

Marine Estate Research Report

Coastal change in historic times – linking offshore bathymetric changes and cliff recession in Suffolk



**Coastal changes in historic times – linking offshore bathymetry
changes and cliff recession in Suffolk**

The Crown Estate – Caird Research Fellowship

Dr Susan M Brooks

Department of Geography & Developmental Studies

Birkbeck College

University of London



© Crown Copyright 2010

ISBN: 978-1-906410-21-6

Published by The Crown Estate on behalf of the Marine Estate.

This report is available on The Crown Estate website at www.thecrownestate.co.uk

Dissemination Statement

This publication (excluding the logos) may be re-used free of charge in any format or medium. It may only be re-used accurately and not in a misleading context. The material must be acknowledged as Crown Estate copyright and use of it must give the title of the source publication. Where third party copyright material has been identified, further use of that material requires permission from the copyright holders concerned.

Disclaimer

The opinions expressed in this report are entirely those of the author and do not necessarily reflect the view of The Crown Estate, and The Crown Estate is not liable for the accuracy of the information provided or responsible for any use of the content.

Suggested Citation

Brooks, S.M. 2010.

‘Coastal change in historic times – linking offshore bathymetry changes and cliff recession in Suffolk’.

The Crown Estate, 92 pages. ISBN: 978-1-906410-21-6 First published 2010

Contents List

Executive Summary	v
1. Introduction	1
2. Location and physical setting of the study region	2
2.1 <i>Study site location</i>	2
2.2 <i>Geological setting</i>	5
2.3 <i>Process environment in the southern North Sea</i>	6
2.3.1 Waves	7
2.3.2 Tides	7
2.3.3 Surges	7
2.3.4 Sea level trends	7
2.3.5 Influences from nearshore bathymetry	7
3. Data sources and techniques to assess historic and contemporary coastal change	9
3.1 <i>Historical maps</i>	9
3.2 <i>Aerial photographs</i>	11
3.3 <i>Field survey of cliff profiles</i>	13
3.4 <i>Elevation coverage</i>	15
3.5 <i>Admiralty Charts and Environment Agency bathymetric surveys</i>	18
3.6 <i>GIS capabilities for analysis of shoreline dynamics</i>	20
3.6.1 The Digital Shoreline Analysis System (DSAS)	20
3.6.2 The Surface Spot tool	22
4. Coastal change over recent and historic timescales for the Suffolk coast	23
4.1 <i>Coastal retreat rates along the Suffolk Coast, 1880's – present day</i>	23
4.2 <i>Cliff retreat for individual cliff sections, 1882 – present day</i>	27
4.2.1 Dunwich – Minsmere	28
4.2.2 Easton Cliffs	30
4.2.3 Northend Warren	31
4.2.4 Easton Wood	32
4.2.5 Covehithe	33
4.2.6 The Benacre Cliffs	34
4.3 <i>Contemporary cliff retreat rates between Benacre and Southwold</i>	37

5. Sediment release from the retreating Suffolk Cliffs	39
<i>5.1 Cliff elevation, 2001-8</i>	40
<i>5.2 Calculating sediment volumes released between 2001 and 2008</i>	43
<i>5.3 Cliff retreat and sediment release over the past two decades</i>	46
6. Future predictions of shoreline movement and sediment release	48
<i>6.1 Shoreline positions in the coming century</i>	48
<i>6.2 Future clifflines associated with coastal retreat</i>	53
<i>6.3 Sediment release from the retreating coastline of Benacre – Southwold</i>	56
7. Bathymetric change over historic timescales	63
<i>7.1 Contemporary nearshore bathymetry between Benacre and Southwold</i>	63
<i>7.2 Historical nearshore bathymetry</i>	68
<i>7.3 Bathymetric changes over historical times</i>	69
8. Discussion and conclusions	72
9. Acknowledgements	75
10. References	76

Executive Summary

The coastline of Suffolk, UK has the fastest rate of contemporary recession in the UK, reaching 5 m a^{-1} locally. Along this coastline historical recession has continued for as long as there is archival data (old maps, Admiralty Charts, anecdotes, diaries, parish records, OS maps, aerial photographs, elevation/bathymetric surveying). There has been much interest focussed on Dunwich (the site of lost churches and historic buildings – once a thriving port) while other cliffs appear to have attracted fewer detailed studies. However, this whole coastal region has undergone considerable morphological change involving both the coastline position as well as the associated nearshore bathymetry. The cliffs between Benacre Ness and Southwold, 7-15 km to the north of Dunwich, are currently characterised by the fastest recorded recession rates in the UK. This study reports the results of a detailed historical investigation of coastline retreat for both Dunwich-Minsmere and Benacre-Southwold. The cliffs of Benacre-Southwold have elevations of between 10 and 15 m above sea level, and stretch for several kilometers alongshore. The geology comprises soft, sandy sediments of the pre-glacial Norwich Crag Formation. Hence recession in these cliffs is particularly important for sediment release into the southern North Sea. Since sources of sediment are highly dynamic, shifting as the foci of cliff retreat changes, continual reassessment of cliff retreat is required and reliance should not be placed on previous studies which fall out-of-date very rapidly in such dynamic settings. In particular, cliff sediments are important for the maintenance of nearshore banks and shoreline features (eg: growth in Sizewell-Dunwich Bank system; movement of Benacre Ness), with feedbacks into continued coastal erosion through regional changes in wave heights and local currents. This study has quantified contemporary and historical retreat rates using the recently-developed Digital Shoreline Analysis System (Thieler et al., 2005), an extension of ArcMap. A new methodology has been derived, combining DSAS analysis of recession rate with Surface Spot data on cliff elevation and extent (using NextMap Digital Terrain Models), to quantify contemporary volumes of sediment released. This has revealed considerable differences in the sediment sources from previously published estimates. The new methodology for rapid assessment of changing location and quantity of sediment sources from retreating cliffs has been used further to assess future sediment sources for the cliffs of Suffolk, where coastal management presents particular challenges. Finally the nearshore bathymetry has been evaluated for the present day and for the past 100 years. Links have been established between the changing bathymetric configuration of the nearshore region and the recent acceleration in cliff retreat, particularly notable in the cliffs of Covehithe and Benacre.

1. Introduction

Coastlines delimit a highly dynamic boundary line between terrestrial and marine environments. Their precise location varies in response to sea level change; variations in wave, tidal and surge conditions; alteration in the location of sediment sources and sinks; and as a result of anthropogenic management. Communities in the near-coastal zone are affected by coastline advance and retreat. The size of such communities globally is expected to rise significantly, from 1.2 billion (1990) to between 1.8 and 5.2 billion by the 2080s (Nicholls et al., 2007). Coastal *retreat* especially, is an issue of pressing global significance, involving loss of land with consequent undermining of the economic base of affected communities. Against a background of global sea level rise (Woodworth et al., 2009), coastal retreat is likely to accelerate, particularly in places characterised by high historic rates of change. Land loss and flooding are two of the most obvious consequences of accelerating sea level rise but along coastlines where cliffs alternate with low-lying areas, the sediment sources and sinks will also undergo considerable variation. Changing sediment supply has further consequences for coastal retreat through its influence on nearshore bathymetry, and associated modifications of the wave and water levels at the shore.

This report focuses on coastal retreat, sediment release and bathymetric change in the rapidly retreating cliffs of the Suffolk coast, UK. The region between Southwold (in the south) and Benacre (in the north) is highlighted throughout this report for several reasons. Firstly, historic and contemporary coastal retreat rates here are among the highest found globally as well as within the UK. Secondly, this area contains several cliff sections which, while not particularly high, stretch for significant distances alongshore. Hence as well as large land loss there are accompanying large land volumes involved in the retreat process. Thirdly, the geology of the cliff sections makes them prone to high retreat rates but also delivers large quantities of sand-sized sediment to the nearshore zone. Fourthly, this coastal stretch is located between two major nearshore sandbank systems, Dunwich-Sizewell to the South, and the Great Yarmouth-Lowestoft Bank system to the north. These sandbanks have shown considerable change in historic times (Robinson, 1966; Carr, 1979; Robinson, 1980; Reeve and Fleming, 1997; Horillo-Caraballo and Reeve, 2008; Pye and Blott, 2006) so present an opportunity to link changes in sediment sources with associated locations of sediment sinks. Finally, this area has seen little direct involvement of coastal management schemes so presents an opportunity for relatively uncomplicated analysis

and assessment of historic, contemporary and future change in the shoreline. Furthermore, for all the above reasons, this coastline presents one of the greatest future management challenges for the region in particular and the UK as a whole as it undergoes such rapid retreat. Issues of relevance have recently been highlighted in the Draft Shoreline Management Plan (phase 2) for sediment sub-cell 3b (<http://www.suffolksmp2.org.uk/policy/index.php>). This report develops and applies a new methodology for assessing the consequences of coastline change which has significance for coastal management planning in the future. The methodology enables prediction of future shoreline location, develops a means of deriving the associated topography of new clifflines that develop as a result of coastline movement and enables calculation of their sediment release potential.

This study draws upon a range of new data sources available for the region, and integrates them with more traditional data sources. It then utilises the most recent advances in GIS techniques based primarily around ArcMap software (<http://www.esri.com/>). Hence this report presents a state-of-the-art investigation of the patterns and processes of coastal change in both the terrestrial and marine environments in the region shown in Figure 1a and 1b, combining a range of approaches. Background information on the study region is provided in Section 2. Data sources and associated techniques are outlined fully in Section 3. Section 4 provides a detailed analysis of historic and contemporary coastal change, while Section 5 builds upon this with use of elevation data to provide the most up-to-date and detailed assessment of contemporary sediment release from the retreating cliffs. Section 6 considers issues of future shoreline change and associated sediment release for the coming century and Section 7 provides an assessment of the role of bathymetric change in coastal retreat rates.

2. Location and physical setting of the study region

2.1 Study site location

The general study region is shown in Figure 1a. Specifically the Suffolk coastline is composed of an alternating mixture of low-lying, valley-floor wetlands or Broad, and cliffs reaching elevations of up to 17 m above sea level. A short distance inland from the current cliffline, land elevation increases to a maximum of 25 m above sea level, as shown in Figure 1b.

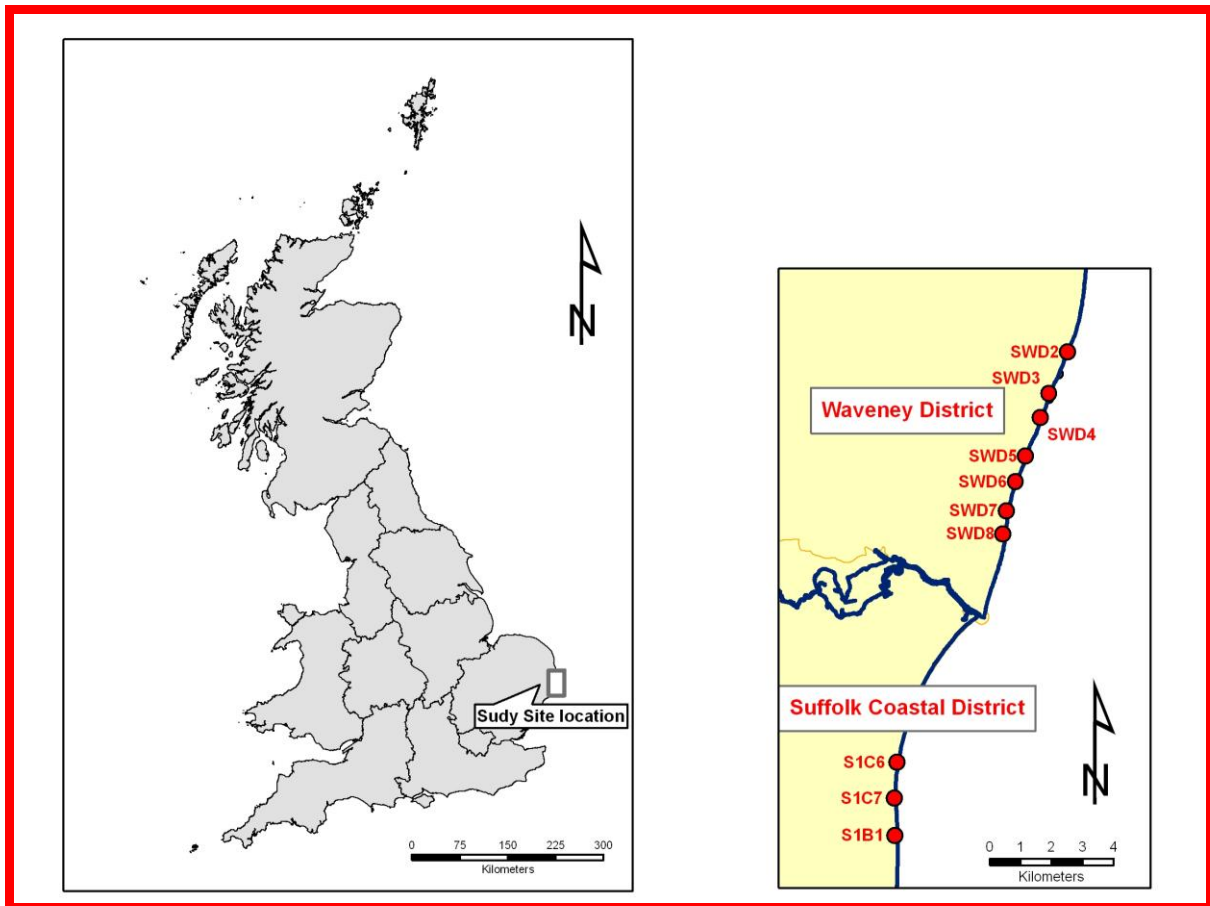


Figure 1a: General setting of the Study Site between Benacre (North) and Minsmere (South). Also shown are the Environment Agency Sea Defence Monitoring Survey Locations for the cliffs between Benacre and Southwold (SWD2 to SWD8) and Dunwich – Minsmere (S1C6 to S1B1) (Contains Ordnance Survey data © Crown copyright and database right 2010)

Hence the topography in the near-coastal zone is highly variable. There are three major cliffed sections along this part of the Suffolk coast, comprising a 3km stretch in the vicinity of Pakefield, an 8km stretch between Benacre and Southwold and a 3km cliffline between Dunwich and Minsmere in the south. These locations are shown in detail in Figure 1b.

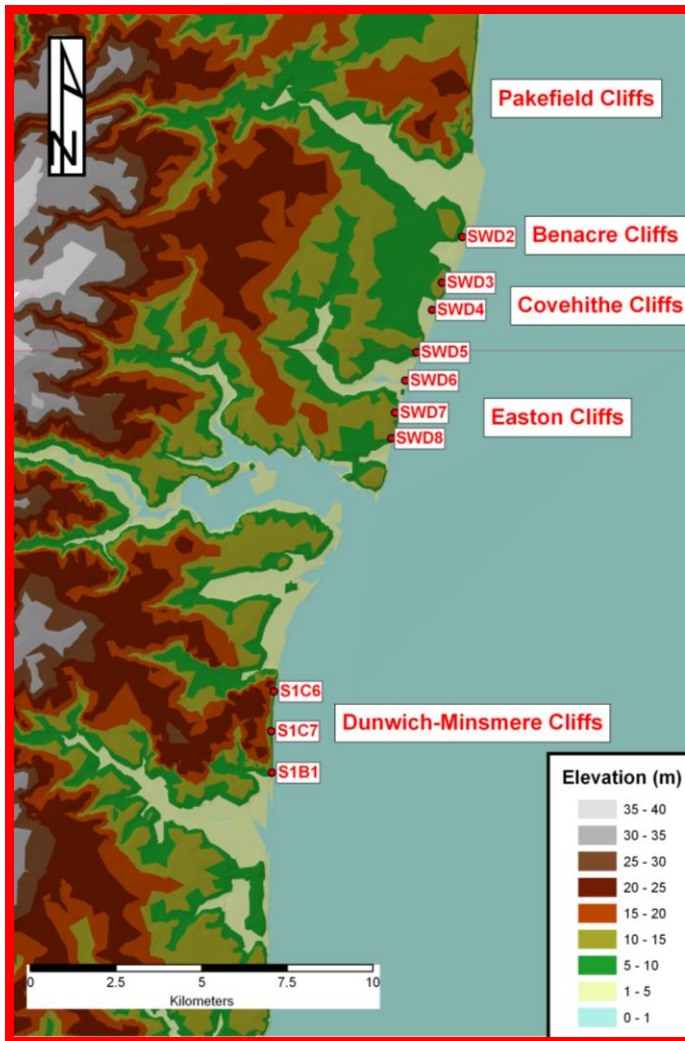


Figure 1b: The cliffs of the Suffolk coastline showing elevations (Contains Ordnance Survey data © Crown copyright and database right 2010)

The Dunwich-Minsmere cliffs to the south reach a maximum elevation of around 17 m. These cliffs are often cited as having notably high rates of historic retreat, between 1 and 2 m a⁻¹ from 1880s to the present day. Recent research has suggested a slowing of rates since the 1920's to values between 0.5 and 1 m a⁻¹ in recent years (Pontee, 2005; Pye and Blott, 2006). Possible reasons for this are the development of the Sizewell-Dunwich sandbank and the development of a coarse-grained protective beach from material released from the retreating cliffs. It seems that as a sediment source these cliffs have been potentially significant in past periods, although it is likely that this has declined in significance more recently. The cliffed coastline to the north around Pakefield is also undergoing significant decline in cliff retreat due to the northward migration of Benacre Ness with associated protection of the cliffbase.

In between these two cliffs, from Southwold to Benacre the contemporary coastline has 5 distinct cliffed sections comprising Easton Cliffs, Northend Warren, Easton Woods, Covehithe and Benacre. All appear to be undergoing rapid retreat at the present day. They range in maximum elevation from around 8m at Benacre to up to 14 m at Covehithe and Easton Woods. Each cliffed section is separated from the next by low-lying Broads, fronted by a gravel and shingle barrier offering some protection from inundation of saltwater under high tidal levels and wave attack. However, these barriers can be subject to breaching under storm surge conditions (Pye and Blott, 2009). Historical retreat rates along this stretch of coastline are high, in excess of 2 m a^{-1} (Carr, 1979; Cambers, 1975, 1976; McCave, 1978; Vincent 1979; Clayton et al., 1983) for the period between the 1880s and the 1950s. There appears to be a significant trend towards higher rates in the north, reaching up to 4 m a^{-1} in the vicinity of Covehithe. Further north historical shoreline change has been affected by the movement of Benacre Ness, thought to be around 23 m a^{-1} (with short-term rates being up to $70 - 100 \text{ m a}^{-1}$) (Williams and Fryer, 1953; Robinson, 1966; Babbie Group and Birkbeck College, 2000; Foody et al., 2005). The long-term average cliff retreat rate masks shorter periods of significantly higher rates associated with storm surges in the southern North Sea (see Section 2.3). At Covehithe, for example, a major period of short-term retreat was identified from 1951 to 1953, involving between 12 and 27 m of coastline retreat partly as a result of the 1953 storm surge event on 31 January/1st February (Steers, 1953; Williams, 1956). An earlier period of high retreat was recorded at 18.3 m for 1887 (Whitaker, 1907). More recently there was 34.8 m of retreat between 1977 and 1979, also related in part to a storm surge event on 11 January 1978 (Steers et al., 1979). 15.8 m of recession is recorded in Environment Agency Ground Survey Monitoring between winter 1993 and winter 1994 (Lee, 2008). Contemporary and historic retreat rates for these cliffs are analysed and discussed further in Section 4 of this report.

2.2 *Geological Setting*

The geological platform in the coastal region of East Anglia comprises Pliocene to Early/Mid Pleistocene marine deposits overlying eroded Palaeogene and Cretaceous basement rocks (Hamblin et al., 1997; Gibbard and Zalasiewicz, 1988; Gibbard et al., 1998). Borehole studies between Aldeburgh and Orford in the south suggest Calcarenes are present (Coralline Crag from the late Early/Middle Pliocene) as well as coarse-grained shelly sands (iron-stained Red Crag from the later Pliocene to early Pleistocene) below about -5m OD (Zalasiewicz et al., 1988), which also outcrops offshore in the region (Balson, et al., 1993). These early Pliocene to early Pleistocene deposits are overlain by the more recent Norwich Crag Formation, consisting of alternating and

complex strata of sands and clays. The Chillesford Sand Member of the Norwich Crag, a well-sorted fine to medium sand, is dominant in the south of the region. On moving northward this disappears and is replaced laterally by coarser-grained, shelly sands which are very similar in character to the older, underlying Red Crag (Gibbard and Zalasiewicz, 1988). At places alongshore sediments of the Crag reflect deposition as intertidal mudflats, and are composed of grey silty-clay with thin layers of fine-grained sand. Worm borrows and small crustacea are often present (Larwood and Martin, 1952-54; West et al., 1980; Mottram, 1989), as typified by exposures in the cliffs of Easton Bavents. These silty-clays are thought to date from a cold stage of the Early Pleistocene, the Baventian/pre-Pastonian stage (Funnell and West, 1962; Zalasiewicz et al., 1988).

The Norwich Crag can also be seen further to the north in the cliffs of Easton Woods and at the southernmost end of the Covehithe cliffs (Mottram, 1989; Long, 1974). The Baventian clays overlying the Crag here dip northwards from Easton Woods for about 1 km, and it is in the cliffs of Covehithe that the coarser sand and gravel deposits of the Westleton Beds become evident, overlying the clays (West, 1980). The Westleton Beds at Covehithe contain gravel lenses (Hey, 1967) with rounded flints, possibly resulting from rip-currents cut into the sands of the beach face (Mathers and Zalasiewicz, 1996). Overlying the Westleton Beds at Covehithe we see the appearance of the Kesgrave Formation, predominantly gravels, and the overlying Corton sands assigned to the Anglian Glacial Period (Ehlers and Gibbard, 1991; Gibbard et al., 2007). Above the Corton Sands in places there is a capping of decalcified Lowestoft Formation (Anglian) till, also seen at Dunwich (Mottram, 1989). Further north the cliffs of Benacre comprise a lower Baventian Clay overlain by Westleton Bed marine sands and gravels, which in turn are overlain by Corton sands of Anglian age, with inclusion of recent blown sand (Boreham, pers comm).

2.3 Process environment in the southern North Sea

Critical to coastal erosion is the magnitude of wave runup (Ruggerio et al., 2001) and the frequency at which the beach and cliff base is affected by wave processes (Richards and Lorriman, 1987; Lee, 2008) as it is the interplay between sediment supply from the cliffs and removal by the waves that determines the rate of coastal retreat. Whether sediment supply from the cliffs acts independently of basal removal rate, or results directly from it, is linked to the geological composition, height and morphology of the cliffs alongside driving factors such as rainfall total and intensity (Brooks and Spencer, 2010). Regardless of the cause-effect relationship, basal removal is largely determined by the combined influences of prevailing waves,

tidal regime, surge levels and sea level trends and how these are modified by the local and regional bathymetry.

2.3.1 Waves

In the southern North Sea waves are typically of low-moderate energy, attaining average heights of 0.4-0.5m (Fortnum and Hardcastle, 1979). Wind rose data from the region suggest that Southwesterlies are dominant but with a clear secondary influence of Northeasterlies. When the wind regime is translated to wave response, as was done using the UK Meteorological Office Waters Wave Model between 1986 and 1999 for a location 48km offshore from Dunwich, the largest waves (>2.2m) originated from the northeast as a result of the higher fetch from this direction (Pye and Blott, 2006).

2.3.2 Tides

The spring tidal range at Lowestoft is 1.9m but there is a regional trend towards higher tidal range on moving southward across the region. French and Burningham (2003) quote a spring tidal range at Southwold of 2.0m, while the range increases further to around 2.3m at Orford Ness and 3.1m at Felixstowe. Tides are semi-diurnal in occurrence with the flood tide running in a southerly direction offshore and the ebb tide running northward. There is also evidence for an increase in tidal regime over the past century (Woodworth et al., 1991 quoted in French and Burningham, 2008).

2.3.3 Surges

Surges are common in the southern North Sea, with surge levels exceeding the tidal range on occasion (Pugh, 1987; Muir Wood et al., 2005). Highest Astronomical tide at Lowestoft is 2.98 m above sea level. The storm surge of 31 January-1 February 1953, for example, attained a height of 4.6m OD at Lowestoft (1.62 m above HAT) while the more recent surge of 9 November 2007 reached 4.1m OD at the same location (Horsbaugh et al., 2008). Storm surges have been observed to bring about considerable coastal retreat in the region, as described above.

2.3.4 Sea Level trends

Sea level attained its present position during the seventeenth century (Carr, 1969), prior to which from about 4000 BP it had oscillated around its current position. Over the past century sea level has been gradually rising at a rate of around 2.4 mm a^{-1} . Between 1956 and 2006 sea level

increases in the region were between $2.47 \pm 0.23 \text{ mm a}^{-1}$ and $2.57 \pm 0.33 \text{ mm a}^{-1}$ (Shennan and Horton, 2002; Woodworth et al., 2009). About 0.61 mm a^{-1} of this rise can be attributed to geological subsidence (Cameron et al., 1992) which has continued since the early/mid Pleistocene. For the future, estimates of sea level rise under mid-emissions scenarios have been made by Halcrow (1991) and these are in the region of $5\text{-}6 \text{ mm a}^{-1}$. Although the precise acceleration in sea level rise is difficult to define, an approximate doubling in the rate is felt to be a conservative estimate for the coming century.

2.3.5 Influences from nearshore bathymetry

The combination of the highest waves from the northeast, coinciding with a high spring tide during a storm surge event, will lead to elevated water levels that can cause considerable flooding and coastal erosion. However, there are significant variations in sub-tidal gradients alongshore that may offset the worst effects of such scenarios of elevated water levels. An offshore water depth of 10 m is reached at around 1.5 km offshore at Benacre while the equivalent distance offshore for attainment of a 10m depth at Dunwich is 3 km. The northernmost part of the study region includes the southern end of the Lowestoft Bank system, and its close association with Benacre Ness so has relatively shallow offshore depths. The southernmost part of the region includes the extending northern part of the Dunwich-Sizewell Bank system. In between these locations is a region between Southwold and Benacre where little is known about the detailed bathymetry or the way it has changed in historic times. However, this area is one of considerable coastal retreat. Whether or not sandbanks protect the coast from erosion is much debated (Robinson, 1980; Pye and Blott, 2006). Recent modelling by Halcrow (2001) suggests that the influence of sandbank growth is only experienced locally. However, the coastal realignment that is taking place in the Suffolk coast between Benacre and Southwold towards a more N-S orientation has implications for the potential protection offered against the “worst case” northeasterly wave approach.

