*, 23 (3), 740-748.

Grove, A. T. 1953*. The Sea Flood on the Coasts of Norfolk and Suffolk*. *Geography*, 38, 164-170.

Hails, J. R. 1975. Some aspects of the Quaternary history of Start Bay, Devon. *Field Studies*, 4, 207-222.

Halcrow. 1988. *The Sea Defence Management Study for the Anglian Region: Supplementary Studies Report*. Anglian Water.

Halcrow. 2006. *Kelling to Lowestoft Ness Shoreline Management Plan: First Review*.

Hapke, C. and Richmond, B. 2000. Monitoring beach morphology changes using small-format Aerial Photography and Digital Softcopy Photogrammetry. *Environmental Geosciences*, 7 (1) 32-37.

Harland, M. G. and Harland, H. J. 1980. *The Flooding of Eastern England*. Minimax Books Ltd, Peterborough.

Hedges, A. A. C. 1959. *Yarmouth is an antient town*. Great Yarmouth Corporation, Great Yarmouth.

Horrillo-Caraballo, J. M. and Reeve, D. E. 2008. Morphodynamic behaviour of a nearshore sandbank system: The Great Yarmouth Sandbanks, UK. *Marine Geology*, 254, 91-106.

HR Wallingford. 1998. *Great Yarmouth Outer Harbour: Impact of the Outer Harbour development, report EX 3726*. HW Wallingford, Wallingford.

HR Wallingford. 1999. *Coastal Steepening- the UK view, report TR 91*. HR Wallingford, Wallingford.

HR Wallingford. 2002. *Southern North Sea Sediment Transport Study, Phase 2: Sediment Transport Report, Report EX 4526*. HR Wallingford, Wallingford

Hydrographic Department. 1897. *North Sea Pilot: East coast of England, from Berwick to the North Foreland, including the rivers Thames and Medway, Part 3*. Taylor, Garnett, Evans and Co.

Ives, J. 1803. *Remarks on the Garianonum of the Romans: the site and remains fixed and described, 2nd Edition*. J. D. Downes, Great Yarmouth.

Jardine, W. G. 1979. The Western (UK) shore of the North Sea in Late Pleistocene and Holocene times. In: Oele, E., Schuttenhelm, R. T. E. and Wiggins, A. J. (Editors). *The Quaternary History of the North Sea*. Acta Universitatis Uppsaliensis, Upsala, 159-174.

Lamb, H. 1991. *Historic Storms of the North Sea, British Isles and Northwest Europe*. Cambridge University Press, Cambridge.

Lapinskis, J. 2005. Long-term fluctuations in the volume of beach and foredune deposits along the coast of Latvia. *Baltica*, 18, 38-43.

Lewis, C. 1980. *Great Yarmouth: history, herrings and holidays*. Poppyland, Cromer, Norfolk.

Lowe, J. A., Howard, T. P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S. and Bradley, S. 2009. *UK Climate Projections science report: Marine and coastal projections*. Met Office Hadley Centres, Exeter.

Manship, H. 1845. *The history of Great Yarmouth*. Palmer, C. J. (Editor). Louis Alfred Meall, Great Yarmouth.

Massey, A. C. and Taylor, G. K. 2007. Coastal evolution in south-west England, United Kingdom: An enhanced reconstruction using geophysical surveys. *Marine Geology*, 245, 123-140.

McCave, I. N. 1987. Fine sediment sources and sinks around the East Anglian Coast (UK). *Journal of the Geological Society, London*, 144, 149-152.

McCave, I. N. and Balson, P. S. 1990. *Recent sedimentation of the East Anglian coast and Southern North Sea. Field Guide No. 1, 13th International Sedimentological Congress, Nottingham, UK*. British Sedimentological Research Group. Cambridge.

Meeres, F. 2007. *A history of Great Yarmouth*.

Mosby, J. E. G. 1939. The Horsey Flood, 1938: An example of storm effect on a low coast. *The Geographical Journal*, 93 (5), 413-418.

North Norfolk District Council. 2007. *Kelling to Lowestoft Ness Shoreline Management Plan: Amended Report*.

Ordnance Survey. 2007. The Broads, Wroxham, Beccles, Lowestoft and Great Yarmouth, Outdoor Leisure 40. *1:25,000 series*. Ordnance Survey, Southampton.

