Anglian Offshore Dredging Association

Marine Aggregate Regional Environmental Assessment: Coastal Characterisation

Technical Note TN-DDR4472-02

HR Wallingford

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1. Introduction

When applications are made either for marine aggregate dredging from a new area of the seabed or for further extraction from an existing licensed area, it is necessary to carry out an Environmental Impact Assessment (EIA) of those proposed operations. Inevitably such dredging will alter the seabed and water depths within the extraction area, so altering the waves and tidal flows at least locally. However, there may be changes in the physical environment further afield. In particular, the EIA has to consider and report upon the possibility of changes in waves, tidal currents or sediment movements along nearby coasts.

Within the region considered in this study, there are a number of existing aggregate dredging areas lying offshore of the coastline of East Anglia between Winterton in Norfolk and Southwold in Suffolk. Applications both for further aggregate extraction from these existing areas and for licences for new areas are being considered at present.

Rather than considering the effects of dredging from each area individually, it is important that the EIA for any proposed extraction also takes into account continuing or planned future dredging in other nearby areas. This leads to the need for a regional approach when assessing the environmental effects of aggregate dredging.

The Anglian Offshore Dredging Association (AODA) comprises the companies engaged in or planning to undertake aggregate dredging from the seabed of the coastline of East Anglia, largely to supply the construction industry. As part of the long-term planning for such dredging, AODA has commissioned a Marine Aggregate Regional Environmental Assessment (MAREA), which considers the effects on the marine and coastal environment of all the past and proposed future extraction of sand and gravel from this wide area. This MAREA aims to assist the planning and execution of the EIA studies needed for applications for future extraction licences for each individual area.

On behalf of AODA, Hanson Aggregates Marine Ltd. asked HR Wallingford to carry out a detailed regional assessment of the physical environment of the seabed and waters off the East Anglian coastline, and how this might be altered by future aggregate dredging. Considering whether such dredging could affect the shorelines of East Anglia has been an important part of this overall assessment; such a possibility has been a particular concern not least because of the long-term erosion of this coastline.

As a first step in considering the potential coastal impacts of aggregate dredging, this Technical Note reviews the history and present character of the coastline from Cromer to Orford Ness.

Further Technical Notes consider how aggregate extraction will alter offshore water depths, waves, tidal currents and sediment transport patterns. These studies will help assess if present or proposed future dredging could have any effect on this coastline.

1.1 SCOPE AND STRUCTURE OF THIS REPORT

The area considered in the overall MAREA is shown in Figure 1, along with the locations of the presently licensed aggregate extraction areas. The coastlines of Norfolk and Suffolk considered in this report extend from Cromer to Orford Ness.

From a geological viewpoint, the formation and subsequent changes of the coastline between 20,000 and 5,000 years ago was initially dominated by periglacial processes and then by the increase in sea-level as global temperatures rose and the ice sheets melted at the end of the last Ice Age. This increase in sea-levels resulted in the severing of the land-bridge between East Anglia and The Netherlands and the formation of what is now the southern North Sea. Tidal currents and waves were then able to re-shape the coastlines of this newly-formed sea.

In more recent times, i.e. over the last 500 years, the loss of numerous towns and villages provides good historical evidence of the long-term erosion of the East Anglian coastline. Finally, in the last century, there have been many studies seeking to measure and explain the changes that are occurring, often in the context of concerns about the damage that could be caused by flooding or erosion. The geological, historical and scientific evidence describing the long-term changes in the study coastline is summarised in **Chapter 2** of this report.

This is followed, in **Chapter 3**, by a review of the present-day sediment transport regime along the whole coastline between Cromer and Orford Ness. This review has been divided into four sections, one each of four Coastal Units. These units have been chosen in such a way that the coastline in each is broadly similar in physical character, i.e. its orientation, land-levels, geology and beach types (see Figure 1). Each description of the sediment transport regime starts with a review of the alongshore and landward-seaward transport of beach sediments. Where possible, evidence is presented, and/ or implications are drawn, about sediment transport connections between the coastline and the seabed, since the possibility of aggregate dredging leading to the offshore movement of beach sediments is a frequently-expressed concern in East Anglia.

This is followed by an assessment of sediment transport over the nearshore seabed and an assessment of the seaward limit of the beaches, i.e. where they meet the rocky shore-platform on which they rest. This last aspect of the review is based on an analysis and assessment of coastal cross-sectional surveys provided by the Environment Agency, as described in more detail in an Appendix to this report.

In **Chapter 4**, four sections describe, the morphology of each Coastal Unit, followed by a brief review of the present-day defences installed to reduce the threats of coastal erosion and/ or coastal flooding and how they are managed. Finally, for each Unit, we have provided an assessment of the main threats to and vulnerability of the coastal hinterland both now and in the future. To summarise the description of these four Units, coastal characterisation maps (Maps 1 to 3) have been produced to inform future EIAs of likely sensitivities at the coastline. These maps are accompanied/ supplemented by the text within this report, which covers the most important aspects of the coastline that need to be considered when assessing the possible effects of offshore aggregate dredging.

Finally, **Chapter 5** presents the main conclusions reached during this review and goes on to make specific recommendations about the way that any potential effects of offshore aggregate dredging on this coastline need to be assessed and, if necessary, avoided.

2. *Historical review*

2.1 INTRODUCTION

The specific context for this report is the need to consider whether changes along the coastline between Cromer and Orford Ness could be affected by offshore aggregate dredging. To help in this, it is helpful to review changes that took place before any significant aggregate dredging off the coastline of East Anglia took place.

This chapter starts with a brief description of the changes to the coast that took place in the recent geological past, i.e. during the last 10,000 years. This is followed by a summary of evidence from historical records and maps that document changes since the Middle Ages, i.e. over approximately the last 600 years. The final part of this chapter then considers the more recent literature, covering the last 100 to 150 years, during which more detailed maps and records of coastal change have been compiled.

2.2 RECENT GEOLOGICAL EVOLUTION

It is useful to first summarise the formation and subsequent changes of this coastline since the end of the last Ice Age. Figure 2.1 shows a simplified interpretation of a possible historical morphology of part of the study area towards the end of the last glaciation, i.e. about 20,000 years ago. This landscape has been interpreted by the aggregate dredging industry from seabed contours and sub-surface geophysical profiles (Bellamy, A. G., *pers. comm.*, 2010). Melt-water from the ice-sheets to the west and north would have fed much larger rivers than found in the UK today. In addition spring thaw of winter snow and permafrost in the periglacial environment existing in East Anglia and the North Sea (akin to present-day arctic Canada) would have produced significant seasonal river flows. These flows would have carried very large quantities of sand and gravel downstream and, as the floods subsided, deposited them over broad floodplains.

As global temperatures increased and the ice sheets and glaciers melted, the sea-level started to rise and the southern part of the North Sea began to form. The initial rate of sea-level increase was extremely rapid, averaging about 2 metres/ century (20mm/year) between about 10,000 and 8,000 years ago. To describe the development of the coastlines of Norfolk and Suffolk during this period, we have relied on Shennan *et al*. (2000), reproducing some of the figures presented in that paper to illustrate this chapter.

About 10,000 years ago, i.e. about 8000BC, sea-levels were so low that what is now East Anglia was part of a low-lying plain stretching from Yorkshire to Denmark and extending south into the English Channel (see Figure 2.2). As the massive ice sheets melted, sea-levels rose to the extent that by about 7000 BC the last "land bridge" to mainland Europe, between North Norfolk to the Netherlands, was becoming narrower. At this time, sea-levels would have been about 35m lower than today. The English Channel had been opened and would have extended to the north of the Straits of Dover, forming a narrow channel/ estuary lying offshore from Suffolk (see Figure 2.3).

Figure 2.4 is an interpretation of how the coastlines of north-east Norfolk and Suffolk would have looked in about 6000BC, based on the same evidence used to produce Figure 2.1. Sea-levels at this time would have been between 15m and 20m lower than at present.

By about 4000BC, the southern North Sea had largely been formed (see Figure 2.5), although there was an island in the area of Dogger Bank. At this time, sea-levels would have been about 9m lower than today and the coastlines of Lincolnshire and North Norfolk would have extended considerably further north-east than at present. By this time, low-lying land around the edges of this new sea was not only being slowly submerged by the still-rising sea-levels but also being altered by the tidal currents and waves in the newly formed southern North Sea.

Since that time, sea-levels have risen a further 5m or so, although at a much slower rate than during the preceding 6000 years. The rate of sea-level rise over the last 4000 years deduced from geological evidence, of about 1mm/year, is close to the measured values in recent decades. Some 2000 years ago, i.e. in about year 0BC, the shape of the British Isles and most of the eastern coastlines of mainland Europe would have looked much the same, at least at the scale shown in Figure 2.6, as they do today. A comparison of Figures 2.4, 2.5 and 2.6 shows that there would have been rapid erosion of the coastlines of Suffolk and Norfolk between 4000BC and 0BC, resulting for example in the formation of The Wash and the Thames Estuary.

During this long period of sea-level rise, large areas of land would have been submerged, including the lower reaches of river valleys. Where the advancing sea met higher ground, large quantities of sediment would have been eroded from the newly formed and then rapidly eroded shorelines, especially where the sediments commonly comprised poorly consolidated sands and clays as found in the southern North Sea and East Anglian. Some of this sediment would have been redistributed along these new coasts, for example partly infilling estuaries such as that depicted in Figure 2.4 or forming gravel barrier beaches such as those seen along much of the present coastline of North Norfolk and Suffolk. Some of these older shorelines were then have been submerged themselves as sea-levels rose further, or transgressed ever further landwards as waves and tides over-washed the beaches and carried their sediments inland.

This general pattern of marine erosion of the higher ground, forming cliffs, and the retreat of narrow barrier beaches spanning the old river valleys that ran between the areas of higher ground, continues today. To obtain a more detailed history of how quickly this process has been occurring in the last few centuries, however, attention is turned from the geological evidence to the historical records of this part of the coastline.

2.3 REVIEW OF HISTORICAL RECORDS OF COASTLINE CHANGE

Even before the accurate maps of the early to mid-19th Century, there is a great deal of evidence of long-term erosion of the East Anglian coastline stretching back over the last 500 to 1000 years. Figure 2.7 has been compiled using from the book “Claimed by the Sea” (Weston & Weston, 1994), which provides an excellent description of historic coastal changes along the shoreline between Cromer and Great Yarmouth, together with online information on the history and erosion along the Suffolk coastline (see http://www.southwoldmuseum.org/thesea_Coastal%20erosion.htm).

The 1994 book by Weston & Weston summarises the well-recorded losses of numerous communities along the coast in the past few hundred years, for example Shipden (off Cromer), Whimpwell (off Happisburgh), Waxham Parva (off Waxham), Ness (off Winterton), and Newton Cross (off Hopton), and provides good historical evidence of the long-term trend for coastal erosion and retreat from mediaeval times. In terms of the rates and extent of the long-term recession of the glacial till cliffs, BGS (see http://www.bgs.ac.uk/landslides/happisburgh.html) recently concluded “although now a coastal village, Happisburgh was once some distance from the sea, parted from the coast by the parish of Whimpwell, long since eroded away. Historic records indicate that over 250m of land were lost between 1600 and 1850", i.e. concluding a natural rate of recession averaging 1m per annum.

At Eccles, there was once a whole village, not just the line of bungalows and caravans that now lie behind the dunes. By 1604, following a ferocious storm, all that remained were 14 houses, and by 1895 St Mary's church finally fell into the sea. Victorian photographs show the church ruined and lost offshore as a result of coastal retreat.

This pattern of erosion is not confined to Norfolk but extends southwards into Suffolk and Essex. Some of what were once the largest towns in Suffolk have also been partly or almost entirely lost, including Aldeburgh and Dunwich. As far as can be judged the historic erosion rate, between 1587 and 1975, has averaged at over 1 metre per year (Royal Haskoning, 2009). In Norman times Dunwich was a prosperous port of comparable size and importance to London. However, the mouth of the river Blyth became blocked with sand and shingle during a particularly severe storm in January 1326, causing the river to become diverted northwards. Dunwich was then abandoned and suffered rapid coastal erosion, so that very little of the town now remains.

More quantitative evidence for the rates of coastal change along the East Anglian coastline is provided by the first report issued by the Royal Commission on Coastal Erosion in 1907. The commission heard evidence from a wide range of people and asked for written evidence from local authorities, landowners, drainage boards etc. In many cases this evidence was not qualitative, but for some frontages more detailed information was provided. The following excerpts, rearranged in order from North to South, give a good impression of the situation in the early years of the 20th century.

Blakeney to Weybourne

"From careful enquiry from old inhabitants and from the study of ancient maps it is clear that the erosion has proceeded very rapidly during the last fifty years, that is to say probably at the rate of about two yards per annum, which is now accelerating".

Sheringham Urban District Council

"The whole of the sea-board of the urban district is subject to erosion by the sea except where effective protection woks exist… from the best information available the rate of erosion is estimated on the average at over 2 feet per annum.

The causes of erosion of the foreshore may be summarised as follows:

(a) Denudation of the foreshore by wave and tidal action
(b) Erosion of the glacial cliffs by wave action at high tide
(c) Erosion of the cliffs by land drainage, water and rain
(d) The action of frost on the saturated and fissured cliffs, which consist of glacial deposits overlying the chalk."

Urban District Council of Cromer

"By a comparison made between an old map of 1747 and the Ordnance Survey of 1885, it would appear that there has been lost by the encroachment of the sea during the intervening period a strip of land of an average depth of about 100 yards, varying from about 160 yards at the westward boundary to 107 at the eastward… The cliffs, which are compared of sand, gravel, sand-marl and clay, are being continually wasted by the action of the sea, the primary cause being the washing away of the foot, causing falls of the cliffs. In some instances "the falls" are brought about by land springs, but where the foot of the cliff is protected by a wall and the wall protected by groynes the land spring have little effect. Sand, ballast and beach stones have been removed in large quantities, but not in recent years, although a proposal has been made this year to do so."

Cromer to Paston

"The land between the limits above referred to is subject to erosion and not accretion, there having apparently for centuries been a falling away of the cliff caused principally by the action of land springs, which are very numerous in this district, causing a considerable fall of cliff from time to time which in due course is washed away by the action of the tides, which run from east to west on this coast and west to east, a high beach being left with one tide and washed away by the other."

Erpingham Rural District Council

"The entire coastline of the Erpingham Union, which extends for distance of 18 miles (*from Sheringham to Overstrand*), is liable to erosion; of this, 15 miles is in the rural district (exclusive of Cromer and Sheringham).

In the opinion of this authority this erosion (where the beach was unprotected) is due to the combined action of undermining land springs and heavy seas. Possibly a general advance of high-water mark has increased this erosion."

Commissioners for Sewers of the Eastern Hundreds of Norfolk

"The duty of the Commissioners is to maintain the sea banks along the low-lying coastline (about twelve miles) between Happisburgh and Winterton, thereby protecting from inundation the low lands lying chiefly in the valleys of the Bure and the Yare and (on its Norfolk side) the Waveney…

Formerly the river known as "The Hundred Stream" or Thurne, used to discharge itself at Horsey through a gap in the sand hills known as the Long Breach, which is now closed by an artificial raised sandbank.

Erosion but no accretion has occurred along the whole length of coast line protected by the works of the Commissioners, viz. from Happisburgh and Winterton. The erosion is caused principally by the scouring action of high tides. Erosion is most serious when high tides synchronise with winds blowing from the direction of the north-west and the north, and particularly when such winds follow strong gales from the south-east. Denuded of its normal covering of sand and shingle the beach is lowered, and the footings of the sand dunes are exposed and eroded. Thus undermined, the sand hills subside seaward and the material is dispersed. The direction of the littoral drift is to the south or south-east."

Parishes of Corton, Gunton, Hopton etc.

"This estate extends from the Borough of Lowestoft to the parish boundary of Gorleston, a distance of about 4¼ miles, the whole length of which on the east side abuts in to the North Sea. At the southern end the natural protection against the encroachments of the sea is a "marrum bank" which has been strengthened by the construction of a box wall (i.e. a double row of planks filled in with sand). The cliffs immediately opposite the village of Corton have been protected, and very successfully, by a series of groynes and breast-work which have been constructed at an enormous outlay. The northern end about 2½ miles in length has not been protected in any way…

The Ordnance Survey maps, surveyed 1882-3 published 1884 have from time to time have been revised and show that the cliffs at the north end are being washed into the sea at the rate of about one yard in width per annum."

Borough of Lowestoft

"Length of sea frontage just under 3 miles, all of which is subject to erosion, except a small length north of the harbour, where an accretion of about 6 acres has taken place during the last twenty years. We have maps, and measurements have also been made, showing the extent of the erosion during the last twenty years, which show, on the north beach, an annual loss of 20.6 feet and a lost area, during the last twenty years, of 62 acres. On the south beach an average loss per year of 7 feet and a loss of beach, in the twenty years, of about 22½ acres. Erosion takes place during on-shore gales and abnormal high tides. In this locality north-east to south-east winds cause the most erosion. Lowestoft's coastline is far more exposed than in years gone by, when it was entirely protected by sand-banks, which were dry at low water."

Rural District Council of Blything

"The whole of the sea-board of the district, i.e. (1) from the boundary of Kessingland to that of Southwold: (2) from that of Southwold to that of Leiston; and (3) from that of Leiston to that of Aldeburgh is subject to erosion.

In the opinion of the Council high north-westerly winds with spring tides had led to this erosion".

Borough of Southwold

"Practically the whole sea frontage of the Borough of Southold is subject to erosion. A trifling accretion has take place near the harbour…

(The erosion at Southwold) is probably caused by the set of the tide and sea round the Barnard Sand on the north, which has washed away Easton Ness which formerly projected and furnished material for the protection of Southwold; there is consequently not so much material passing and the town of Southwold now stands out into the sea instead of lying at the bottom of a bay."

Dunwich Town Trustees (Miles Barne esq.)

"I am interested in about 5¼ miles of coast either as owner or as chairman of Dunwich Town Trustees. All of this is subject to erosion, or if not actually erosion, to the land being rendered valueless by being covered with shingle.

In the last sixty-eight years, 1680 acres 1 rood 22 poles have disappeared, which is at the rate of 2 acres 1 rood 36 poles per annum, or on about an average of 130 yards in the sixty-eight years, for the whole distance.

The prime cause is the sinking of the land into the sea, and the sandy nature of the soil accelerates the erosion by being unable to withstand the action of the sea. This is much helped by rain-water working its way through the soil. The erosion occurs principally during a combination of strong north-west winds, spring tides and a wet season."

Minsmere Level Commissioners

"There are about 1,600 acres … which are liable to be flooded by the sea in case of a breach in the artificial sea wall erected by the Minsmere Level Commissioners… The whole sea front lying to seaward of the wall, say for the length of one mile, is subject to erosion. The land to the north of the northern end of the sea wall rise in sand cliffs up to and beyond Dunwich Abbey – all this line of cliffs is subject to erosion, but this erosion does not directly affect the lands comprised in the Minsmere level.

Since the erection of the artificial sea wall the process of erosion has been substantially arrested. On two or three occasions at long intervals, in consequence of a gale following upon an abnormal high tide, a breach has been made in the wall, but such breaches have been repaired and the flood water drained off by degrees by means of the culverts that drain the marshes.

The sand hills or, as they are called locally, benthills, lying between the wall and the sea have been seriously affected and eroded by the sea. No maps exist showing the extent of the damage as the *sea has not actually advanced* beyond the high-water mark of 1810, although it has torn away and in places levelled the natural barriers of the sand hills.

The sea tends to encroach all along the coast of Suffolk. The causes producing this tendency are obscure. The immediate cause of this erosion arises roughly in this way. If a north-westerly wind blows strongly for two or three days it piles up the water in the channel so that the level of low tide is as high as the ordinary high-water level. As the tide then rises it overflows those parts of the beach which are usually uncovered and washes up against the base of the cliffs. This of itself causes a fall of cliff. But on the top of the abnormally high tide there comes a strong-gale from the *north-east*, then the water rushes along the coast like a millrace and scoops out great mass of the cliff, causing heavy falls from above, and all the earth that falls is washed into and dispersed in the sea."