3. Data sources and techniques to assess historic and contemporary coastal change

3.1 Historical maps

Investigation of shoreline change has commonly utilised historical maps constructed from ground surveys at various time periods in the past. Historical maps of the county of Suffolk have been produced back to the sixteenth century, one of the earliest being the map by Christopher Saxton dating from around 1575. Subsequent maps include those of William Blau (1640), Richard Blome (1673), Emanuel Bowen and John Owen (1720) and Thomas Badeslade (1741) and Hodskinson's map of 1783. The map of Thomas Badeslade, shown in Figure 2, depicts the Suffolk coast as highly irregular, consisting of a series of promontories and inlets of varying size and scale.



Figure 2: The Suffolk Coast in 1741, after Thomas Badeslade

(http://web.ukonline.co.uk/badeslade/title_ded.html)

The Ordnance Survey of England and Wales has produced historic maps of the region since the mid nineteenth century but it is only after around 1880 that mapping surveys became sufficiently accurate for their general use to study coastline development over time (Oliver, 1996). The main problems relate to the irregularly-spaced dates of publication, the survey dates for each new edition not coinciding precisely with the date of map publication, the survey dates being different for different coastal tracts (which matters when coastline change is rapid), the errors present from the ground survey (Moore, 2000) and the selection of an unambiguous line that best depicts the prevailing shoreline. Commonly the line of mean high water of spring tides (MHWS) is used as this is likely to be associated with greater accuracy in the ground survey than the line of mean low water spring tides (MLWS) on historic OS maps (Oliver, 1996). However, studies of cliff retreat such as those in this study might be best served using the actual line of the clifftop, especially when combined with aerial photographs which present difficulties when defining MHWS or MLWS.

It has been estimated that the level of accuracy possible for georeferenced, digitised shoreline position from historic maps is $\pm 4\text{m}$ at a scale of 1:10 560 (Pye and Blott, 2006). For the Suffolk coast historic OS maps at this scale are available from 1883, 1905, 1928, 1957 and 1983 (dates of publication). Establishment of a higher level of precision in actual survey dates was made possible through the University of Cambridge Map Library, where holdings include provisional maps drafted between publication dates, thus allowing more precise survey dates to be ascertained for each map. Along the Suffolk coast it is clear that the cliffline was surveyed regularly through the twentieth century but often several years prior to publication of the final version of the respective historic map. Furthermore, not all parts of the Suffolk coastline were surveyed in the same year (or even successive years). For example, TM57NW published in 1976, covering the southern part of the Easton cliffs to Southwold, has survey dates of 1970/1 for MHWS, 1970/2 for MLWS and 1974 for clifftop survey. The cliffs immediately to the north, from Easton to Benacre had a map publication date of 1983, but with all three potential shoreline indicators surveyed in 1981. This makes defining a continuous shoreline highly problematic, since the 7 year difference in cliff top surveys results in a coastline that translates into a 20 m discontinuity on the maps.

Direct overlay of historical maps is possible using GIS software, provided suitable ground control points are available for accurate georeferencing. Stable features that persist from map to map

include churches, field boundaries, road intersections and farm buildings. These need to be spaced across the map but reside sufficiently close to the coastline to enable image rectification without distortion along the area of interest. Within the region St Andrew's Church at Covehithe, Beach Farm at Benacre, Porters Farm west of Covehithe Broad, the Sacred Heart church in Southwold, the Old Franciscan Friary and Bridge Farm at Dunwich and the Coastguard Cottages at Minsmere, as well as various well-defined and persistent road junctions and field boundaries were used for georeferencing. The persistence and clarity of these features has the additional benefit of allowing alternative data sets for the region to be accurately overlain and permit inclusion of a wider range of shoreline dates. Additional shorelines can be derived from other data sources, and aerial photographs represent one such possibility related to more recent periods than historic maps.

3.2 Aerial photographs

The earliest aerial photographic coverage available for the study region dates from the 1940s when general coverage in the UK improved upon earlier times. The photograph dates from 1947 and was supplied through www.ukaerialphotos.com. Since that time there have been major technological advances and accompanying improvements in quality and quantity of aerial photographic coverage available for much of the UK. The Shoreline Management Group (EA Anglian Region) of the Environment Agency supplied annual aerial photographic coverage (in some cases as georectified images) for the coastline between the Kessingland and Minsmere dating back to 1992.

Figure 3 depicts a rapidly-eroding section of the Suffolk coast in the vicinity of Covehithe, using the aerial photograph taken in 1947 supplied through www.ukaerialphotos.com as the base. Georeferencing of this photograph was based upon the same ground control points as for the historic maps, and shorelines taken from the 1883 and 1957 OS historic maps are also shown. As outlined in Section 3.1, the survey date for the shoreline depicted on the OS 1:10 560 map (published 1957) is 1947. This shoreline was digitised using the MHWS from the 1957 OS map, and the correspondence between this and the shoreline from the aerial photograph is evident (further discussion on the georeferencing methodology can be found in Section 3.6). Also shown on Figure 3 is the 1883 shoreline, the 2008 shoreline (from Environment Agency aerial photographs) and the approximate position of the 100-year future shoreline as presented in the

draft 2010 revised shoreline management plan (phase 2) for sub-cell 3c

(<http://www.suffolksmp2.org.uk/policy/index.php>).

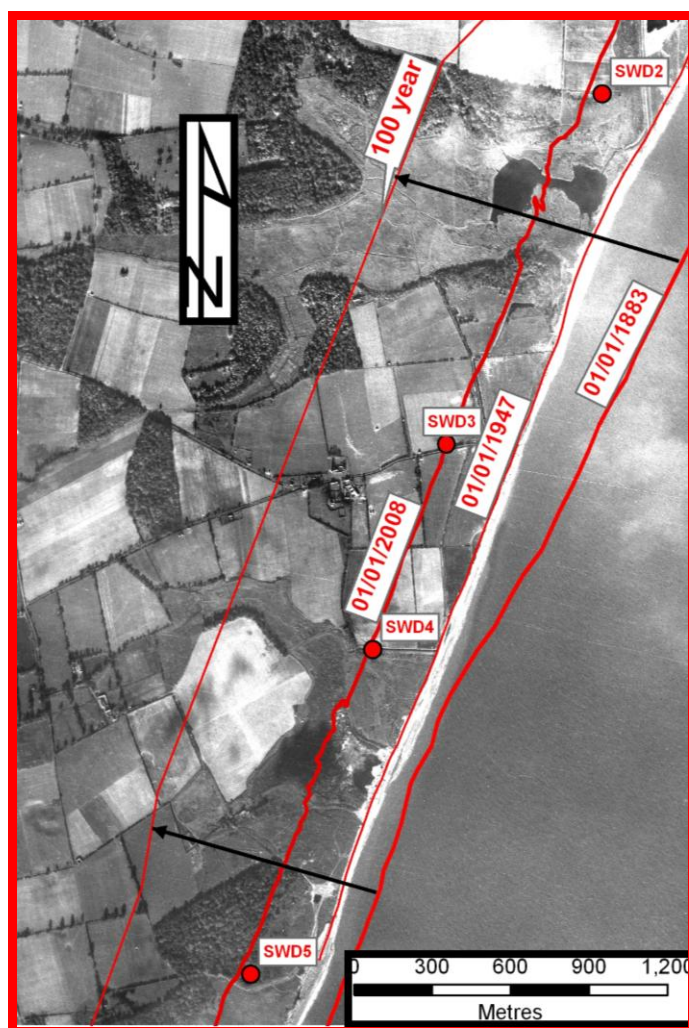


Figure 3: The coastline in the vicinity of Covehithe in 1947. Also shown are the shorelines from 1883 and 1947 derived from historic maps, and the 2008 shoreline derived from Environment Agency aerial photography. The predicted 100-year coastline is also included, discussed in Section 6 (original aerial photograph supplied by UK aerial photographs (www.ukaerialphotographs.com))

More recent aerial photographs for the region around Covehithe were also available for this study, the earliest dating from 1978. Since 1992 the Environment Agency has taken annual aerial photographs of the whole of the Lincolnshire, Norfolk, Suffolk and Essex coastlines as part of their Sea Defence Management System (SDMS) project. All imagery was made available for this study. The photographs were supplied in part georectified and in part as raster images in tiff format. Where necessary, images were geocorrected within ArcMap, described in Section 3.6. For coastlines undergoing rapid retreat, annual intervals are sufficient to show changes on aerial

photographs. Under such temporal detail using aerial photographs, the only unambiguous and clear marker of shoreline position that can be used is the actual clifftop. Investigation based upon the MHWS or MLWS is inadequate, as these are difficult to define accurately using aerial photographs. For analysis at this level of detail there is therefore a dual requirement for rapid shoreline change and the presence of a clear, unambiguous shoreline marker.

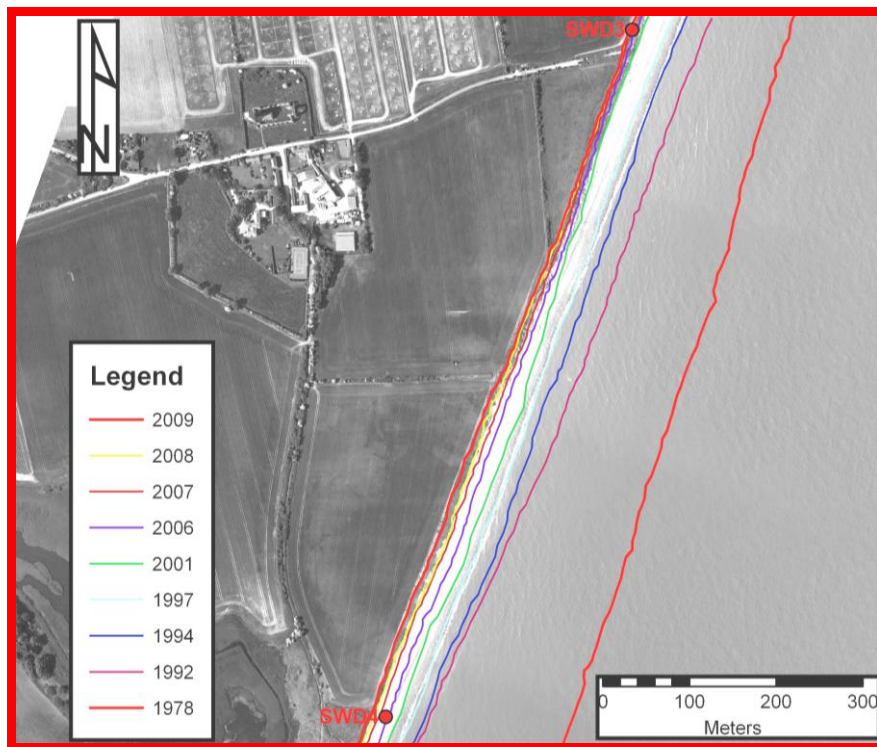


Figure 4: Recent shoreline change between SDMS monitoring sites SWD3 and SWD4 (1992-2008) based upon Environment Agency aerial photographs. The 1978 shoreline was digitised from an aerial photograph supplied via the Unit for Landscape Modelling, University of Cambridge. The clifftop was used as the unambiguous marker for shoreline position.

Shorelines for the cliffs of Covehithe are shown for the years 1978, 1992, 1994, 1997, 2001, 2006, 2007, 2008 and 2009 in Figure 4, suggesting the possibility for analysis at an unprecedented level of temporal detail in association with complete spatial continuity. This issue is discussed further in Section 3.5, with closer analysis of this data set discussed in Section 4.2.5.

3.3 *Field Survey of cliff profiles*

The advent of Differential Global Positioning Systems (dGPS) has lead to significant improvement in data availability and accuracy based upon surveys conducted in the field. The Environment Agency Sea Defence Management Systems (SDMS) augments the collection of aerial imagery,

discussed above, with bi-annual field surveys of the coastal profile at points spaced at 1km intervals also stretching from the Humber to the Thames Estuary. Thus from 1992 to the present there is now a detailed temporal record of coast profile change spanning over 18 years. However, with the data being largely focussed on beach changes, cliff profiles have not always been surveyed completely and at a high level of topographic detail. Sometimes they have not been surveyed at all and the record is incomplete.

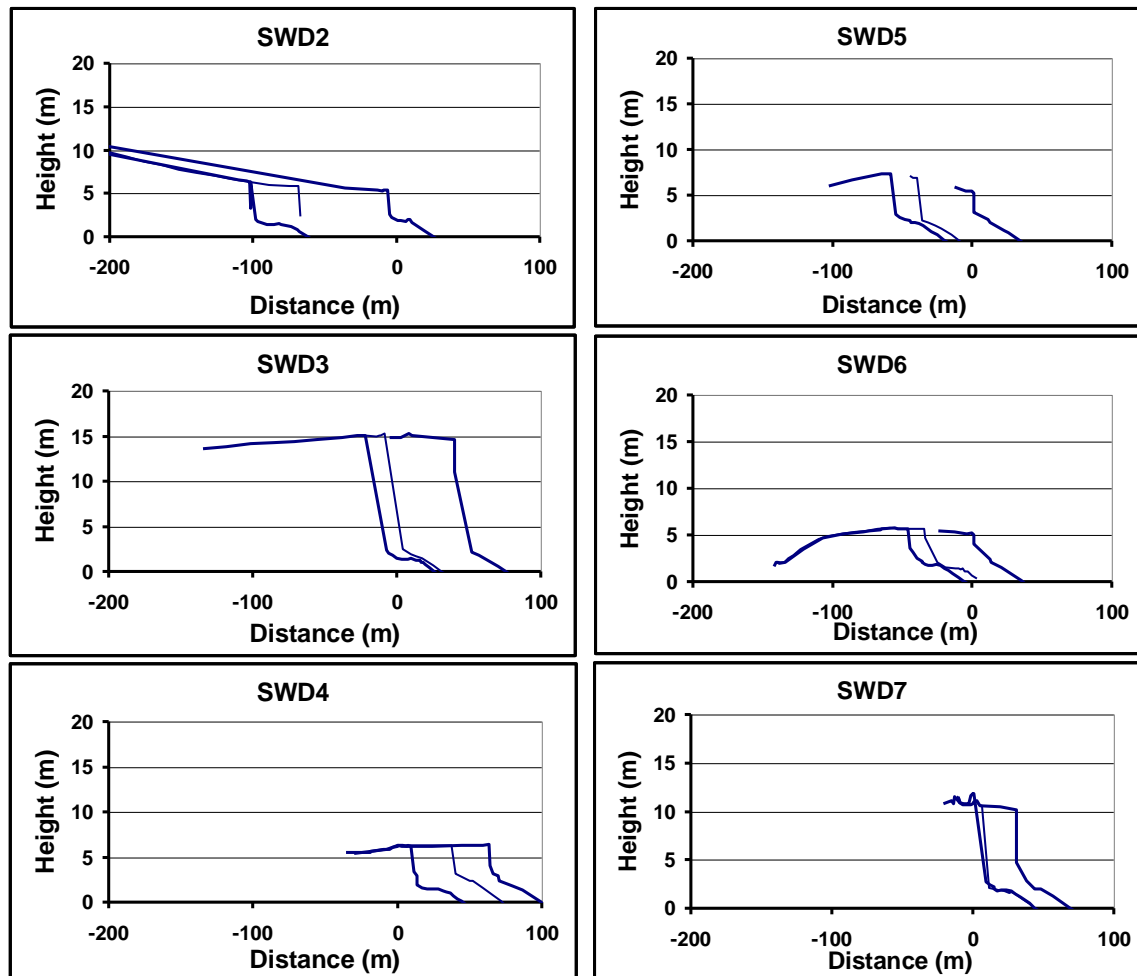


Figure 5: Typical cliff profile data available for the Suffolk Coast, UK for the years 1992, 2001 and 2008 at SDMS monitoring sites SWD2 to SWD7 (data supplied by the Shoreline Management Group (EA Anglian Region) of the UK Environment Agency (for locations see Figures 1a and 1b)).

Typical Environment Agency cliff profile data for locations relevant to this study is shown in Figure 5. Two time periods are emphasised, 1992-2001 and 2001-8. This division was chosen due to the availability of more recent and detailed elevation data since 2002 outlined in the following section. From these ground survey cliff profiles it is possible to construct at-a-point recession

rates for the past 18 years and where recession rates are high a more detailed record of annual change in cliff top position can be constructed for comparison with the aerial photographs.

3.4 Elevation coverage

The volume of sediment released from retreating cliffs is a product of the *retreat rate* and the *cliff elevation*. Data sources for reconstructing retreat rates have been outlined above and have proliferated in the past 20 years. The associated elevation data has also increased, but only more recently. The two data sets can now be combined to provide rapid and detailed assessment of sediment release from retreating cliffs. Previously sediment release for the cliffs of Suffolk (Cambers, 1975) relied upon spot heights and contours on historic OS maps to provide elevation coverage. While field surveys, such as described in the previous section, can now provide accurate ground elevation, the data are essentially discontinuous temporally (bi-annually) and spatially (1km alongshore spacing). Close inspection of these at-a-point cliff profiles suggests that retreating cliffs can potentially gain or lose elevation as they migrate inland over relatively short distances. Site SWD2 in Figure 5 suggests retreat is being accompanied by the development of a cliffline that is gaining elevation, while site SWD6 appears to be a location where the low cliffline will disappear entirely as the shoreline retreats inland.

Initial inspection of historic maps also suggests that clifflines can change in extent, emerging and disappearing as the shoreline position changes. For example the cliffline at Easton Wood (SWD5; Figure 6), currently a significant point of rapid erosion into cliffs of 12m elevation stretching over 500m alongshore, was not present at all on the 1883 1:10 560 OS map. Here the 1883 shoreline was a Warren liable to floods, running from Covehithe Broad in the North to Easton Broad in the South. It initially appears on the 1:10 000 map from 1983 (TM58SW) as a cliffline of over 600m in extent.



Figure 6: The cliffline at Easton Wood looking south from Covehithe Broad (photograph T Spencer, 27 December 2009).

The emergence and disappearance of clifflines associated with significant alongshore and cross-shore variability in topography suggests that the use of spot heights, contours and at-a-point field surveys provides partial information upon which to assess sediment release. In February 2002 the first airborne IfSAR (Interferometric Synthetic Aperture Radar) collection of elevation data was carried out for the Suffolk cliffs, resulting in the availability of elevation data at 5m intervals produced on a regular grid. The coverage at this level of detail is currently available as NextMap tiles through the NERC Earth Observation Data Centre (<http://neodc.nerc.ac.uk/>). The accuracy of the NextMap data set has been examined in detail against other datasets (Dowman et al., 2003) and is potentially able to attain a vertical accuracy of under 1m. However this is only possible in open field situations where there are no significant buildings, woodland or hedges.

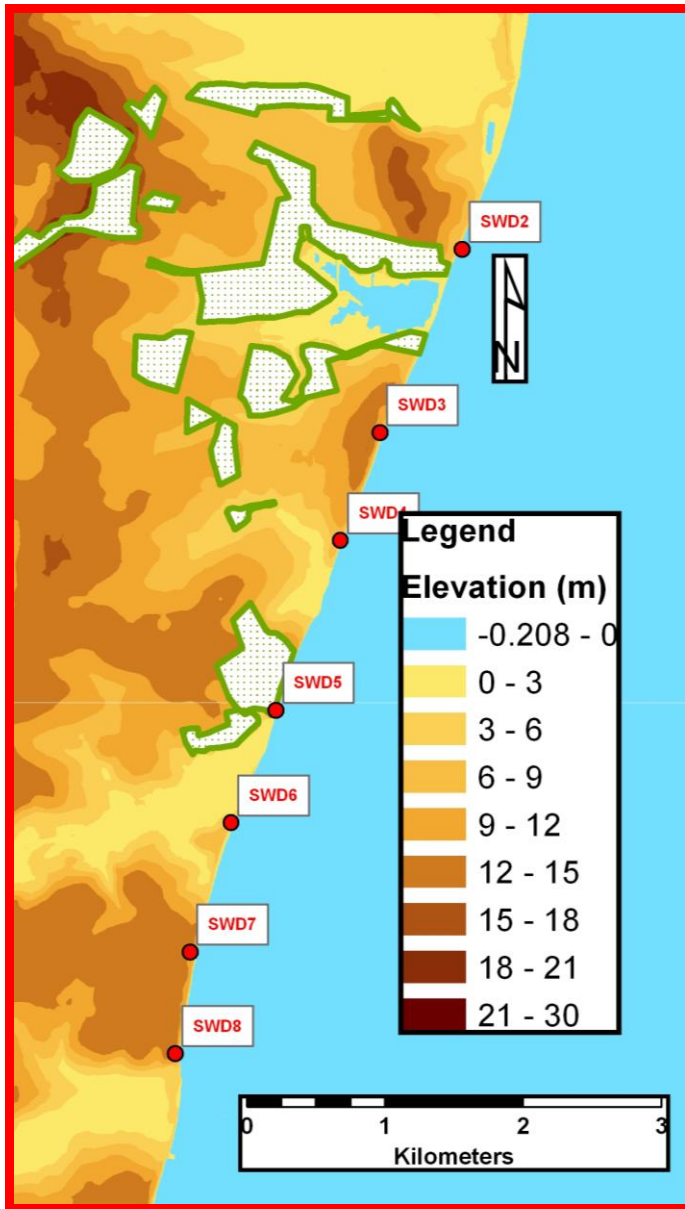


Figure 7: Ground elevation derived from NextMap tiles for the study region. Also shown are areas of woodland where elevations are potentially distorted from their true value.

Figure 7 shows ground elevations derived from the Raster Nextmap tiles tm-57 and tm-58 for the region between Southwold and Benacre Ness used in the analysis of cliff elevations outlined in Section 5. The areas marked in green indicate woodland regions. The distortion in elevation in these areas is clear but there is good correspondence ($r^2=0.85$) between ground survey elevations for the clifftops from 10 of the EA SDMS monitoring sites (shown in Figure 1a and b) and elevations derived from the NextMap tiles (Figure 8).

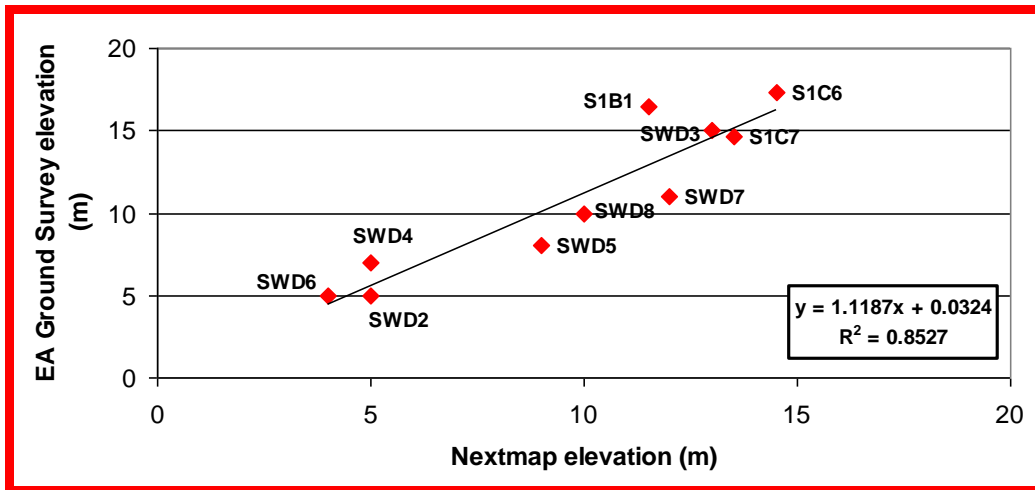


Figure 8: Comparison of NextMap elevations and ground survey elevations for the clifftop at the 10 EA SDMS sites used in this study (for locations see Figure 1a and b).

Woodland areas are not particularly extensive in the region close to the cliffline, apart from Easton Wood and an area inland in the vicinity of Minsmere. The NextMap data are considered to provide the most accurate and detailed representation of ground elevations throughout the study region available for this study. The data provided from the NextMap tiles offers considerable potential in the assessment of sediment release dynamics from rapidly retreating cliffs, which will be outlined fully in Section 5.

3.5 Admiralty Charts and Environment Agency bathymetric surveys

Admiralty Charts published by the UK Hydrographic Office, present an opportunity to investigate changes in nearshore bathymetry that accompany shoreline retreat. Charts have been regularly published throughout the eighteenth, nineteenth and twentieth centuries, although precise spatial location and the reference datum for the soundings become increasingly uncertain for the early charts. Burningham and French (2009) suggest that charts published prior to 1800 preclude direct spatial overlay. From 1900 onwards it becomes possible to georeference and overlay charts and to work out relative depths from soundings.

There are two main issues that give rise to positional and depth inaccuracy resulting from georeferencing and digitising Admiralty Charts over historic timescales. Firstly, there is the gradual sea level rise that has characterised the southern North Sea over the past century (estimated at approximately 2 mm a^{-1} (Shennan and Horton, 2002; French and Burningham, 2003; Pye and Blott, 2006) which would imply a change in sea level between 1882 and 2009 of 254 mm.

Secondly, spatial and temporal variation in tidal responses that occur from place to place result in the need for different corrections between OD Newlyn and Chart Datum for different locations. Burningham and French (2009) used a trend surface analysis to correct for this effect when reconstructing the historic bathymetry of the Greater Thames Estuary, a study which covered an area in excess of 5000 km², with a north-south distance of 100km. However, they did not take into account uncertainty arising from the first factor of historic sea level change given its relatively small magnitude compared with the depth variations involved in the study.

It is suggested for the current study, that the distances and areas involved in the bathymetric analysis are relatively small so similar tidal harmonics are assumed to characterise the region. Hence the same correction can be made to all soundings for any given chart. The precise correction needed to convert the soundings to depths relative to OD Newlyn varies with chart publication date. Since 1968 charts have used Lowest Astronomical Tide (LAT) as the Chart Datum (-1.5 m OD Newlyn at Lowestoft and -1.3 m OD Newlyn at Southwold). Prior to this, different datum levels are used, including MLWS, MLW, 1 foot below MLW, 8" below MLWS, all of which are discussed and assessed by Burningham and French (2009).

A further source of error results from the difficulty of establishing precise survey dates. Recent charts provide source diagrams with survey dates included but these can potentially span a decade or more. On earlier charts, dates for major corrections are listed and it is possible to use previously published charts to see if information on the earlier chart has been revised or carried through to the later chart. On short timescales this is an issue for ascertaining bathymetric change, but comparing charts spaced over a longer time interval overcomes this difficulty.