Palmer, C. J. 1853. *The history of Great Yarmouth, designed as a continuation of Manship's history of that town*. Louis Alfred Meall, Great Yarmouth.

Park, H. –B. and Vincent, C. E. 2007. Evolution of Scroby Sands in the East Anglian coast, UK. *Journal of Coastal Research, Special Issue* 50, 868-873.

Parker, J. A. and Foden, D. 2009. High-resolution measurement of a North Sea Storm Surge. *Journal of Coastal Research, Special Issue*, 56, 1656-1600.

Parkin, C. 1776. *The history of Great Yarmouth collected from antient records and other authentic materials*. W. Whittinghan, Lynn.

Podgórski, K., Rychlik, I., Rydén, J. and Sjö, E. 2000. How big are the big waves in a Gaussian Sea? *International Journal of Offshore and Polar Engineering*, 10 (3), 1053-5381.

Press, M. 1956. The seven Havens of Great Yarmouth and their bridges. *The Edgar Allen News*, 34 (414), 272-274.

Rampino, M. R. and San, J. E. 1980. Holocene Transgression in South-Central Long Island, New York. *Journal of Sedimentary Research*, 50, 1063-1080.

Reeve, D. E., Li, B. and Thurston, N. 2001. Eigenfunction analysis of decadal fluctuations in sandbank morphology at Great Yarmouth. *Journal of Coastal Research*, 17 (2), 371-382.

Reeve, D. E. Horrillo-Caraballo, J. E. and Magar, V., 2008. Statistical analysis and forecasts of long-term sandbank evolution at Great Yarmouth, UK. Estuarine, *Coastal and Self Science*, 79, 387-399.

Rennie, J. 1819. *Report made the 29th day of May 1818 to the Commissioners of the Haven and Piers at Great Yarmouth, Norfolk on the state of the Bar and Haven, and the measures advisable to be adopted for improving the same*. C Sloman, Great Yarmouth.

Roberts, T. M., Wang, P. and Kraus, N. C. 2007. Limits of Beach and Dune Erosion in Response to Wave Runup Elucidated from SUPERTANK. *Proceedings Coastal Sediments 2007 Conference*. ASCE Press, Reston, VA, 1961-1974.

Rogerson, A. 1976. Excavations on Fuller's Hill, Great Yarmouth. *East Anglian Archaeology*, 2, 131-246.

Rossiter, J. R. 1954. The North Sea Storm Surge of 31st January and 1st February 1953. Philosophical Transactions of the Royal Society (A), 246, 317-400.

Saul, A. 1982. English towns in the late middle ages: the case of Great Yarmouth. *Journal of Medieval History*, 8, 75-88.

Shennan, I., Bradley, S., Milne, G., Brooks, A., Bassett, S. and Hamilton, S. 2006. Relative sea-level changes, glacial isostatic modelling and ice-sheet reconstructions from the British Isles since the Last Glacial Maximum. *Journal of Quaternary Science*, 21 (6), 585-599.

Shennan, I., Milne, G. and Bradley, S. 2009. Late Holocene relative land- and sea-level changes: Providing information for stakeholders. GSA Today, 19 (9), 52-53.

Shih-Chiao, C. and Evans, G. 1992. Source of sediment and sediment transport on the east coast of England: Significant or coincidental phenomena? *Marine Geology*, 107, 283-288.

Shrestha, R. L., Carter, W. E., Sartori, M., Luzum, B. J. and Slatton, K. C. 2005. Airborne Laser Swath Mapping: Quantifying changes in sandy beaches over time scales of weeks to years. *Journal of Photogrammetry and Remote Sensing*, 59, 222-232.

Skempton, A. W. 2002. *The biographical dictionary of Civil Engineers in Great Britain and Ireland, volume 1:1500-1830. Everyman Publishers plc and English Heritage, London.*

Steers, J. A., Stoddart, D. R., Bayliss-Smith, T. P., Spencer, T. and Durbidge, P. M. 1979. The Storm Surge of 11th January 1978 on the East Coast of England. *The Geographical Journal*, 145, 192-205.

Summers, D. 1978. *The East Coast Floods*. David & Charles, Newton Abbot.

Swinden, H. 1772. *The history and antiquities of the ancient burgh of Great Yarmouth in the county of Norfolk collected from the Corporation Charters, Records and Evidence, and other the most authentic materials*. J. Crouse, Norwich.