The above excerpts present a rather uniform view of the state of the coast of Norfolk and Suffolk in the first few years of the 20th century. The reported rates of recession of cliffs and beaches varied from place to place, and proceeded at different rates at different times, but were widespread and generally rapid at rates of 1m/ year or more.

There was clearly a general net drift to the east and south from Sheringham all the way down the coast of Norfolk and into Suffolk, at least as far as Southwold Harbour.

The role of sandbanks in protecting the coastline, and the effects of changes in these sandbanks was mentioned several times, and while not explicitly mentioned, the role of North Sea tidal surges in causing rapid erosion and flooding was clearly recognised.

Coastal defences in the form of seawalls and groynes had obviously been built along stretches of the coastline to protect some of the coastal towns, e.g. at Sheringham, Cromer, Hopton and Corton, and where this was done, the coastal erosion had been stemmed. Elsewhere, for example between Happisburgh and Winterton, considerable efforts were being made to strengthen the natural protection provided by beaches and dunes by use of faggots, gabions and the planting of marram grass, but flooding still was occurring, particularly when tidal levels were exceptionally high.

For more recent information on the rates of coastal change, there have been a number of scientific papers that provide more quantitative estimates.
Evidence for the retreat of the cliffs at Dunwich was reviewed by Robinson (1980) who produced the following rates of cliff retreat using maps:

Table 1 Cliff recession rates at Dunwich (1589 – 1977)

From	To	Rate (m/year)
1589	1753	1.6
1753	1824	0.9
1824	1884	1.5
1884	1925	1.1
1925	1977	0.15

A recent analysis of cross-sectional coastal surveys commissioned by the Environment Agency (2007) indicates that the rate of beach recession at different locations along the cliffs at Dunwich between 1991 and 2007 varied between 0.03 and 1.7m per annum. While these figures are not directly comparable with the rates of cliff top recession in Table 1, they do suggest that the present rate of cliff retreat at Dunwich is still substantially less than it was prior to 1925.

The erosion of the North Norfolk cliffs, especially between Cromer and Happisburgh, has also attracted attention with numerous papers written from the late 1970s onwards, for example Cambers (1976), Clayton, Mc Cave and Vincent (1983) and Clayton (1989). The retreat rates of the Norfolk and Suffolk cliffs were measured in these studies using Ordnance Survey large scale maps. The cliffs between Weybourne and Happisburgh (a distance of 30km) were shown to have receded at an average rate of just under 1m/year between 1880 and 1985. The highest average rates (1.4-1.7m/ year) occur in the area of Trimingham. However, Cambers (1976) pointed out that recession rates as large as 13m / year had been recorded locally.

As part of a study undertaken in 1995/96, a review of cliff retreat rates was also undertaken, but in this case focussed around Happisburgh (Halcrow 1995 & 1996), based on the coastlines shown on Ordnance Survey maps dated 1886, 1906, 1938, 1970 and 1986. From 1991 onwards, North Norfolk DC also undertook coastline surveys. When analysing erosion rates before any defences were installed along this frontage (1886 to 1938 maps), it was found that the averaged erosion rate varied between 0.4 and 0.8 m/year according to location. It was suggested that the varying erosion rate correlated with the differing geological profile of the cliffs, for example an increasing thickness of base clay resulting in a lower erosion rate.

It is worth noting that recent scientific interest in the evolution of this coastline has concentrated on cliff recession; there is apparently less in the way of studies of the retreat of the beaches between the areas of higher ground, although the papers of Pye and Blott (2006, 2009) on the shingle barrier beach between Walberswick and Thorpeness are notable exceptions. In terms of its long-term evolution, they wrote “The Dunwich - Walberswick barrier has shown a consistent trend of landward retreat for at least the last 400 years, although the rate of retreat in recent decades has been lower than the historical long-term trend. The construction of the piers at the mouth of the Blyth River from the 17th century onwards created a hard point which helped to slow the rate of barrier recession at the northern end. Coastal management measures in the last 30 - 40 years have also helped to slow the rate of shoreline recession but have failed to stop it”. The authors go on to present maps showing a recession of the beach of some 400m in the period from 1587 to 1970, i.e. approximately 1m/year. It would be expected that without any intervention, the beaches that protect the low-lying land between the high ground along this coastline will retreat at the same rate as the cliffs at each end of them.

In summary, until parts of the frontage between Cromer and Orford Ness were protected by seawalls and groynes, there is a large body of evidence to show this coastline had eroded ever since mediaeval times. The long-term average rate of recession caused by natural processes, namely tides, winds and a continuing sea-level rise is about 1 metre per annum. There has always been variability in the rates of erosion at different locations at different times, in part related to the movements and changes in the volume of the numerous shifting nearshore sandbanks that partly protect this coast.

3. Sediment transport

3.1 INTRODUCTION

The movement of sediments on beaches and over the nearshore seabed are crucially important in the evolution of this coastline. Beaches with ample sediment will prevent or reduce erosion (for example of coastal cliffs) and/ or reduce the threats of the flooding of low-lying hinterland. However, wave action and tidal currents along this coastline are almost continually moving sediment, altering beaches and affecting the long-term changes in the position and character of this coastline.

The movements of individual sediment particles are very complicated, and take place in all three dimensions. To simplify the description of how the movements of sediment alters this coastline, we adopt here a standard approach, namely to concentrate on the net long-term movements of sediment along the coast (longshore) and perpendicular to it (cross-shore). For clarity:

- **Net long-term** sediment transport means the overall result of many hours of to-and-fro movements of sediment particles over a year or more;
- **Longshore** sediment transport affects the plan shape of coast, e.g. beach widths; and
- **Cross-shore** transport moves sediment between cliffs, dunes, beaches and the nearshore seabed.

Along the East Anglian coastline, these aspects of sediment transport were reviewed in great detail in the second phase of Southern North Sea Sediment Transport Study (see www.sns2.org). This study provided both a broad appreciation and a detailed understanding of sediment transport along the coastline of England between Flamborough Head in Yorkshire and North Foreland in Kent. The aim of this study was to understand sediment movements thoroughly so as to improve the data on which Shoreline Management Plans (SMPs) and the assessment of dredging licence applications are based. A fuller understanding of sediment movements also facilitates a greater awareness of issues affecting the management of beaches and coastal defences, and of the coastline and the sediment resources on and under the offshore seabed.

The Southern North Sea Sediment Transport Study (Phase 2) (SNS2) was undertaken between 2000 and 2002 by a consortium including HR Wallingford, Cefas (Lowestoft Laboratory) and the University of East Anglia. The study was commissioned by a group of nine local authorities, together with the Environment Agency and English Nature and the dredging industry and was part funded by the Department for Environment, Food & Rural Affairs (DEFRA). Great Yarmouth Borough Council was the client group leader. The present report makes extensive use of the SNS2 study, together with information gathered during subsequent coastal defence studies, i.e. Shoreline Management Plans and Coastal Strategy Studies, and observations made during the site visit to the coastline undertaken during this study.

Starting at the northern end of the study frontage, i.e. at Cromer, this chapter describes the origins or sources of the sediments found on the beaches, how it moves along the coast and where it goes to. As part of this description, particular attention is paid to any evidence for sediment moving onto the beaches from the offshore seabed and /or evidence of net offshore transport of beach sand or gravel.

3.2 CROMER TO CART GAP (ECCLES)

3.2.1 *Beach sediment longshore transport*

At Cromer, the longshore transport of beach sediments is predominantly eastwards. The sand and shingle here mainly arrives from the beaches further west, from as far as Sheringham and, at present, perhaps a little further west. The amount of beach sediment travelling along this part of the coastline is added to by the erosion of the largely undefended cliffs between Sheringham and Cromer and from some of the cliffs west of Sheringham. These cliffs have been formed in a thick layer of glacial drift deposited during the last Ice Age, and as they erode they provide a mixture of gravel, sand and finer-grained sediment particles. Much of the clay and silt that is deposited onto the beach as the cliffs recede is dispersed by wave action and eventually carried offshore, suspended within the seawater, and may travel long-distance before settling again into deep water areas of the southern North Sea or within the estuaries around its shores.

The remaining coarser sediments, i.e. sand, gravel and pebbles, augment the volumes of beach sediment at the base of the cliffs before being carried along the coast by alongshore currents generated by both obliquely incident waves and by tides. This section of the coastline of East Anglia is unusual in that the fastest tidal currents occur close to the times of high and low water. As a consequence, a combination of a high tidal level and large storm waves approaching from the north-west sector produces a very strong eastwards movement of material along the beaches at and near Cromer.

The consequences of the net easterly longshore drift at Cromer can be seen particularly well at the eastern end of the town, where the long concrete groynes have retained higher beach levels to their west, at the expense of the beaches just to their east, which are much narrower and lower. The interruption of the longshore drift by these groynes and its reduction by wave reflections from the seawall itself, results in a reduction in the amount of beach sediment reaching the coastline just to the east of Cromer. As a consequence, the beaches in front of the cliffs between Cromer and Overstrand are narrow, allowing waves to erode the base of the cliffs and resulting in their recession.

A similar pattern of eastward or south-eastward drift occurs along the entire coast past Mundesley, Bacton, Walcott and Happisburgh to Cart Gap at Eccles where the glacial drift cliffs disappear. At the downdrift end of various sections of coastline protected by seawalls or revetments, i.e. just beyond their eastern or south-eastern ends, there is a similar problem of erosion to that seen east of Cromer, resulting in narrow beaches in front of the cliffs which recede more rapidly in these locations.

As well as the effects of the net longshore drift being evident from the observed erosion downdrift of the coastal defences, and to a lesser extent by the accumulation of beach material on the western or north-western side of groynes and seawalls, McCave (1978) has pointed out that the changing size of the sand grains on the beaches also provides evidence that the net longshore transport is from Cromer to Happisburgh and beyond, i.e. towards Great Yarmouth and Lowestoft.

Appendix 11 of the SNS2 (HR Wallingford, 2002a) study provides estimates of the average longshore drift rates along this stretch of coastline. These indicate an increase in the potential net longshore drift rate from about 50,000 cubic metres per annum at Cromer to greater than 400,000 cubic metres per annum at Happisburgh. It is this increase in longshore transport rate that results in the beaches continually eroding and, where not defended, in the cliffs behind them receding. In practice, the potential longshore drift rates have been modified by the presence of the defences that have been built to protect various stretches of this frontage, and pointed out in the strategy study (HR Wallingford, 2002b). These structures both restrict the capacity of waves and currents to transport sediment along some parts of this coast. They also reduce the amounts of sediment available to be transported along the sections of beach immediately to the east or south-east of the defences. Nevertheless, there is still a general tendency for an increase in the actual net rate of alongshore sediment transport from west to east all along this part of the Norfolk coastline.

It is important to note that the above discussion of longshore transport rates only refers to <u>average</u> annual transport rates. Despite the large eastward or south-eastward values that have been calculated, several authors have noted that the net transport could be reversed, usually as a result more frequent and intense south-easterly winds during any particular year. During such times, there will be an increase in beach widths to the south-east or east of seawalls and groynes and a tendency for erosion just to the west or north-west of them.

3.2.2 Beach sediment cross-shore transport

As remarked above, the sand and gravel eroded from cliffs between Weybourne and Cart Gap is the main source of beach sediments along this frontage. Before coastal defences were built, it estimated that cliff erosion along this frontage supplied, on average, about 400,000 cubic metres annually (see Cambers (1973) and SNS2 (2002a)) although Clayton (1989) and McCave (1987) suggested rather greater rates, of 500,000 and 655,000 tonnes per annum respectively. These figures are of the same magnitude as the rates at which beach sediment is calculated to leave this stretch of coastline, travelling along the shoreline towards Great Yarmouth.

The coastal defences along parts of the coast between Cromer and Cart Gap have reduced the rate at which sediment is now added to those beaches by the erosion of previously undefended cliffs. It is likely that this has led to a decrease in the total amount of sediment being added to the beaches. However, an increased rate of cliff erosion just to the south of the defended frontages and the rapid retreat of cliffs that occurs if the defences are allowed to fall into disrepair, as at Happisburgh Village, may partly balance the reduction in sediment that would have come from the now defended cliffs.

There is no evidence for any net onshore movement of sand from the seabed onto the beaches between Cromer and Cart Gap, save for the eroding chalk shore-platform offshore from Cromer which occasionally provides flint pebbles that travel onto the beaches there.

A percentage of the glacial drift sediments that make up the cliffs is rapidly lost offshore following a cliff fall, particularly the finer-grained sediments, i.e. silt, clay and fine grained sand. Such losses will not always occur immediately after a cliff fall, but later after longshore transport has carried a mixture of shingle, sand and the finer sediments further along the coast. This results in the beach sediments gradually becoming coarser as they travel east and south, as noted by McCave (1978).

There is no evidence of any substantial offshore loss of coarser sand of shingle from this section of coast. While beach gradients will typically become flatter during storms, with an associated offshore movement of some of the sediment from the upper part of the beach, such losses are only temporary. The sediment that is displaced does not travel far offshore and is returned to the upper beach during calmer weather. The seaward extents of such short-term or seasonal changes in beach profiles are discussed in section 3.2.4.

3.2.3 Nearshore sediment transport

The evidence for the transport of sediment over the nearshore seabed off this coastline was reviewed during the SNS2 study (HR Wallingford, 2002a) and this review was supplemented by numerical modelling. Both of these sources of information indicated that the direction of seabed sediment transport was parallel to the coastline, but that there were no clear indications from the shape of sand-waves or megaripples on the nearshore seabed that indicated the net direction of that transport.

The numerical modelling was carried out for a variety of different tidal ranges (i.e. for Neap, Spring and Spring plus tidal surge conditions) and a range of different grain sizes. Most of these simulations indicated that the net transport direction in water depths of less than 10m (below lowest tide) is roughly from north-west to south-east off the coastline between Cromer and Cart Gap, i.e. in the same direction as the net longshore transport along the beaches. Just to the west of Cromer, however, the net transport in shallow water reverses, to run westwards along the northern Norfolk coast from Blakeney to Hunstanton. This too closely matches the observed net transport along the beaches of this shoreline.

Further offshore, e.g. in depths of 20m below the lowest tidal level, the net transport of seabed sediments is eastwards from offshore of Hunstanton and then turns south-eastwards as it passes Cromer and travels on towards Winterton Ness.

No evidence was found for either any sediment transport pathway towards or away from the coastline between Cromer and Cart Gap.

Figure 3.1 shows the evidence for sediment transport over the nearshore seabed for this part of the coastline that was compiled during the SNS2 study using analysis of seabed features such as sand waves and using numerical modelling under a variety of different tidal conditions.

3.2.4 Beach toe limits

An important issue in the consideration of offshore aggregate dredging plans is to ensure that any such operations only take place well seawards of and in deeper water than the lower limit of beach profile changes. This constraint will avoid any danger of beach sediments being drawn-down into a dredging area, and is explained in more detail in Appendix 1 to this report.

To establish the lower limit of beach profile changes, the beach toe, this study has reviewed and analysed beach cross-sections were provided by the Environment Agency at Peterborough (see Appendix 1 for further details of their analysis). These profiles have been established at an approximate spacing of 1 km along the whole of the coastline of East Anglia, and have been surveyed on four occasions between 1991/2 and 2007.

Some examples of the analysis of the 25 beach cross-sections along the frontage between Cromer and Cart Gap are presented below.

Profile N3E5 lies about 2 km east of Cromer, and the surveys along this section (see Figure 3.2) show the toe of the unprotected cliffs meets the beach crest at about 2m ODN. From here seawards there is evidence of changes in beach levels of up to 75cm down to about the -4.5m OD contour, which lies about 300m seaward of the mid-tide beach contour. Beyond this level, the profile surveys show a fairly constant slope, down to about -9.5m OD, i.e. about 700m offshore. There is also a reduced variability between the four surveys in the recorded levels between -4.5m and -9m OD, and these changes may be largely or completely the result of inaccuracies in the surveys this far offshore. Further seaward than the -9.5m OD contour, the profiles become noticeably flatter, and it is concluded that this part of the profile is a bed-rock shore platform. Our interpretation of these surveys it that the seaward limit of beach profile changes at this location lies between -4.5m and -9.5m OD.

In Figure 3.3, the surveys along Profile N3C1, about 1km north of Mundesley, show only small variations in beach levels behind the timber revetment that protects the cliffs here. From this revetment (about 50m offshore) down to the -2m contour, the beach slopes at about 1 on 20, with small variations in its level. Between the -2m and -5m OD contours, the overall slope is flatter, at about 1 in 70, and there appear to be two troughs and two bars on most of the four individual surveys. Beyond the -5m contour, about 600m offshore, the recorded variations in bed levels become smaller and virtually disappear at 800m offshore, where the bed level is about -9.5m OD. Beyond this point, the seabed slope becomes flatter and is presumed to be a bed-rock shore platform. Our interpretation of these surveys it that the seaward limit of beach profile changes at this location lies between -5m and -9.5m OD.

At Walcott Gap, surveys along Profile N3C8 (see Figure 3.4) show considerable variability of beach levels in front of the seawall (chainage c10m) and then a rather steep upper beach, with a gradient of about 1 in 15 down to a nearshore trough which forms between about 70m and 130m in front of the seawall. To seawards of this trough, the bed levels rise again to a bar, which has a crest of between -2m and -3m OD. There is evidence of a similar trough and bar on the lower beach profiles along much of the frontage between Mundesley and Winterton Ness, as pointed out in the SNS2 study in 2002. From the crest of the bar on Profile N3C8, the cross-sections slope downwards at about a gradient of 1 on 30, and the variation in bed levels becomes smaller as the water depths increase. The position of the transition from a shallow beach gradient to a shallowly-inclined shore-platform cut into the bed rock here is difficult to determine from these profile surveys; we have estimated that the beach toe lies between about -9 and -11m OD, i.e. between 350m and 500m seaward of the mid-tide beach contour at this location. There appears to be a consistent vertical change in bed levels of about 1m in the 1996 survey of this profile, and along nearby profiles, which we have assumed to be a survey error.

Finally for this section of the coast, Figure 3.5 shows the surveys at Profile N3B3, at Happisburgh, which show that the whole beach/ seabed profile at this location has retreated landwards a considerable distance between the 1990/91 and the 2007 surveys. Here, the upper part of the beach profile falls steeply (gradient about 1 on 20) down to a trough, some 120m to 140m offshore. Further seawards, the bed levels rise again to the crest of a bar at about -2.5 to -3.5m below OD. From this point the profile slopes seawards at a gentler gradient (about 1 in 30) and the surveys show a decreasing variation in the recorded levels as the water depths increase. The three most recent surveys show that these variations in depth are very small by the time the -10m OD contour is reached, and that the bed becomes almost horizontal at little further seawards at a level of about -11.5m OD, and this is presumed to be the shore-platform. Our conclusion is that the beach toe lies between these two contours, i.e. between 400m and 600m seaward of the mid-tide beach contour at this location. The higher bed levels between chainages 430m and 630m shown in the earliest survey are interpreted to be a temporary accumulation of sediment above this platform.

In summary, we have found that the toe of the beaches along the frontage between Cromer and Cart Gap may in places extend as far as 800m offshore and down to about the -11.0m OD contour, i.e. about 8.5m to 9.5m below the lowest tidal level. Along the northern part of this frontage, near Cromer, in places the beach toe is in much shallower water than this, perhaps only 2m below Lowest Astronomical Tide. These estimates of the depth of the beach toe are similar to those presented in the report by Sir William Halcrow & Partners (1991).

3.3 CART GAP (ECCLES) TO GREAT YARMOUTH

3.3.1 Beach sediment longshore transport

The net littoral drift along the frontage from Cart Gap as far as Winterton Ness is generally strong and southwards. The detached breakwaters installed offshore between Sea Palling and Waxham have considerably reduced the natural drift rate along the beaches to landwards of them. However, it appears that the drift rate has increased again near Horsey, some 4km down-drift from the breakwaters. As part of the management of the coastal defences behind the breakwaters, several large sand recharge schemes have been undertaken in this area to restore the supply of beach sediments to beaches further south.

South of Winterton Ness, the net drift rate is such lower, although still generally to the south-east. The beaches and dunes at both Winterton Ness and at North Denes near Great Yarmouth act as temporary storage areas for beach sand, and there is thought to be a localised reversal, i.e. a net northwards drift, just to the south of both of these features (HR Wallingford, 2002a and Royal Haskoning, 2009).