UK Hydrographic Office Admiralty Charts were available for the region via the National Maritime Museum at Greenwich, supplied as raster images in tiff format scanned at 300dpi. The charts used in this study form a sub-set of all available charts, selected upon the basis of clarity, existence of features suitable for image georeferencing, scale, year of publication and survey date, as well as location. Following the suggestion that pre-1864 charts produce significant georectification errors (Burningham and French, 2009) and since the availability of accurate shoreline surveys on Ordnance Survey terrestrial maps dates from around 1883 (Oliver, 1996), the earliest Admiralty Chart used was originally published in 1868 (Pakefield Gateway to Orfordness, with major corrections up until 1872). Additional charts were carefully selected to

provide sufficiently large temporal intervals between publication dates for bathymetric change to be evident. Charts were also selected where the dates of major corrections were clearly evident. The survey periods for the selected charts were 1872, 1931-4, 1952, 1962-9, and 1981-7.

Georeferencing was based upon churches, road junctions, Martello Towers and significant buildings, as far as possible replicating the main features used for the georectification and/or cross-checking of historic OS maps and aerial photographs described in Sections 3.1 and 3.2. Georeferencing possibilities based upon control points are limited within the offshore zone, hence it was also necessary to use grid references for fixing spatial locations. The depth contours and soundings were then digitised and corrected to OD Newlyn. From the depth data, a raster image was generated on a regular 10m x 10m grid using nearest neighbour analysis, as well as a Triangular Irregular Network (TIN). These two surface types were then used to provide an assessment of bathymetric change for a sample of the survey periods listed above.

The historic bathymetric data was supplemented with actual surveys of nearshore bathymetry, also provided through the Environment Agency. Since 1992 and for the same SDMS monitoring sites as for the cliff profiles, transects have been run to a depth of around 15m (approximately 3km offshore). These recent bathymetric soundings have been collected at 10 year intervals and were also available for this study.

3.6 GIS capabilities for analysis of shoreline dynamics

3.6.1 The Digital Shoreline Analysis System (DSAS)

The data sources described in the previous sections can be combined, and thereby gain greater utility, through their incorporation into a Geographic Information System. ArcMap (www.esri.com) was used as the main software package to perform detailed analysis of historic and contemporary shoreline dynamics. For initial investigation of historic shoreline change a recently developed ArcMap extension, the Digital Shoreline Analysis System (DSAS) (available via the USGS at (<http://woodshole.er.usgs.gov/project-pages/dsas/>)) was chosen. Version 3.2 was used in this study (Thieler et al., 2005) but additional modifications have subsequently been made to the DSAS software and version 4 is now the supported version (Thieler et al., 2009). The system was originally developed in the early 1990's (Danforth and Thieler, 1992), and with version 3.2 being available in 2005, it arises from a 20-year history of development, application

and testing. Applications have been widely published for many regions of the world (Schupp et al., 2006; Van To and Thau, 2006; Limber et al., 2007, Addo et al., 2008), but its use in the assessment of UK shorelines is relatively limited (but see Esteves et al., 2009).

DSAS can be used in the study of any dataset involving polylines from different time periods, but it is particularly suited to assessment of ongoing shoreline retreat. Shorelines are digitised as polylines and appended to a single feature class file. This is then imported into a geodatabase. A baseline is created either by manual digitising to a polyline shapefile or by buffering an existing shoreline. The former method was used here as the coastline being studied is relatively straight and runs in the same NE-SW orientation along its entire length. Care needs to be taken over creating the baseline, especially where shorelines involve substantial and frequent changes in orientation. It is possible to set the baseline either offshore or onshore, which then affects the cast direction of each transect. The baseline is imported into the geodatabase along with the shoreline feature class file. Within ArcMap transects are then cast perpendicular to the baseline at any user-defined alongshore spacing, which makes this extension particularly powerful where a high level of spatial detail is required. In this study a spacing of 10 m was selected along the ~8 km stretch of coast between Benacre Ness and Southwold, producing a total of 816 transects. Assessment of the shorter stretch of retreating cliffs between Dunwich and Minsmere, stretching over 3km, generated a further set of 300 transects.

Three attribute tables, produced using DSAS, provide information on the distance of each shoreline from the baseline, the x-y co-ordinates of every intersection between transects and shorelines, along with statistical assessments of shoreline movement. Examples include Net Shoreline Movement (NSM), defined as the distance between the oldest and youngest shorelines, the Shoreline Change Envelope (SCE) which is the distance between shorelines furthest and closest to the baseline (this may not necessarily be the oldest and youngest shoreline), the End Point Rate (EPR) where the distance between the oldest and youngest shoreline is divided by the time period between them to give an average annual rate of change, and the Linear regression rate-of-change (LRR), where a least squares regression line is fitted to all shoreline intersections along each transect. In the current study the EPR was used primarily as the best way of assessing change in shorelines that move consistently in a single direction (ie: in this case, retreat inland). The historic period of analysis, 1883 - 2008, was disaggregated into smaller time periods to allow

the EPR to be derived for sub-periods, to investigate whether there have been changes in retreat rates over historical timescales.

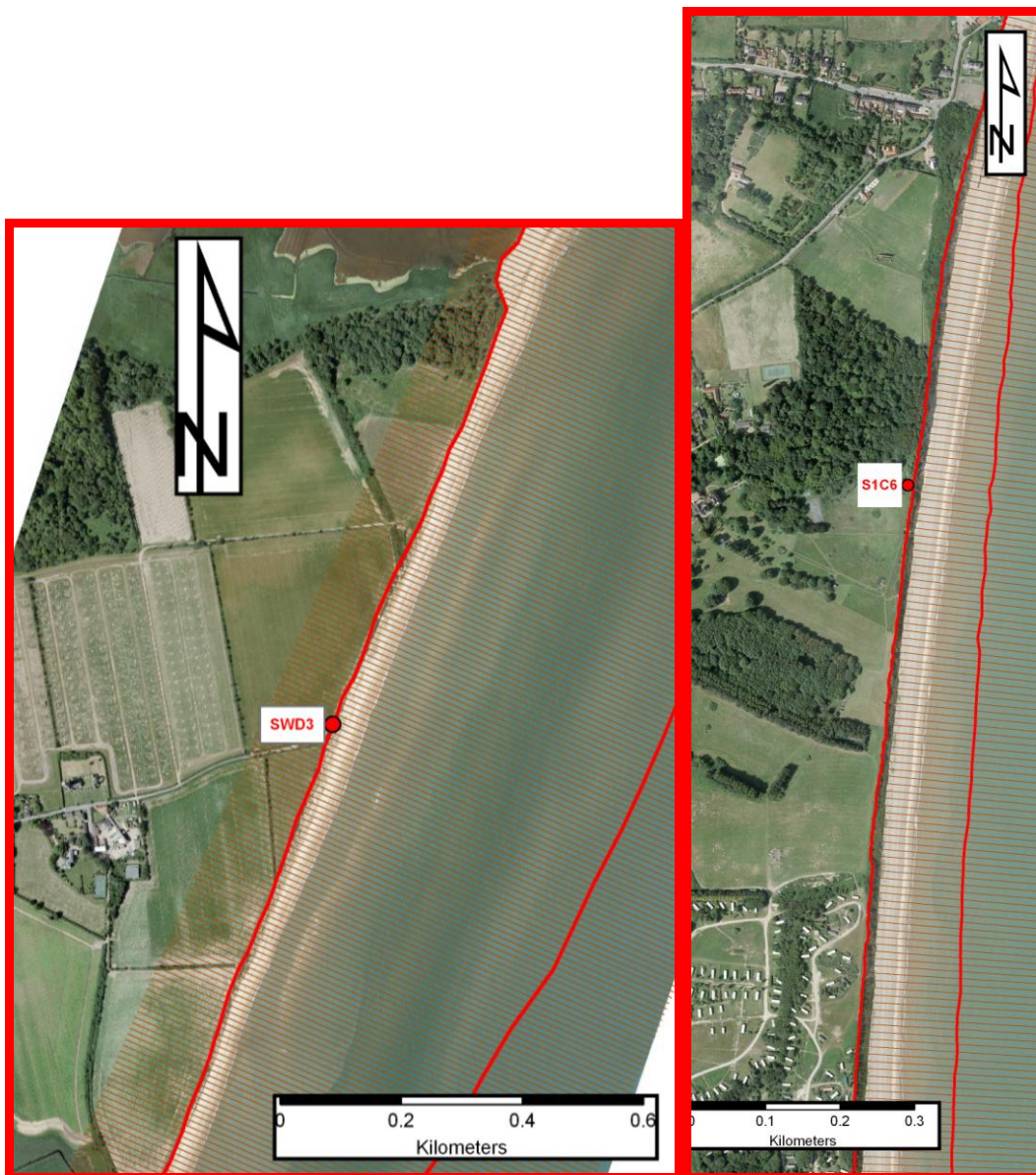


Figure 9: Transects cast at 10m intervals alongshore for the regions of Covehithe and Dunwich-Minsmere (the former location had a total of 800 transects while the latter had a total of 300 transects). Aerial photographs supplied by the Shoreline Management Group (Anglia Region), Environment Agency from 2008.

Transects cast by DSAS for a sample sections of the Suffolk coast in the vicinity of Covehithe and Duwich-Minsmere are shown in Figure 9. Results based around the End Point Rate (EPR) are discussed in detail in Section 4.

3.6.2 The Surface Spot tool

The second main ArcMap capability that was used in this study was the Surface Spot tool. This tool uses a point shapefile along with an elevation surface to interpolate the heights of each of the points. It appends a field to the original shapefile containing the height of each point, and this can then be used to provide a plot for the topography. Appropriate point shapefiles can be readily developed from the intersections of shorelines with DSAS transects, as the x-y co-ordinates are automatically generated within DSAS and written to the Intersect Attribute Table.

The Surface Spot tool derives point elevations using one of two possible methods. Linear interpolation can be used to obtain point-specific heights from the three nodes of the triangle containing the interpolation point when a TIN is used for elevation data. Alternatively, for a raster image, the surface spot tool generates interpolated heights using bilinear interpolation based upon a weighted average of the heights at the four closest cell centres surrounding the interpolation point. Since elevation data has been available since 2001 this method allows the topography of the entire coastline between Benacre and Southwold, as well as between Dunwich and Minsmere, to be extracted at 10m spacings with a vertical accuracy of 1m. This was done for transects along the 2008 shoreline, to provide a basis for investigating sediment release from the cliffline. However, the method is particularly suited to assessing future shoreline dynamics as there are detailed elevation data available inland from the existing clifflines. This provides an unprecedented opportunity to investigate sediment release dynamics of retreating clifflines which can inform management decisions in future. This important issue related to future shoreline positions, elevations and sediment dynamics is discussed in detail in Section 6.

4. Coastal change over recent and historic timescales for the Suffolk Coast

4.1 *Coastal retreat rates along the Suffolk Coast, 1880s - present day*

Initially, analysis of retreat along the whole length of each coastal stretch was carried out for the period 1883-2008 using MHWS as the basis for digitising the shorelines. This was necessary as the entire shoreline is not solely composed of clifflines and defining the shoreline for low-lying areas between the cliff sections requires consistency. This initial approach also enabled comparisons to be made with previous publications that utilised MHWS as the shoreline and, at this broad scale,

the approach provided a representative picture of large-scale historic movement in the position of the Suffolk coastline.

The EPR generated by DSAS was used as the platform for analysis and, as well as the period 1883-2008, the EPR was also calculated for the 1880s to the 1950s. The period from the 1880s to the 1950s has previously been assessed in detail using the historic OS maps from 1883 and 1957 (Cambers, 1975), with analysis of shoreline change between these two periods having been carried out for the whole coastline, but at 250m spacing. The actually survey dates corresponding to each time period are 1882 and, depending on location, 1941 or 1947. The main purpose of this initial assessment was to compare results from the DSAS methodology with the traditional method.

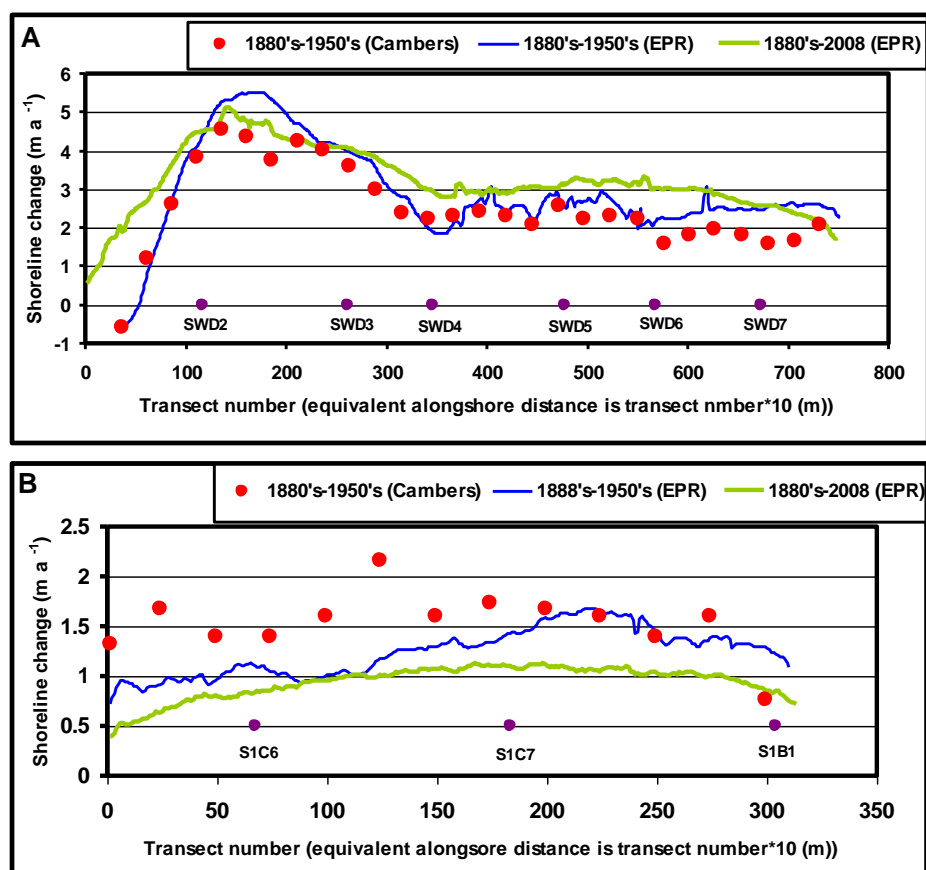


Figure 10: Shoreline recession rates (m a^{-1} ; EPR statistic from DSAS) for the coastline between (A) Benacre and Southwold and (B) Dunwich-Minsmere, for the 1880s to the 1950s and for 1880s-2008. Also shown are results from an earlier study by Cambers (1975) at 250m spacings, as well as the locations of the EA SDMS (SWD2 – SWD7; S1C6 – S1B1) for reference.

Figure 10 presents the results for the two selected time periods, using both traditional and new methodologies. In both plots, transect 1 is at the northern end of the shoreline and alongshore distances (transect numbers) increase from North to South. The locations used in the calculations of Cambers at 250m interval spacings are plotted at their equivalent alongshore location to enable direct comparison of the two methods. Also shown are the locations of the Environment Agency SDMS profiles. Figure 10(a) shows clearly that high retreat rates have characterised the coastline between Benacre and Southwold, ranging between 2 and 3m a⁻¹, but reaching values of over 4 and 5ma⁻¹ at the SDMS locations of SWD3 (Covehithe) and SWD2 (Benacre) respectively. On moving northward from SWD2 there is an abrupt switch in shoreline behaviour from retreating to advancing occurring at around transect 50. The correspondence between the rates found by Cambers and those found using DSAS is good, especially in the central section between transects 200 and 550. Along the southern part of the shoreline (transects 550 to 750) there appears to be a tendency for the Cambers methodology to produce slightly lower estimates of retreat rates. Comparison with rates for the whole period of 1882-2008 suggests that high rates have been maintained through this 125-year period. Northward of SWD2, there is a very clear increase in retreat rates of up to 2m a⁻¹ when comparing 1880s-1950s with 1880s-2008. Furthermore, a slight increase in retreat rates can be seen in the central to southern section of the coastline, south of SWD3. The possible trend towards higher retreat rates since the 1950's is assessed in greater detail in the following section.

From Figure 10(b) emerge three sharp contrasts with Figure 10(a). Firstly, historic retreat rates in the Dunwich-Minsmere cliff system are far lower in general than those of Benacre Ness to Southwold, being between 1 and 2m a⁻¹ for the 1880s to 1950s compared with 2 to 5m a⁻¹. There appears to be a southerly trend (from transect 1 to transect 220) towards higher rates but only of the order 0.5m a⁻¹. Secondly, retreat rates have slowed noticeably since the 1950s, where the range for 1880s-2008 falls to between 0.5 and 1ma⁻¹. Thirdly, there is a greater difference between retreat rates of Cambers and that of the current study when compared with differences at Benacre Ness-Southwold. The discrepancies are most apparent in the northern cliff section, around Dunwich (S1C6). Since retreat rates are significantly lower at this location, both methods are problematic to apply. For example, at a retreat rate of 1m a⁻¹, between the 1880s and 1950s there would have been around 65 m of retreat compared with almost 200m at rates of 3m a⁻¹ and over 300m at 5m a⁻¹. At a scale of 1:10 000, 65m of retreat is 6.5mm on a map (compared with 20-30mm for the higher rates). Hence difficulties with traditional measurements using direct

overlaying of historic maps at this scale are readily appreciated. Even with advances in GIS technology, georeferencing and digitising errors become more significant when retreat rates are lower. For Dunwich-Minsmere, fewer reliable ground control points were available at suitable locations for georeferencing. Pye and Blott (2006) suggest a need for 6 georeferencing points to calibrate maps at a precision of around 1m, but it was difficult to find 6 reliable control points in this region close to the coastline. Hence errors arising from georeferencing might, in part, explain the discrepancies between the two methods at this location.

Historic retreat rates for Dunwich-Minsmere have been reported elsewhere. Pye and Blott (2006) assessed historic retreat at two of the SDMS locations, S1C7 and S1B1, but did not include the northern location of S1C6 around the Dunwich cliffs. Their estimates for 1883-1953 were 1.7 m a^{-1} for S1C7 and 1.4 m a^{-1} for S1B1. However, these points are widely spaced at 1km and occur on a stretch of coast where the differences in rates found from the two methods are not particularly significant anyway. For this cliffline as a whole, Pye and Blott (2006) suggest retreat rates of 1.3 m a^{-1} for 1903-1953 and 0.6 m a^{-1} between 1953 and 2003. These estimates compare favourably with those from the DSAS methodology in this study, and also indicate the more recent slowing of rates. Pontee (2005) has also suggested longterm rates of retreat at Dunwich of around 1 m a^{-1} since the start of the 16th century, similar to those found using DSAS and much lower than Cambers' estimates. However, Pontee (2005) suggests typical rates of between 0.16 and 0.24 m a^{-1} from the 1880s to the present day. Hence these rates are comparable but much lower than those found from the current methodology. Pontee (2005) does raise the issue of temporal variability in retreat rates that is masked when taking averages over decades or centuries, just as using SDMS 1 km spaced locations masks the spatial variability. Both are potentially important considerations in the overall analysis of coastline change.

The DSAS extension of ArcMap produces estimates of cliff retreat over hundred-year timescales that compare well with previously published estimates, especially in rapidly-retreating cliff systems. The methodology has the capacity to incorporate the considerable spatial variability that is commonly observed in these processes (Cambers, 1975; Pontee, 2005; Pye and Blott, 2006) to an unprecedented degree. Use of DSAS along with greater precision in spatial positioning from a range of data sources represents a considerable advance in our ability to assess in detail rates of shoreline change.

This section of the report has introduced a methodology that can reveal the considerable spatial variability in retreat rates. The section that follows extends this methodology to provide a similarly detailed inclusion of temporal variability in coastal retreat rates.

4.2 Cliff retreat for individual cliff sections, 1882-present day

The DSAS approach was applied to a series of historic maps and aerial photographs to evaluate temporal variability in rates of shoreline change. The methodology adopted for this differs slightly from the larger scale assessment of spatial variability in recession. Since the initial assessment approach was for relatively long coastal sections with different physical features alongshore, the mean high water spring tides (MHWS) was used as the unambiguous marker for the shoreline position. When datasets are compiled from both aerial photographs and historic maps, it can be problematic to locate the position of MHWS precisely. Since the detailed temporal analysis focuses on the cliffs alone it was considered optimal to use the actual cliff top as the shoreline marker. This has the advantage of being easily defined on both historic maps and on aerial photographs. Shorelines were digitised using the clifftop for all available survey dates on historic maps since 1882. These were then supplemented with aerial photographs from 1992 and 2008. The shoreline recession (EPR statistic) for each time period was derived separately for the cliffs of Dunwich-Minsmere, Easton Cliffs, Northend Warren, Easton Wood, Covehithe and Benacre.

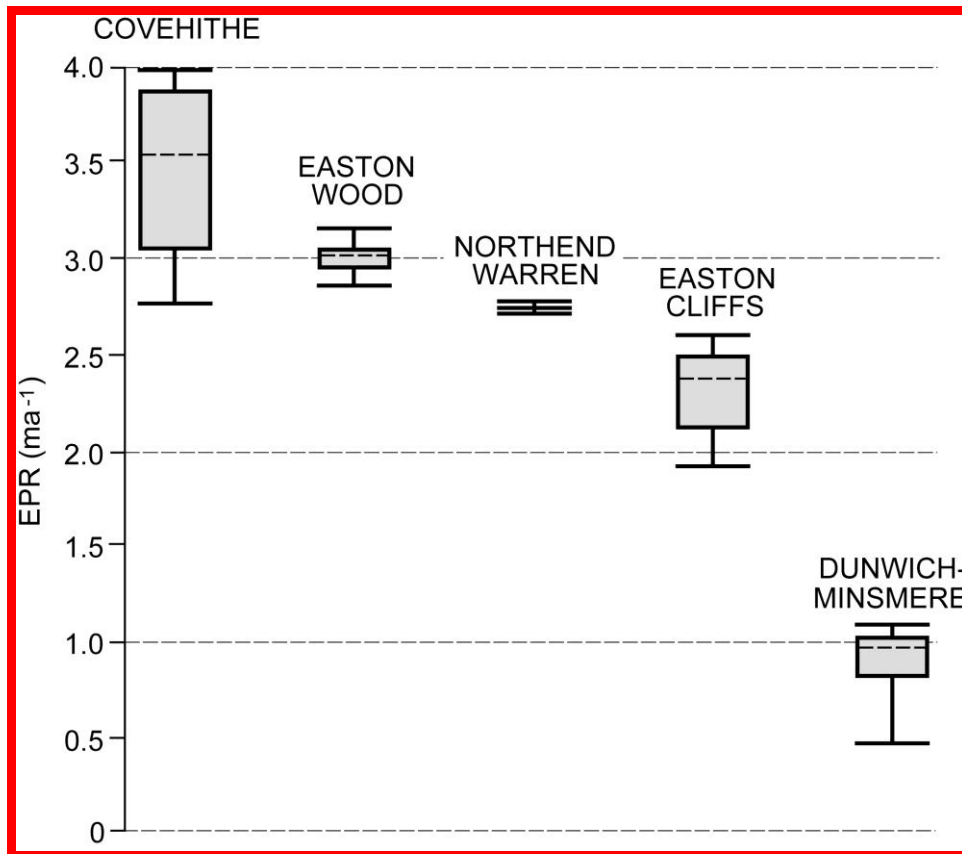


Figure 11: Shoreline recession for each of the major clifflines between 1882 and 2008. Benacre lies to the north of Covehithe and could not be included as it does not have an historic cliffline.

Figure 11 shows the EPR for each cliff section from 1882 to 2008. Benacre is omitted since a cliffline has only developed at this location since 1981 so is not present on historic maps. For Easton Wood the cliffline has only been present since 1903. The latter site is included, however, as the record is sufficiently long for comparative assessment over similar timescales to the other locations. Since DSAS averages the EPR between the actual dates supplied, the rates presented are directly comparable. For each cliffline the sample size is different, reflecting the length of the cliffline and number of 10m transects required to define each cliffline. Only the transects that coincide with a cliffline that has been present since 1882 (or 1903 in the case of Easton Woods) were included in Figure 11 as the cliff edges have varied in location as the shoreline has retreated. Hence the narrow range in EPR at Northend Warren is, to some extent, explained by the fewer transects that characterise this short cliffline.

The box-whisker plots (Tukey, 1977) in Figure 11 show the median EPR at each location as a dashed horizontal line, while the ends of the boxes represent the upper and lower quartiles in the distribution. The whisker lengths show the highest/lowest data point that lies within 1.5x the box

length from the upper/lower quartile respectively. Hence the whiskers provide an indication of the range in each data set.

The contrast between the EPR at Dunwich-Minsmere and locations further north is clear with rates in the former location being less than one-third of the northernmost location of Covehithe. The north-south trend is apparent and appears to have persisted historically, leading to a general reorientation of the coastline from a more NE-SW orientation to a more N-S one. Greater detail in temporal variability in clifftop recession rates was investigated for each of the main cliff sections individually.

4.2.1 Dunwich-Minsmere

The clifftop recession rate at Dunwich-Minsmere is the lowest of all the locations, with a longterm median rate of 0.9m a^{-1} . Figure 12 disaggregates the past 125 year period into 6 separate time intervals based upon the survey dates of the OS 1:10 000 maps between 1883 and 1981 and the dates of selected EA aerial photographs, from 1992 and 2008.

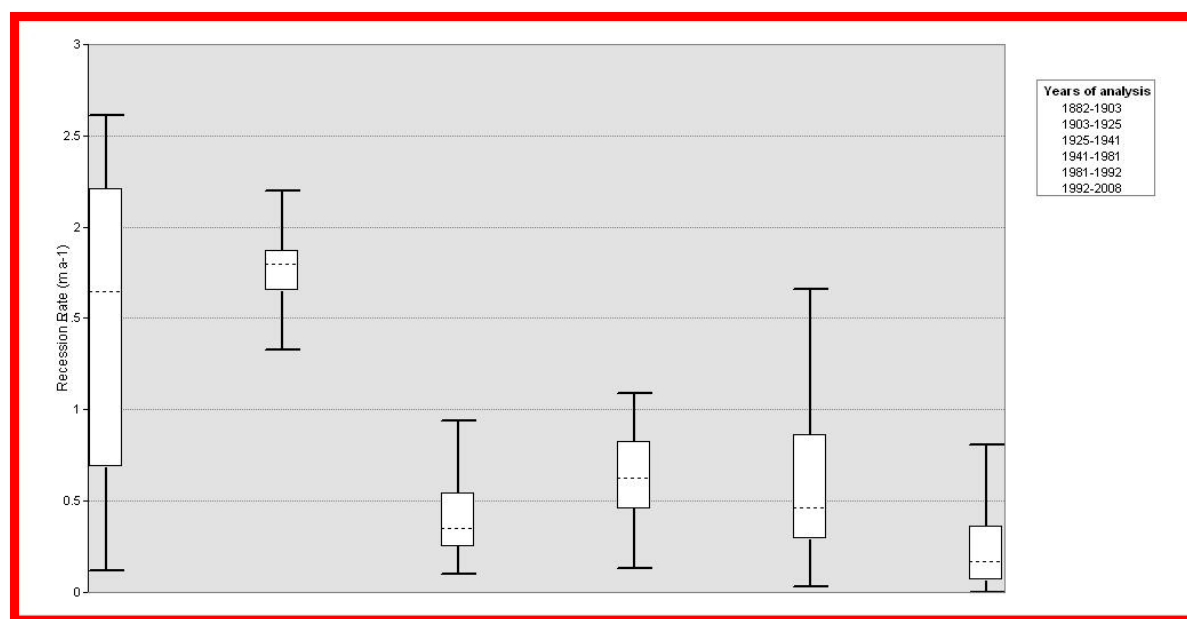


Figure 12: Temporal variation in shoreline recession rates (m a^{-1}) for the cliffs of Dunwich-Minsmere.