United Kingdom Hydrographic Office. 2009a. *Great Yarmouth and Approaches Admiralty Chart 1534*. United Kingdom Hydrographic Office, Taunton.

United Kingdom Hydrographic Office. 2009b. *Lowestoft and Approaches Admiralty Chart 1535*. United Kingdom Hydrographic Office, Taunton.

van Heteren, S., FitzGerald, D. M., Barber, D. C., Kelley, J. T. and Belknap, D. F. 1996. Volumetric analysis of a New England Barrier system using Ground-Penetrating-Radar and Coring Techniques. *Journal of Geology*, 104 (4), 471-483.

Walcott, M. E. C. 1861. *The east coast of England: from the Thames to the Tweed descriptive of natural scenery, historical, archaeological and legendary*. London.

Ward, E. M. 1922. *English Coastal Evolution*. Melthuen & Co., London.

Wessex Archaeology. 2008. *Seabed Prehistory: Gauging the Effects of Marine Aggregate Dredging. Round 2: Final Report. Volume IV: Great Yarmouth.* Wessex Archaeology, Salisbury.

Whittaker, W. 1907. *First report of the Royal Commission on erosion and the reclamation of tidal lands.* The Royal Commission.

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Colleagues at the BGS specifically, Russell Lawley, Peter Balson, Steve Booth, Ricky Terrington and Jon Lee for invaluable help throughout the project.

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NEXTMap Britain elevation data from Intermap Technologies.

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7. Appendices

7.1 Appendix 1: Published maps consulted

7.1.1 Non-Ordnance Survey maps consulted

Publisher/Surveyor	Date	Title
Unknown	1000	The Hutch Map (original title unknown)
Yorke, E.	1588	A manuscript map of the country around Yarmouth, from Wraxham in the north to Lowestoft in the south, showing also the courses, south of Yarmouth, of the Rivers Bure, Yare and Waveney.
Doncker, H.	1661	Pas-Caert van Texel tot aen de Hoofden. In: De Zee-Atlas ofter Water-wareld.
Thornton, J.	1667	MS chart of the North Sea, England east coast. In: Atlas Maritimus.
Thornton, J.	1685	A chart of the sea coasts of England, Flanders and Holland. In: Atlas Maritimus.
Blaeu, J.	1693	North Sea
Greenvile, C.	1698	East coast of England: Thames Estuary to the Wash
Mount, R & Page, T.	1700	A chart of part of the North Sea from ye south Forelands to Burnham Flats and from Callis to Schelling Isle.
Mount, R & Page, T.	1700	Chart of the North Sea: Norway to the Dover Straights
Trinity House	1801	East coast from Lowestoft to Cromer on which are laid down Yarmouth Roads, and Haisborough Gat
British Admiralty	1846	BA 1630 England East Coast from Southwold to Cromer
Hobbs, J. S.	1857	A chart of the east coast of England from Harwich to Kingston-upon-Hull.
British Admiralty	1866	BA 1543 England East Coast: Yarmouth and Lowestoft Roads
Imray, J & Son.	1870	The East Coast of England from Dungeness to Flamborough Head
Norie, J. W. & Wilson, C.	1875	Harwich, Yarmouth and Lynn Deeps
Imray, J & Son.	1885	East Coast of England
British Admiralty	1886	BA 1543 England East Coast: Yarmouth and Lowestoft Roads
British Admiralty	1888	England East Coast: Orford Ness to Blakeney with the offlying shoals between Smiths Knoll and the Outer Dowsing
British Admiralty	1912	BA 1543 England East Coast: Yarmouth and Lowestoft Roads
British Admiralty	1936	BA 1543 England East Coast: Yarmouth and Lowestoft Roads
British Admiralty	1948	BA 1543 England East Coast: Yarmouth and Lowestoft Roads

7.1.2 Ordnance Survey maps consulted

OS 6 inch maps (1:10,560) County Series first edition

County	Sheet No.	Published	Surveyed
Norfolk	66NE	1884	1883-4
Norfolk	66SE	1885	1883-4
Norfolk	78NE	1885	1882-3
Norfolk (Suffolk)	78SE (2)	1885	1882-3
Suffolk	04NE	1884	1882-3

OS 6 inch maps (1:10,560) County Series second edition

County	Sheet No.	Published	Surveyed	Revised
Norfolk	66NE	1907	1883-4	1903-4
Norfolk	66SE	1907	1883-4	1903-4
Norfolk (Suffolk)	78NE (2)	1906	1882-3	1904
Norfolk (Suffolk)	78SE (2)	1906	1882-3	1903-4
Suffolk	04NE	1906	1882-3	1904