While there has been a modest increase in the width of the beach at and close to Winterton Ness in recent times, and a corresponding growth in the sand dunes, this accretion is slower than would be expected from the difference in the rate of sand arriving from the north and that leaving towards North Denes to the south. This discrepancy is evidence of an offshore loss of sediment from the beaches just north of the Ness, a process discussed further in the next section of this report.

Various estimates of the average net longshore transport rates at different points along this frontage are presented in Appendix 11 of the SNS2 study report (Tables 7.1 to 7.3) that support the above discussion and conclusion. However, there is considerable variation in the estimates of the rates given by different authors for the same locations.

Further south, near Caister-on-Sea, a series of detached rock breakwaters built close inshore and parallel to the coast have resulted in the accumulation of a wide beach behind and to the north of them, as would be expected given the net southward longshore transport of sand. Downdrift of the most southerly of these breakwaters, the beach width becomes much narrower, again consistent with the deduced direction of the net drift.

The long sand-spit just north of the entrance to Great Yarmouth Haven developed under the influence of this drift and diverted the mouth of the estuary to the south over a long period before the entrance position was stabilised by the construction of the masonry walls on either side of it. This is a clear indication of the long-term net southward transport of beach sand along the Great Yarmouth seafront, although various recent estimates of the longshore drift between Caister and the Haven entrance indicate that the net transport rate is low at present (See Appendix 11 of SNS2 (HR Wallingford, 2002a).

3.3.2 Beach sediment cross-shore transport

As discussed in the SNS2 study (HR Wallingford, 2002a) Winterton Ness has been recognised to be an important location at which sediment transport changes direction and so reduces the amount of material that can be transported southwards due to a reversal in the rotation of the tidal current. Overall there is a consistent pattern of development with material moving south along the shore from the north, leaving the shore at Winterton Ness to feed into the Caister and Scroby banks. There is an indication of occasional onshore transport of sediment to the beach immediately south of Winterton Ness. The inferred offshore and onshore transport pathways at Winterton Ness connect the beaches to the nearshore sandbank just offshore from it, and this type of sediment interchange was deduced in the SNS2 study (HR Wallingford, 2002a) to also occur at Caister Ness/ North Denes, just to the north of Lowestoft and at Benacre Ness.

This study also concluded that it was not certain whether sediment entering the nearshore sandbank system at these nesses is still adding to the overall volume of those banks. Both McCave (1978) and Clayton (1989) concluded that these banks were formed from sediments provided by the eroding cliffs between Weybourne and Cart Gap, with the latter paper equating the volumes of beach sediments obtained from the cliff recession over approximately the last 5,000 years and the amount of sand present in the nearshore bank system.

What is not entirely clear is whether sediment is now being lost from the southern ends of the sandbanks at approximately the same rate as it is being supplied from the beaches north and west of Winterton Ness. Some southward loss of sediment from these banks has been deduced to be likely (HR Wallingford, 2002a) as there are several indicators of a southward bedload movement of sand in this region, west of approximately 1º 55' E. If this is the case then the sandbanks are operating as a temporary sink for some of the eroded products of the North Norfolk coastline, and a little sand is then passing southwards towards the outer Thames Estuary.

3.3.3 Nearshore sediment transport

Offshore from the coastline between Cart Gap and Great Yarmouth, the SNS2 study deduced that there was, both under spring and surge tides, a broad stream of sediment transport extending a considerable distance out to sea. In general, the net direction of this nearshore transport pathway.

The pattern of sediment flow is such that while being relatively shore parallel over much of the coast it tends to set against the coast closer to Winterton Ness. Figure 3.6 shows the evidence for sediment transport over the nearshore seabed for this part of the coastline that was compiled during the SNS2 study using analysis of seabed features such as sand waves and using numerical modelling under a variety of different tidal conditions.

3.3.4 Beach toe limits

Figure 3.7 shows the surveys along Profile N3A1 at Sea Palling. Here the seawall is fronted by a series of shore-parallel low-crested breakwaters, located about 300m offshore, and these structures will undoubtedly affect the landward part of the profiles shown in this figure. About 350m to 400m further offshore, there is an evidence of a bar forming on the beach profile, and changes in beach levels appear to extend further offshore still, down to about the -10m OD contour, about 1000m seaward of the seawall. It is uncertain whether changes in level further seawards than this are genuine or simply reflect inaccuracies in the surveys so far offshore, but there is a distinct change in profile gradient at about 1150m offshore, where the level is about -13m OD. Seawards of this point the surveys show a nearly-horizontal surface, presumed to be a bedrock shore platform.

At Horsey, the surveys along Profile N3A6 shown in Figure 3.8 show a persistent trough and bar, with the bar crest level about 2m below OD, i.e. just about as the same level as that of the lowest tides at this location. Beyond this bar, the surveys show clear changes in bed level down to about 7.5m below OD, where the available survey lines coalesce. It is possible that the beach toe is this depth, i.e. about 650m from the seawall. Further seawards, however, the profiles slope gently downward at an approximate gradient of 1 in 125 to a level of -15m OD, and there is evidence of small changes in the recorded levels, suggesting some movement of sediment. Beyond this contour, which lies about 1850m from the seawall, the profiles become steeper, and this must be seaward of the beach toe. Further investigations and survey data would be needed to be certain where the beach toe lies, but to err on the side of caution, we suggest assuming it to be at the -15m OD contour here.

Proceeding further south, the interpretation of the profile surveys becomes more difficult, because they are affected by the presence of tidal channels and banks that run closer to the shoreline as they approach Winterton Ness. Figure 3.9 shows that the first three surveys along Profile N4D3 suggest that the changes in beach level extend out to about 600m offshore, at a level of -7m OD. Beyond this point, these earlier surveys indicate bed slope of about 1 on 50, with little change in level between surveys, interpreted as bed-rock, forming the landward bank of a nearshore channel. The latest survey indicates that this side of the channel has moved landwards, and that bed and beach levels closer inshore became substantially lower between November 2002 and October 2003.

In the context of beach sediment moving offshore, at this location that sediment would first have to enter the tidal channel and then travel up and over the sandbank on the seaward side of that channel to progress further seawards. The depth in the bottom of this channel is greater than the depth of seasonal changes in beach profiles along the coastline further north, so it is unlikely that this could occur.

At this location, provided that any dredging took place to seawards of this sandbank, i.e. further than 2500m offshore, beach sediments could not travel directly into the dredged area. The concern here is therefore not of seasonal draw-down of the beach into a dredged depression but the possibility of the dredging affecting the stability of the nearshore sandbanks.

The surveys along Profile N4B2, see Figure 3.10, show that north of Caister-on-Sea there are large variations in beach and seabed profile to about -5m OD. It is interesting to note the substantial increase in beach width between the 1996 and 2002 surveys, and this likely to be a consequence of the construction of nearshore reefs just to the south of this location. Even after this change in the beach width, there has been no substantial change in levels beyond about the -5m OD contour, which can be taken as the limit of beach profile changes at this location. This contour lies less than 250m from the mid tide contour on the beach face here. Further seawards, there have been substantial changes to the nearshore sandbank. Although this bank has moved towards the coastline by as much as 400m between 1992 and 2007, there is no obvious change either in the depth of the channel that runs inshore of it, or in the bed levels to the landwards of this channel.

Figure 3.11 shows the surveys from the next profile to the south, N4B3. This too suggests the beach toe is at about -5m OD, i.e. less than 300m offshore from the id tide beach contour. Above this level, the beach width and gradients have remained very similar despite the onshore movement of the sandbank, of some 300m, over the 15 year period. This strongly suggests that any changes in bed levels in deeper water and further seaward than this bank would have no effect on the beaches.

Profile N4A5 is situated about 2km north of the entrance to Great Yarmouth Haven, and the surveys here, see Figure 3.12, show changes in bed levels landward of the -5.5m OD contour and a noticeable break in the gradient of the bed where the level is about -8.5m OD. It is concluded that the beach toe here lies between these two contours, i.e. only about 100m to 100m offshore from the mid tide beach contour.

Overall, the review of the cross-sectional surveys taken along the coastline between Cart Gap and Great Yarmouth shows that the lower limit of beach profiles may, exceptionally, reach down to a level of -15m OD to the north of Winterton Ness. More commonly, however, the beach toe appears to be in a water depth of about 7m below mean tide level, or about 600m offshore.

To the south of this point, where the beaches lie landwards of the sandbanks that extend from near Winterton Ness past Great Yarmouth and further south the beach toe appears to be at about -5m OD, reflecting the more sheltered wave environment. The beach changes along this latter part of the coast do not seem to reflect the often substantial changes in the position, the shape and the crest levels of the sandbank that lies in front of them. In this area, therefore, it can be concluded any modest changes in bed levels in deeper water seaward of this bank are very unlikely to affect the beaches.

3.4 GORLESTON TO SOUTHWOLD HARBOUR

3.4.1 Beach sediment longshore transport

Between Gorleston and Lowestoft, the direction of the net longshore transport of beach sediments is generally southward, but has fluctuated over time in several places. At present there is thought to be a northward transport at Gorleston, with wide sand beaches being present to the south of the harbour. In the Hopton area, the net sediment transport is southward and continues as far south as Lowestoft Denes. Between here and Lowestoft Ness, there is no sign of beach widths increasing, implying either a localised reverse, i.e. northward, net drift towards Lowestoft Denes and/ or that sand is being transported offshore here.

There is a localised reversal in drift direction immediately south of Lowestoft Harbour, leading to wide beaches at Children’s Corner. Beyond this, on South Beach, Lowestoft, there are wide beaches that extend south to Pakefield.

The shingle forming the wide beaches in front of Pakefield cliffs is the product of cliff erosion locally or further south, since the cliffs backing South Beach have long been defended. Some 70 years ago, the cliffs at Pakefield were regarded as the location of the most rapid coastal erosion in England, with the sand and shingle released being carried south by longshore drift. At present, the net drift can be inferred to be northwards towards Pakefield where it reduces to close to zero.

There is uncertainty regarding even the direction of the longshore drift between Pakefield and Kessingland, although the SNS2 study concluded that between these locations the net drift was northerly. The large shingle “ness”, previously referred to as Benacre Ness but now closer to Kessingland, has been gradually moving north for many years. The long-term rate of the migration of this ness has been calculated as about 20m per annum (Birkbeck College and Babtie, 2002) who also showed the total volume of sediment there had increased. However there is still uncertainty about how this occurs, and to what extent the increase in volume is partly caused by an onshore movement of sediment from the nearshore seabed.

Further south, at a point between Kessingland village and Benacre Broad, the general pattern of southward littoral drift is re-established. The massive accumulation of shingle on the north side of Southwold Harbour has been produced over many years by this net southward littoral drift.

Appendix 11 of SNS2 (HR Wallingford, 2002a) summarises estimates of drift rates between Gorleston and Southwold Harbour produced by various authors. As far south as Lowestoft, as for the frontage between Winterton Ness and Great Yarmouth, there are considerable differences in those estimates, partly due to considering different time periods and different nearshore seabed bathymetries, particularly as a result of the continual varying of the nearshore sandbanks.

3.4.2 Beach sediment cross-shore transport

The glacial drift cliffs between Gorleston and Southwold Harbour have been subject to long-term erosion. As they have receded, they have produced substantial quantities of sand and gravel which have generally been carried southwards by longshore drift. Some of these cliffs have been defended for many years, e.g. behind South Beach at Lowestoft and at Southwold, while other sections continue to recede rapidly, for example at Benacre, Covehithe and at Easton Bavents. The variability in the longshore drift rates along this coastline and at different times results in variable beach widths, so that other sections of cliff that once eroded are now well protected and vice versa.

In addition, there is thought to be an interchange of sediments between the nearshore banks and the beaches, for example just to the south of Lowestoft Harbour where sand appears to come ashore onto South Beach. There may also be both onshore and offshore movements of sediment near the ness at Kessingland, as at Winterton Ness further north, although this is still speculative. It is clear, however, that such putative onshore/ offshore sediment movements are complicated, may change over time and have been inferred, rather than being directly measured.

3.4.3 Nearshore sediment transport

This section of coast, and the nearshore sandbanks that front much of it, have a complicated sediment transport regime which changes over time as the sandbanks and channels alter their positions and change shape.

Figure 3.13 shows the evidence for sediment transport over the nearshore seabed for this part of the coastline compiled during the SNS2 study using both an analysis of seabed features such as sand waves and using numerical modelling under a variety of different tidal conditions. This figure can be interpreted, from the viewpoint of beach evolution, as suggesting an onshore transport of sediment (mainly sand) from the nearshore bank system to the beaches just south of Lowestoft Harbour and again to the coastline just south of Kessingland/ Benacre Ness.

Between Benacre and Southwold, to seaward of the beaches themselves, there appears to be no clear net transport direction in the nearshore zone, and there is an implication of a convergence of seabed transport pathways further offshore from Kessingland/ Benacre Ness.

3.4.4 Beach toe limits

Figure 3.14 shows that along Profile SWG2, at Gorleston-on-Sea, beach levels vary more noticeably above the -5mOD than further seawards and that there is a change in the seabed slope about 850m offshore, where the bed level is about 10.5m below OD. It is likely that the beach toe is closer to the former level, as along the frontage north of Great Yarmouth, but taking the limit as -10.5m OD would err on the side of caution when considering beach drawdown at this location.

Surveys along Profile SWF7 close to Lowestoft Ness, presented in Figure 3.15, show deep water close inshore and no distinction between the inter-tidal and the sub-tidal bed slope. There is some indication of more noticeable, perhaps seasonal, changes in levels landwards of the -5m OD contour and a marked change in bed gradient at about the -8m OD contour, i.e. about 180m offshore. Given the steepness of this inshore slope would not be surprising if sediment eroded from the beach was drawn down to a depth of about -8m OD, and then transported alongshore by tidal currents.

It is worth remarking that the beach width and gradient here have shown little sign of change despite the considerable lowering and onshore movement of the sandbank which lies 2 km to 2.5 km offshore. Dredging in deep water seaward of this sandbank is unlikely to affect the beach, for example by causing any drawdown of sand.

In Figure 3.16 the surveys of Profile SWE8 off Kessingland, the beach width has increased by some 250m between 1992 and 2007, forming a roughly horizontal crest at about 3mOD. There have been noticeable changes in the levels on the face of this steep shingle beach down to about -5m OD. Between chainages of about 1150m and 1200m, there appears to be less variability, suggesting that this part of the profile which forms the landward side of a shallow channel, may be exposed bedrock. Beyond this channel there is a low-relief bank which has moved onshore over the same period. Dredging of the seabed beyond about 3500m from the coastline here would seem very unlikely to directly affect the beaches that are partly sheltered by the bank, for example by inducing any drawdown and offshore transport of beach sediments into the dredged depression.

South of the pier at Southwold, surveys along Profile SWD9 (see Figure 3.17) show the inter-tidal beach is narrow and drops relatively steeply (at a gradient of about 1 in 16) into what appears to be a double trough and bar system. The first channel lies some 80m to 100m offshore, and the second a further 280m offshore. There are bars seaward of each trough with crest levels of about -2m OD and -4m OD respectively. The bed profile flattens 600m offshore at a level of about -9m OD and it seems likely from the small variations in recorded levels that this is a bedrock platform that extends a further 250m seawards. There has been, however, a gradual increase in bed levels between about chainages 800m and 1100m, with the gradient (at 1 in 50) of the seabed suggesting an accumulation of sediment this far seawards. A similar pattern is shown on the next profile to the south (not shown in this report). It is unclear whether this sediment has travelled offshore, parallel to it or some combination of both.

In the light of this, it is considered that it would be prudent to treat the seaward limit of the beach profile in this area as about -15m OD, i.e. about 1200m offshore at the base of the change in bed levels shown in Figure 3.17. This low level for the toe of the beach at Southwold is considerably greater than the maximum depth indicated in the 1991 study undertaken by Sir William Halcrow & Partners.

In summary, the lowest estimated depth along the coastline between Gorleston and Southwold Harbour at which there may be seasonal changes in beach levels is conservatively estimated at -15m OD, or about 13.5m below lowest tidal level, thus possibly extending as far as 1500m off the mid tide contour on the beach face. This is much deeper than the previously estimated maximum depth for the beach toe along the East Coast of England, and may be an over-conservative interpretation of the cross-sectional survey data provided by the Environment Agency.

3.5 WALBERSWICK TO ORFORD NESS

3.5.1 Beach sediment longshore transport

There is a general north to south alongshore transport along this stretch of coastline. At Walberswick, the beach just to the south of Southwold Harbour experiences a net northward drift, and has remained stable, in part benefiting from the transfer of sand that is carried in suspension across the harbour entrance from the beaches further south. It is unclear whether any gravel manages to bypass the harbour mouth.

The entrance to Southwold Harbour and the Blyth Estuary further upstream was entrained as early as the 16th Century and the effects on interrupting the longshore drift at least partly explains the recession of the coastline further south, estimated to be 120m by Taylor and Marsden (1983). This southward drift has historically led to the southward transport and loss of beach sediments from this part of the coast, exposing the cliffs at Dunwich to wave action and resulting in their recession, as described in Chapter 2 above. Clayton et al. (1983) estimated the long-term rate of sediment supply to the beaches from the erosion of these cliffs as about 40,000 cubic metres per annum.

Calculations of the net rates of sediment transport along the stretch of coastline between Walberswick and Dunwich were reviewed by Pye and Blott (2009) who concluded "Modelling by Halcrow (2001) suggested net southerly sediment transport of 9,000m^3 / yr along the Corporation Marshes frontage and net southerly transport of 12,100m^3 / yr at Dunwich. On the other hand, modelling by Black and Veatch (2006) suggested a net northerly transport of 8,000 m^3/yr for 10mm gravel and 27,500m^3 for 2mm gravel off Reedland Marshes, with a net southerly transport of 3,800m^3/yr and 13,900m^3/yr for 10 mm and 2mm gravel, respectively, at Dunwich Cliffs. A net sediment transport divide may therefore exist between Dunwich and Walberswick, the exact location of which depends on wave conditions and beach morphology, which are time-variant".

More generally, it is believed that the longshore sediment transport between Southwold Harbour entrance and Thorpeness is affected by wave transformation over the Sizewell-Dunwich banks, which appear to be growing in volume. Appendix 11 of the SNS2 study provides, in Tables 8.1 and 8.2, other estimates of the net annual drift rates, which vary considerably between different papers and reports. For example, two of the calculated drift rates at Sizewell are 85,000 and 3,450 cubic metres/ year; there is an even greater variation in predictions of drift rates along the beach near Thorpeness.

At present the rates of recession of the beach from Walberswick to Dunwich and beyond seem to be low, suggesting the net longshore drift along this gently concave section of coastline is small, and the cliffs at Dunwich are retreating only very slowly. Recession of the barrier beach between Walberswick and Dunwich seems to being caused by over-washing of the narrow shingle ridge during severe storms rather than by more sediment leaving to the south than the small amount arriving from further north.

Further south, just to the north of Thorpeness village, there is a modest shingle ness and the interactions between the ness and the banks offshore are thought to involve an interchange of sediments between the seabed and the beaches.

From Thorpeness past Aldeburgh towards Orford Ness, the longshore drift regime seems to be more straightforward, with the net southward transport of shingle having produced a long spit that has deflected the mouth of the River Alde a long way south. There has been a recurring problem of beach erosion at and south of Aldeburgh because the drift rate there can exceed the rate of arrival of beach sediment from further north. As discussed above, there have been significant variations in both the rates of longshore drift approaching Thorpeness and in the rate at which cliff erosion at Dunwich provides extra beach sediment. The historical erosion and the losses of much of Aldeburgh itself, mentioned in Chapter 2, have been stemmed by building seawalls and groynes but there is a continuing long-term problem of the beach at Slaughden, a little further south, becoming very narrow and liable to breach. Beach recharge has been carried out there in recent decades to prevent this occurring.

3.5.2 Beach sediment cross-shore transport

The beaches between Walberswick and Orford Ness are composed primarily of medium to fine-grained shingle. Some shingle probably manages to reach the beach near Walberswick from further north, having crossed the mouth of Southwold Harbour, but the main supply of the shingle found on the beaches between here and Orford Ness comes from the 3km long stretch of cliffs at Dunwich. The erosion of these cliffs will also provide some sand adding to that which travels in suspension past Southwold Harbour entrance. Along most of this section of coastline, sand is usually limited to the lower foreshore, i.e. below mean tide level, or to the nearshore sub-tidal seabed. However, there are dunes at Minsmere, just south of Dunwich Heath, where sand covers the crest of the shingle ridge.