The earlier time periods have a median cliff top recession rate for the 300 transects between Dunwich and Minsmere of 1.6m a^{-1} , slightly higher than that suggested for Dunwich in previous publications. However, there is a clear drop in median recession rate after 1925, to a value of 0.3m a^{-1} and these low rates are sustained for the remainder of the analysis period. For the most

recent period 1992-2008, the median recession rate is just 0.2m a^{-1} . Hence the longterm median of 0.9m a^{-1} reported above for 1882-2008 appears to consist of an early period of high rates of recession in excess of 1m a^{-1} followed by a period when rates are reduced to less than one third of their earlier values. These results are consistent with the suggestion of a system that is “shutting down” and this appears to take place between 1925 and 1941. Low recession rates now typify the cliffs between Dunwich and Minsmere.

4.2.2 Easton Cliffs

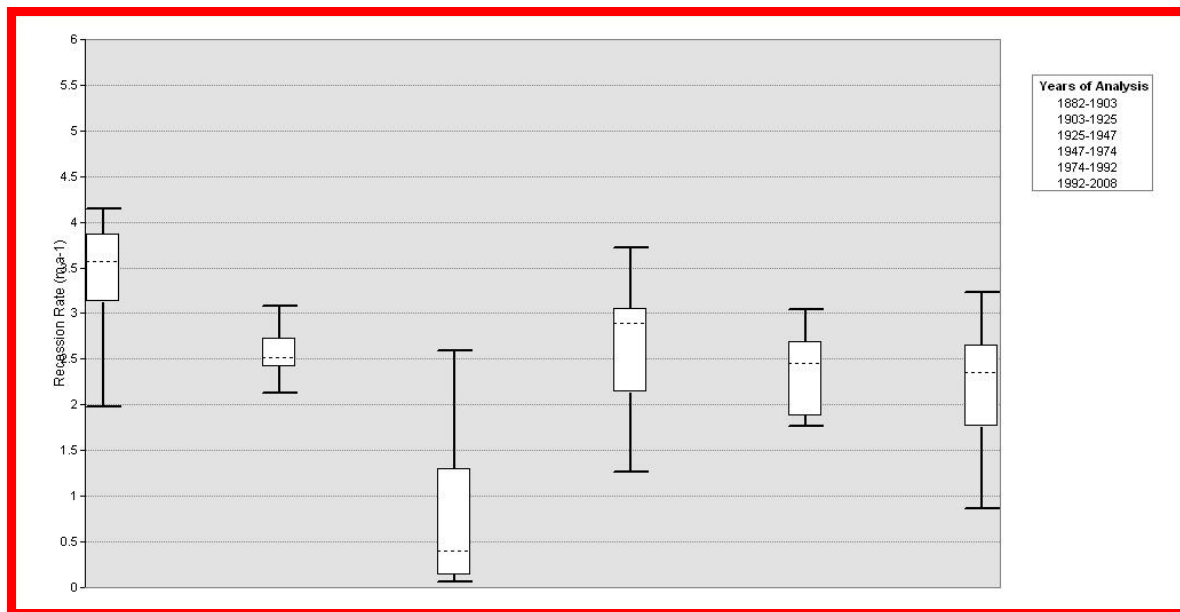


Figure 13: Temporal variation in shoreline recession rate (m a^{-1}) for the Easton Cliffs.

The longterm median recession rate along the Easton Cliffs has been 2.4m a^{-1} . Detailed temporal analysis, again based upon 6 time periods, suggests that this rate has not varied significantly throughout the whole 125 year period of record. The cliffline has been in place through the entire period with little change in length and elevation. It can be assumed therefore, that the sediment supply from this cliffline has been relatively constant between 1882 and 2008.

4.2.3 Northend Warren

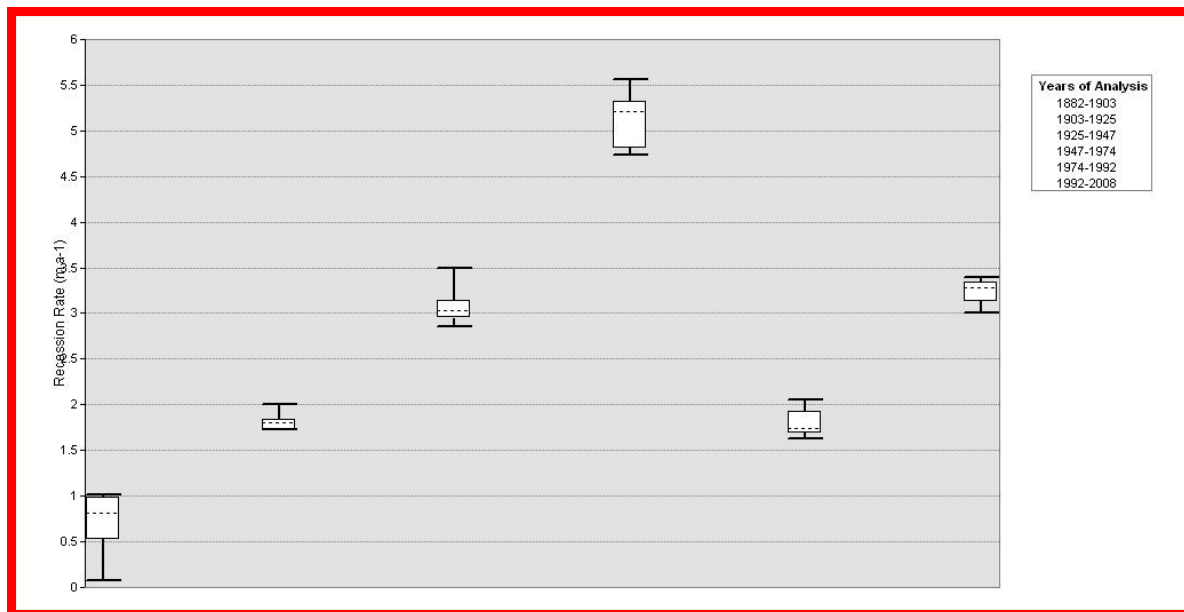


Figure 14: Temporal variation in shoreline recession rate (m a^{-1}) for the cliffs at Northend Warren.

Longterm retreat rates at Northend Warren have been slightly higher than for Easton Cliffs, at just under 3 m a^{-1} , but this cliffline is only around 300m in length. However, the longterm rate masks considerable temporal variability in retreat rate at this location, where there appears to have been a steady increase in cliff retreat from 1882 (less than 1 m a^{-1}) to 1974 (in excess of 5 m a^{-1}). This was then followed by a period when rates returned to values closer to 3 m a^{-1} .

4.2.4 Easton Wood

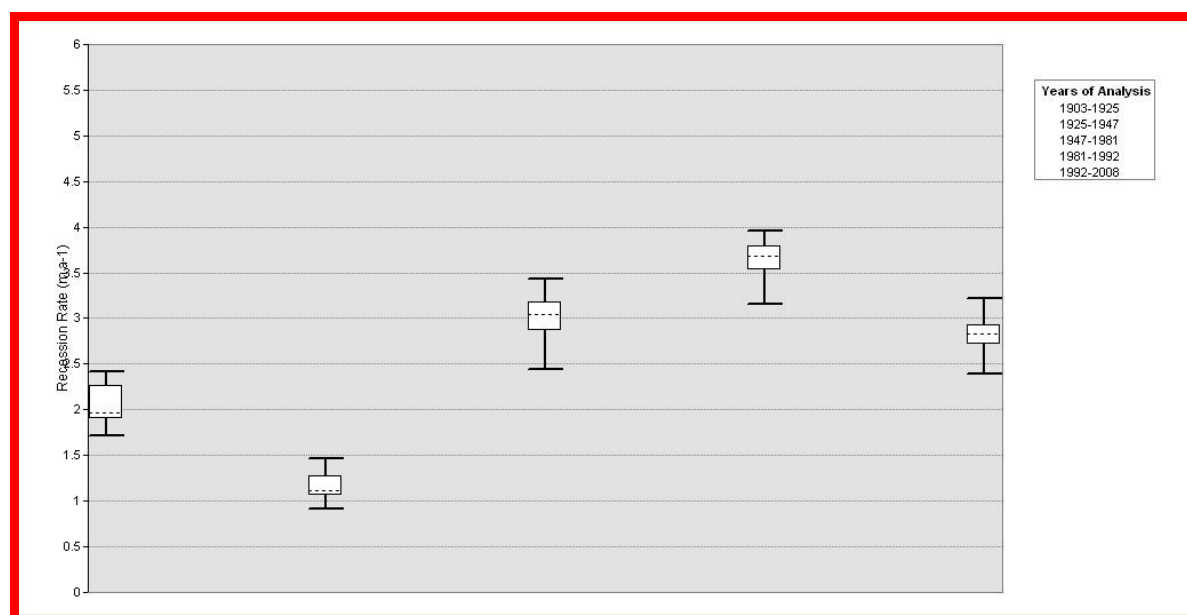


Figure 15: Temporal variability in shoreline recession rate (m a^{-1}) in the cliffs at Easton Wood.

The cliffline at Easton Wood was analysed from 1903 onwards, since there was no cliffline at this location in the earlier period. Easton Wood exhibits longterm retreat of 3m a^{-1} . Like the Dunwich-Minsmere cliff system, this longterm rate appears to be made up of two distinct periods of recession response. An earlier period between 1903 and 1947 with rates well below the longterm value was followed by a period after 1947 when rates were higher than previously. While the Dunwich-Minsmere cliffs appear to be “shutting down”, the cliffs of Easton Wood appear to be “switching on”. From 1882-1903, there is no cliffline present at all at this location but in 2008 the Environment Agency aerial photographs depict a clear and sharp cliffline of over 700m in length. This cliffline, as well as retreating at a higher rate in recent periods, has been growing in extent through the period since its first appearance as a 300m long cliffline in 1903. It is also increasing in elevation (as discussed in Section 5 of this report).

4.2.5 Covehithe

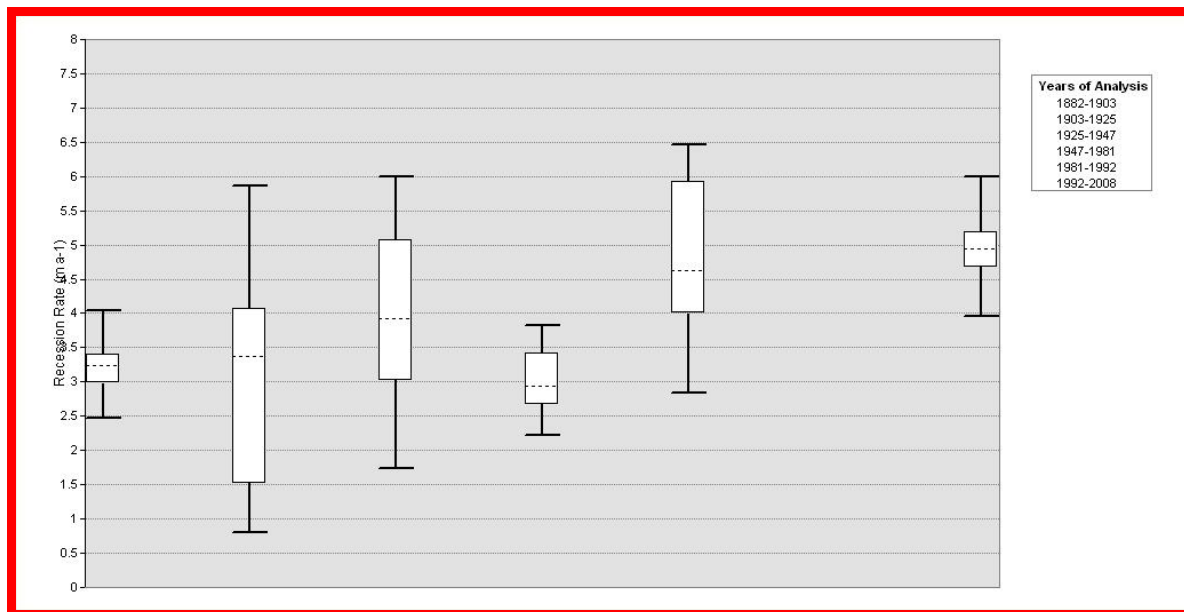


Figure 16: Temporal variation in shoreline recession rate (m a^{-1}) for the cliffs of Covehithe.

The cliffs around Covehithe have been cited as supplying the vast majority of sediment from this coastline (Cambers, 1975). They extend a significant distance alongshore and reach the highest elevations of all the cliff systems between Benacre and Southwold. These cliffs have exhibited longterm retreat that is higher than the more southerly locations, having a median retreat rate of 3.5 m a^{-1} . Over the analysis period since 1882, there appear to be four earlier periods (up until 1981) where retreat rates oscillate around a value of 3.5 m a^{-1} . Since 1981 retreat rates have risen steadily, firstly to 4.6 m a^{-1} between 1981 and 1992, and subsequently attaining a median rate of almost 5 m a^{-1} between 1992 and 2008. From historic maps we can also determine that the increase in retreat rate has been accompanied by an extension of the cliffline, of the order of 165m since 1947.

4.2.6 The Benacre cliffs

Analysis of the retreating cliffline of Benacre is problematic since this location has not had a cliffline historically. In 1882 the frontage was the southern extension of Benacre Ness, a low-lying feature that has progressively moved northward since this period, and continues to do so in the present day. The cliffline that now exists is almost 1km in length, and first appeared on the 1981 OS 1:10 000 map as a very short (200m) emerging cliffline. Hence analysis of temporal variation in retreat could only be based upon a small number of transects (20) and was restricted to the periods 1981-1992 and 1992-2008.

The range in retreat rate along this cliffline was 2.04 to 3.02m a⁻¹ between 1981 and 1992, with a mean value of 2.68 m a⁻¹. By comparison for the period 1992-2008, the range was from 6.59 to 7.16m a⁻¹, with a mean retreat rate of 7.02 m a⁻¹, almost a three-fold increase.

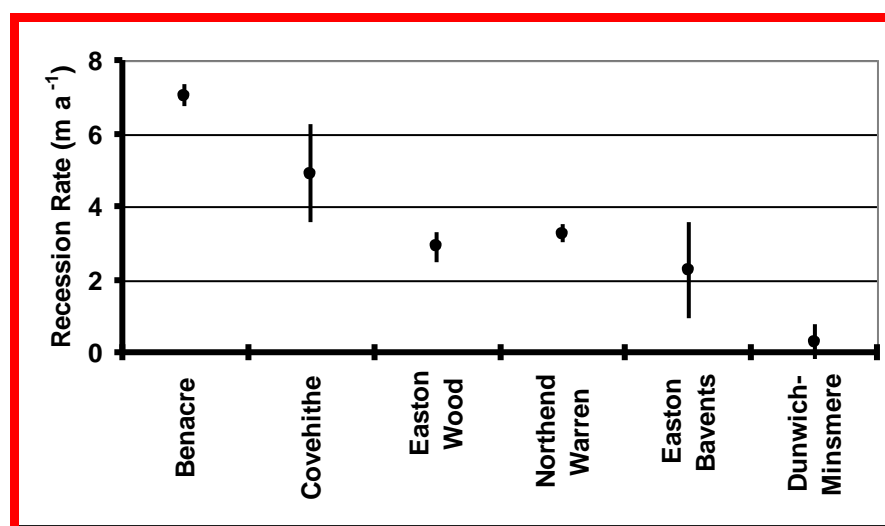


Figure 17: Retreat in the six clifflines along the Suffolk coast in the period 1992-2008.

Figure 17 shows retreat rates for the period 1992-2008 for all locations in this study, suggesting a strong N-S trend towards lower rates of retreat and emphasising the importance of Benacre compared with the other locations alongshore. Over the past 16 years the recession rate at Benacre has been in excess of that at Covehithe (where rates in themselves are among the highest in the UK) by over 2m a⁻¹. Retreat rates at Dunwich-Minsmere are almost 2 orders of magnitude lower and represent a situation of little significance in the contemporary story of coastal retreat.

The historic pattern of retreat along the Suffolk coast has undergone dramatic change over the twentieth century and into the contemporary period. To the south the coastline has had a long and continuing history of retreat in excess of 1m a^{-1} , providing a focus for many studies on coastal retreat in the region. However, this cliffline has shut down since the 1920's and now appears to be retreating very slowly, if at all. Figure 18 shows the cliffs in the region of Minsmere near EA SDMS profile S1B1. While there is evidence of clifftop activity, the cliff base appears to be stabilised by a combination of well-vegetated basal deposits from the cliff and a shingle beach. This extends along the 3km cliffline, into the lower-lying central section and towards the cliffs of Dunwich. At this southernmost point there is some evidence of cliffline activity and some attempts at stabilisation have been introduced (Figure 19).



Figure 18: The cliffs at Minsmere looking north towards Dunwich, which is 3km distant (15th December, 2009).



Figure 19: The cliffs of Dunwich (EA SDMS site S1C6) looking south towards Minsmere (15th December 2009).

In the north of the region systems continue to “switch on” as exemplified by Easton Woods and, in particular, Benacre where the appearance and enlargement of a new cliffline accompanies increasing rates of retreat (Figure 20).



Figure 20: The cliffs of Benacre in the region of EA SDMS site SWD2, looking north towards Benacre Ness (30th March, 2010) (prior to 1981 there was no cliffline at this location and on the

1928 OS 1: 10 560 map the frontage known at The Denes was a low-lying Warren extending a 1000 feet seawards).

This historic analysis has emphasised the highly dynamic nature of clifflines on shorelines of rapid retreat. Clifflines appear and disappear, extend and contract, gain and lose elevation over timescales of decades. Analysis of sediment sources falls out-of-date very quickly and the last study, published in 1975, still provides the most recent analysis of sediment supply along this coastline. A detailed study of contemporary retreat and associated sediment sources in this cliffline has now been undertaken and the results are reported in the following sections.

4.3 Contemporary cliff retreat rates between Benacre and Southwold

The section of the Suffolk coast that has been retreating the most rapidly in contemporary periods is that between Benacre and Southwold, where rates locally may exceed 7 m a^{-1} . Information about contemporary recession rates is potentially the most relevant to planning decisions related to coastal management in the near future, although historic rates are often used as the basis for planning. A detailed analysis of contemporary rates, based upon the most recently available information (aerial photographs and ground survey) provided by the Environment Agency, and making use of the DSAS methodology was undertaken for the period 1992-2008. This period was sub-divided into two decadal periods (1992-2001 and 2001-8) related to the availability of associated elevation data, which is used in Section 5 in the derivation of sediment sources. Each period was assessed separately using DSAS to derive the shoreline recession rate (m a^{-1}) for two digitised shorelines based on clifftop position for the start and the end of each time period.

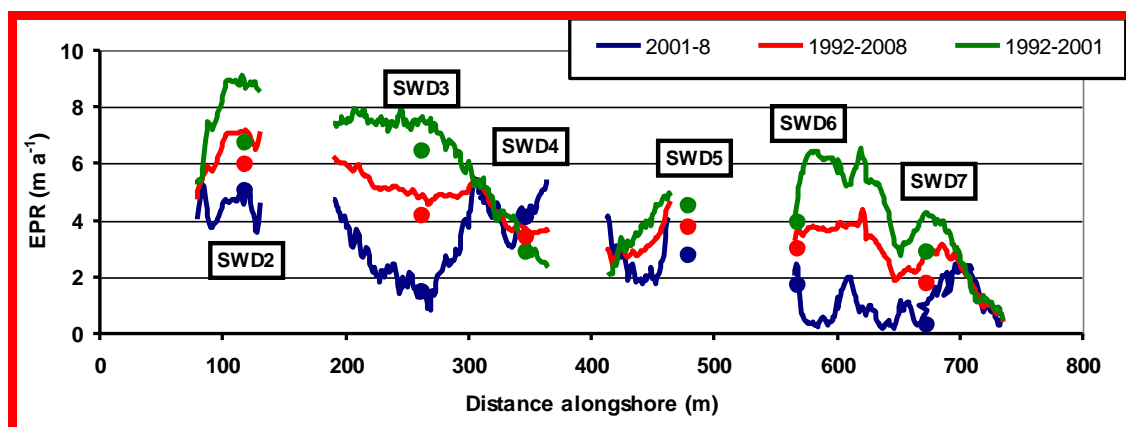


Figure 21: The shoreline recession rate (m a^{-1}) between Benacre and Southwold for the period 1992-2008, and the sub-periods 1992-2001 and 2001-8. The locations of each EA SDMS are also shown, along with retreat rates at each location for each period derived from the ground survey data (shown as circles).

Figure 21 presents the results of applying the DSAS methodology to the cliffline, with the EA ground survey point data plotted for comparison. There is reasonable consistency between these two methods of assessing coastline change, although the ground survey data under-represent the highest retreat rates evident from the DSAS analysis (eg; the green circle at SWD2 and SWD3 appear to underestimate retreat compared with the analysis based upon aerial photographs). Where cliffs are retreating very rapidly this is likely to produce inconsistency in precise shoreline position if the dates of the ground surveys differ significantly from those of the aerial photographs.

The results in Figure 21 suggest that even an assessment of coastal retreat conducted over comparatively short (decadal) time periods can mask considerable temporal variability in retreat patterns (compare the 1992-2001 and the 2001-8 rates). There also appear to be slightly different variability responses along the cliff line. The dominant behaviour exhibited is a considerable change in retreat rates from higher rates in 1992-2001 compared with 2001-8. In places, such as at Covehithe, rates were in excess of 7 m a^{-1} in the earlier period, dropping to around 2 m a^{-1} in the latter period, producing an average of around 5 m a^{-1} over the total period. There can also be rate changes in the opposite sense, such as around SWD4, where rates in 2001-8 were higher than for 1992-2001, but with a less pronounced difference as well as greater spatial restriction. Finally, there are short stretches of the cliffline where rates were very similar throughout the whole period, such as in the southern section of the Covehithe cliffs, the northern section of the cliffs at Easton Wood and the southern section of the Easton cliffs. Possible reasons for this variability in retreat behaviour have been suggested by Brooks and Spencer, 2010, based around the stratigraphy and composition of the cliff-forming materials.

The identification of spatially and temporally variable retreat behaviour over very short timescales has been made possible by recent advances in both accurate data capture as well as the means to assess the data within a GIS framework. Just as cliff systems have been shown to appear and disappear over historic timescales, their response can change over decadal periods. It

is therefore not possible to characterise a retreating coastline in terms of a particular rate of recession along its entire length. Spatial and temporal variability in rates should inform management strategies as this variability establishes the envelope within which decisions should be made. One area that is of particular significance is the associated sediment supply, and a new method to rapidly analyse this in detail is developed in the following section.

5. Sediment release from the retreating Suffolk Cliffs

Sediment sources for coastal sandbanks are derived from river sediments, can be brought to the near shore region from further offshore or arise from cliff erosion as the coastline retreats. The importance of sandbank development in offering coastal protection has been emphasised by Robinson (1980) and more recently by Stansby et al. (2006) and Horillo-Caraballo and Reeve (2008), with the growth of the Dunwich-Sizewell Bank being cited as a potential reason why coastal recession rates have slowed in the region. Pye and Blott (2009) have presented evidence for the link between sandbank development and associated cliff retreat rate decline at Dunwich-Minsmere. The publications by Carr (1981), as well as Pye and Blott (2009), suggest one possible sediment source for the growth of the Bank is from cliffs to the north, namely Easton cliffs and Covehithe. The general southerly direction of sediment transport in the nearshore zone of the region has been continuously referred to, although not proven, and the latest draft Shoreline Management Plan (SMP, 2010) cites the need to allow coastal recession to continue at Covehithe in order to maintain the sediment supply for beaches and sandbanks to the south.

Coastal protection is also afforded through maintenance of wide and/or high beaches, the character of which depends on the wave energy and grain size of the beach-forming material. Whether the cliff base is exposed to erosion depends on the continued supply of sediment that can remain in place, with coarser material being harder to transport. Beaches are maintained by a throughput of sediment from up drift locations to compensate for down-drift losses, or from material eroding from the cliff. Both the quantity as well as the calibre of the material coming from the cliff is therefore important.

The sandy cliffs of the Suffolk coastline are moderately high, stretch long distances alongshore and are receding rapidly. Whether or not to protect these cliffs is a difficult decision as it has

regional (down drift) as well as local implications for the sediment supply involved. Despite this, there have been few attempts to quantify the contemporary sediment supply. No study takes into account the dynamic issues involved in coastal recession assessed and discussed in the previous section. This section outlines a methodology for assessment and quantification of sediment release that can be easily applied in assessment of likely future sediment sources as the coast migrates inland. The new methodology builds upon the DSAS assessment of retreat rates outlined in the previous section.

5.1 Contemporary cliff elevation, 2001-8

Sediment volumes are the product of retreat rate, cliff length and cliff elevation. Hitherto establishing cliff elevations was based upon spot heights and contours from Ordnance Survey Maps. Since 2001 detailed ground elevation data have been available using IfSAR technology, as discussed in section 3.4. NextMap elevation data produced on a 5m x 5m grid was used to produce both a Triangular Irregular Network (TIN) and an Inverse Distance Weighted (IDW) continuous surface of elevations through interpolation over the region of interest between Benacre and Southwold as well as Dunwich-Minsmere. The intersection table generated using DSAS provides the x-y co-ordinates of every transect as it intersects every shoreline. Using DSAS the digitised 2008 shoreline, from aerial photographs, was used to create a point shapefile, with a point being generated at each 10m interval alongshore. The Surface Spot tool was then used to generate elevations for each point alongshore.