OS 6 inch maps (1:10,560) County Series 1920s edition

County	Sheet No.	Published	Surveyed	Revised
Norfolk	66NE	1929	1883-4	1926
Norfolk	66SE	1929	1883-4	1926
Norfolk	78NE	1928	1882-3	1926
Norfolk (Suffolk)	78SE (2)	1928	1882-3	1926
Suffolk	04NE	1928	1882-3	1926

OS 6 inch maps (1:10,560) County Series 1950s edition

County	Sheet No.	Published	Surveyed	Revised
Norfolk	66NE	1951	1883-4	1946
Norfolk	66SE	1951	1883-4	1947
Norfolk	78NE	1951	1882-3	1946
Norfolk	78SE	1951	1882-3	1946-7
Suffolk	04NE	1951	1882-3	1946-7

OS 1:10,000 maps 2007 edition

Sheet No.	Published
TG51SW	2007
TG50NW	2007
TG50SW	2007
TM59SW	2007

7.2 Appendix 2: Aerial photographs consulted

Flown by	Date	Sortie number	Frame number/ Identifier	Scale
RAF	18/08/1940	RAF/2A/BR190	33	1:10,000
RAF	18/08/1940	RAF/2A/BR190	35	1:10,000
RAF	18/08/1940	RAF/2A/BR190	37	1:10,000
RAF	18/08/1940	RAF/2A/BR190	41	1:10,000
RAF	18/08/1940	RAF/2A/BR190	43	1:10,000
RAF	18/08/1940	RAF/2A/BR190	46	1:10,000
RAF	08/09/1945	RAF/106G/UK/778	6018	1:2,500
RAF	08/09/1945	RAF/106G/UK/778	6020	1:2,500
RAF	08/09/1945	RAF/106G/UK/778	6022	1:2,500
RAF	08/09/1945	RAF/106G/UK/778	6024	1:2,500
RAF	08/09/1945	RAF/106G/UK/778	6026	1:2,500
RAF	08/09/1945	RAF/106G/UK/778	6028	1:2,500
RAF	08/09/1945	RAF/106G/UK/778	6030	1:2,500
RAF	08/09/1945	RAF/106G/UK/778	6032	1:2,500
RAF	08/09/1945	RAF/106G/UK/778	6034	1:2,500
RAF	08/09/1945	RAF/106G/UK/778	6036	1:2,500
RAF	20/04/1951	RAF/540/465	4001	1:10,200
RAF	20/04/1951	RAF/540/465	4023	1:10,200
RAF	20/04/1951	RAF/540/465	4055	1:10,200
RAF	06/06/1955	RAF/82/1214	382	1:10,000
RAF	06/06/1955	RAF/82/1214	420	1:10,000
RAF	06/06/1955	RAF/82/1214	422	1:10,000
RAF	06/06/1955	RAF/82/1214	424	1:10,000
RAF	06/06/1955	RAF/82/1214	426	1:10,000
RAF	06/06/1955	RAF/82/1214	428	1:10,000
RAF	06/06/1955	RAF/82/1214	430	1:10,000
OS	30/04/1965	OS/65054	8	1:10,000
OS	30/04/1965	OS/65054	10	1:10,000
OS	30/04/1965	OS/65054	14	1:10,000