The movement of shingle by wave action is preferentially landwards and the amount of material ‘lost’ seaward during periods of beach drawdown (winter storms, for example) is thought to be small. However, the ebb currents through the mouth of the Ore/Alde estuary are sufficiently strong to deflect the shingle seawards, so that the shingle spits at its mouth extend seaward to about the -4m OD contour. Some shingle may therefore be moved even deeper seaward at this location.

Sand is able to be transported seaward by severe wave action and indeed is thought to feed into the nearshore bank systems (British Geological Survey, 1988). There is no evidence of any landward sediment transport in this area, and it is more likely that sand travelling south of Minsmere is lost offshore.

As noted in the previous section, there is evidence that the volume of the Sizewell - Dunwich banks is increasing. Robinson (1980) concluded that “there was no indication that it supplies any large quantity of sediment to the adjacent beach at Dunwich”, while noting that Sizewell Bank had moved slightly closer towards the coast.

Overall, there is an inference that beach sediments are being lost offshore from this frontage, and that the nearshore sandbanks are increasing in volume.

3.5.3 Nearshore sediment transport

The nesses along the East Anglian coast are thought to be points of transfer of sediment between the coast and the nearshore seabed. Orford Ness is a shingle spit that is contiguous with the Aldeburgh beaches to the north, but separated from the coastline to the landward and southward by the River Ore. Sand is believed to be transported seaward at the ness, whilst shingle tends to be transported southwards along the spit itself, to ‘rejoin’ the coastline at Shingle Street.

The Southern North Sea Sediment Transport Study (HR Wallingford, 2002a) indicates that there is no major supply of sediment to the coast from offshore (see Figure 3.13).

The nearshore banks off this coast probably do not provide material for the beaches (i.e. there are no sediment transport pathways from the Shipwash, Bawdsey or Whiting Banks to the nearshore zone, for example).

3.5.4 Beach toe limits

At Walberswick, the surveys along Profile S1C3 (see Figure 3.18) show the landward retreat and lowering of the shingle barrier beach crest which was over-washed and damaged further in a storm in November 2007, soon after the latest of the surveys shown. There is either a break in the steep slope of the shingle beach, or an indistinct trough at about -1m OD before the beach slopes down again into a more persistent trough about 180m offshore. There is a small bar beyond this trough, and from its crest the profile slope gradually decreases so that by between 500m and 700m offshore it is virtually horizontal. Here, at a depth of between -6.5m and -7.5m there is no clear sign of variations in level other than those expected as a result of survey inaccuracies, and the beach toe here is therefore concluded to be no deeper than about -7.5m OD.

Further south off Sizewell Power Station, the cross sectional surveys, for EA Profile S1B6, presented in Figure 3.19 show two troughs with bars to seawards of them, the more seaward bar being more distinct. From the crest of this bar, the profile slope gradually decreases so that by between 600m and 700m offshore it is virtually horizontal. At this location, there is no clear evidence of changes in level at or beyond a depth of about -8.5 OD and this is concluded to be the level of the beach toe at this location.

Within the stable embayment between Thorpeness and Aldeburgh there is a wide backshore (shingle) with a steep inter-tidal face that extends down to about -4mOD, as shown in Figure 3.20 (Profile S1A3). Beyond that there is a very shallow seabed gradient, becoming virtually horizontal some 700m offshore. The limit of substantial changes in bed levels along this profile, bearing in mind the discrepancies between the surveys which become more apparent further offshore, appears to be at about -5m OD and this may well be level of the beach toe here. However, to err on the side of caution we feel it would be safer to assume the beach may extend down to the break in slope about 700m offshore, where the level is about -9m OD.

Figure 3.21 shows the surveys for the whole of Profile S1A, i.e. extending out from the coastline to and over Aldeburgh Ridge. There are very clear indications of changes in the beach profile down to about -8.5m OD and a subtle break in bed slope at about 500m where the level is -10m OD. The beach toe lies between these two depths at this location. The onshore movement and lowering of Aldeburgh Ridge and the seaward advance and widening of the shingle beach shown in this figure do not suggest any transfer of sediment between the two; it is more likely that the changing position and shape of the bank has altered the waves travelling over it, and this in turn has altered the plan shape of the beach north of Orford Ness.

Overall, therefore, the maximum depth of the beach toe between Walberswick and Orford Ness appears to occur at the very southern end of this frontage, despite the partial shelter provided by Aldeburgh Ridge, at a level of about -10m OD, or about 8.5m below the lowest tidal level, and typically no more than about 600m offshore of the beach face.

3.6 SUMMARY

In this chapter, we have provided an overview of the transport of sediments on the beaches and across the nearshore seabed between Cromer and Orford Ness.

The predominant cause of beach changes along this coastline is the variation in the longshore transport of sediments, and in places the longshore transport regime is strongly affected by the changes in the positions and levels of sandbanks, especially between Winterton Ness and Lowestoft.

Overall, the beaches receive sediment from erosion of sections of the glacial till cliffs that are not protected by seawalls, and much of the sand that is supplied by this erosion eventually travels offshore. There is little in the way of any net onshore movement of sediment from the seabed to the beaches except south of Lowestoft Harbour where some of the sand that previously left the Norfolk coast near Winterton Ness returns to the shoreline after travelling through the extensive nearshore sandbank system between these two locations. To the north of Winterton Ness and to the south of Walberswick, the evidence suggests only offshore losses of beach sediments.

To contribute to the guidance needed on the minimum water depth where aggregate extraction might be considered with no risk of beach sediments being drawn-down into the dredged area, we have reviewed cross-sectional surveys commissioned by the Environment Agency to establish the lower limit of the beaches. This review has typically produced, at each location, a conservative estimate of the depth to which changes in beach level are apparent and a greater depth at which the slope of the profile changes suggesting a transition from beach sediments to a bedrock shore-platform.

To the north of Winterton Ness and to the south of Lowestoft, this analysis suggests beach profiles may, in places, reach a bedrock platform at depths of up to -15m OD, and perhaps up to 1800m offshore from the mid-tide beach contour. This estimated depth is considerably lower than for the suggested beach toe limits in the 1991 report produced by Sir William Halcrow & Partners, but in this report we have deliberately taken a very conservative approach, to err of the side of caution.

Where there are nearshore sandbanks, the depth to which beach levels have been seen to alter; in some places the beach toe may only inshore of the -5m OD contour. This is generally the case between Winterton Ness and Lowestoft. Along this stretch of coastline, however, the presence of one or more tidal channels and banks means that direct draw-down of beach sediments into a dredging area located seawards of the banks will not occur. Off much of the coastline between Cromer and Orford Ness, therefore, the nearshore limits of any proposed aggregate extraction area need to be considered in the context of whether the dredging might cause offshore sand transport and lowering of the sandbanks that lie closest to the area’s inshore boundary, rather than there being any risk of beach sediments being drawn-down into the dredged depressions.

4. *Coastal defences, management and vulnerability*

The information for this part of the study has been gathered from Shoreline Management Plans, coastal defence Strategy Studies, FutureCoast (Halcrow 2000), and previous Coastal Impact Studies for offshore aggregate dredging applications, supplemented by dedicated site visits undertaken by an experienced coastal engineer.

4.1 CROMER TO CART GAP (ECCLES)

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4.1.1 Description of the coastline

This stretch of the North Norfolk coastline is characterised by unconsolidated Quaternary sand, gravel and assorted glacial deposits that overlie an eroded chalk platform. Erosion of these deposits has produced unstable cliffs that are prone to rapid erosion. The erosion has been most rapid within this coastal unit, with cliff recession, averaged over the frontage, being of the order of about 1 metre per year prior to the construction of coastal defences (Cambers, 1976).

These cliffs have been protected over parts of this frontage, typically by seawalls in built up areas and timber revetments on the less densely populated frontages. Differences in the protection afforded, together with differences in lithology, have resulted in wide variations in the rates of the average cliff retreat, being as low as 0.5 metres per year between Cromer and Overstrand and as high as 1.3 metres per year between Overstrand and Trimingham (HR Wallingford, 2005). Now that the timber revetments are reaching the end of their useful life, increases in the cliff recession rate can be expected. This is of great importance as these cliffs are the main provider of beach sediments for this region (North Norfolk District Council, 2007).

The cliffs at Overstrand, Sidestrand and Trimingham, as well as Mundesley, are designated Sites of Special Scientific Interest (SSSI). Within this stretch of cliffs is a Special Area of Conservation and there are three County Wildlife Sites, so the continuance of cliff erosion will enable the geology of these eroding coastal cliffs to be inspected.

The beaches themselves are predominantly sandy at the surface, with underlying pebbles accumulations tending to be exposed in runnels and also collecting in the troughs at the base of seawalls. Because of differential rates of erosion and varying substrata the inter-tidal beach width varies greatly, but generally tending to be narrowest where defences are seaward of the natural plan alignment of the coast (Overstrand, for example). The trapping of sediment by these promontories results in an uneven distribution of beach material along this coastal unit.

The cliffs are vital to the downdrift coastlines, supplying some 400,000 cubic metres of sand and gravel per year to the sediment budget. This is approximately two-thirds of the volume eroded and the remaining third, comprising finer sands, silts and clays, is mainly transported offshore in suspension.

4.1.2 Coastal defences and management

Between Cromer and Overstrand the coastline is groyned but has no backshore defences, so that cliff erosion continues, providing relatively wide beaches.

On the northern outskirts of Overstrand, there is a timber revetment and groynes. This frontage is well stocked with beach material (Plate 1).

By contrast, the adjoining concrete seawall at Overstrand has had its footings extended several times as beach levels have fallen, further narrowing the inter-tidal beach (see Plate 2). This frontage is exposed to wave attack and the cliffs backing the seawall have themselves been stabilised by gabion baskets filled with stone. This frontage now forms a “promontory” due to rapid rates of erosion on either side of it. The timber revetment to the south of the wall is no longer protecting the cliff toe effectively and the cliffs behind it have undergone slippage and their toe has had to be weighted with rock armour.

The lightly populated frontage between Overstrand and Trimingham remains unprotected. The predominantly sandy beach along this frontage is backed by cliffs that are part of a SSSI. These are subject to large failures and slumping, as well as rapid erosion as the material is removed from their toe. The highest rates of cliff recession are found here, averaging over 1.5 metres per year over the last century.

Periodic failures of the cliffs have caused extensive damage at the northern of the timber revetment fronting Trimingham, so that the backshore defences there are now discontinuous. Further failures can be expected as the revetments deteriorate (there are no plans to maintain them). The protection by timber revetments and groynes extends to the concrete block cribwork before the well-maintained seawall at Mundesley is reached (see Plate 3).

Timber revetments extend from Mundesley to Bacton, where they protect the Bacton Gas Site, located near the cliff top. Both the revetments and the groynes are in reasonable condition along this frontage, whilst the cliffs themselves are more stable than on the frontages further northward/ westward. Cliff recession has averaged at over 1 metre per year over the last century, but has now substantially reduced. Some rock armour protection has been provided to the lower part of the cliff face at Paston (see Plate 4).

Between Bacton and Ostend the concrete seawall is fronted by permeable timber groynes. The low-lying frontage between Bacton and Walcott is susceptible to wave overtopping, since the inter-tidal beach there is quite narrow, not being to readjust its profile as erosion progresses in front of the wall (Plate 5).

The lightly populated frontage from Ostend to Happisburgh is protected by timber revetments and groynes. The revetment south of Ostend was built in the 1990s, has been recently maintained and is in good condition. However, at the southern end of this frontage there is a marked deterioration in the condition of the defences, with the timber revetment and groynes at Happisburgh now being totally destroyed. Some rock armour has recently been to the cliff toe, but this protection is very localised (Plate 6). Any increase in wave energy would have a significant impact on cliff erosion rates that are already very rapid.

Between Happisburgh and Eccles the cliffs were earlier protected by timber revetments and groynes, but these defences are no longer present. Erosion along this frontage has produced a pronounced embayment that acts to trap the southward transport of beach material.

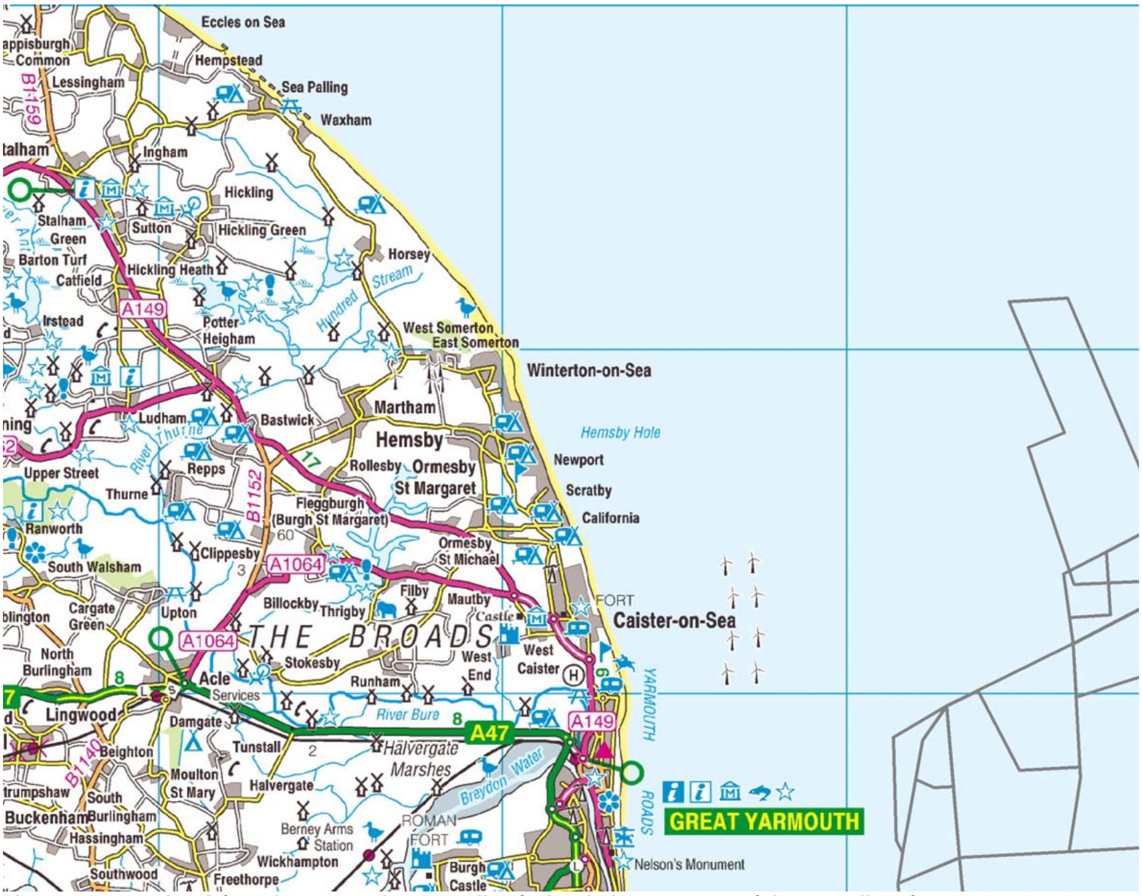
4.1.3 Coastal vulnerability

Much of this coastline is extremely vulnerable to wave action. Timber defences are reaching the end of their useful life in a number of places (e.g. Trimingham and Happisburgh) and once they become ineffective the rates of cliff retreat will accelerate in many frontages (as has occurred in recent years at Happisburgh).

The protected stretches are also vulnerable, with beach levels in front of the seawalls falling, requiring the extension of footings so as to prevent undermining (as at Overstrand). As beach levels fall, so the rates of wave overtopping will increase.

Between Bacton and Walcott, where the coast road runs close to/ parallel to the shoreline there is already a flood risk, which would be exacerbated by any increase in wave activity.

4.2 CART GAP (ECCLES) TO GREAT YARMOUTH



Note: The grey polygons indicate relinquished, licensed, application and prospecting Licence Areas.

4.2.1 Description of the coastline

To the south of Happisburgh the cliffs become lower and finally, near Sea Palling the land becomes low-lying and fronted by sand dunes. Erosion has often led to sea breaches and flooding. Notable breach events include one at Horsey in 1938. During the most recent breach at Sea Palling, during the 1953 surge, much of the hinterland was flooded.

Backshore levels increase at Winterton Ness, where dune ridges have accreted in front of the former cliff line. However, the ness is migrating northwards and as it does so, it leaves a zone of erosion on its southward flank. Thus, the sandy cliffs at Hemsby, just south of Winterton Ness, are experiencing erosion. The interaction of the ness and the nearshore seabed movements is poorly understood and its future development is difficult to predict. However there is a generally held view amongst coastal geomorphologists that nesses are locations where sand is transported offshore to accumulate on the nearshore sandbanks, which act as temporary sediment stores.

Further southwards there is a deficit in sediment supply and cliff erosion has been estimated as being of the order of 0.8 metres per year to the north of Caister. The frontage from Scratby to California is now protected by a shore parallel rock sill.

Further southward, at Caister-on-Sea, rock reefs and groyne have been used to build up beach levels. The recent accretion in this area coincides with the onshore movement of the nearshore sandbank, as described in the section “Beach Toe Limit”).

From Caister southwards to Great Yarmouth conditions rapidly improve, so much so that the old sea defences are now fronted by a belt of sand dunes. Royal Haskoning (2009) refer to a possible interchange of sand between the nearshore sandbanks and the shoreline in recent years.

4.2.2 Coastal defences and management

The low cliffs at Eccles are protected by a concrete seawall, but in earlier centuries they were subject to rapid retreat over several centuries, causing several villages in this area to be “lost to the sea”.

The continuous line of sea defences that extends from Eccles southwards to Winterton Ness was built as part of the reconstruction work that was carried out after 1953 surge. The emergency works included seawalls constructed of “sand-cement” bags stacked against the eroded dune face, but these were subsequently replaced by a concrete seawall (see Plate 7). Beach levels nevertheless continued to fall and nine shore parallel offshore reefs were constructed between Eccles and Waxham between 1993 and 1997 (see Plate 8). The beaches are monitored regularly and maintained by means of beach recharge and/or recycling.

The seawall extends to Winterton Ness, where it disappears behind the line of sand dunes that provide natural protection for the hinterland. The ness appears to have migrated southwards some 1.5km between 1833 and 1966, but has moved northwards in recent years. This alongshore migration is thought to be related to changes in wave activity caused by movements of offshore sandbanks. The area of accretion extends southward to Winterton-on-Sea (see Plate 9), but from there southwards to Hemsby, the beach/backshore width reduces.

From Hemsby southwards, the beach is sufficiently narrow to allow waves to reach the cliff toe (see Plate 10, showing the cliff erosion at Hemsby Hole). This frontage is undefended. However, from Scratby southwards to California, the eroding cliffs of sands and clays are protected by a rock sill placed near the cliff toe (see Plate 11).

South of California land levels drop and sea defences extend from Caister-on-Sea southwards to Great Yarmouth harbour entrance. In the past the northern part of this frontage was affected by severe erosion and the seawall at Caister-on-Sea was badly damaged in the 1970’s, with the destroyed northern end of the seawall being subsequently replaced by an asphaltic revetment. More recently a number of rock reefs and groynes have been installed along this frontage and there is now a considerable sand build-up in this area (see Plate 12). This frontage to the southward is also relatively healthy and the seawalls that extend southward to Great Yarmouth are now virtually redundant and are engulfed by sand dunes at Caister Point, for example. Thus, the defences south of Caister Point require little attention at present.

At the north end of the Great Yarmouth seafront, sand has accreted to form a ness feature at North Denes, which lies in the shelter of Middle Scroby Sand. The Ness has been prograding since the 1930's, since when it has advance seawards over 300m. However, the beach has not been accreting very much in recent years at the southern end of this frontage (near the mouth of the Yare). There is circumstantial evidence that the patterns of southwards littoral drift may be modified locally and that the net transport may now be northward towards the ness. Thus, at the present time the frontage between Caister and Great Yarmouth is healthy, with the exception of some narrowing of the beach near the harbour as a result of the possible localised reversal in drift direction.