The accuracy of the NextMap dataset was discussed in Section 3.4. In this analysis, corrections only needed to be made to the data in the region of Easton Woods (the only region with any significant surface structure, in the form of a woodland canopy, along the 2008 shoreline) and the corrections were based upon the contours and spot heights of the most recent OS map. Elevations generated by the NextMap data in this region could reach up to 28m in places, clearly reflecting the combination of ground elevation and tree height. Where such heights were recorded in the NextMap data, ground elevations were set at 12.5m, consistent with information on the map. The NextMap data also showed some distortion at the coastline, but by 2008 the shoreline had retreated to between 35m and 14m inland (higher in the north reflecting higher retreat rates). However, coastline position has seen negligible change at Dunwich-Minsmere since 2002. Hence issues of data accuracy in steeply-sloping areas were more relevant to the latter location. To overcome this problem the 2008 coastline was buffered at 10m to produce an

identical coastline but located 10m inland from the actual 2008 coastline. In the Dunwich-Minsmere region no correction was required for woodland areas or those of significant surface structures, since the near-coastal region is predominantly heathland.

Figure 22 shows the clifflines generated from the Nextmap elevation data using the IDW surface for a) Benacre to Southwold and b) Dunwich to Minsmere. The coastline between Benacre and Covehithe has variable topography with the sections of cliffline clearly shown separated by the low-lying broads. The effect of the correction to the area of Easton Woods is evident. The cliffs of Covehithe are the longest sub-unit of all the cliffed sub-units and they also attain the greatest elevation. The Easton cliffs are also a pronounced feature. The Benacre cliffs are relatively modest, being just 7-8m in height and stretching alongshore for around 800m. The coastline at Dunwich Minsmere comprises a single 3km long cliffed section attaining elevations of up to 17m.

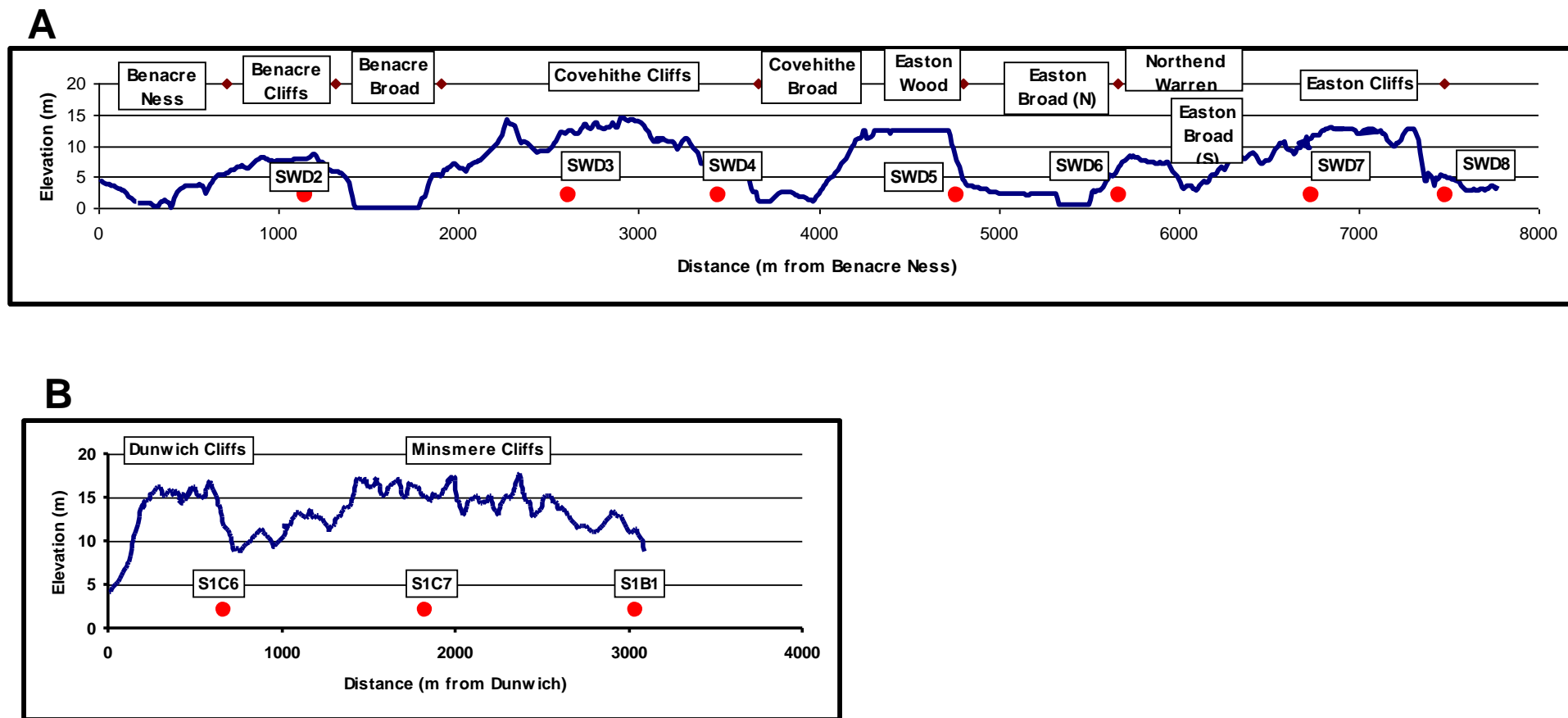


Figure 22: The clifflines of (A) Benacre to Southwold and (B) Dunwich-Minsmere derived from NextMap data for the 2008 shoreline position. Also shown are the locations of the EA SDMS sites.

5.2 Calculating sediment volumes released between 2001 and 2008.

Shoreline retreat rates generated at each 10m transect using DSAS, described in Section 4, were combined with the elevation data generated using the Surface Spot tool to generate a volumetric loss in the cliffs. This was done using the field calculator tool in ArcMap to generate a new field in the point shapefile for the 2008 coastline, found by multiplying the point elevation (m) by the average annual recession rate (EPR) between 2001 and 2008 (m a^{-1}) by 10 (m), the transect spacing. Transects were selected to define the boundaries of each of the major cliff systems of Benacre, Covehithe, Easton Wood, Northend Warren, Easton Cliffs and Dunwich-Minsmere. Each cliff system was then analysed separately to derive the volumetric loss that each experienced over this period. Figure 23 shows the way these systems have been defined and the data that are relevant to the calculations. It also provides the values for the volume of cliff loss in $\text{m}^3 \text{a}^{-1}$.

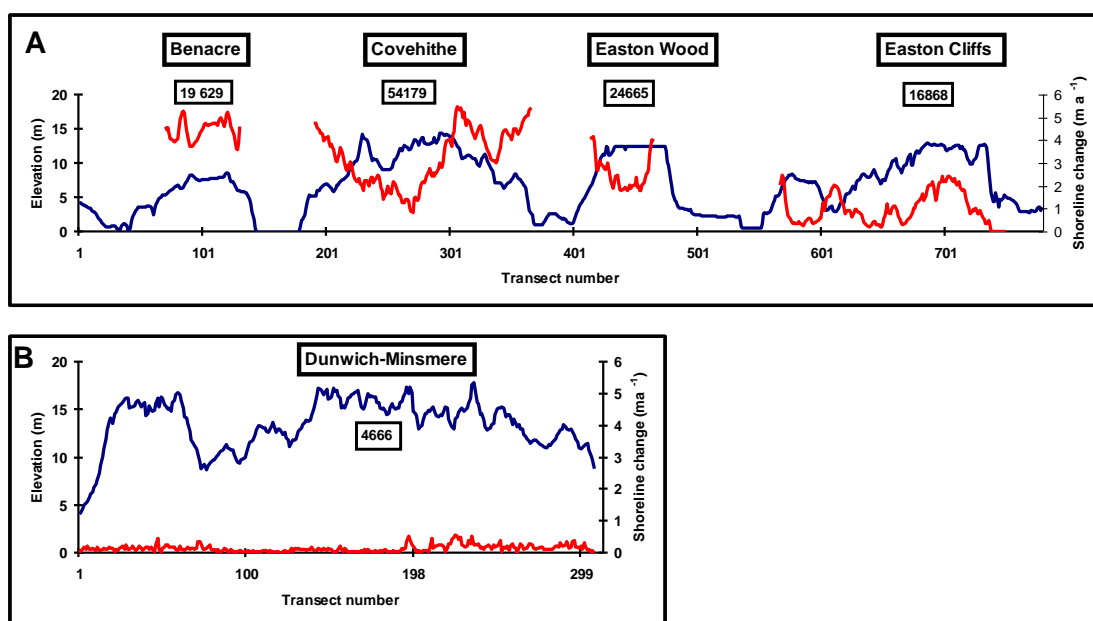


Figure 23: Calculation of volumetric loss (in boxes) for each cliff system. The blue lines provide elevations while the red lines show the shoreline recession rate (m a^{-1}) from 2001-8 for the cliffs, with the low-lying Broads being removed from the plots. Volumetric loss was calculated for each transect by multiplying shoreline recession rate (m a^{-1}) and elevation, and then multiplying by 10 (the transect spacing). The resulting volumes are shown for each cliff system in $\text{m}^3 \text{a}^{-1}$.

The total volumetric loss in the cliff systems between Benacre and Southwold for the period 2001 to 2008 was $115\,341 \text{ m}^3 \text{a}^{-1}$. This compares with just $4\,666 \text{ m}^3 \text{a}^{-1}$ in the Dunwich-Minsmere cliffs

which, despite their greater alongshore extent and higher elevation, are receding very slowly. The Covehithe cliffs are experiencing the greatest total volumetric loss at the present day and are therefore providing the largest quantity of sediment to the nearshore circulatory system. The three cliff systems of Benacre, Easton Woods and Easton Cliffs together provide an almost equivalent total, but slightly higher than Covehithe alone.

The composition of the cliff-forming material also needs to be taken into account. Data from British Geological Survey cliff face survey logs taken in May/June 1995 (Janes and Lewis, 1996) emphasises the predominantly sandy nature of the cliff sediments, being highest in the regions around Covehithe and Dunwich. Benacre and Northen Warren show a comparatively greater proportion of silt/clay while more gravel is present at Easton Wood and Minsmere. These figures are based around point locations so may not be representative of the area as a whole in these highly variable depositional environments, but a detailed study of the Covehithe cliffs undertaken in 2009 (Figure 24) confirms that throughout this 800m-long cliff section there is clear dominance of sand-sized material. Further assessment of cliff materials is ongoing but is beyond the scope of this study.

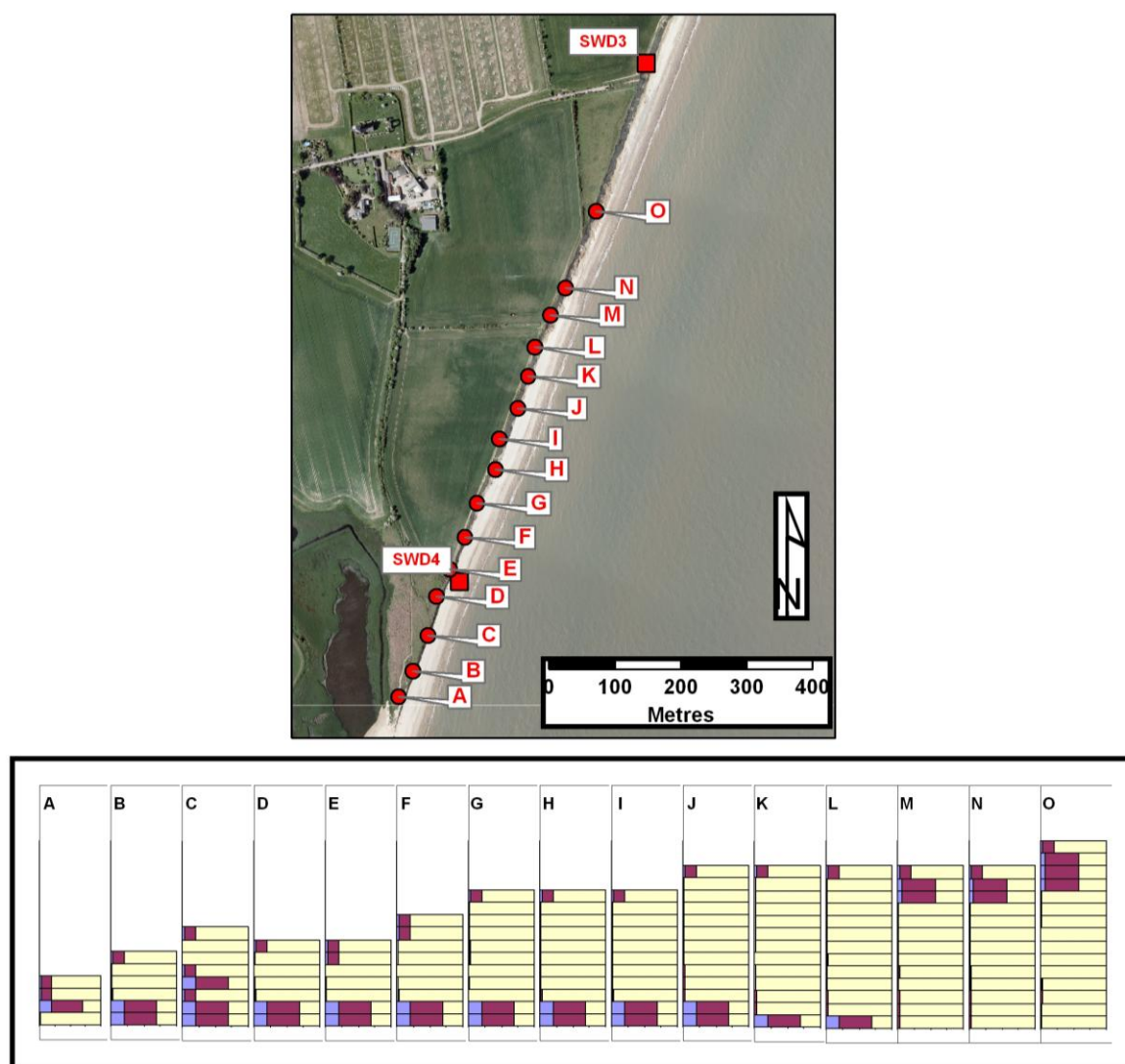


Figure 24: Locations of field sites A to O between SWD3 and SWD4 where detailed sediment sampling was carried out to assess the percentage of sand-sized material (marked in yellow), silt-sized material (marked in purple) and clay-sized material (marked in blue). Each horizontal box represents 100% and the number of boxes at each field site represents the cliff elevation (each subdivision at an individual site is 1m high).

The combination of high volumetric loss and a high proportion of sand-sized material ensures that each of these cliff systems between Benacre and Southwold potentially provides a significant sediment supply to the downdrift beaches and nearshore sandbars.

5.3 Cliff retreat and sediment release over the past two decades

As NextMap elevation data have only been available since 2001 the information on cliff topography prior to this period remains patchy and dependent largely on OS spot heights and interpolated contours. However, the DSAS analysis of contemporary coastal retreat since 1992, suggest that the period from 1992-2001 was one of considerably higher retreat rates than 2001-8. The consequences of elevated retreat rates for contemporary sediment supply were investigated further using the same methodology as described above. The 2008 shoreline was used as the base for the elevations and the higher retreat rates were used to find the associated volumetric loss, again assessing each cliff system separately. Finally, the volumetric loss for the whole period from 1992 to 2008 was assessed for comparison.

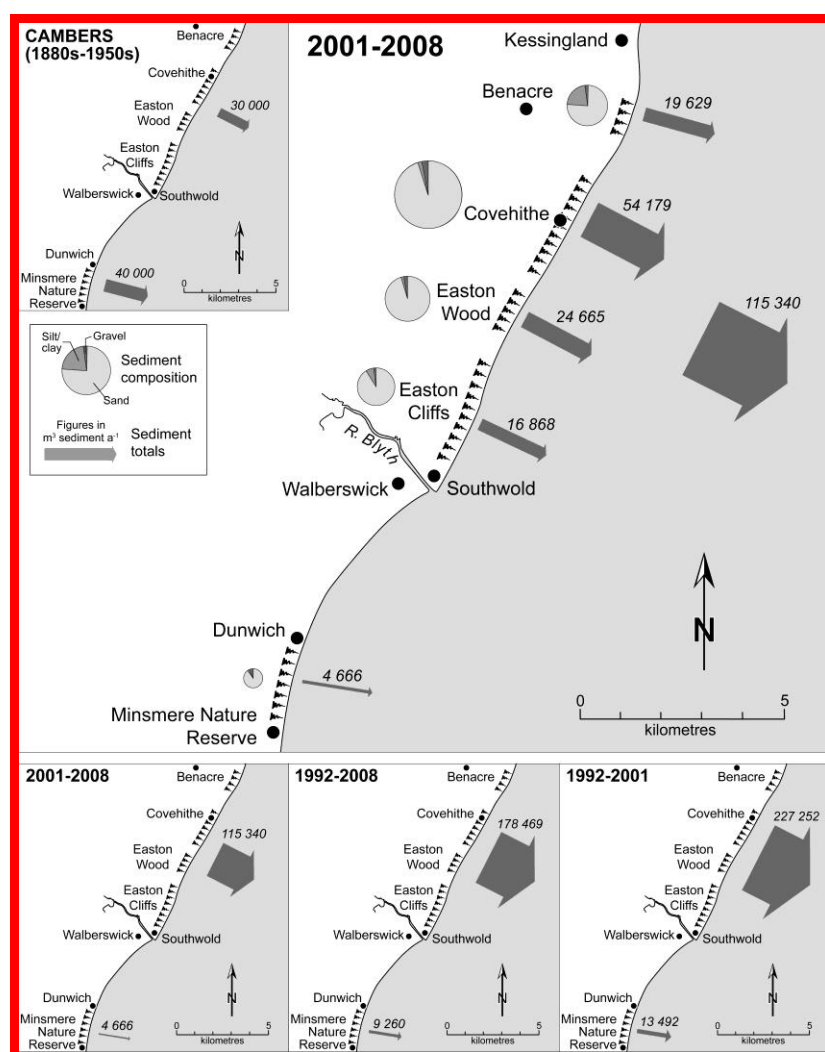


Fig 25: Reprinted from
Geomorphology, Vol 124,
1-2, Brooks, S.M. and
Spencer, T., 'Temporal
and spatial variations in
recession rates and
sediment release from
soft rock cliffs, Suffolk
coast, UK', 26-41, 2010,
with permission from
Elsevier

Figure 25: Volumetric loss ($\text{m}^3 \text{a}^{-1}$) in cliff systems along the Suffolk coast between 2001 and 2008, showing the locations of the sediment source as well as its composition and magnitude. Also shown are the equivalent data for the periods 1992-2008 and 1992-2001, the latter corresponding to a period of very high recession.

Figure 25 shows the volumetric losses for each of the cliff systems for the selected periods and suggests that considerable variability in sediment sources exists on annual-decadal timescales. On these timescales variability in retreat rate appears to be a primary control on variability in the magnitude of sediment sources alongshore. In the period 2001-2008 recession rates along this coastline were in general much lower than in the preceding period of 1992-2001 (although Section 4.3 identifies restricted locations where retreat rates were similar in the two periods as well as locations which had higher rates). The total volumetric loss from this coast almost doubles in response to changes in retreat rates, from $115\,000\text{ m}^3\text{ a}^{-1}$ (2001-2008) to $230\,000\text{ m}^3\text{ a}^{-1}$ (1992-2001). Furthermore, results for all contemporary periods analysed suggest that sediment supply is up to 4 times that of previous estimates (Cambers, 1975) even when retreat rates are in a low phase, but can be up to almost 10 times higher than previously published estimates when retreat rate is elevated. This is related to clifflines appearing and gaining elevation as the coast retreats (eg: EastonWood and Benacre), clifflines lengthening alongshore (eg: Covehithe and Northend Warren) and retreat rates increasing between 1880-1950 and 1950-2008, but particularly since 1992. The new assessment also suggests that the role of the Dunwich-Minsmere cliffs as a sediment source is comparatively insignificant relative to the cliffs to the north at the present day.

Planning decisions cannot be based simply on historic information. Up-to-date and detailed assessment is needed with a means for continual and rapid update. The methodology presented in this study, involving a combination of DSAS and Surface Spot within ArcMap, facilitates rapid reassessment of retreat rates and associated sediment sources at a detailed level. It has been used to show how the magnitude and source of the sediment supply can shift dramatically, either spatially or temporally or in both ways. This raises a number of questions over where the sediment is going, how it might be protecting sections of the coast proximal or distal from the source, and how the sediment supply inter-relates to other controls on coastal behaviour, such as waves, tides, currents and surges which can also change over short timescales. Issues such as these are examined further in Section 8.

6. Future predictions of shoreline movement and sediment release

The revised draft Shoreline Management Plan for Policy Development Zone 2 (Benacre Ness to Easton Broad) emphasises the importance of sediment supply from the retreating cliffs of this region for the maintenance of the beaches and protection of the town of Southwold, on the assumption that the sediment drift is predominantly southward. The management plan suggests areas that might be protected (and the financial cost implications of doing, and continuing to do, so) and other areas that might not be protected, sacrificially giving up sediment to allow the maintenance of the down drift beaches. A detailed assessment of the actual volumetric losses that might be involved under different future scenarios is required to inform these decisions. The new methodology in this report was applied in this capacity to assess future scenarios of shoreline change and associated sediment sources that are likely to result.

6.1 *Shoreline positions in the coming century*

It is a comparatively straightforward task to produce digitised shorelines for historic periods because there are many sources which depict actual former shoreline positions and their associated dates. However, prediction of the position of future shorelines as the coastline retreats presents potentially the greatest challenge to the assessment of future sediment sources from receding clifflines. Many models have been suggested for prediction of how shorelines respond to sea level rise and inland migration (Bruun, 1962; Bray and Hooke, 1997; Walkden and Hall, 2005; Dickson et al., 2007), but at best these only provide estimates, since none can take into account fully the interactions that exist between all controlling variables. As Addo et al. (2008) have observed, historic rates of shoreline change cannot be assumed to continue into the future since the controlling variables will change. In particular, the potential effect of sea level rise is continuously emphasised in studies of coastline recession (IPCC, 2007), but there are likely to be associated changes in wave climate, tidal and surge dynamics as well as in climatological controls, such as wind direction and rainfall characteristics. As coastlines migrate inland they potentially intersect with different geologies which may affect the mechanisms and rates of further retreat.

Three models for predicting future shoreline positions were used in this study. The first is a simple extrapolation of historical rates found from the DSAS analysis since 1882, thus spanning a

period which covers the whole of the twentieth century. The benefit of using DSAS allows a separate rate to be assigned to each closely-spaced transect, rather than making the assumption that the whole coastline will undergo change at the same rate and retreat in a simple parallel fashion. This approach can therefore take into account the potential coastline realignment, from the current NE-SW trend to a more N-S orientation that has historically characterised coastal retreat between Benacre and Southwold. However simple extrapolation of historic rates is unlikely to provide the true position of future coastlines against a background of accelerated sea level rise, estimated to be up to 6 mm a^{-1} for the coming century. This model is likely to provide the “best case” scenario, involving the least amount of coastal retreat of all the models.

The Bruun Rule (1962) has long been used in the assessment of how shorelines respond to sea level change. The rule suggests that as sea level rises the 2-D profile remains unchanging as sediment is moved from the upper shoreface and deposited offshore to maintain an equilibrium water depth. This rule has provided the basis for the historical trend analysis model of (Leatherman, 1990) and Bray and Hooke (1997) which suggests a coastal retreat rate that is in direct proportion to the acceleration in sea level rise. The historic trend analysis model was also used to predict the position of the future shoreline as this represents the maximum extent of coastal retreat likely to result from rising sea level. Hence it is thought to provide the “worst case” outcome, with the greatest amount of shoreline retreat.

Since the Bruun rule was derived and used, models have been developed that include greater complexity and a firmer process basis. One such model is the Soft Cliff And Platform Erosion (SCAPE) model (Walkden and Hall, 2005), which accounts for greater complexity in coastal systems, with abstract representations of processes operating in the nearshore zone, on the shore platform as well as within the cliff system, including basal protection from the beach (Addo et al., 2008). The study by Addo et al. (2008), predicting future shorelines along the Accra coast of Ghana, used a modified version of SCAPE where there are soft cliffs with low-volume beaches. Under such circumstances, similar to those along the stretch of the Suffolk Coast in this study, the parameterisation can be greatly simplified and a straightforward relationship between shoreline retreat and sea level rise is generated (Walkden and Dickson, 2007). This model predicts rates of shoreline recession that are intermediate between those of simple historical extrapolation and those found from using historical trend analysis.

The digitised shorelines for 1882 and 2008 were used to derive the EPR (the longterm historical retreat rate) for each alongshore transect. Each of the models described above was then used to predict the position of the shoreline for the years 2050 and 2100, assuming a doubling of sea level rise from 2 mm a^{-1} to 4 mm a^{-1} , potentially a conservative estimate for the region (Burningham and French, 2008; Pye and Blott, 2009). A total of six shorelines was thereby generated in total, 3 for each of the two years in question corresponding to each of the three predictive models. The predicted inland translation of each of these shorelines is shown in Figure 26.

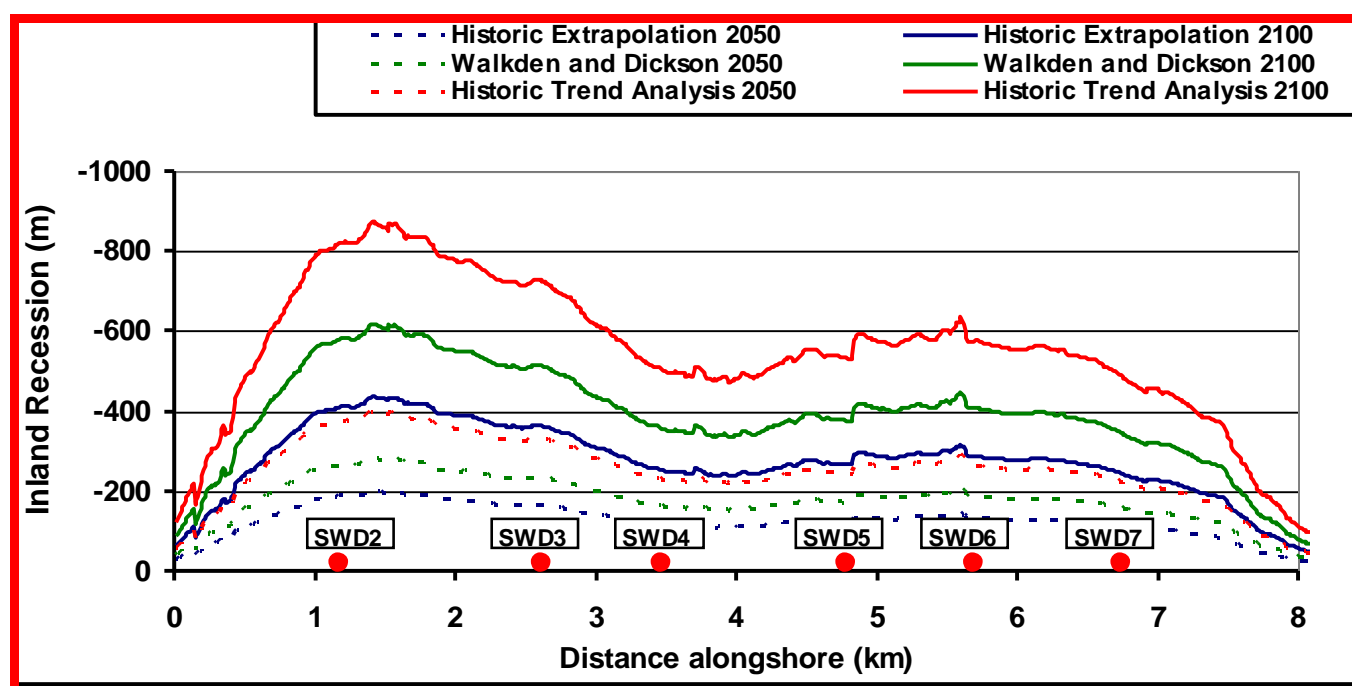


Figure 26: Inland movement of the shoreline under three predictive models for the years 2050 and 2100 for the coastline between Benacre and Southwold, involving separate predictions for each transect.