Flown by	**Date**	**Sortie number**	**Frame number/ Identifier**	**Scale**
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OS	30/04/1965	OS/65054	20	1:10,000
OS	19/06/1978	OS/78105	2	1:10,000
OS	19/06/1978	OS/78105	4	1:10,000
OS	19/06/1978	OS/78105	6	1:10,000
OS	19/06/1978	OS/78105	8	1:10,000
OS	19/06/1978	OS/78105	10	1:10,000
OS	17/08/1981	OS/81082	211	1:10,000
OS	17/08/1981	OS/81082	213	1:10,000
OS	17/08/1981	OS/81082	215	1:10,000
OS	17/08/1981	OS/81082	217	1:10,000
OS	17/08/1981	OS/81082	219	1:10,000
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FB	1988	UAG/1072/152.24	4062	1:10,000
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FB	1988	UAG/1072/152.24	4082	1:10,000
FB	1988	UAG/1072/152.24	4787	1:10,000
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EA	29/07/1992	AF/92	TG5203_92	1:5,000
EA	29/07/1992	AF/92	TG5211_92	1:5,000
EA	29/07/1992	AF/92	TG5212_92	1:5,000
EA	29/07/1992	AF/92	TG5213_92	1:5,000
EA	29/07/1992	AF/92	TG5214_92	1:5,000
EA	29/07/1992	AF/92	TG5300_92	1:5,000
EA	29/07/1992	AF/92	TG5301_92	1:5,000
EA	29/07/1992	AF/92	TG5302_92	1:5,000
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EA	29/07/1992	AF/92	TG5304_92	1:5,000
EA	29/07/1992	AF/92	TG5305_92	1:5,000
EA	29/07/1992	AF/92	TG5306_92	1:5,000
EA	29/07/1992	AF/92	TG5307_92	1:5,000
EA	29/07/1992	AF/92	TG5308_92	1:5,000
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EA	02/09/1997	AF/97	Tg5203_97	1:5,000
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EA	02/09/1997	AF/97	Tg5213_97	1:5,000
EA	02/09/1997	AF/97	Tg5214_97	1:5,000
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EA	02/09/1997	AF/97	Tg5301_97	1:5,000
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EA	02/09/1997	AF/97	Tg5303_97	1:5,000
EA	02/09/1997	AF/97	Tg5304_97	1:5,000
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EA	02/09/1997	AF/97	Tg5310_97	1:5,000
EA	02/09/1997	AF/97	Tg5311_97	1:5,000
EA	15/08/2001	AF/01c	TG5114_01	1:5,000
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EA	15/08/2001	AF/01c	TG5203_01	1:5,000
EA	15/08/2001	AF/01c	TG5211_01	1:5,000
EA	15/08/2001	AF/01c	TG5212_01	1:5,000
EA	15/08/2001	AF/01c	TG5213_01	1:5,000
EA	15/08/2001	AF/01c	TG5214_01	1:5,000
EA	15/08/2001	AF/01c	TG5300_01	1:5,000
EA	15/08/2001	AF/01c	TG5301_01	1:5,000
EA	15/08/2001	AF/01c	TG5302_01	1:5,000
EA	15/08/2001	AF/01c	TG5303_01	1:5,000
EA	15/08/2001	AF/01c	TG5304_01	1:5,000
EA	15/08/2001	AF/01c	TG5305_01	1:5,000
EA	15/08/2001	AF/01c	TG5306_01	1:5,000
EA	15/08/2001	AF/01c	TG5307_01	1:5,000
EA	15/08/2001	AF/01c	TG5308_01	1:5,000
EA	15/08/2001	AF/01c	TG5309_01	1:5,000
EA	15/08/2001	AF/01c	TG5310_01	1:5,000
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EA	21/06/2005	AF/05	Tg5213_05	1:5,000
EA	21/06/2005	AF/05	Tg5214_05	1:5,000
EA	21/06/2005	AF/05	Tg5300_05	1:5,000
EA	21/06/2005	AF/05	Tg5301_05	1:5,000
EA	21/06/2005	AF/05	Tg5302_05	1:5,000
EA	21/06/2005	AF/05	Tg5303_05	1:5,000
EA	21/06/2005	AF/05	Tg5304_05	1:5,000
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EA	21/06/2005	AF/05	Tg5306_05	1:5,000
EA	21/06/2005	AF/05	Tg5307_05	1:5,000
EA	21/06/2005	AF/05	Tg5308_05	1:5,000
EA	21/06/2005	AF/05	Tg5309_05	1:5,000
EA	21/06/2005	AF/05	Tg5310_05	1:5,000
EA	21/06/2005	AF/05	Tg5311_05	1:5,000
EA	01/07/2008	AF/08	TG5114_08	1:5,000
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Flown by	Date	Sortie number	Frame number/ Identifier	Scale
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EA	01/07/2008	AF/08	TG5307_08	1:5,000
EA	01/07/2008	AF/08	TG5308_08	1:5,000
EA	01/07/2008	AF/08	TG5309_08	1:5,000
EA	01/07/2008	AF/08	TG5310_08	1:5,000
EA	01/07/2008	AF/08	TG5311_08	1:5,000

Where RAF = Royal Air Force, OS= Ordnance Survey, FB = Fugro BKS and EA = Environment Agency.

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