4.2.3 Coastal vulnerability

The stretch of the coastline from Eccles to Winterton has experienced long-term coastal retreat, with the dunes being vulnerable to breaching. After the 1953 surge, which caused disastrous flooding of the hinterland, seawalls were installed along this frontage. However, beach levels in front of these walls have continued to fall. Offshore reefs were constructed in the 1990s, so as to counter this tendency. However, whilst these reefs have stabilised localised stretches of coast, the fundamental problem of an inadequate sediment supply from the north remains. It will therefore be necessary to continue to recharge the beaches as part of their maintenance, and, in addition, it may also be necessary to recycle/bypass beach material around the reefs themselves.

Further south, near Winterton Ness, there is large scale sand accretion at the present time and the sand dune belt is sufficiently wide to be unlikely to be breached. By contrast, the eroding coastline between Hemsby and Caister is vulnerable to any increase in wave activity that would accelerate the rates of cliff erosion. From Caister to Great Yarmouth the beaches are presently healthy, but the situated could be reversed if the sediment supply reduced, or if the patterns of sediment transport altered (by changes in the positions or heights of nearshore sandbanks, for example).

4.3 GORLESTON TO SOUTHWOLD HARBOUR

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Note: The grey polygons indicate relinquished, licensed, application and prospecting Licence Areas.

4.3.1 *Description of the coastline*

This coastline has been modified by both natural and man made changes. Historically there was a strong southward littoral drift at Great Yarmouth, producing a massive sand spit on which the town has developed. This spit once extended 4km southwards, as far as Corton. Development of the harbour interrupted the southward drift, so that this spit rapidly declined, re-exposing the coastline from Gorleston to Corton (formerly in the lee of the spit) to direct wave action.

Although the coastline immediately south of the harbour is strongly “set back”, the sand beach just to the south of the harbour mouth is presently relatively stable, possibly due to a local reversal in drift direction.

Further southward, towards Corton, the southward littoral drift is re-established and erosion predominates. Whilst the erosion may be caused principally by a lack of supply from the northward, the patterns of erosion and accretion in this area are also thought to be affected by changes in the morphology of the nearshore sand bank, Scroby Sands (HR Wallingford, 1998). At Corton there are derelict sea defences to the seaward of the present defences, which are evidence of the coastal retreat.

In direct contrast, between Corton and Lowestoft there is a massive area of accretion of sand and shingle and the former cliffs are now well to the landward. However, erosion is now taking place between Lowestoft Ness and the North Pier. The ness feature at Lowestoft may have formed where littoral drift from the northward may have converged with a small amount travelling north from the cliffs of the Suffolk coast (although at present drift is southward on both the northern and southern flanks of the Ness). Lowestoft Ness has suffered progressive erosion over the last century (the zone of present accretion is now some 1.5km to the northward). Lowestoft Ness is now heavily defended, so as to protect industrial development in the immediate hinterland.

South of Lowestoft the beaches are generally healthy, due to a reversal in drift direction. However, at Pakefield, to the south of Lowestoft the beach is predominantly shingle, possibly the result of the northward migration of Benacre Ness. From there southward there is a line of eroding cliffs that extend almost to Kessingland. Long term cliff retreat has been of the order of 0.1 to 0.3 metres per year (Royal Haskoning, 2009). By the time the northern outskirts of Kessingland are reached there is a widening beach due to the northward migration of Benacre Ness. Kessingland itself is fronted is fronted by a massive accumulation of shingle, with the vegetated shingle backshore being up to 200m wide (this was a frontage where erosion was dominant only 40 years ago). The accumulation is due to the northward movement of Benacre Ness, which has been taking place at a rate of about 20m/year (Birbeck College and Babtie, 2000).

South of Benacre Ness the sandy cliffs extend southwards to the northward outskirts of Southwold at Easton Bavents. These cliffs are eroding rapidly as Benacre Ness continues to migrate northward. Recession rates of up to 4.5 metres per year have been recorded over parts of this frontage (Royal Haskoning, 2009). These cliffs are separated by stretches of low-lying land backed by saltmarsh. These were once small river estuaries draining low-lying inland areas. The estuaries became blocked by the southward movement of beach material, forming storm ridges. Upstream, the estuaries were filled by sediment and fringing marshes developed. The storm ridges are migrating landwards at approximately the same rate as the cliff retreat.

This rapid cliff erosion is providing sediment to the beaches at Southwold, whilst also feeding Benacre Ness during periods of reverse drift. However, there has been a variation in the source material from gravel to sand with time, as the gravel in the cliffs occurs in discrete, discontinuous sheets and lenses. Moreover, continued coastal retreat threatens the stability of the shingle ridges that protect the Norfolk Broads against saline intrusion. McCave (1978) reported that from Kessingland and Covehithe the shingle percentage increases from 60% up to 100% at Orford, indicating that sand is most likely to be transported offshore, possibly at Southwold Harbour.

Since Southwold has been defended by concrete walls for a long time, continuing cliff recession to the north has resulted in the town’s defences gradually projecting further seaward than the natural line of the coast on either side of them, although to the south this tendency has been offset by the accretion that has taken place against the north pier of Southwold Harbour.

4.3.2 Coastal defences and management

Immediately to the south of Great Yarmouth’s harbour mouth there appears to be a localised drift reversal and the beaches there are healthy. Between Gorleston and Corton there is a variety of defences, with seawalls protecting the developed frontages at Gorleston, Hopton and Corton, and timber revetments protecting the less densely populated stretches between. The sand beaches over this frontage are groyned. Whilst the beaches at Gorleston are presently so wide as to almost envelop the groynes, they become quite narrow by the time one reaches Hopton (see Plate 13). Note the poor state of the seaward ends of the groynes at Hopton.

Conditions deteriorate further still at Corton, where it has proved difficult to maintain the integrity of the defences, due to falling beach levels. Protection is now provided by rock armour, which is placed in front of the sheet steel piling, and on the cliff face itself (the groynes that were present in front of the earlier defences have not been replaced). Plate 14 shows remnants of old sea defences well to the seaward of the line of the present defences. The frontage at Corton now forms a slight promontory and is extremely sensitive to any increase in wave activity (beach lowering is taking place in front of the defences).

The backshore width increases south of the Corton seawall and the cliffs at Gunton Warren are now situated well landward of the active beach. This frontage was the northward flank of Lowestoft Ness when this area was accreting. From North Beach southwards, the beach in front of the concrete seawall becomes narrower, so that by the time Lowestoft Ness (now a misnomer) is reached, the inter-tidal zone is now very narrow. Here, the defences are constructed over the old shingle ness. Plate 15 shows the rock armour protection on the seaward face of the seawall. This frontage is groyned, but the groynes are generally in a poor state of repair and not providing much useful function.

The sand beaches from the harbour southwards as far as Pakefield are groyned and increase in width in a southward direction, so much so that the groynes are virtually buried over much of the frontage. The accretion may be the result of northerly local littoral drift. The sloping cliffs along this frontage are protected by a concrete seawall that, at present, reduces the capacity of waves to erode them. Indeed, sand has accreted to the crest of the wall in places.

At Pakefield, the coastline has a very pronounced landward “set-back”, due to cliff recession in the past. This frontage now has a massive shingle foreshore that provides an effective backshore protection. The accretion is probably the result of the northward migration of Benacre Ness. The rapidity of change from erosion to accretion is illustrated in Plates 16 and 17, dating from 1967 and 1996 respectively.

South of Pakefield and as far as Kessingland the shingle beach is quite narrow and the cliffs (known as Pakefield Cliffs) are subject to erosion (this frontage has no defences).

Conditions improve again at Kessingland, where the seawall is now fronted by a very wide sand and shingle beach, the result of the northward migration of Benacre Ness (see Plate 18). This beach is more than 200m wide in front of the village.

The coastline from Kessingland southwards to Easton Bavents has no formal defences. Whilst Benacre Ness offers a high degree of protection at Kessingland, its northward migration produces erosion on its southern flank. Plate 19 shows the rock armour protection to the outfall at Benacre Pumping Station.

The coastline between Benacre Ness and Southwold is undulating, with eroding sandy cliffs interspersed by low ground and drowned river valleys containing Benacre Broad, Covehithe Broad and Easton Broad. The cliffs along this frontage are eroding extremely rapidly. The broads themselves are fronted by sand and shingle ridges, which are in the process of roll-back, as the coastline retreats. The ridge fronting Benacre Broad is still substantial, but old tree stumps on the seaward side of the crest testify to the rapid retreat that is now taking place there. The other two broads are in an area that has been retreating for a much longer period of time and the shingle ridges there have to be maintained to reduce the threat of breaching/ overtopping and saline intrusion into the broads. Despite the maintenance, the shingle ridges can be overtopped and flooding has extended within Easton Broad as far inland as the B1127 road (Royal Haskoning, 2009).

The cliffs extend to the northern outskirts of Southwold. At the southern end of the Easton Bavents cliffs, local residents previously installed and maintained informal sea defences, by banking imported fill material against the lower part of the cliff face. These attempts to reduce the rate of cliff recession have now been discontinued, and the material placed has been eroded, and then transported both offshore and alongshore by wave action. Where the cliffs abut the northern end of the Southwold sea defences a concrete block revetment was constructed so as to prevent the seawall from being outflanked (the low-lying land behind the seawall might then have become prone to flooding).

A concrete seawall and groynes extend over the low-lying frontage immediately to the north of the town and the cliffs at the town itself. With long-term erosion of the cliffs to the north having taken place in the historic past, Southwold now forms a promontory, so that the beaches in front of the seawall are prone to beach drawdown. Beach levels were improved by artificial recharge with marine aggregate in the recent past, new rock and timber groynes also being added, together with seawall improvements also being made. Plate 20 shows that this frontage nevertheless remains vulnerable to erosion. Note the northward littoral drift in May, 2009, at the time the photograph was taken. The drift along this frontage is predominantly southward and is responsible for the massive sand and shingle accretion on the north side of Southwold Harbour. However, the net drift is of the order of only 3000 cubic metres per year, and with frequent reversals of direction (Royal Haskoning, 2009).

Between Southwold and Southwold Harbour there is a stretch of low-lying land fronted by a wide sand and shingle beach that has accumulated on the north side of the Southwold Harbour’s north pier. This beach forms a natural line of defence for this frontage, and is likely to continue doing so while the pier remains in place and whilst there continues to be a supply of material from the eroding cliffs north of Southwold. Indeed, it is the pier that forms the major control over coastal processes at the division between this coastal unit and the adjacent one, to the southward, not the defences at Southwold itself.

4.3.3 *Coastal vulnerability*

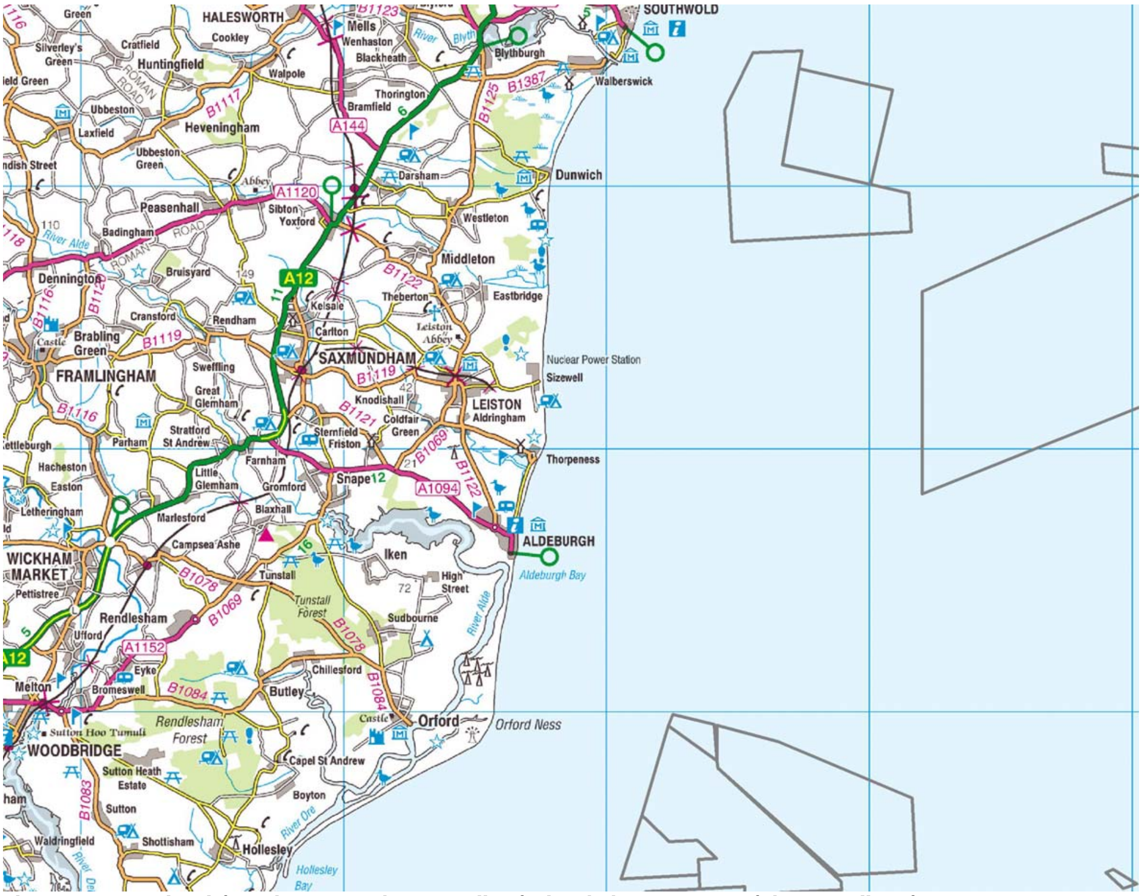
The coastline in this area is affected by movements of nearshore sandbanks, which produce changes in the littoral drift, as well as possibly interacting with the ness features. Beach changes in this coastal cell are thus largely unpredictable.

At the present time the coastline between Hopton and Corton is undergoing erosion, and at Corton, where the cliffs are protected, beach levels in front of the defences are falling. The sea defences at Lowestoft Ness are also under threat and have required reconstruction on several occasions. Thus, any changes in wave activity would be felt strongly in these areas.

By contrast, there are also areas that were once subject to erosion but are now areas of sediment deposition (at Pakefield and Kessingland, for example). These healthy beaches will, nevertheless, be sensitive to any changes in the direction of wave approach.

The cliffs between Benacre Ness and Southwold are also subject to rapid erosion and any changes in wave activity could not only accelerate the rates of cliff retreat, but might also result in breaching of shingle spits that protect Benacre, Covehithe and Easton Broads. This could result in increased saline intrusion and the alteration of habitats within the broads.

4.4 WALBERSWICK TO ORFORD NESS



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Note: The grey polygons indicate relinquished, licensed, application and prospecting Licence Areas.

4.4.1 Description of the coastline

The coastline from Southwold Harbour to Orford Ness is lightly populated and relies primarily on the shingle beaches to provide protection against wave attack (concrete seawalls are restricted to some 2.5km of frontage at Aldeburgh).

Southwold Harbour forms a major discontinuity at the northern end of this coastal unit. Sand and shingle has accreted to the north of the harbour. This indicates a pronounced southward littoral drift at this point. However, whilst there is a very large setback to the south of the harbour the embayment between there and Dunwich appears to be in a state of dynamic equilibrium (Royal Haskoning, 2009) suggesting that the littoral drift is extremely low and fluctuating in direction. However, the general trend is a net southward littoral drift along the whole of the Southwold to Orford Ness frontage, except for a possible localised drift reversal just south of Thorpeness.

The shingle ridge between Southwold Harbour and the beginning of the cliffs at Dunwich is vulnerable to wave overtopping. It used to be artificially raised in crest level, so as to prevent the low-lying hinterland from being flooded. It is no longer maintained in this fashion and breaching/wave overtopping in the future is likely (extensive flooding occurred here, when the spit approximately midway between Walberswick and Dunwich was breached in 2006 and again in 2007, see Pye and Blott, 2009).

To the south of this shingle ridge there is a line of cliffs that extend southwards to the Minsmere river valley. The cliff sections, called the Dunwich and Minsmere cliffs, have been affected by erosion rates that have been very variable, at times as low as 0.06 metres per year, and at other times as high as 3.53 metres per year.

To the south of the Dunwich and Minsmere cliffs is the Minsmere river valley that is protected against flooding by a shingle ridge, with a secondary defence consisting of a retarded flood bank and ditch. There have been occasions when this ridge has been breached, but on one occasion, following a breach in 1857, the ridge self-healed. Its rate of recession is lower than the rate of cliff retreat to the northward. The net result is that the coastline here is forward of the general coastal alignment. It is thought that the Dunwich and Sizewell nearshore sand banks (whose crests are both about -3mCD) provide protection to this frontage. However, accretion against the outfall of a sluice may also be a contributory factor. This frontage is assessed as being “mobile but quite stable” (Royal Haskoning, 2000).

To the south of this sluice there is a stretch of low-lying land, fronted by a shingle ridge. The land then rises slightly over the Sizewell frontage. The long term rate of erosion along this frontage has been assessed as being of the order of 0.1 metres per year (Royal Haskoning, 2009). However, there is no evidence of any coastal retreat at the present time. This frontage is also protected by the Dunwich and Sizewell banks.

South of Sizewell the land rises again, but accretion has produced a wide shingle backshore and has resulted in the cliffs from Sizewell to Thorpeness being unaffected by wave action. They are well vegetated and are now separate from the active beach system. This frontage is assessed as having no measurable cliff retreat (Royal Haskoning, 2009). Again, this frontage is protected by the Dunwich and Sizewell banks.

Thorpe Ness, in contrast to the more northerly nesses, has remained fairly stable over historical times, but whilst it has not migrated northward or southward, it has been undergoing some recession in recent years (Robinson, 1980). The accumulation of shingle at the ness is backed by a former cliff of sands and clays, which was grassed over and beyond the reach of wave until the present erosion phase. There is circumstantial evidence that there is a localised drift reversal just south of the ness (Royal Haskoning, 2009), and recent erosion there is perhaps evidence of the drift divide close the northern end of the village.

Within the shallow embayment stretching southwards from Thorpeness village to Aldeburgh, the shingle has accumulated to form a very wide shingle backshore that forms a natural defence against the action of the sea. It is interesting to note that whilst the shingle ridge was not breached during the 1953 surge that caused so much havoc on this coastline, there was some wave overtopping that produced wash-over fans of shingle (Royal Haskoning, 2009).

Whilst the littoral drift in the embayment between Thorpeness village and Aldeburgh is thought to be weak, with northward and southward transport being almost balanced, there is undoubtedly a southward transport at the southern end of this frontage. Shingle has accumulated south of Fort Green, which projects slightly seaward of the general line of the coast. However, to the south of Fort Green, between there and just south of the Martello Tower, there is a deficit in shingle supply and erosion has been taking place, so that a concrete wall was constructed to prevent the shingle spit from breaching (the shingle spit can become very narrow at Slaughden, immediately south of Aldeburgh).

The frontage from Aldeburgh southwards was once part of a very long shingle spit, Orford Spit, which was formed by the southward transport of shingle across the former mouth of the river Alde. The southward growth of the spit caused the river to be deflected by as much as 15km, to terminate at North Weir Point, near Shingle Street (these are outside the study area). The spit has a north-south alignment until Orford Ness is reached, at which point it takes on a south-westerly alignment. This corresponds to the widest part of the spit and there the shingle backshore still exhibits the pattern of shingle ridges that illustrate its historic development.

Orford Spit owes its existence to the Dunwich and Minsmere cliffs to the northward, erosion of which produced large quantities of shingle in the historic past. However, these cliffs are not homogeneous and for some years they have been providing mainly sand by their erosion. Also, over the last 50 years or so, shingle has tended to accumulate in the embayment in which Aldeburgh is situated, resulting in erosion taking place between Aldeburgh and Orford Ness. This has resulted in requirement for defences on the Slaughden frontage to prevent the spit being breached. In addition shingle recycling has been carried out in order to maintain beach levels in front of the sea defences and to reduce the “cutback” immediately south of the seawall.