Since all models rely upon established historic rates, the position of the future coastline varies with location alongshore, with faster rates to the north of the study region. Coastal realignment is predicted under each of these models for the coming 90 years reflecting the alongshore trends in historic recession rates. Each model predicts a different degree of inland migration, spanning likely “best” and “worst” case scenarios. The coastline position in 2050 as predicted using historical trend analysis is, for example, very close to the predicted coastline in 2100 based upon simple historical extrapolation.

Table 1 summarises the inland retreat predicted for each cliff system using each of the different models of coastline response to sea level rise for the years 2050 and 2100. Also shown is the associated total land loss behind each of the clifflines. Historic extrapolation of retreat rates is associated with the smallest inland migration of the coastline and therefore the lowest loss of land area. The greatest response to accelerated sea level rise arises from the historic trend analysis model, which suggests a doubling of retreat rates and land loss in the future. However, this model may not be the most suited to retreating clifflines where processes of cliff failures and their associated controls are complex and varied, so the intermediate predictions based upon the modified SCAPE model might be the most applicable. The land loss behind the cliffline of Covehithe is predicted to be the greatest, while that associated with the Easton Wood cliff is the lowest, reflecting the different lengths of the clifflines and the associated retreat rates.

Table 1:

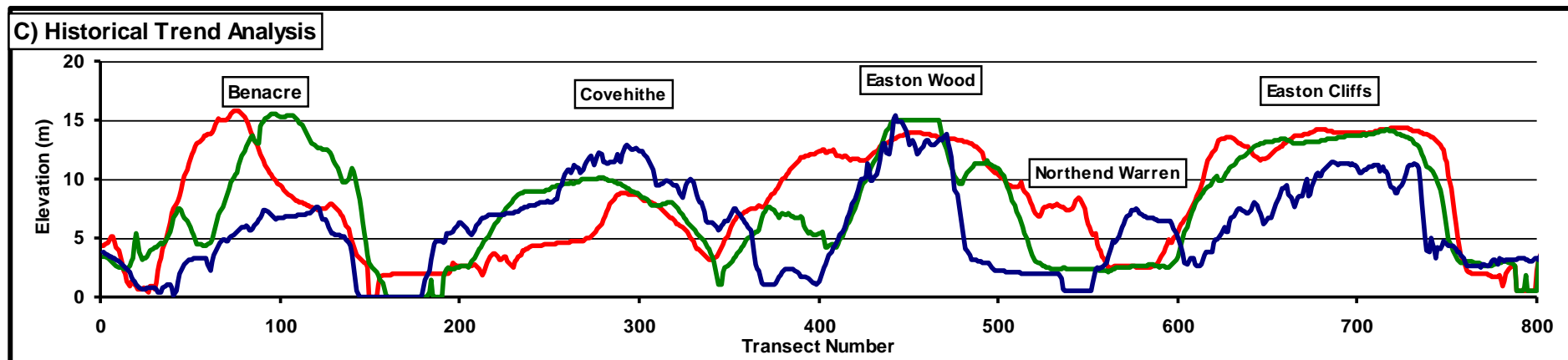
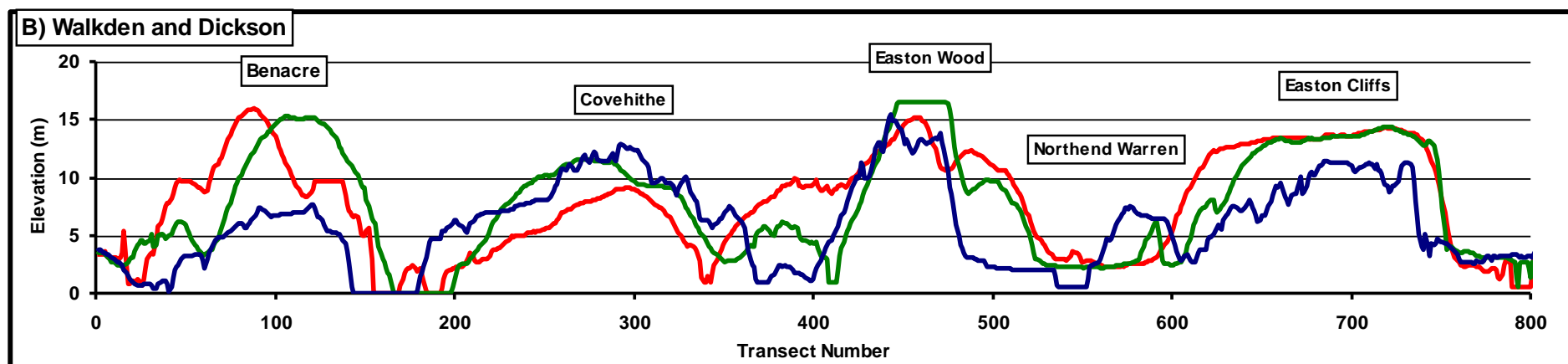
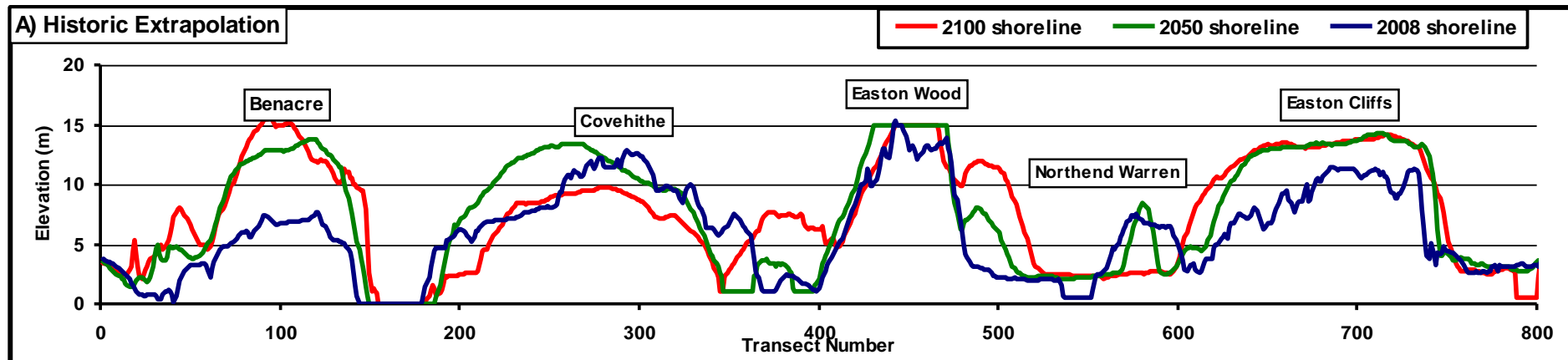
	Benacre			Covehithe			Easton Woods			Easton Bavents		
Model scanario	Predicted retreat based on 1882- 2008 (m)	Retreat rate (m a ⁻¹)	Area of land lost (m ²)	Predicted retreat based on 1882- 2008 (m)	Retreat rate (m a ⁻¹)	Area of land lost (m ²)	Predicted retreat based on 1882- 2008 (m)	Retreat rate (m a ⁻¹)	Area of land lost (m ²)	Predicted retreat based on 1882- 2008 (m)	Retreat rate (m a ⁻¹)	Area of land lost (m ²)
Historic			74			115			69			96
Extrapolation (2050)	184	4.39	431	140	3.34	962	127	3.02	481	93	2.21	872
Walkden and			106			164			97			132
Dickson (2050)	261	6.21	862	199	4.73	438	179	4.27	559	131	3.12	259
Historic Trend			149			226			134			187
Analysis (2050)	369	8.78	032	281	6.69	978	278	6.61	929	186	4.42	508
Historic			163			249			146			199
Extrapolation (2100)	404	4.39	629	308	3.35	662	278	3.02	738	203	2.21	722
Walkden and			229			358			203			282
Dickson (2100)	571	6.21	663	435	4.73	983	392	4.27	271	287	3.12	180
Historic Trend			317			503			281			394
Analysis (2100)	808	8.78	767	615	6.69	973	555	6.03	950	407	4.42	112

6.2 *Future clifflines associated with coastal retreat*

It is the combination of elevation of the retreating cliffline along with rate of retreat that determines the sediment supply to the nearshore region. While historically it is comparatively straightforward to gain an idea of the coastline position, establishing accurate elevation data in clifflines that have long since disappeared has been highly problematic for calculation of sediment release. For predictions of future sediment release, however, it is the prediction of the shoreline position that is more problematic than establishing detailed cliffline elevations. Data for land elevation in coastal and inland regions can be provided by the NextMap data set. The Surface Spot tool was used with predicted positions of future shorelines described in the previous section to generate the alongshore elevations of the future clifflines from the NextMap data.

A point shapefile was produced for each of the predicted future coastlines based upon their intersection with each of the DSAS transects projected inland, thereby generating 800 inland points along each future shoreline. The NextMap tiles tm-57 and tm-58 were used to generate both a TIN and an Inverse Distance Weighted surface. It made little difference to the elevations generated with the surface spot tool which method was used. The Surface Spot tool was then used to generate elevations at each 10m point alongshore for the predicted position in 2050 and 2100 for the three models. Where there were areas of woodland the data were cleaned to exclude elevations in excess of the regional average found from contours and OS spot heights. This was a particular problem for Easton Woods, as previously noted, but also for localised areas on the fringes of Benacre Broad (both to the north and the south).

Figure 27: (overleaf) Predicted future clifflines for each of the different models of shoreline prediction. (A) represents the least rate of inland recession under the historic extrapolation model; (B) represents the clifflines under the Walkden and Dickson model; (C) depicts the clifflines for the furthest inland retreat under the historic trend analysis model. Also shown on each figure is the 2008 cliffline for comparison.



The main issues to note are as follows. Firstly, the cliffs of Benacre will more than double in elevation over the coming century, with elevations of around 15m being attained by 2050. There will also be an increase in alongshore extent of this cliffline both to the north and to the south. By 2100 there will be a cliffline of almost 1 km in alongshore extent reaching elevations in excess of 15m, which is the highest elevation currently found along this coastline. Secondly, by contrast, the cliffline around Covehithe will increase in elevation until 2050 in its northern section. Thereafter elevations fall to less than their present values, with the 2100 cliffline being much more restricted in alongshore extent as well as attaining lower elevations. Thirdly, the cliffs of Easton Wood are likely to extend significantly alongshore both to the north and south, particularly between 2050 and 2100. The elevation data are hard to use for this location as they are influenced by the presence of woodland, but cliff elevations do not appear to be changing significantly, even though the length of the cliffline looks to be changing significantly. The area of Covehithe Broad is likely to disappear, with the low-lying ground being replaced by an area of 6m high cliffs by 2100. Fourthly, the small cliffline currently seen at Northend Warren will disappear completely as the coastline retreats. Finally, the Easton Cliffs will remain approximately at their current alongshore extent but will gain about 4m of elevation by 2050 after which there will be little further change.

The models of Walkden and Dickson (Figure 27 (b)) and Historic Trend Analysis (Figure 27 (c)) illustrate what will happen under more extreme scenarios of coastal recession where inland migration of the shoreline is much greater, as discussed in the previous section. The longterm evolution of the Benacre cliffs seems to suggest the attainment and maintenance of 15m elevation, with a migration alongshore northwards of the position of the highest cliffs. Here the future cliffline is significantly different from 2008. The evolution of the cliffs at Covehithe is towards lower elevations of under 10m, with a restriction of their alongshore extent. The cliffs of Easton Wood are predicted to expand significantly to the north and to the south removing Covehithe Broad entirely and significantly reducing the alongshore extent of Easton Broad to the south. Elevations will not change significantly here. All scenarios suggest the removal of the Northend Warren cliffs sometime around 2050, depending upon which predictive model is employed. Finally, the Easton Cliffs will attain greater elevations and alongshore extent by 2050, after which they appear to undergo little further change.

6.3 *Sediment release from the retreating coastline of Benacre-Southwold*

Determining future volumetric loss in the cliff systems was carried out at two temporal scales. Firstly an overall picture was developed of the entire volumetric loss likely to be experienced under each of the different shoreline response models from 2008 to the years 2050 and 2100 AD. A polygon was generated for each cliff system at Benacre, Covehithe, Easton Wood and Easton Cliffs (including Northend Warren). The polygon boundaries were the coastline position in 2008, along with each of the predicted future shorelines for 2050 and 2100, with the northern and southern limits based upon transects at the ends of the cliff lines. This generated a total of 6 polygons for each cliff system. The elevation distribution was derived from the NextMap tiles using the clip tool and the resulting TIN's were generated within ArcMap. The TINs for each shoreline position between SWD3 and SWD4 (Covehithe) are shown in figure 28.

From Figure 28 the greater inland migration associated with the 2100 shoreline is apparent for each of the shoreline predictive models. Each model also generates a different extent of inland movement that is also apparent from the figure. Associated with these different inland movements will be variation in the volumetric loss. This was approximated as the volume above 0 m OD for each of the cliff systems and the results are reported in Table 2.

	Benacre				Covehithe			
Model scenario	Predicted retreat based on 1883-2008 (m)	Retreat rate (m/y)	Area of land lost (m ²)	Cliff Volume loss (m ³)	Predicted retreat based on 1883-2008 (m)	Retreat rate (m/y)	Area of land lost (m ²)	Cliff Volume loss (m ³)
Historic Extrapolation (2050)	184	4.39	74431	782146	140	3.34	115962	1330354
Walkden and Dickson (2050)	261	6.21	106862	1250664	199	4.73	164438	1820708
Historic Trend Analysis (2050)	369	8.78	149032	1831924	281	6.69	226978	2403106
Historic Extrapolation (2100)	404	4.39	163629	2033166	308	3.35	249662	2597653
Walkden and Dickson (2100)	571	6.21	229663	2857700	435	4.73	358983	3456303
Historic Trend Analysis (2100)	808	8.78	317767	3727792	615	6.69	503973	4498895
	Easton Woods				Easton Bavents			
Model scenario	Predicted retreat based on 1883-2008 (m)	Retreat rate (m/y)	Area of land lost (m ²)	Cliff Volume loss (m ³)	Predicted retreat based on 1883-2008 (m)	Retreat rate (m/y)	Area of land lost (m ²)	Cliff Volume loss (m ³)
Historic Extrapolation (2050)	127	3.02	69481	827231	93	2.21	96872	1092253
Walkden and Dickson (2050)	179	4.27	97559	1182903	131	3.12	132259	1567691
Historic Trend Analysis (2050)	278	6.61	134929	1660471	186	4.42	187508	2302383
Historic Extrapolation (2100)	278	3.02	146738	1813968	203	2.21	199722	2475945
Walkden and Dickson (2100)	392	4.27	203271	2542019	287	3.12	282180	3610724
Historic Trend Analysis (2100)	555	6.03	281950	3662791	407	4.42	394112	5134437

Table 2: Predicted coastline retreat for three shoreline response models, based upon historic retreat rates (sea level rise assumed to increase from 2 mm a⁻¹ to 4 mm a⁻¹). Also shown are associated losses of land and volumetric loss in the cliffs.

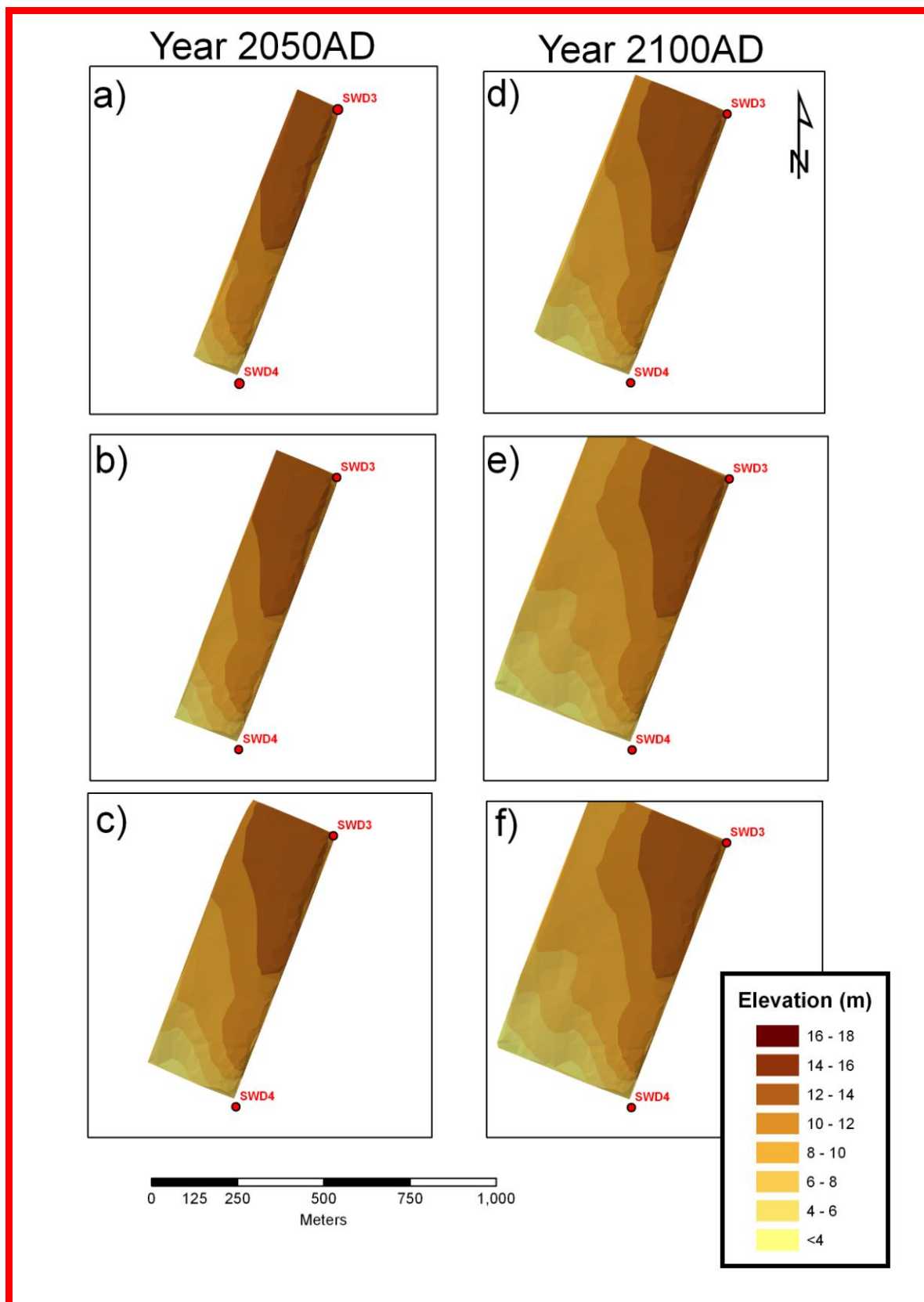


Figure 28: Triangular Irregular Networks (TINs) for the cliffs between SWD3 and SWD4 at Covehithe showing elevation distributions (derived from NextMap data).

Table 2 provides an overall total volume for the periods 2008-2050 as well as 2008-2100.

However, it is possible to refine these estimates over shorter time periods using the Surface Spot tool to extract alongshore cliff elevations (shown in Figure 27) and combining this with retreat rate for each transect generated within DSAS. This was done for each of the three shoreline response models and the volumetric loss in each cliff system was calculated for the years 2050 and 2100. In this way, estimates of future temporal variation in sediment loss can be derived.

The 2008 shoreline was used as a basis for comparison of future volumetric losses with those of the present day. Three estimates of volumetric loss were derived for 2008, representing the three different retreat rates associated with each shoreline response model. These were then compared with the likely volumetric loss in 2050 and 2100. The results are reported in Table 3 and illustrated in Figure 29.

	2008			2050			2100		
	2008	WD	HTA	2050	WD	HTA	2100	WD	HTA
Benacre	21,286	30,103	42,572	42,928	73,262	97,077	48,579	46,747	81,113
Covehithe	54,923	77,673	109,846	61,582	66,412	87,284	42,350	33,192	61,377
Easton Wood	33,806	47,809	67,613	41,042	67,880	99,933	51,389	57,559	132,907
Easton Cliffs	36,680	54,317	76,816	49,490	68,209	99,164	49,927	52,605	107,081

Table 3: Current (2008) and future (2050 and 2100) volumetric loss ($\text{m}^3 \text{a}^{-1}$) in the cliff systems between Benacre and Southwold.

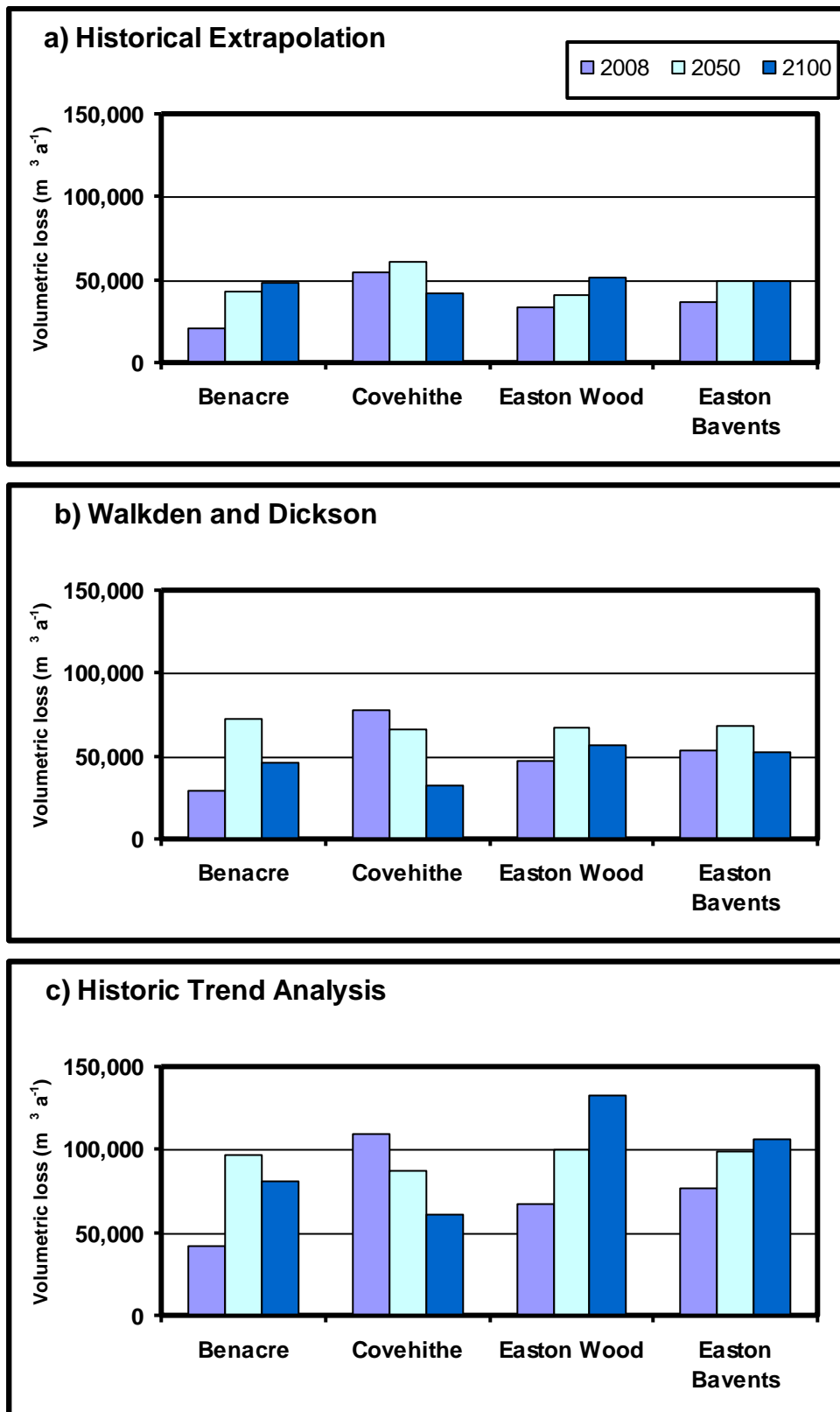


Figure 28: Comparison of present (2008) and future (2050 and 2100) cliff volumetric loss under the three models of shoreline response for each cliff system.

In 2008 the largest contributor to sediment release was the cliff system at Covehithe, as shown previously. Somewhat lower volumes typified the Easton Cliffs and those at Easton Wood, with Benacre being the least significant. This position remains the same for all recession rates that apply to each of the different models of shoreline response to sea level rise. For example, at Covehithe using historic retreat rates combined with 2008 elevations produced a volumetric loss of $54\,923\text{ m}^3\text{ a}^{-1}$, while the higher retreat rate of the Historic Trend Analysis model leads to a doubling of the volume to $109\,846\text{ m}^3\text{ a}^{-1}$. A difficult issue that cannot be accommodated in the analysis is the potential lag between any acceleration in sea level rise and the resulting shoreline response. Hence the figures are indicative rather than absolute and provide the basis for a comparative assessment of the cliffs as future sediment sources.

New cliff elevations resulting from future inland positions of the shoreline will change the volumes of material being released from the cliffs, determined by elevation gain or loss combined with the lengthening or shortening of the cliffline. The likely trends are shown in Figure 29. Taking the situation in 2050, the cliffs of Benacre show the greatest increase, reflecting both the increasing elevation and the alongshore growth of this cliff system. Sediment release is predicted to be around twice that of the 2008 levels for all models of shoreline response. There will be a greater increase in sediment release in the cliffs of Benacre between the present day and 2050 than there will be between 2050 and 2100. Between 2050 and 2100 the cliffline becomes slightly more restricted in both alongshore extent and elevation, particularly to the south of Benacre compared with 2008 to 2050. The cliffs of Benacre represent a system that is currently active (“switching on”) and will continue to grow in significance as a sediment source in the absence of management intervention.

The cliffs of Covehithe have provided the historical focus for sediment release, due to a combination of rapid retreat and relatively high elevation in these cliffs. This high sediment release appears to be continuing in the present day, as evidenced by the 2008 figures, but the future situation is somewhat different. As this section of coastline retreats the sediment release will “shut down” to a large extent such that by 2100 these cliffs will be contributing the least sediment of all the cliff systems. Depending on which model of shoreline response is chosen, this could even be the case by 2050, as evidenced by the historical trend analysis model. By 2100 sediment release will be approximately half of the current levels for these cliffs.

While the cliffs of Benacre are likely to undergo the biggest increase in volumetric loss to 2050, it is the cliffline at Easton Wood that is appears to show the largest increase thereafter. By 2100 the cliffs of Easton Wood are predicted to become the largest contributor to sediment release, due to their expansion northward towards the present-day cliffs at Covehithe. This process will be accompanied by the loss of Covehithe Broad.

The Easton Cliffs, while having high contemporary sediment release due to a greater elevation and alongshore extent compared with the other cliff systems, show the least departure from current levels as the cliffline retreats inland. The increase in elevation along the Easton Cliffs combined with the total loss of the cliffs at Northend Warren offset each other to make this cliffline relatively stable in terms of sediment release as it retreats inland.

Discussion of issues related to the management of this stretch of coastline will benefit from such detailed spatial and temporal information, with the combination of shoreline response and surface spot elevation extraction now possible at an unprecedented level of detail. This report has highlighted and developed a new methodology that could be of considerable benefit to coastal management decision-making. It permits the calculation of volumetric loss and sediment release in cliff systems before an intervention is planned. In situations where coastlines are retreating very rapidly, the ones that are likely to present the greatest challenges to management, the methodology presented here could readily be extended to include greater temporal detail, perhaps at temporal intervals of 5 or 10 years. Topographic variation of retreating shorelines has been shown to be highly significant to sediment sources. Assessment using the DSAS transects combined with different models of shoreline retreat and the surface spot tool allows instantaneous alongshore release of sediment to be estimated over short periods as the shoreline retreats.

7. Bathymetric change over historic timescales

The changing nearshore bathymetry of the region between Benacre Ness (in the north) and the Sizewell-Dunwich Bank (in the south) has not previously been studied. The purpose of the bathymetric assessment in this study is to link it to shoreline change in a rapidly retreating setting. The nearshore region has become progressively part of the southern North Sea basin (around 500m since 1883), which might potentially have involved a progressively deepening nearshore basin or sandbank development and change. The sediment quantities released from the combination of eroding cliffs and associated bathymetric change may be contributing to the Sizewell-Dunwich Bank, as suggested by Carr (1979) and mentioned recently by Pye and Blott (2009) and/or may be assisting in the development of the region around Benacre Ness, as implied by McCave (1978). Recent publications assume a general southerly drift of sediment in the region but it is not proven and the possibility for sediment movement both northward and southward is not widely discussed. Few studies consider the interplay between the retreating shoreline and the deepening seabed (but see Newsham et al., 2002 for the Holderness Cliffs), although it is thought to be quantitatively significant to sediment sources and sinks in the region (Carr, 1981).

An important issue for assessing sediment budgets in rapidly-changing coastal settings is the accompanying dynamic in the nearshore bathymetry. This study also sought to assess bathymetric change for this stretch of coastline between Benacre Ness and Southwold, since this has not previously been attempted and no information exists on how the nearshore bathymetry of this dynamic coastline has changed historically. Several data sources were available for this part of the study, outlined in section 3 but focussing on Admiralty Charts supplied through the National Maritime Museum at Greenwich and bathymetric soundings supplied by the Environment Agency.

7.1 *Contemporary nearshore bathymetry between Benacre and Southwold*

The two main sources available for this study of contemporary bathymetry were the most recently available Admiralty Chart and the bathymetric surveys conducted by the Environment Agency as part of their SDMS programme, at 1 km spatial intervals and 5 year time intervals. The most recently available Admiralty Chart was published in 2005 by the United Kingdom

Hydrographic Office including surveys taken up to 2004. However for the stretch of coastline of concern here, the most recent surveys were carried out by the British Government at a scale of 1:25 000 for the period 1981-1987. This survey information also appears on previously published charts, and the revised 12th edition of chart 1543 published in December 1998 (originally published in 1974) contains the surveys from 1981-1987 for the region. This chart was made available through the National Maritime Museum Library at Greenwich as a scanned TIFF at 300dpi. The section of the chart between Benacre and Southwold was georeferenced within ArcMap, using ground control points in near-coastal locations that could clearly be observed on both the chart itself and on georeferenced aerial photographs and Ordnance Survey maps discussed earlier in this report.

Depth contours and soundings were then digitised manually from the georeferenced image. The chart datum for the surveys between 1981 and 1987 was Lowest Astronomical Tide (LAT) with soundings provided in metres. Hence the depths were corrected to OD Newlyn. As described in section 3.5, LAT varies spatially, being further below OD Newlyn in the north of the region. While Burningham and French (2009) adopted a trend surface analysis to overcome this effect, the difference in LAT between Benacre and Southwold of just 10cm was not felt to be sufficient to require this correction. Hence all depths were corrected to a chart datum (LAT) of -1.4m OD.

The 1981-1987 bathymetry is shown in Figure 29. The red line marks shoreline position in 1883 as digitised using MHWS described above. Shallower nearshore regions to the north and south of the study area are evident, consistent with previous bathymetric assessments (Horillo-Caraballo and Reeve, 2008; Pye and Blott, 2009). This study area is typified by a comparatively steep offshore gradient, with depths of 10m being attained at around 2km offshore. The rapid retreat in this stretch of coastline appears to have resulted in the 1883 shoreline position coinciding in places with 1981 water depths of up to 6m.

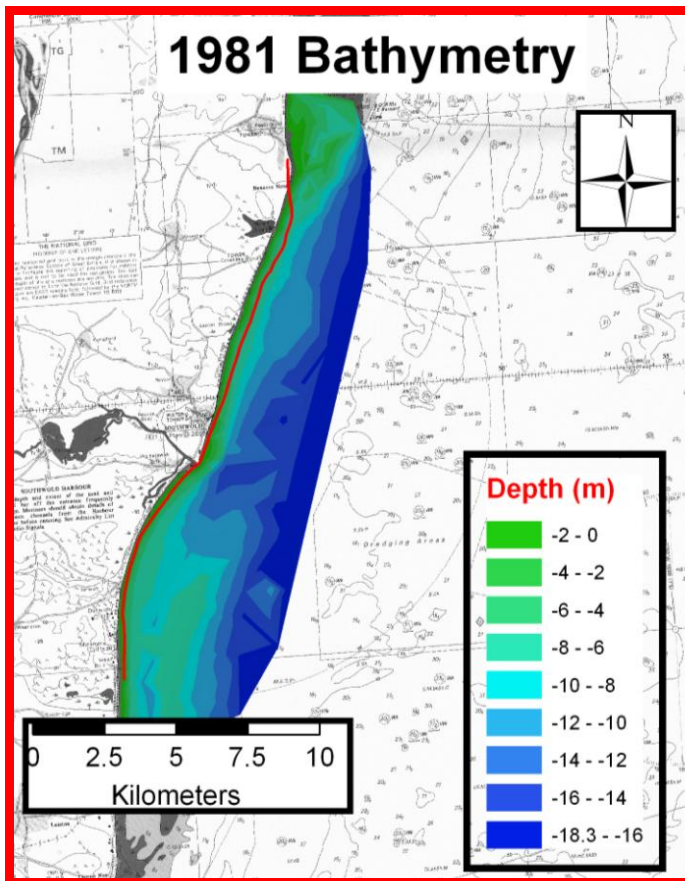
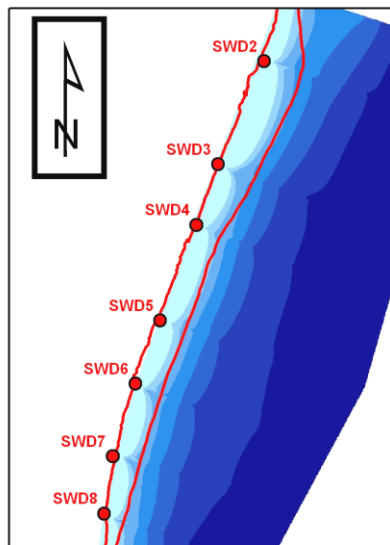


Figure 29: Bathymetry of the study site based upon digitised soundings taken between 1981 and 1987 and published on Admiralty Chart 1543 (2005).

Bathymetric data are also available for the region from recent Environment Agency surveys. These are shown in Figure 30 for two selected years of 1992 and 2007. To produce these figures the raw data were read into ArcMap as a series of profiles at 1 km spacing from SWD2 to SWD8, a point shapefile was created and then used in an interpolation based upon nearest neighbour analysis to produce a 10m x 10m raster grid of depths. The depths are depicted at 2m depth intervals and the position of the shorelines in 1883 and 2008 are also shown. The effect of using linear profile data with a concentration of points at specific locations is clear but there is consistency between the bathymetry generated from the EA profiles and the Admiralty Charts. For the Environment Agency data the 1883 shoreline again follows the approximate position of the current -6m water depth contour becoming rather deeper to the north of the study site.

1992 Bathymetry



2007 Bathymetry

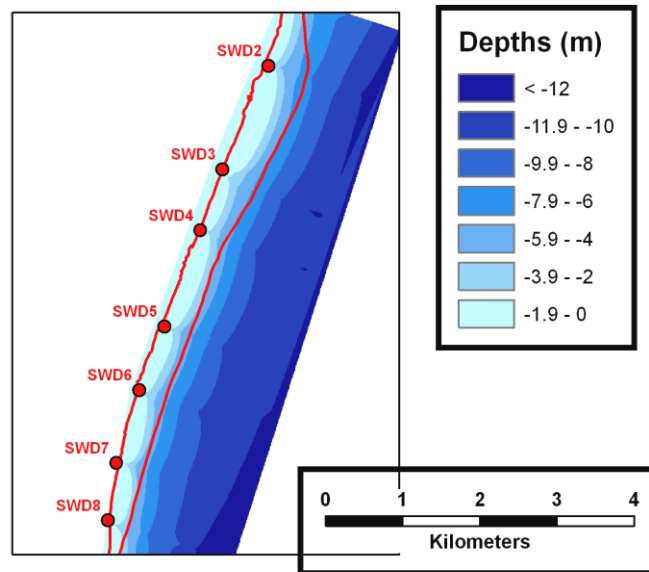


Figure 30: Bathymetry generated using Environment Agency soundings taken at the SDMS study sites at 1km alongshore spacings for 1992 and 2007.

The time periods of 1981-1987, 1992 and 2007 have been presented at different spatial scales, with the Environment Agency data providing a more detailed, if spatially discontinuous bathymetry for the study site. The surface spot tool was used in conjunction with the 1883 shoreline to extract depths for every transect generated within DSAS. This enabled comparison of contemporary bathymetry between SWD2 and SWD8 and provided a more detailed picture of depths along the former 1883 shoreline. The results are shown in Figure 31.

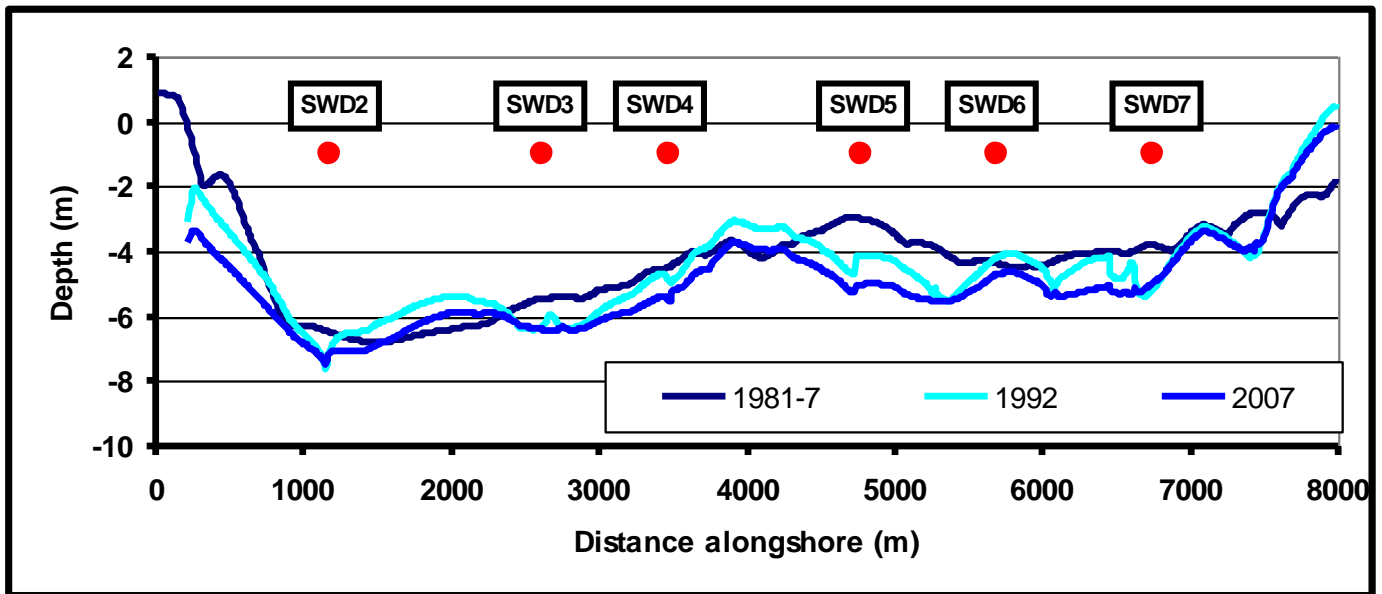


Figure 31: Alongshore seabed depths between Environment Agency profiles SWD2 and SWD8 following the position of the 1883 coastline (representing linear bathymetric change over the past 125 years).

In general the nearshore bathymetry is very similar from all three plots. Any differences, such as those in the vicinity of SWD5, cannot be ascribed to temporal evolution on this timescale, spanning just 30 years, since they might equally arise from differences in methodological approach between the use of Admiralty Charts for the 1980s and the Environment Agency field data from 1992 and 2007. However, the general trend appears to be similar on all plots with the area to the north of SWD2 sloping upwards as Benacre Ness is approached. Here it is known that the coastline is changing rapidly as Benacre Ness moves northwards, and in 1981 there appears to be a significant region of ground above 0 m OD, marking the southernmost end of the Ness. Over time there does appear to have been a deepening in the seabed in this region. From SWD2 to SWD4 the seabed gradually rises from the lowest point around -6m in the immediate vicinity of SWD2 to become about -4m at SWD4. Further progression southward is accompanied by near-continuous depths of between -5 and -4m. On reaching the southernmost location, SWD7 there does appear to be a recent decrease in water depth to the south which may be “real” or be a reflection of the methodological approach and data source.

7.2 Historical nearshore bathymetry

To investigate evolution of the nearshore seabed over the region as a whole, longer timescales need to be considered. The oldest Admiralty Chart available that enables consistent georeferencing against modern charts and control points, dates from 1872. The Admiralty Chart from Pakefield Gateway to Orfordness was originally published in 1868 but with large corrections included on the 1872 publication, just 4 years later. The bathymetry derived from the georeferenced and digitised scan is shown in Figure 32.

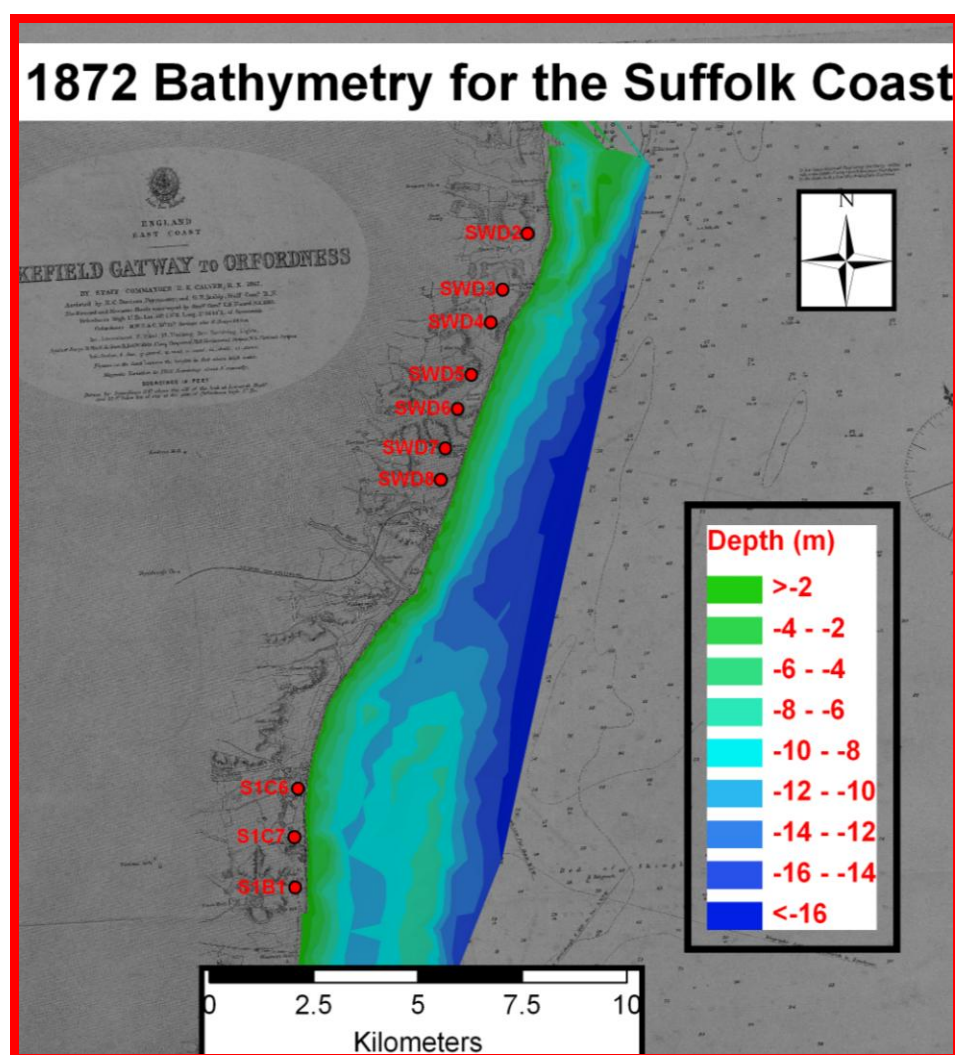


Figure 32: The bathymetry of the study region in 1872 (source: Admiralty Chart 1867, Pakefield Gateway to Orfordness, published 1872)

Again in 1872, steep offshore gradients characterise much of the central part of the study site when compared with areas to the north and the south. To the north the Covehithe Channel is a

clear feature that separates Benacre Ness from the mainland. This channel reaches depths of up to 8m and extends southward to the region just offshore from the EA SDMS SWD3. The immediate offshore region fronting SWD2 is comparatively shallow, with water depths of less than 2m and even offshore from SWD3 and SWD4 the water depths are shallow for some distance seaward. It is the region southward from site SWD5 that contains the steepest seabed gradients. At that time, in 1872, there were no cliffs at SWD5 as this report has earlier discussed. Since 1883 the cliffs of SWD7-SWD8, Easton Cliffs, have had recession rates that have declined from their highest level between 1882 and 1903, when median rates were around 3.5 m a^{-1} . In contrast the cliff recession rates at Covehithe (SWD3 and SWD4) between 1882 and 1903 were in the region of 3 m a^{-1} , slightly lower than further south, but have undergone considerable increases since that time. Contemporary rates of coastal recession between SWD7 and SWD8 are around 2.4 m a^{-1} while those at SWD3 are twice that at 5 m a^{-1} . From these data it appears that the development of steeper bathymetric gradients might be associated with faster rates of shoreline recession. This can be further investigated by direct comparison of the 1872 and 1980 seabed.

7.3 *Bathymetric changes over historical times*

In the north of the study region there has been considerable change in shoreline position (MHWS) which potentially has been accompanied by significant bathymetric change. The observations based on mean high water spring tide level (MHWS) present a picture of how Benacre Ness has migrated, exposing the cliffs to the south. The 1947 Ordnance Survey shoreline data published on the 1957 map show that the region around Benacre was fully protected by the southern end of the Ness (The Denes), a low-lying region, and there was no cliffline present at this time. By the time of publication of the 1983 Ordnance Survey map the southern end of the Ness was some 400m to the north, representing a migration rate of around 12 m a^{-1} . Others have placed this rate higher (Babtie and Birkbeck College, 2000) but around the same order of magnitude. On the 1983 map there was a cliffline stretching 200m alongshore, about 90m seaward of the present location of SWD2 and in 2008 that cliffline had extended to 800m.

At the same time recession in the cliffs of Dunwich-Minsmere has slowed from rates of up to 2 m a^{-1} to rate of around 0.5 m a^{-1} . This has been linked with growth and northward extension of the Dunwich-Sizewell bank system.

Figure 33 plots the 3-dimensional bathymetry in 1980 and in 1872 with the SDMS monitoring sites for reference, based upon the two Admiralty Charts used in the previous sections of this report. In 1872 the immediate offshore region around SWD2 was significantly shallower and even as far south as SWD3/4 the protective effect of the shallow bathymetry is evident. On moving further south there is greater exposure of the cliffline with a basin greater than 10m deep being evident southward of SWD8 on the 1872 bathymetry. Further to the south again, the cliffline of Dunwich-Minsmere does have shallower offshore depths, with the bank system being evident at this time.

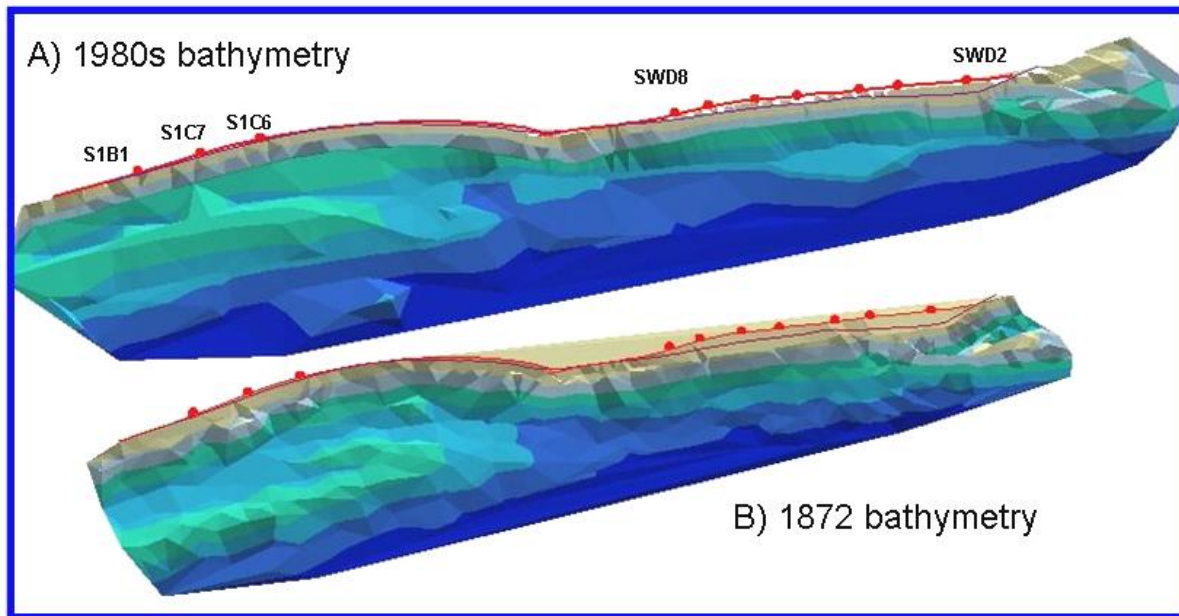


Figure 33: Regional bathymetry in 1872 and 1980s.

The 1980 bathymetry suggests there are 4 main changes in the bathymetry since 1872. Firstly, the near and offshore region in the north of the study site appears significantly steeper and deeper associated with the migration of Benacre Ness. Secondly the nearshore zone of the central region between SWD4 and SWD7 also appears to be deepening but to a somewhat lesser extent. Thirdly, south of SWD8 the basin evident in 1872 appears to be filling in and shallowing. Finally, the Dunwich-Sizewell Bank in the south appears to be growing northward and filling in landward, as noted in previous published studies.

These four bathymetric changes are more evident on Figure 34. Using the Tin_Diff tool in Arcmap the overlaid TINs from 1872 and 1980 were compared and the difference in elevation calculated across the surface. This makes changes easier to identify than simply comparing the two bathymetries separately and reveals a fifth observation that there appears to be shallowing occurring at around 2-3 km offshore through the region, particularly evident offshore from SWD2 to SWD8.