4.4.2 Coastal defences and management

Between Southwold Harbour and Dunwich there is continuous shingle ridge that was until recently maintained by profile re-profiling, so to maintain its crest height and so reduce wave overtopping. This ridge is no longer managed, and is now vulnerable to breaching. In 2006 and 2007 this ridge was temporarily breached, and much of the hinterland was flooded (note that the village of Walberswick has its own encircling flood embankments as protection). It is possible that a major breach, if sufficiently large, could spread out the beach material over the low-lying land to the landward and produce a discontinuity in the barrier beach alignment.

The shingle ridge is presently contiguous with the beach fronting the Dunwich cliffs to the southward. These cliffs, extending from Dunwich to the Minsmere river valley are largely unprotected. However, at Dunwich, trials have been carried out to provide low-cost protection to the cliff toe. The protection is in the form of geotextile bags filled with beach material placed on the upper beach, together with sand fencing at the cliff toe. This protection is restricted to the northern end of the Dunwich cliffs and is limited in effectiveness (see Plate 21). Further southwards the cliffs are completely unprotected, but they are well vegetated, suggesting that cliff recession is low and sporadic.

The Minsmere river valley is protected by the sand and shingle ridge that is contiguous with the cliff line to the north and south, but there are also secondary defences consisting of a manmade channel and earth flood embankment that runs parallel to, and landward of, the beach ridge. The shingle ridge forms a slight bulge in the coastal alignment. This is thought to be the result of the shelter provided by the nearshore sand banks, which undoubtedly reduce wave intensity at the toe of the ridge (the banks have a crest that is only 3m below Chart Datum).

Just to the south, the backshore is protected by a wide shingle beach backed by old shingle ridges. Sizewell Power Station is fronted by a healthy shingle beach, with additional protection against flooding being afforded by two earth banks set-back from the active beach zone (see Plate 22).

The land rises south of Sizewell and the wide shingle beach and backshore prevent wave action at the cliff toe, for as far southward as Thorpe Ness (see Plate 23). The position of Thorpe Ness may be connected with the position of the nearshore sandbanks, which appear to be “anchored” off the ness and which extend northward, partly sheltering the coastline between Thorpe Ness and Minsmere, as mentioned above. There is little tendency for the ness to migrate alongshore as a result.

There is no such sheltering effect on the south side of Thorpe Ness, and as a result, the width of the beach decreases and there is some slow cliff erosion on the south flank of the ness, potentially putting a line of cliff top properties at risk. However, by the time Thorpeness village is reached (1km south of the ness) the beach has widened to such an extent that the backshore is again well protected against wave action (see Plate 24).

Between Thorpeness and Aldeburgh the shingle beach provides protection to the low-lying land behind it. This beach has increased in width since the 1960s. At the southern end of this frontage the beach narrows and the town frontage has a concrete seawall that extends southwards beyond the Martello Tower at Slaughden. The beach in front of the seawall north of Fort Green has also increased in width over the last 50 years or so (see Plates 25 and 26) so that the groynes over this frontage are now buried.

The shingle spit from Aldeburgh to some distance south of the Slaughden Martello Tower is very narrow, being constrained by the river Alde to the rear. The ridge would be very vulnerable to breaching were it not for the sea defences that maintain the line of the coast slightly forward of its natural alignment (the rear of the ridge is unprotected). The defences along this frontage originally consisted of a field of timber groynes. A concrete seawall was constructed at some time in the late 1950s/ early1960s and subsequent maintenance requirements for this frontage have been high, due to its exposure to wave action. By 1986 the groyne field had become so dilapidated that many of the groynes were no longer retaining material and beach levels in front of the wall had become seriously low. Following hydraulic investigations the “set-back” in the coastal alignment to the south of the seawall was infilled with shingle and the groynes extended southwards, to provide a buffer between the defended and undefended parts of the shingle spit. Subsequent maintenance operations have included shingle recycling from downdrift borrow areas (i.e. from southward, toward Orford Ness) plus addition of rock armour adjacent to the southern end of the seawall. Plate 27 shows the large discontinuity in coastal alignment in 1983, at the southern end of the Slaughden seawall. Plate 28 shows the improved beach in 2008. Note that the frontage immediately southward of the seawall remains vulnerable to “roll-back”.

4.4.3 Coastal vulnerability

The shingle ridge between Southwold Harbour and Dunwich protects a large area of low-lying land against flooding. It is understood that this ridge is no longer maintained by reprofiling, or by addition of material to maintain its height and width. Future breaching is likely and one such event has already occurred in the recent past (in 2005). Any increase in wave activity would increase the risk of breaching.

The cliffs between Dunwich and Sizewell are presently eroding relatively slowly, as is evident by the partly vegetated cliff face. However, cliff erosion was very rapid in the historic past, resulting in the loss of much of Dunwich. Any increase in wave activity or a change in the mean wave direction could accelerate the erosion again. Around Sizewell there are no significant erosion problems at the present time. However, this could change if there was an increase in wave activity near the shoreline (at present nearshore sandbanks shelter much of this frontage).

The beaches at Aldeburgh are also relatively stable at the present time. The southward littoral drift within the embayment in which Aldeburgh is situated is low, but increases at the southern end of the town frontage and very dominantly southward at Slaughden. Any increase in wave activity could threaten the integrity of the defences, by causing beach drawdown in front of the Slaughden seawall. This could pose a risk of breaching as the spit is only 50m wide at its narrowest point. There is also a risk that if littoral drift accelerated, then the coastline south of the Slaughden seawall might well be affected by serious downdrift erosion, as it was in the recent past. This could conceivably cause a coastal “set-back” alignment, and eventually a breach to the south of the seawall.

5. Conclusions and recommendations

5.1 CONCLUSIONS

This report has reviewed the long-term evolution of the coastline between Cromer and Orford Ness, and summarised existing knowledge of the movements of sediment on the beaches and over the nearshore seabed along this frontage.

There is no doubt that this part of the East Anglian coastline has been eroding for many centuries, since the formation of the southern North Sea between 10,000 and 5,000 years ago. The higher areas of ground have slowly retreated, at a long-term average rate of about 1m per annum, and as the coastal cliffs formed in these areas have eroded, large quantities of sand and gravel have been released onto the beaches and into the nearshore zone.

Along the Norfolk coastline, the sand and gravel produced by the erosion of the cliffs between Sheringham and Happisburgh has been transported as far south as Winterton Ness, with the majority of that sediment then moving offshore to form and maintain the extensive system of nearshore sandbanks that extend as far as Lowestoft. A little beach sediment, however, travels on down the coast towards Caister and Great Yarmouth.

From Gorleston to South Beach, Lowestoft, the beach sediments have principally been derived from erosion of the cliffs at Corton, Hopton and Gunton, although some sediment has moved onshore from the nearshore sandbanks on occasions.

South of Lowestoft, erosion of the glacial till and the sand and gravel cliffs that extend intermittently almost as far as Aldeburgh has historically provided beach sediment that is carried predominantly southwards, forming barrier beaches in front of the river valleys that run between the areas of higher ground. Along this coastline, as for the frontage between Winterton Ness and Lowestoft, the evolution of the beaches is modified by the shifting nearshore sandbanks that extend as far as Orford Ness. The changing positions and heights of these banks affect the direction and the height of waves that reach the coast, and this in turn alters the rates and even the directions of longshore transport along the beaches behind them.

The long-term recession of this coastline has led to the total or partial loss of many villages and towns within recorded history. Seawalls and groynes have been installed along parts of this frontage and, in places, have been successful in virtually halting cliff recession for example at Cromer and Lowestoft, although there is a continuing problem of lowering of the inter-tidal zone in front of such defences. Other man-made structures, for example the harbour arms/breakwaters at Great Yarmouth, Lowestoft and Southwold, have had an influence on the evolution of this coastline, typically resulting in wider beaches to the north and narrower beaches further south.

In the context of offshore aggregate dredging, it is worth reproducing text from the Kelling to Lowestoft Ness SMP (AECOM, May 2009) which states that;

“Licensed aggregate dredging is often cited as a cause of erosion but studies conducted to assess this activity indicate that it does not have a noticeable impact upon coastal evolution…

… significant erosion of this coast took place long before present dredging activities commenced”.

Indeed along many parts of the coastline, even where there are no coastal defences, it appears that erosion rates over the last few decades have been slower than the long-term average deduced from the historical review of this frontage.

However, the review of the coastline presented in this report also highlights the numerous areas in which the risks of erosion and flooding remain. There will inevitably be further changes in wave conditions, tidal levels and surges and the positions and heights of the nearshore sandbanks along this coastline. In addition, sea-level rise is not only likely to continue as in the last 4,000 years but to increase as a consequence of global warming. As well as these changes in “natural processes”, there will also be changes caused by the construction of new coastal structures or the deterioration and removal of others, including coastal defences.

Any of these changes may alter parts of this mobile coastline, changing beach widths and the rate of recession of undefended sections of the cliffs. It is against this background that the effects of offshore aggregate extraction need to be considered, both in advance of any dredging and, if necessary, as such operations proceed.

5.2 RECOMMENDATIONS

A number of past scientific studies have looked for and failed to find any evidence linking offshore aggregate dredging with coastal changes between Cromer and Orford Ness (e.g. Gao, Ke and Collins, 1993 and Walkden and Stansby, 2006). Neither this nor the benefits of using of marine dredged sand and gravel to recharge eroding beaches near Sea Palling and at Southwold means, however, that any future studies of aggregate dredging should be any less rigorous than in the past.

One of the most frequently-expressed concerns about offshore aggregate extraction is the risk of beach sand being “drawn down” into dredged depression in the seabed. The Coastal Impact Study carried out for each aggregate extraction licence application specifically checks that beach drawdown into the proposed dredging area cannot occur by limiting the minimum water depths and/ or the distance from the shore where such dredging is permitted. Dredging is only permitted below the lower limit of the seasonal changes in beach profiles. Previously Sir William Halcrow & Partners (1991) suggested a maximum limit of 7 metres below lowest tidal level for such seasonal beach fluctuations along the East Coast of England. The present study has examined more recent beach survey data and found that beach profiles may extend into deeper water than previously assumed, especially north of Winterton Ness and south of Lowestoft where the coastline is not so well protected by offshore sandbanks. Along these parts of the frontage, beach profiles may exceptionally extend down to about 15m below OD, i.e; to 13.5 m CD (i.e. below the lowest tidal level).

This same review also showed that where the coastline was well-sheltered by nearshore banks, particularly between Winterton Ness and Lowestoft, the beach toe is often in much shallower water, often no greater than -5m below the lowest tidal level. Here, however, existing dredging areas lie to seaward of the various tidal sandbanks and channels and the bottom of these channels are well below the observed level of the beach toe. The concern along this part of the frontage, therefore, is not that beach sand could traverse these channels and banks to reach the dredged area, but that the outer edge of the sandbanks might be affected by dredging if it took place too close to them.

The concern therefore transfers from one of causing draw-down of the beach to sediment from the outer edge of the banks moving into a dredged depression. This possibility has been recognised in previous studies of the dredging areas that lie offshore from Great Yarmouth, and explicitly considered. It is recommended that this approach be extended to the regional assessment of aggregate dredging by considering the changes in wave conditions, tidal currents and sediment transport along the outer edges of these sandbanks. The movement of sediment along and over the nearshore sandbanks between Cromer and Orford Ness are largely dominated by tidal flows, rather than by wave action. If aggregate dredging produced any systematic changes in the currents over these banks, this could alter the present sediment transport regime, and hence bank positions and heights. In particular, assessment should focus on the likelihood of any lowering of the heights of the banks that help protect the coast.

Previous studies, and more importantly previous surveys of the banks and the dredging areas to seawards of them, have so far not shown this to have occurred, despite the proximity of some of the dredged depressions to the outer edge of the sandbanks. This survey data should be clearly presented and interpreted in the MAREA study.

In addition, at a later stage in the present study, it will be important to simulate the changes in tidal flows and the associated sediment transport in and around the dredging areas, particularly concentrating on any changes close to the sandbanks. As with other aspects of the MAREA study, the combined effects on the seabed of all past and proposed future dredging off this coastline will need to be included in such modelling.

Finally, it is clear from the reviews both of historical changes along this coastline and of beach profile data that the various nearshore banks affect waves as they travel to the shoreline, especially between Winterton Ness and Lowestoft. Changes in the positions and heights of these banks alter the strength and sometimes the direction of the longshore transport of beach sediments, which in turn leads to changes in beach widths. While such changes will continue in future, whether or not any aggregate dredging takes place, it is important that the lowering of the seabed within existing or proposed extraction areas does not significantly add to the natural variability of wave conditions or of tidal currents along the shoreline.

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Figures

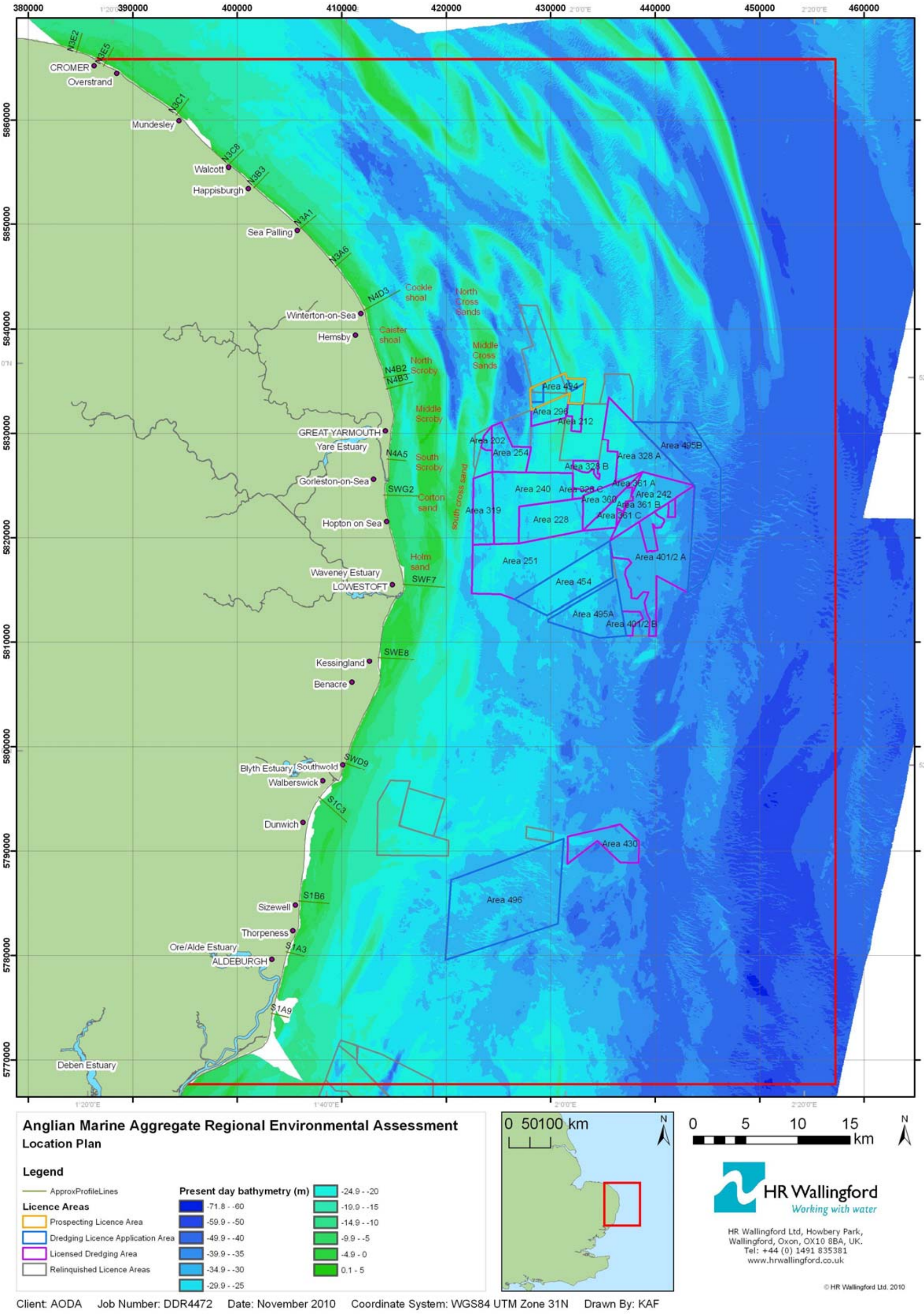


Figure 1 Study region (Cromer to Orford Ness)

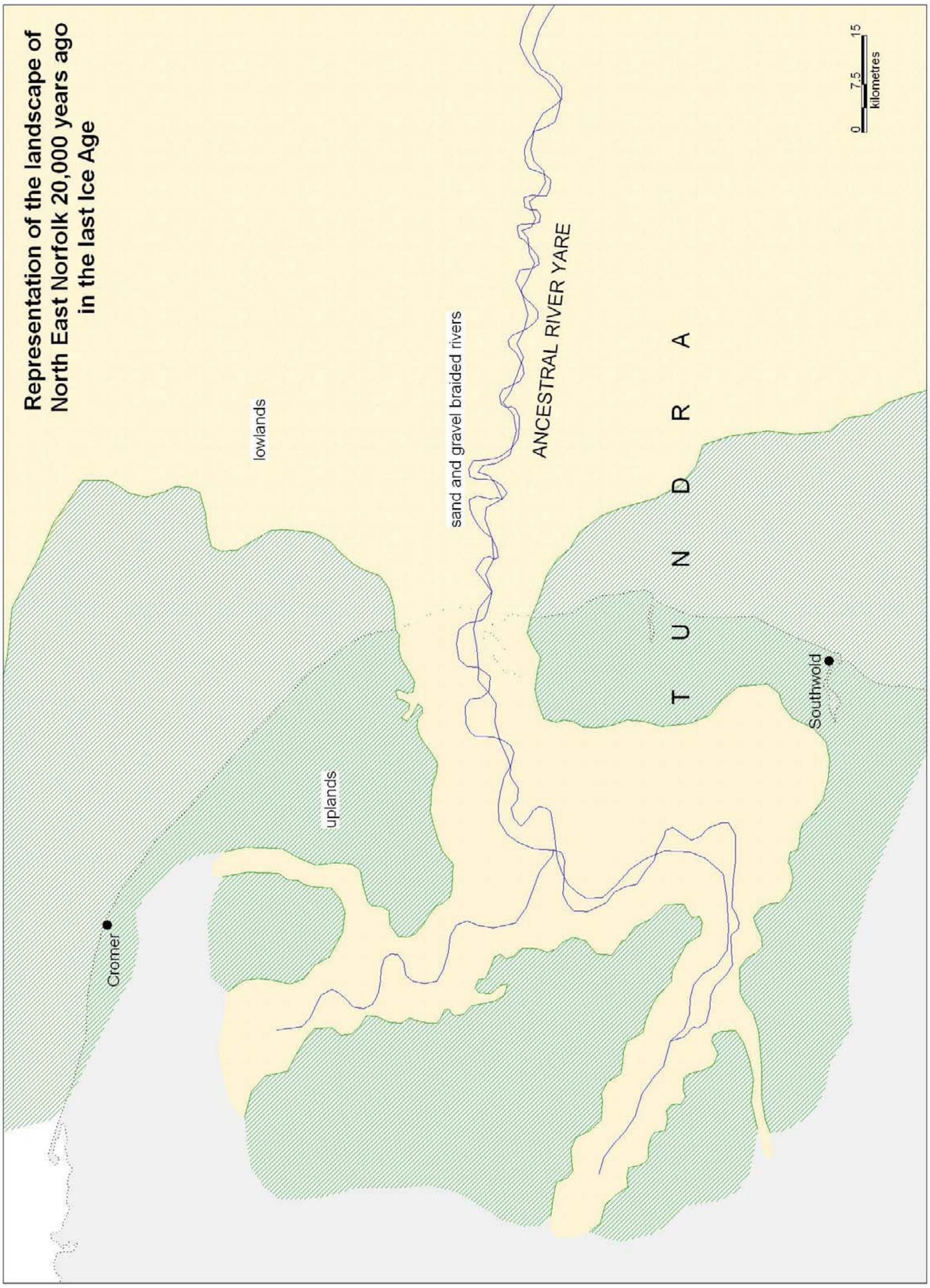


Figure 2.1 Simplified interpretation of eastern Norfolk and its nearshore seabed towards the end of the last glaciation, i.e. about 20,000 years ago

(source: Bellamy A G, pers. comm., 2010)

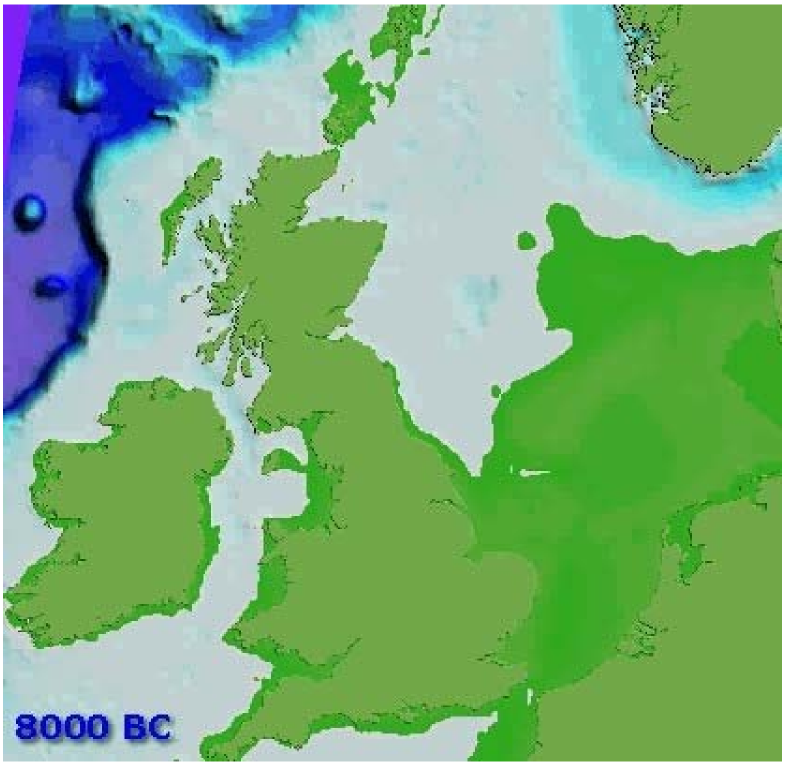


Figure 2.2 British Isles about 10,000 years ago, i.e. about 8000BC

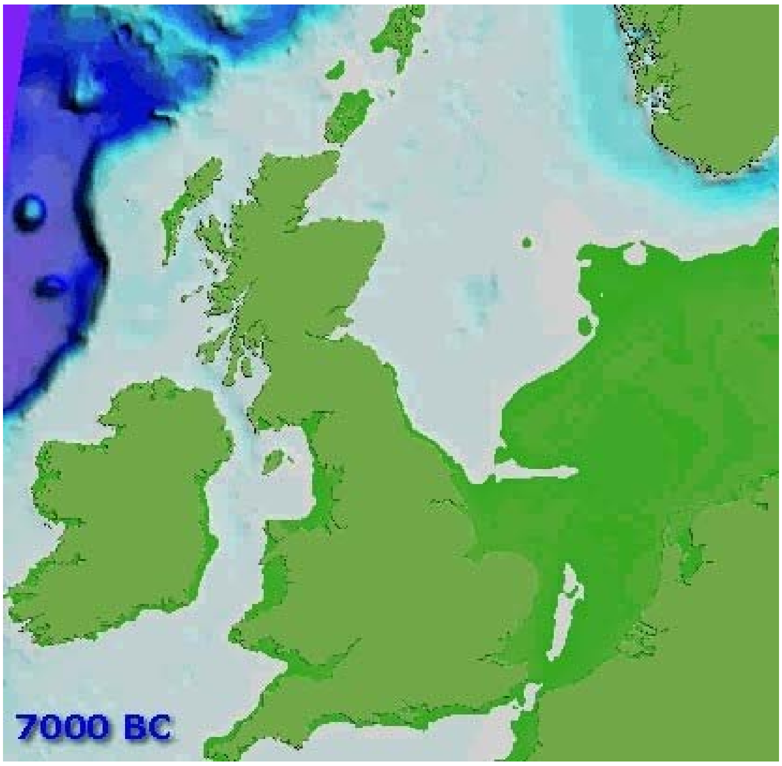


Figure 2.3 British Isles about 7000BC

(source: Shennan et al., 2000)

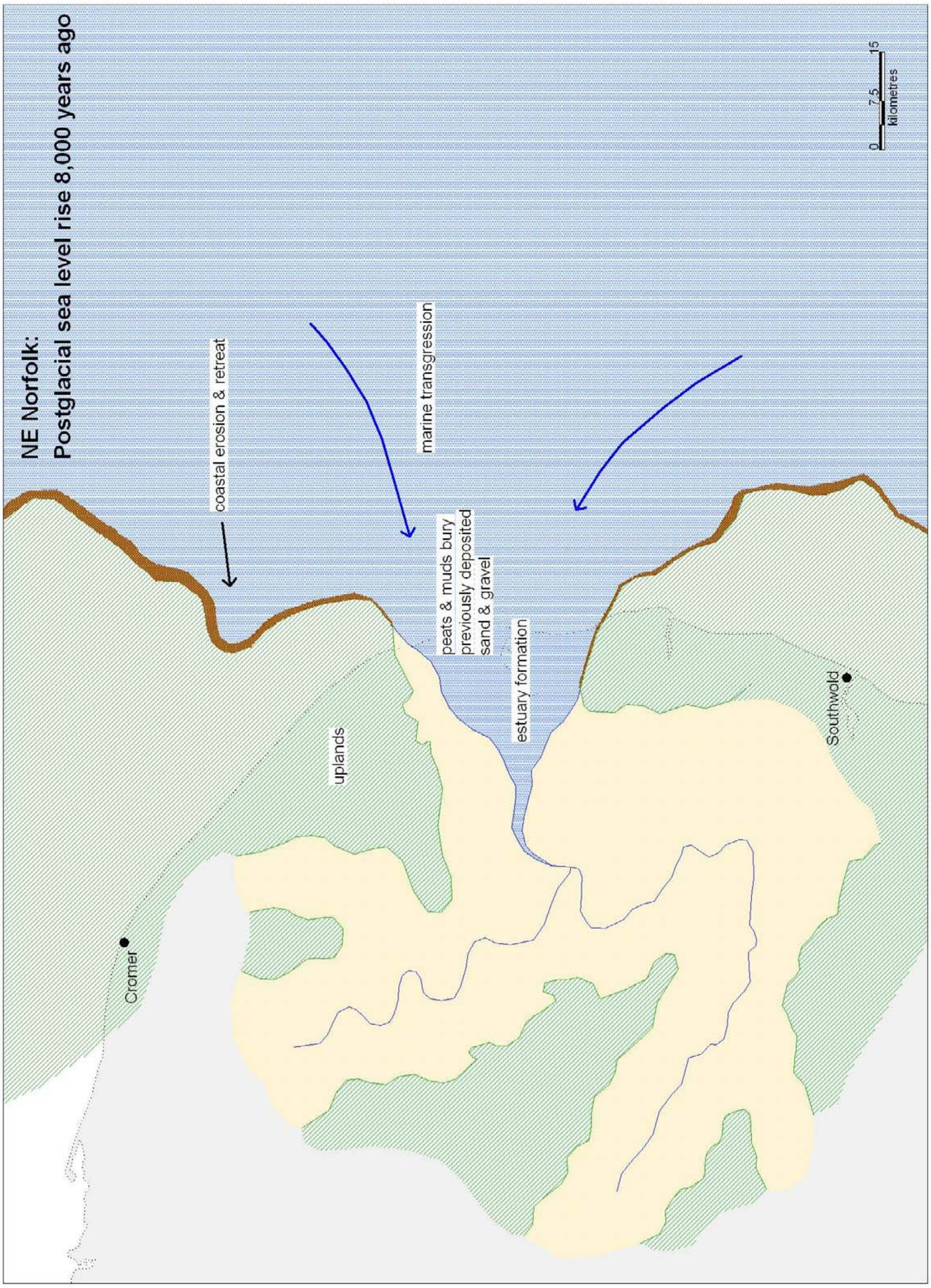


Figure 2.4 Interpretation of the north-east Norfolk and Suffolk coastlines in about 6000BC

(source: Bellamy A G, pers. comm., 2010)

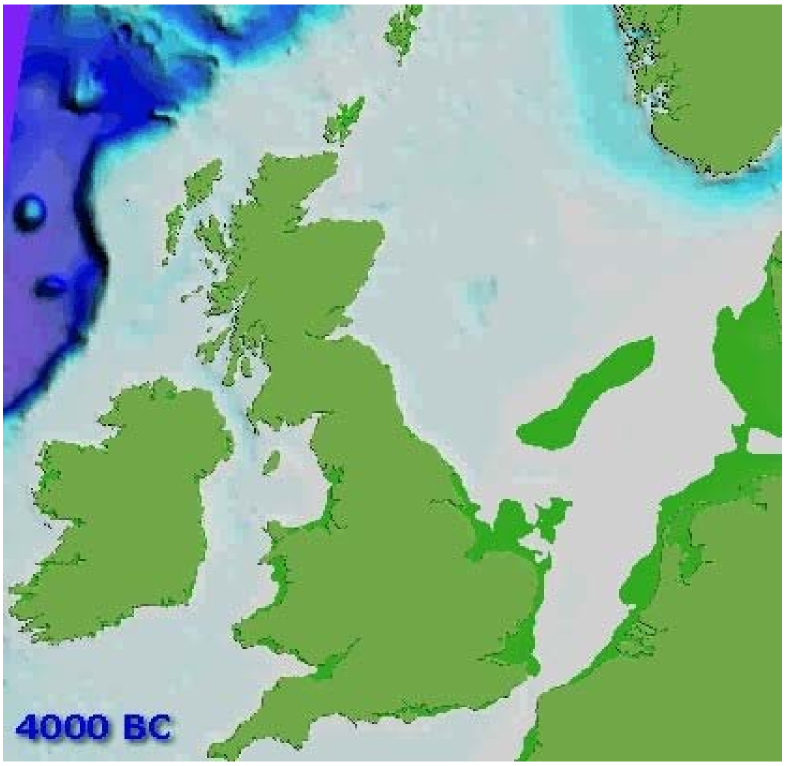


Figure 2.5 Formation of the southern North Sea by about 4000BC

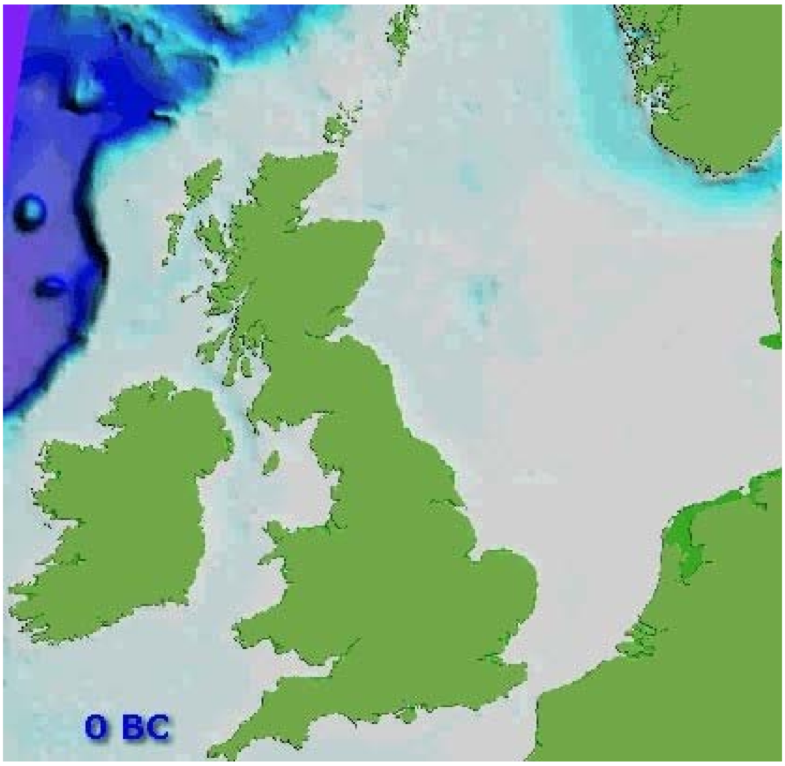


Figure 2.6 British Isles some 2,000 years ago, i.e. in about year 0BC

(source: Shennan et al., 2000)

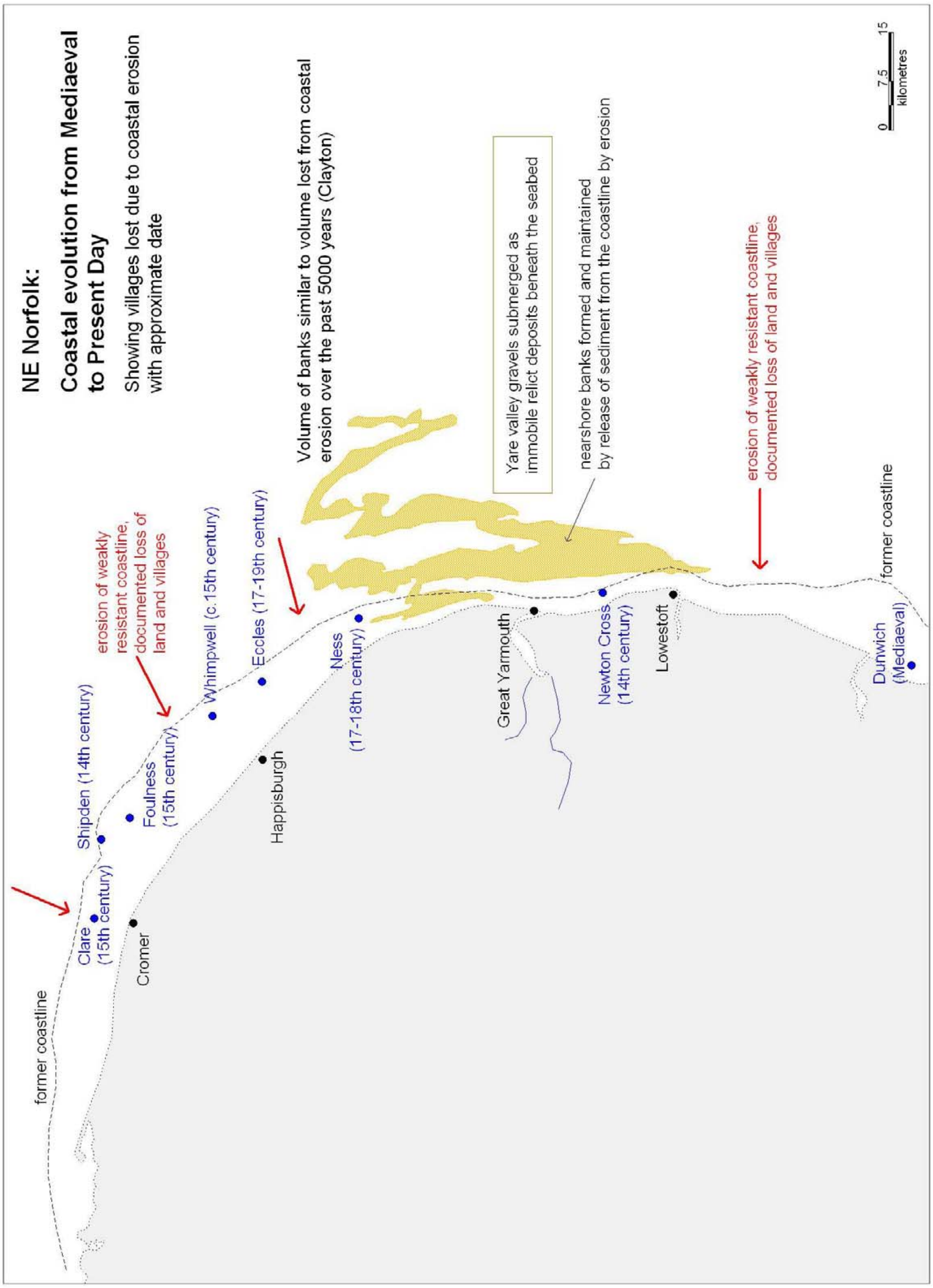


Figure 2.7 Historic coastal changes along the shoreline between Cromer and Great Yarmouth

CHECK SOURCE OF FIGURE **(based upon interpretation of information in Weston and Weston, 1994)**

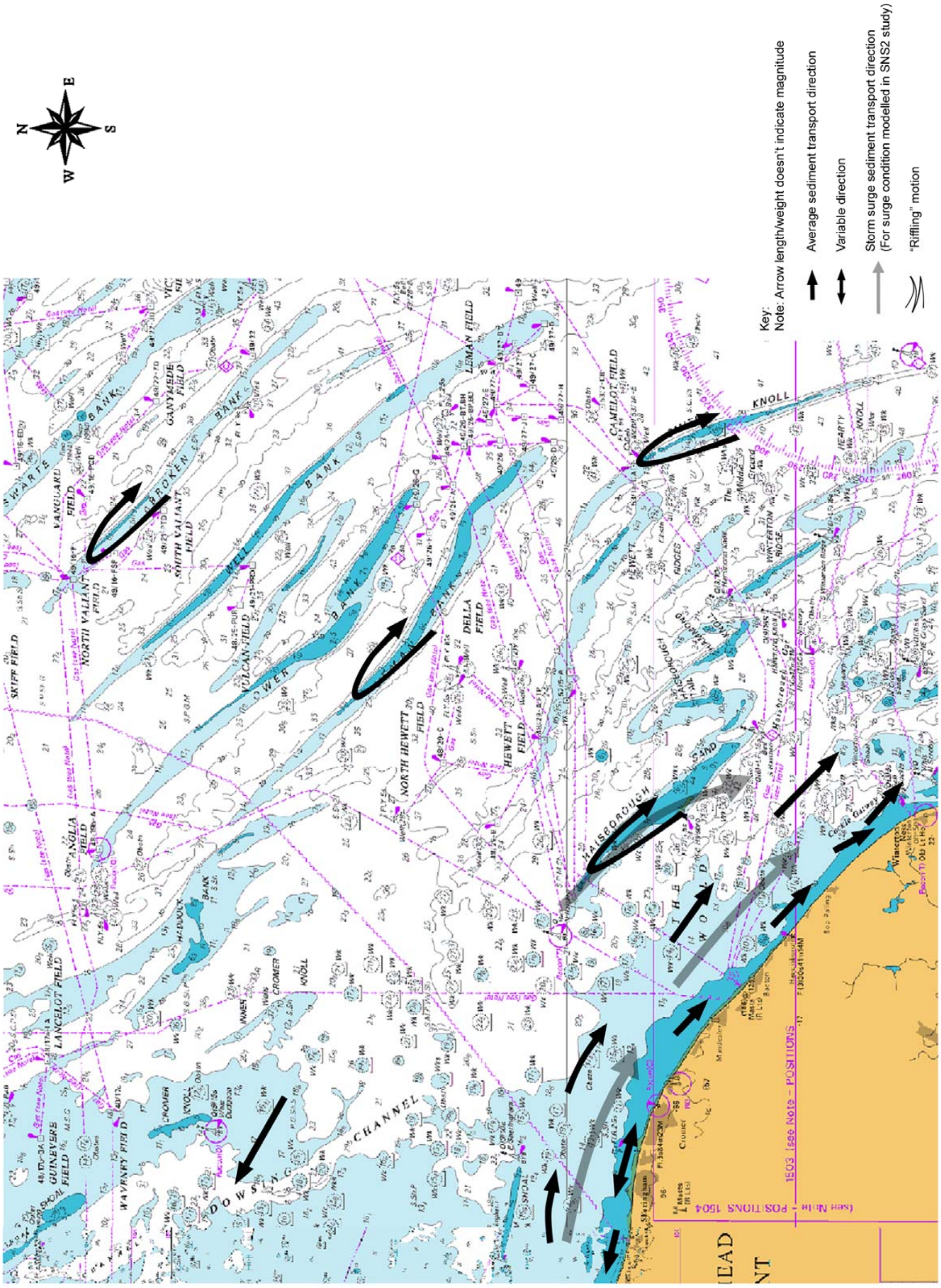


Figure 3.1 North Norfolk schematic sediment transport pathways

(source: SNSSTS2 HR Wallingford et al., 2002)