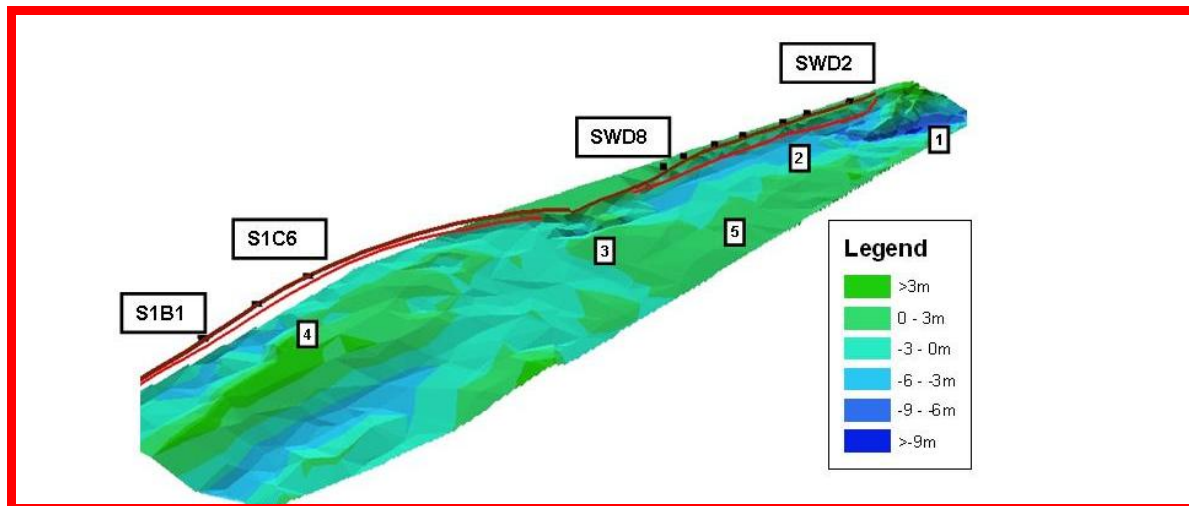


Figure 34: Bathymetric change 1872 - 1980's with 5 main areas of change indicated as follows:

- 1 = more than 9m of seabed deepening to the south of Benacre Ness
- 2 = between 3 and 6m of seabed deepening offshore from cliffs of Covehithe and Easton Wood
- 3 = up to 3m of seabed shallowing offshore from Southwold to Walberswick
- 4 = in excess of 3m of seabed shallowing on the Dunwich-Sizewell Bank
- 5 = offshore seabed shallowing between Benacre and Walberswick

Potentially the most significant change in the nearshore bathymetry off the Suffolk coast in the past century is a deepening of between 3 and 9 m located in the regions of SWD2 and SWD3. Admiralty Charts from the 1930s and 1960s were also georeferenced and digitised, with depths being converted to OD Nelwyn, to generate a more detailed temporal picture of changing bathymetry. The 1883 coastline was used as a baseline to generate points at 10 m intervals alongshore, following the DSAS transects, and the surface spot tool provided depths at each point. The results are shown in Figure 35 and indicate that on a decadal timescale, potentially the most detailed timescale possible for assessment of bathymetric change, the deepening of the sea

bed between SWD2 and SWD4 has been continuous since 1872, associated with shoreline retreat and the northward migration of Benacre Ness.

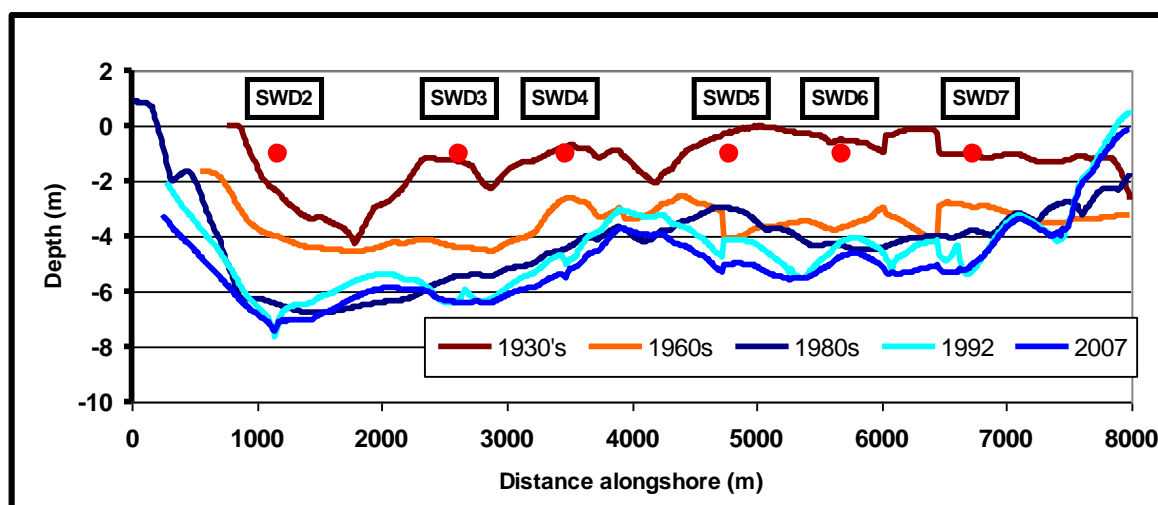


Figure 35: Depths associated with the position of the former 1883 shoreline on the 1930s, 1960s, 1980s, 1992 and 2007.

8. Discussion and conclusions

The methodology introduced in this study has involved initial assemblage of a large database for the rapidly retreating coastal region of Suffolk, for the past 125 years. The database has included historic Ordnance Survey maps, Admiralty Charts, aerial photographs (historic and contemporary), detailed elevation data as well as ground and bathymetric surveys for the period since 1992. In association with a recently developed GIS capability for assessing shoreline change at an unprecedented level of spatial detail (the Digital Shoreline Analysis System) it has been possible to elucidate several aspects of coastline change for the region. Firstly, detailed assessment of shoreline movement (generally retreat is involved for this region) has been possible, broken down into decadal time intervals. This has revealed that the region between Environment Agency profiles SWD2 and SWD8 has been retreating rapidly historically and appears to be undergoing an increase in retreat rate currently comparable with historic rates, especially to the north of the region. To the south the cliffs of Dunwich-Minsmere appear to be “switching off”.

Detailed assessment utilised the less ambiguous shoreline marker, the cliffline, and not the line of MHWS. This has revealed considerable dynamism in cliff location and alongshore extent that arises from shoreline retreat. Clifflines appear and disappear over comparatively short timescales, as shown by the emerging cliffs of Benacre in recent times and the cliffs of Easton Woods since 1903. Clifflines elongate and contract, exemplified by the Covehithe cliffs over the past 125 years. Associated changes in elevation have traditionally been difficult to quantify but since the development of Interferometric Synthetic Aperture Radar (IfSAR) technology and its application in the region in 2001 there is now the possibility for rapid assessment of the elevation of changing clifflines at an unprecedented level of spatial resolution (5 m horizontal) and vertical accuracy ($\pm 70\text{cm}$ for “open field” terrain).

The ability to extract elevation data at high spatial resolution (10 m in this study) along clifflines using the surface spot facility, and to combine this with retreat rates taken at the same spatial reference locations produces highly detailed and accurate estimates for contemporary volumetric loss as cliffs migrate inland. Previous studies have not had access to such a level of depth and detail in their analysis and the application of the new methodology of combining DSAS and ArcMap Surface Spot in estimates of potential sediment yield enables both the changing location and quantity of the sediment source to be defined accurately. The resulting data suggest that previous estimates of sediment yield from this particular study region are an underestimate. The results also show the significant temporal changes in sediment output that can occur in the location and quantity of the sediment source over time periods of just a few years. Along the Suffolk coast between Benacre and Southwold the cliff loss has halved, from $200\,000\text{ m}^3\text{ a}^{-1}$ (1992-2001) to $100\,000\text{ m}^3\text{ a}^{-1}$ (2001-2008) as the coastline has retreated. Previous estimates of sediment output in the region provided figures of around $30\,000\text{ m}^3\text{ a}^{-1}$ and these data have prevailed in shoreline reports for over 35 years since they were first derived. In the southern part of the study site, by contrast, there appears to be an almost total closure of the sediment source from earlier estimates of $40\,000\text{ m}^3\text{ a}^{-1}$ (18802-1950s) to anything between 4 and $14\,000\text{ m}^3\text{ a}^{-1}$ (1992-2008), almost an order of magnitude lower.

The methodology has been used here to assess future scenarios of sediment sources where reliable estimates can be rapidly generated from the superimposition of future shorelines on the Digital Elevation Models derived from IfSAR data. The changing elevation and alongshore extent

of the cliffline is thereby included directly in these estimates and it is possible to predict where the sediment is likely to be derived from in future. The main uncertainty in these estimates arises from the difficulty of predicting the position of future shorelines. Algorithms were derived for three different models that predict shoreline response to future sea level rise, representing the most and least conservative shoreline responses, as well as an intermediate response. This was for a doubling of the rate of sea level rise in the region from 2 mm a^{-1} to 4 mm a^{-1} . The algorithms were used to predict the x-y co-ordinates of the shoreline at 10 m intervals alongshore, based upon the DSAS transects, for the years 2050 and 2100 under the different shoreline response models. The results suggest that the cliffs of Benacre and Easton Wood are the most significant contributors in terms of future sediment yields, while the currently important location of Covehithe will diminish in significance. The Easton Cliffs will continue much as they are today and have been historically. The methodology can be used to inform decisions concerning the management of this vulnerable stretch of coastline, since it can generate information on the consequences for sediment release before the management plan is implemented.

The rate of coastal retreat is a result of many different controls and past publications have linked deceleration in cliffline retreat with growth of nearshore bank systems (Pye and Blott, 2006). That study provided a far greater detail on the southern part of the Suffolk coast than the current study but this report extends the analysis further to the north to cover a region not historically associated with the development of bank systems. It is also a region that has attracted less interest. Bathymetric assessment presented in this report indicates that the region to the north is associated with a combination of nearshore deepening and high rates of coastal retreat. Results also suggest that the highest rates of shoreline change are associated with the greatest bathymetric deepening over time. Along the coast between SWD4 and SWD8 a bathymetric deepening of between 3 and 6 m has been observed over the past 125 years and this region has been characterised by retreat rates of around 3 m a^{-1} . Further to the north the bathymetric deepening has been in excess of 6 m and retreat rates here have been 5 m a^{-1} . Furthermore offshore of the northward moving Beacre Ness, bathymetric deepening has been closer to 9 m. A modelling study by Stansby et al. (2006) has suggested that the growth and development of sandbanks has a significant effect on wave attenuation in the region to the north of the study site, in the vicinity of Lowestoft. Given that the direction of approach of the largest waves is from the North East, then both the magnitude and the orientation of recent bathymetric deepening is

of concern for future cliff erosion. The channel offshore from SWD2 is oriented almost exactly towards the direction of approach of the largest waves, and it is potentially this feature that is enabling the development of the highest known rate of contemporary coastal retreat in the UK, at Benacre (Figure 20). Continued progression of Benacre Ness northward will increase the extent of the shoreline that is exposed to such waves, resulting in higher retreat rates in future and a potential new source of sediment supply.

Under a scenario of southward drift in sediment released from the eroding cliffs it is anticipated that continued infilling should occur in the nearshore zone to the south of Southwold (feature 3 on Figure 34) as well as in the offshore region (feature 5 on Figure 34). The net effect will be to potentially reduce coastal retreat progressively from south to north as the shallowing develops.

In managing this stretch of coastline it is clear that attention needs to be paid to the form of the immediate nearshore zone and, in particular, the unusually high bathymetric deepening that is occurring as Benacre Ness moves north. Any schemes aimed at cliff protection in the region must focus on how bathymetric change is likely to progress in future and the ways in which this will be associated with wave attenuation. Sea level rise has often been emphasised as a major driver of accelerated coastal retreat but the interplay between bathymetry, waves, tides, currents and storm surge magnitude in this highly dynamic setting should be considered in greater detail, particularly for the nearshore zone.

9. Acknowledgements

This research was funded through The Crown Estate in association with The National Maritime Museum under The Crown Estate – Caird Research Fellowship awarded to Dr S. Brooks in 2009. In completing this research the following individuals provided invaluable assistance and input to the project. David Welsh from the Shoreline Management Group of the Environment Agency (Anglian Region) tirelessly supplied aerial photographs and field survey data promptly and efficiently. Field assistance was provided by Dr Steve Boreham, Mr Chris Rolfe and Dr Tom Spencer of the University of Cambridge, and Mr Edward Vere Nicholl of the Benacre Estate provided permission to access the cliffs around Covehithe. Initial advice on digitising and use of Admiralty Charts was provided by Professor Jon French, Coastal & Estuarine Research Unit, University College London.

Further advice on georeferencing was provided by Dr Dan Friess, Department of Biological Sciences, National University of Singapore. The author also wishes to acknowledge the invaluable assistance provided by staff of the National Maritime Museum as well as staff of the University of Cambridge Map Room for providing valuable advice on the use of Admiralty Charts and Ordnance Survey Maps respectively. Dr Tom Spencer, Cambridge Coastal Research Unit, University of Cambridge, reviewed and commented on an earlier draft of this report.

10. References

Addo, K.A., Walkden, M., Mills, J.P., 2008. Detection, measurement and prediction of shoreline recession in Accra, Ghana. *ISPRS Journal of Photogrammetry and Remote Sensing* 63, 543-558.

Babtie Group and Birkbeck College, 2000. Spits and Nesses. Basic processes and effects on long-term coastal morphodynamics. Report produced for MAFF, January 2000. DEFRA, London.

Balson, P.S., Mathers, S.I., Zalasiewicz, J.A., 1993. The lithostratigraphy of the Coralline Crag (Pliocene) of Suffolk. *Proceedings of the Geologists' Association* 104, 59-70.

Bray, M.J., Hooke, J.M., 1997. Prediction of soft-cliff retreat with accelerating sea-level rise. *Journal of Coastal Research* 13, 453-467.

Bruun, P., 1962. Sea level rise as cause of shore erosion. *Am. Soc. Civ. Eng. Proc., J. Waterways Harbors Div.*, 88: 117-130.

Brooks, S.M. and Spencer, T., 2010. Temporal and spatial variations in recession rates and sediment release from soft rock cliffs, Suffolk coast, UK. *Geomorphology* 124, 1-2, 26-41.

Burningham H., French J.R. 2008. Historical changes in the seabed of the greater Thames estuary. The Crown Estate, 54pp.

Burningham H., French J.R. 2009. Seabed mobility in the greater Thames estuary. The Crown Estate, 60pp.

Cambers, G., 1973. The retreat of unconsolidated Quaternary cliffs. Ph.D. thesis, University of East Anglia, Norwich, U.K.

Cambers, G., 1975. Sediment transport and coastal change. East Anglian Coastal Research Programme Report No. 3. University of East Anglia, Norwich, U.K.

Cambers, G., 1976. Temporal scales in coastal erosion systems. Transactions, Institute of British Geographers, New Series 1, 246-256.

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffery, D.H., Lott, G.K., Bulat, J., Harrison, D.J., 1992. United Kingdom offshore regional report: geology of the southern North Sea. British Geological Survey, London, H.M.S.O.

Carr, A.P., 1969. The growth of Orford spit: Cartographic and historical evidence from the 16th century. The Geographical Journal 135, 28-29.

Carr, A.P., 1979. Sizewell-Dunwich Banks Field Study. Topic Report: 2. Long-term changes in the coastline and offshore banks. Report No. 89. Institute of Oceanographic Sciences, Taunton, pp.1-25.

Carr, A.P., 1981. Evidence for the sediment circulation along the coast of East Anglia. Marine Geology 40, M9-M22.

Clayton, K.M., McCave, I.N., 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, (Eds.), Shoreline Protection. Proceedings of a conference organised by the Institute of Civil engineers, University of Southampton, 14-15 September 1982. Thomas Telford, London, pp.63-68.

Danforth, W. W., and Thieler, E. R., 1992, Digital Shoreline Analysis System (DSAS) User's Guide, Version 1.0: U.S. Geological Survey Open-File Report 92-355, 42 p.

Dickson, M.E., Walkden, M.J.A., Hall, J.W., 2007. Systemic impacts of climate change on an eroding coastal region over the twentyfirst century. *Climatic Change* 84 (2), 141–166.

Dowman, I., Balan, P., Renner, K., Fischer, P., 2003. An evaluation of Nextmap terrain data in the context of U.K. national datasets. Report prepared for GetMapping, University College London, Department of Geomatic Engineering.

Ehlers, J., Gibbard, P.L., 1991. Anglian glacial deposits in Britain and the adjoining offshore regions. In: Ehlers, J., Gibbard, P.L., Rose, J., (Eds.), *Glacial Deposits in Great Britain and Ireland*. Balkema, Rotterdam, pp.17-24.

Esteves, L.S., Williams, J.J., Nock, A., Lymbery, G., 2009. Quantifying shoreline changes along the Sefton Coast (UK) and the implications for research-informed coastal management. *Journal of Coastal Research* SI 56 (Proceedings of the 10th International Coastal Symposium), 602 – 606.

Foody, G., Lee, E.M., Pethick, J., 2005. Benacre Ness: prediction of coastal change. In: Rees, S., (Ed.), *Coastal Evolution in Suffolk: An Evaluation of Geomorphological and Habitat Change*. English Nature Research Reports 647. Natural England, Peterborough, pp.61-75.

Fortnum, B.C.H., Hardcastle, P.J., 1979. Waves recorded at Aldeburgh, Dunwich and Southwold on the east coast of England. Institute of Oceanographic Sciences Report 65/79, Taunton, pp.1-9.

French, J.R., Burningham, H. 2003. Tidal marsh sedimentation versus sea level rise: a south-east England Estuarine perspective. *Proceedings of Coastal Sediments*, 1-14.

French, P., 2001. *Coastal Defences: Processes, Problems and Solutions*. Routledge, London.

Funnell, B.M., West, R.G., 1962. The Early Pleistocene of Easton Bavents, Suffolk. *Quarterly Journal of the Geological Society of London* 118, 125-141.

Gibbard, P.L., Zalasiewicz, J.A., Mathers, S.J., 1998. Stratigraphy of the marine Plio-Pleistocene crag deposits of East Anglia. *Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen TNO* 60, 239-262.

Gibbard, P.L., Moscariello, A., Bailey, H.W., Boreham, S., Koch, C., Lord, A.R., Whittaker, J.E., Whiteman, C.A., 2007. Comment: Middle Pleistocene sedimentation at Pakefield, Suffolk, England. J.R. Lee, J. Rose, I. Candy and R.W. Barendregt (2006). *Journal of Quaternary Science* 21, 155-179.

Halcrow, 1991. *The Anglian Sea Defence Management study – Stage III. Study Report*. Report prepared for NRA Anglian Region. Sir William Halcrow and Partners, Swindon, U.K..

Halcrow, 2001. Lowestoft to Thorpeness Coastal Processes and Strategy Study. Volume 2: Coastal Processes. Report produced for Waveney District Council, Suffolk Coastal District Council, Environment Agency. Sir William Halcrow and Partners, Swindon, U.K.

Hamblin, R.J.O., Moorlock, B.S.P., Booth, S.J., Jeffrey, D.H., Morigi, A.N., 1997. The Red Crag and Norwich Crag formations in eastern Suffolk. *Proceedings of the Geologists' Association* 108, 11-23.

Hey, R.W., 1967. The Westleton Beds reconsidered. *Proceedings of the Geologists' Association* 87, 69-82.

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

Horsburgh, K.J., Williams, J.A., Flowerdew, J., Mylne, K., 2008. Aspects of operational forecast model skill during an extreme storm surge event. *Journal of Flood Risk Management* 1, 213-221.

HRWallingford, 2002. Southern North Sea Sediment Transport Study, Phase 2. Sediment Transport Report. HRWallingford Report EX4526, Howbery Park, Wallingford, Oxford, UK.

IPCC, 2007. IPCC Fourth Assessment Report: Climate Change 2007. Working Group I Report. The Physical Science Basis, <http://www.ipcc.ch/ipccreports/ar4-wg1.htm>.

James, J.W.C., Lewis, P.M. 1996. Sediment input from coastal cliff erosion. Technical Report 577/4/A, Environment Agency, Peterborough.

Larwood, G.P., Martin, A.J., 1952-54. Stratigraphy and fauna of the Easton Bavents cliff sections, near Southwold, Suffolk. Transactions of the Suffolk Naturalists' Society 8, 157-170.

Lee, E.M., 2008. Coastal cliff behaviour: Observations on the relationship between beach levels and recession rates. Geomorphology 101, 558-571.

Leatherman, S.P., 1990. Modelling shore response to sea-level rise on sedimentary coasts. Progress in Physical Geography 14, 447-464.

Limber, P.W., List, J.H., Warren, J.D., 2007. Management applications of Lidar-derived mean high water shorelines in North Carolina. Proceedings, Coastal Zone 07 Portland, Ore., 22-26 July 2007. American Society of Civil Engineers, Reston, VA.

Long, P.E., 1974. Norwich Crag at Covehithe, Suffolk. Suffolk Natural History 16, 199-208.

McCave, I.N., 1978. Grain-size trends and transport along beaches: Example from eastern England. Marine Geology 28, M43-M51.

Mathers, S.J., Zalasiewicz, J.A., 1996. A gravel beach-rip channel system; the Westleton Beds (Pleistocene) of Suffolk, England. Proceedings of the Geologists' Association 107, 57-67.

Moore, L.J., 2000. Shoreline mapping techniques. Journal of Coastal Research 16, 111-124.

Mottram, H.B., 1989. The Upper Caenozoic sequences around Long Row, Covehithe. *Suffolk Natural History* 25, 86-91.

Muir Wood, R., Drayton, M., Berger, A., Burgess, P., Wright, T., 2005. Catastrophe loss modelling of storm-surge flood risk in eastern England. *Philosophical Transactions of the Royal Society of London, Series A* 363, 1407-1422.

Newsham, R., Balson, P.S., Tragheim, D.G., Denniss, A.M., 2002. Determination and prediction of sediment yields from recession of the Holderness Coast, NE England. *Journal of Coastal Conservation* 8, 49-54.

Nicholls, R. J., Wong, P.P., Burkett, V.R., Codignotto, J., Hay, J.E., McLean, R.F., Ragoonaden, S., Woodroffe, C.D., 2007. Coastal Systems and Low-lying Areas. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., (Eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp. 315-356.

Oliver, R., 1996. Taking to the water: some examples of OS mapping of the coast. *Sheetlines* 45, 9-27.

Pontee, N., 2005. Management implications of coastal change in Suffolk. *Proceedings of the Institution of Civil Engineers, Maritime Engineering* 158, Issue MA2, 69–83.

Pugh, D.T., 1987. *Tides, Surges, and Mean Sea Level*. John Wiley and Sons, Chichester.

Pye, K., Blott, S.J., 2006. Coastal processes and morphological change in the Dunwich –Sizewell area, Suffolk, UK. *Journal of Coastal Research* 22, 453-473.

Pye, K., Blott, S.J., 2009. Progressive breakdown of a gravel-dominated coastal barrier, Dunwich–Walberswick, Suffolk, U.K.: Processes and implications. *Journal of Coastal Research* 25, 589-602.

Reeve, D.E., Fleming, C.A., 1997. A statistical-dynamical method for predicting long term coastal evolution. *Coastal Engineering* 30, 259-280.

Richards, K.S., Lorriman, N.R., 1987. Basal erosion and mass movement. In: Anderson, M.G., Richards, K.S., (Eds.), *Slope stability*. John Wiley and Son, Chichester, pp. 331-357.

Robinson, A.H.W., 1966. Residual currents in relation to shoreline evolution of the East Anglian coast. *Marine Geology* 4, 57-63, 67-84.

Robinson, A.H.W., 1980. Erosion and accretion along part of the Suffolk coast of East Anglia, England. *Marine Geology* 37,133–146.

Ruggiero, P., Komar, P.D., McDougal, W.G., Marra, J.J., Beach, R.A., 2001. Wave runup, extreme water levels and the erosion of properties backing beaches. *Journal of Coastal Research* 17, 407–419.

Schupp, C.A., McNinch, J.E., List, J.H., 2006. Nearshore oblique bars, gravel outcrops, and their correlation to shoreline change. *Marine Geology* 233, 63-79.

Shennan, I., Horton, B.P., 2002. Relative sea-level changes and crustal movements of the UK. *Journal of Quaternary Science* 16, 511–526.

Shoreline Management Plans Sediment Sub-Cell 3c. 2010. Lowestoft Ness to Fleixstowe Landguard Point. <http://www.suffolksmp2.org.uk/>.

Stansby, P., Cui-Ping Kuang, Laurence, D., Launder, B., 2006. Sandbanks for coastal protection: implications of sea-level rise. Part 1: Application to East Anglia. Tyndall centre for Climate Change Research, Working Paper 86. University of East Anglia, Norwich, U.K.

Steers, J.A., 1953. The East Coast Floods January 31–February 1 1953. *The Geographical Journal* 119, 280-295.

Steers, J.A., Stoddart, D.R., Bayliss-Smith, T.P., Spencer, T., Durbridge, P.M., 1979. The storm surge of 11 January 1978 on the east coast of England. *The Geographical Journal* 145, 192-205.

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L., Miller, T.L., 2005. Digital Shoreline Analysis System (DSAS) version 3.0: An ArcGIS extension for calculating shoreline change. US Geological Survey Open-File Report 2005-1304.

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L., and Ergul, Ayhan, 2009, Digital Shoreline Analysis System (DSAS) version 4.0—An ArcGIS extension for calculating shoreline change: U.S. Geological Survey Open-File Report 2008-1278.

Tukey, J.W., 1977. Exploratory Data Analysis. Addison-Wesley. New York.

Van To, D., Thao, P.T.P., 2006. Shoreline analysis using DSAS in Nam Dinh coastal area.

International Journal of Geoinformatics 4, 37-42.

Valiela, I., 2006. Global Coastal Change. Blackwell Publishing, Oxford.

Vincent, C.E., 1979. Longshore sand transport rates – a simple model for the East Anglian coastline. Coastal Engineering 3, 113-136.

Walkden, M., Dickson, M., 2008. Equilibrium erosion of soft rock shores with a shallow or absent beach under increased sea level rise. Marine Geology 251 (1–2), 75–84.

Walkden, M.J.A., Hall, J.W., 2005. A predictive Mesoscale model of the erosion and profile development of soft rock shores. Coastal Engineering 52, 6, 535–563.

West, R.G., 1980. The pre-glacial Pleistocene of the Norfolk and Suffolk coasts. Cambridge University Press, Cambridge.

West, R.G., Funnell, B.M., Norton, P.E.P., 1980. An early Pleistocene cold marine episode in the North Sea: pollen and faunal assemblages at Covehithe, Suffolk, England. Boreas 9, 1-10.

Whitaker, W., 1907. Evidence to the Royal Commission. Royal Commission on Coast Erosion (Part 1). Wyman & Sons, London, 98-99.

Williams, W.W., 1956. An east coast survey: some recent changes in the coast of East Anglia. *The Geographical Journal* 122, 317–334.

Williams, W.W., Fryer, D.H., 1953. Benacre Ness, an east coast erosion problem. *Journal of The Royal Institution of Chartered Surveyors* 32, 772–781.

Woodworth, P.L., Teferle, R.M., Bingley, R.M., Shennan, I., Williams, S.D.P., 2009. Trends in UK mean sea level revisited. *Geophysical Journal International* 176, 19–30.

Zalasiewicz, J.A., Mathers, S.J., Hughes, M.J., Gibbard, P.L., Peglar, S.M., Harland, R., Nicholson, R.A., Boulton, G.S., Cambridge, P., Wealthall, G.P., 1988. Stratigraphy and palaeoenvironments of the Red Crag and Norwich Crag Formations between Aldeburgh and Sizewell, Suffolk, England. *Philosophical Transactions of the Royal Society of London Series B* 322, 221–272.



The Crown Estate
16 New Burlington Place
London W1S 2HX
Tel: 020 7851 5080

www.thecrownestate.co.uk
ISBN: 978-1-906410-21-6