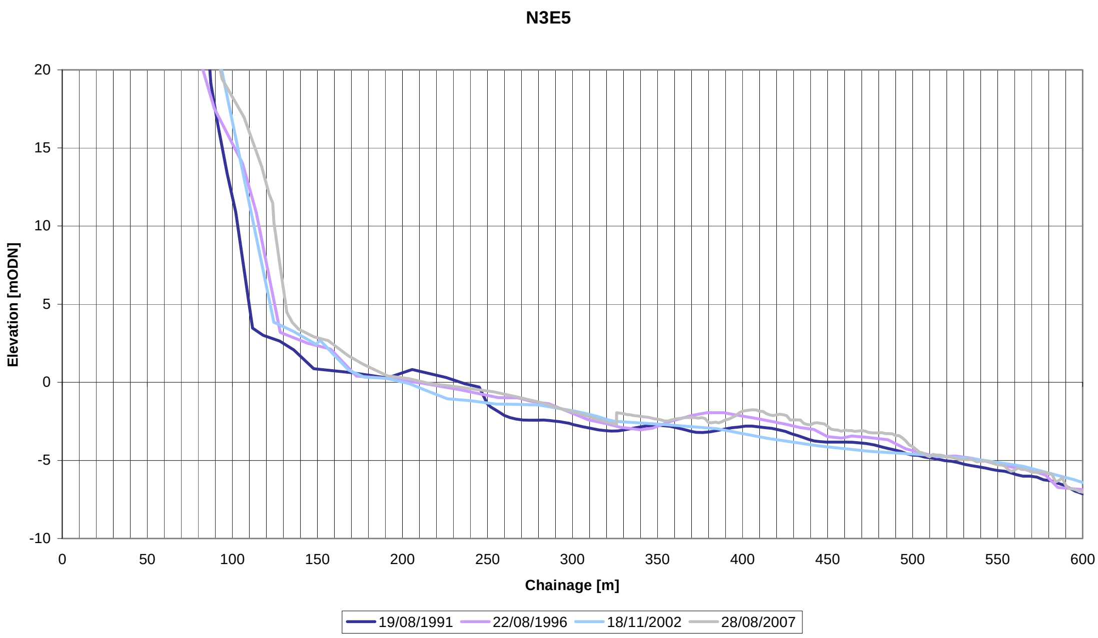


Figure 3.2 Landward part of Profile N3E5: Cromer

(source: Environment Agency)

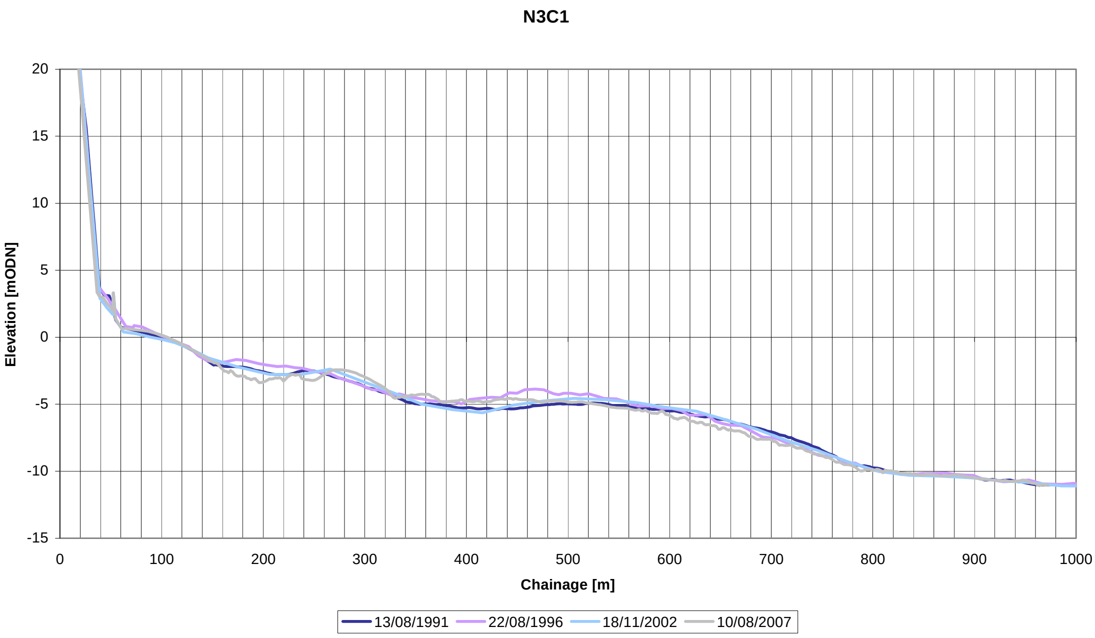


Figure 3.3 Landward part of Profile N3C1: Mundesley

(source: Environment Agency)

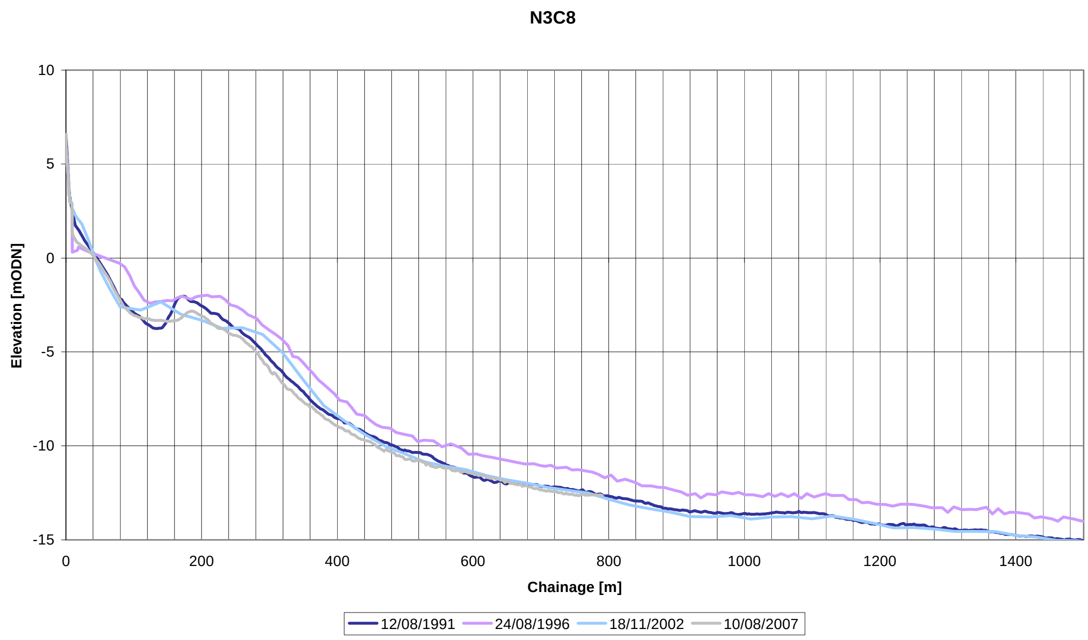


Figure 3.4 Landward part of Profile N3C8: Keswick

(source: Environment Agency)

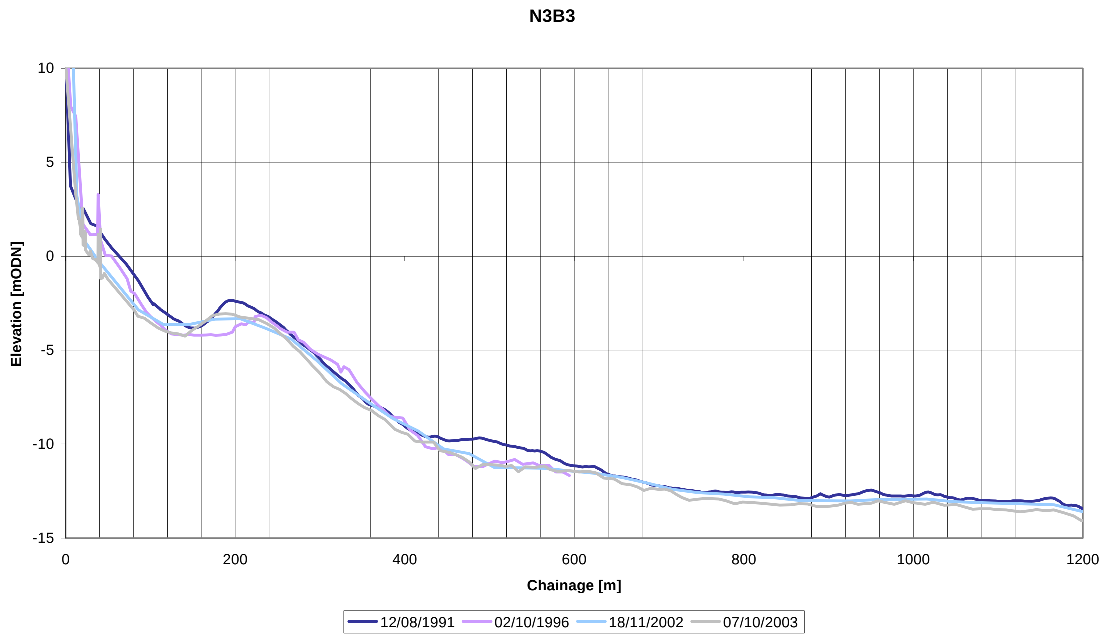


Figure 3.5 Landward part of Profile N3B3: Walcott

(source: Environment Agency)

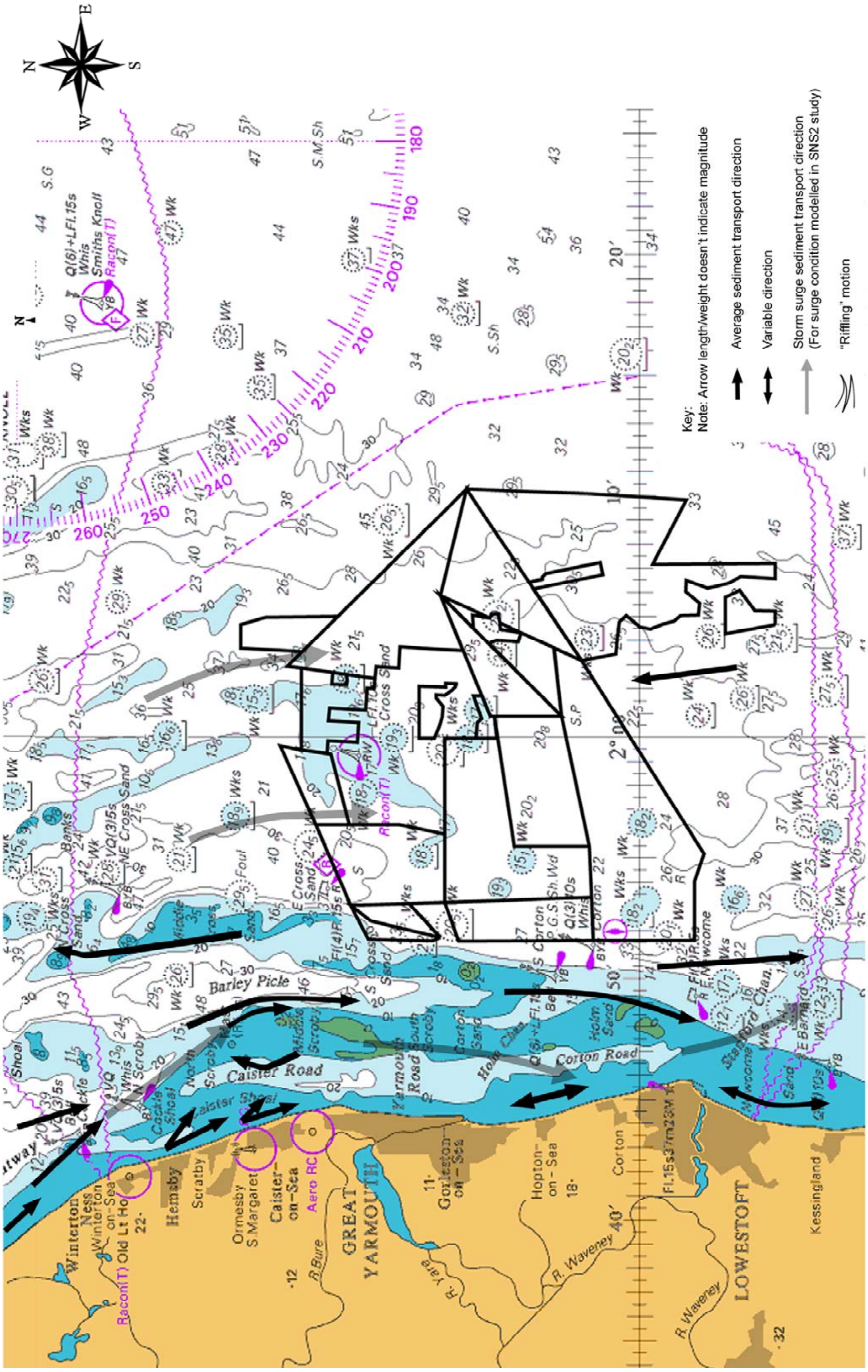


Figure 3.6 East Norfolk and North Suffolk schematic sediment transport pathways

(source: SNSSTS2 HR Wallingford et al., 2002)

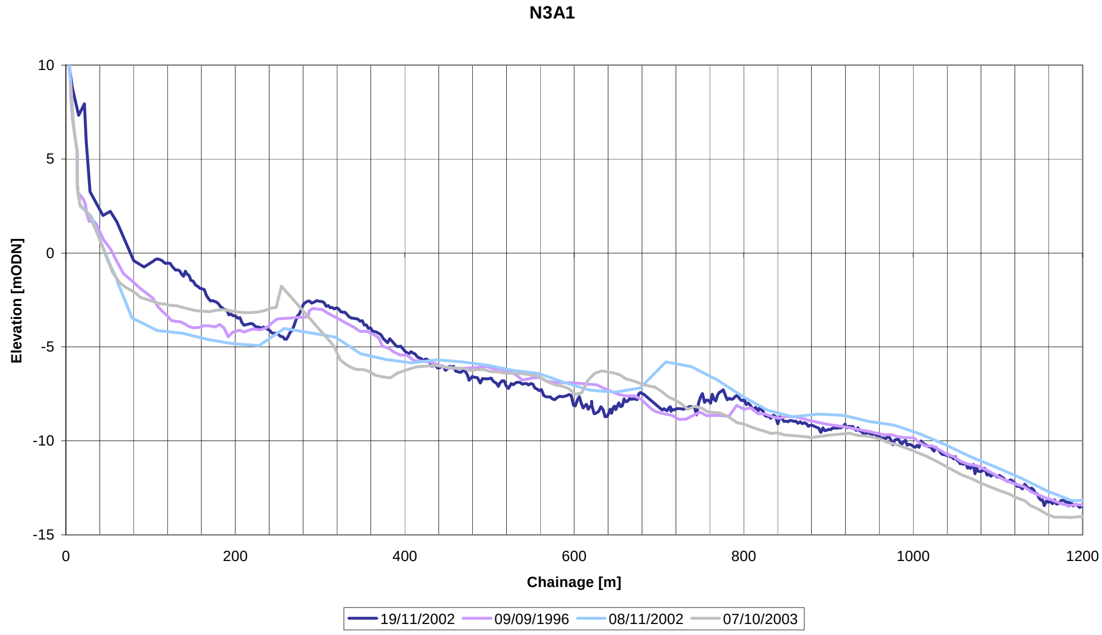


Figure 3.7 Landward part of profile N3A1: Sea Palling

(source: Environment Agency)

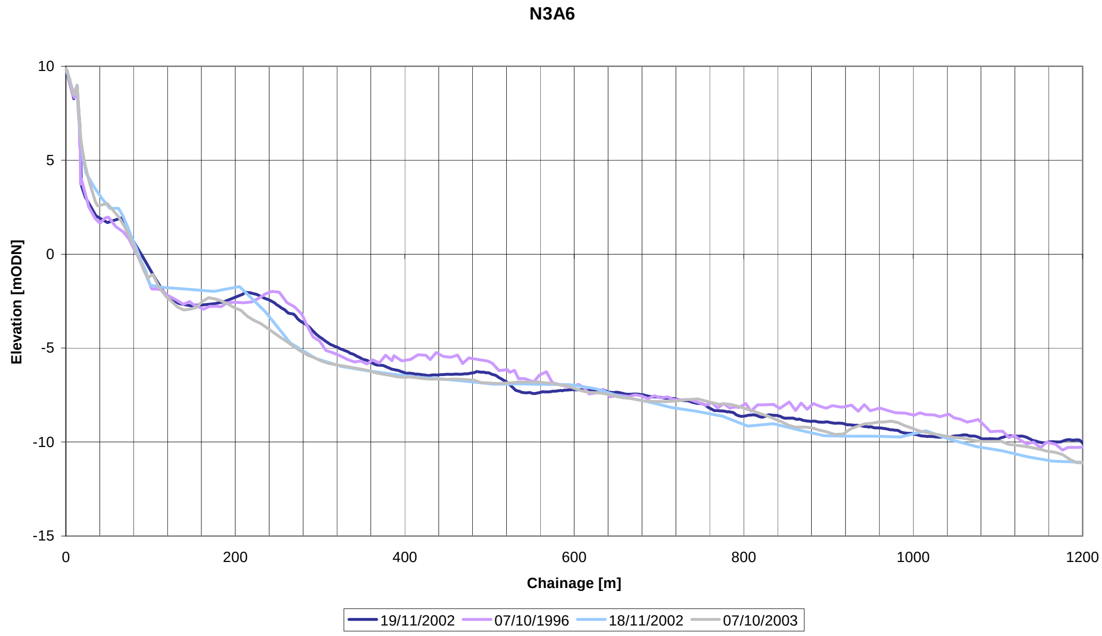


Figure 3.8 Landward part of profile N3A6: Horsey

(source: Environment Agency)

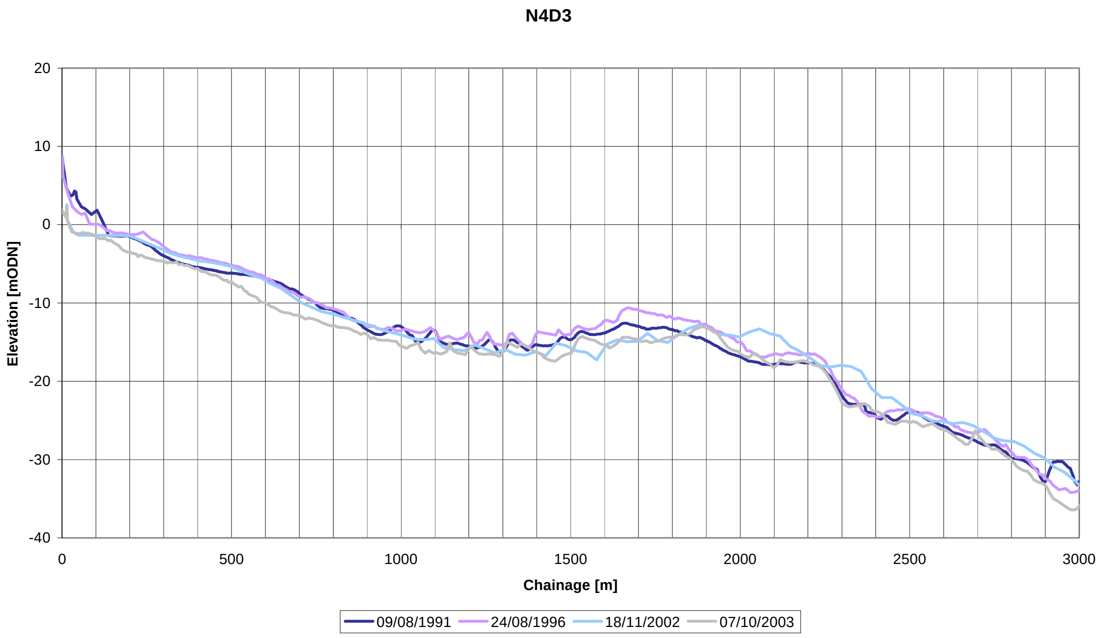


Figure 3.9 Profile N4D3:Winterton-on-Sea

(source: Environment Agency)

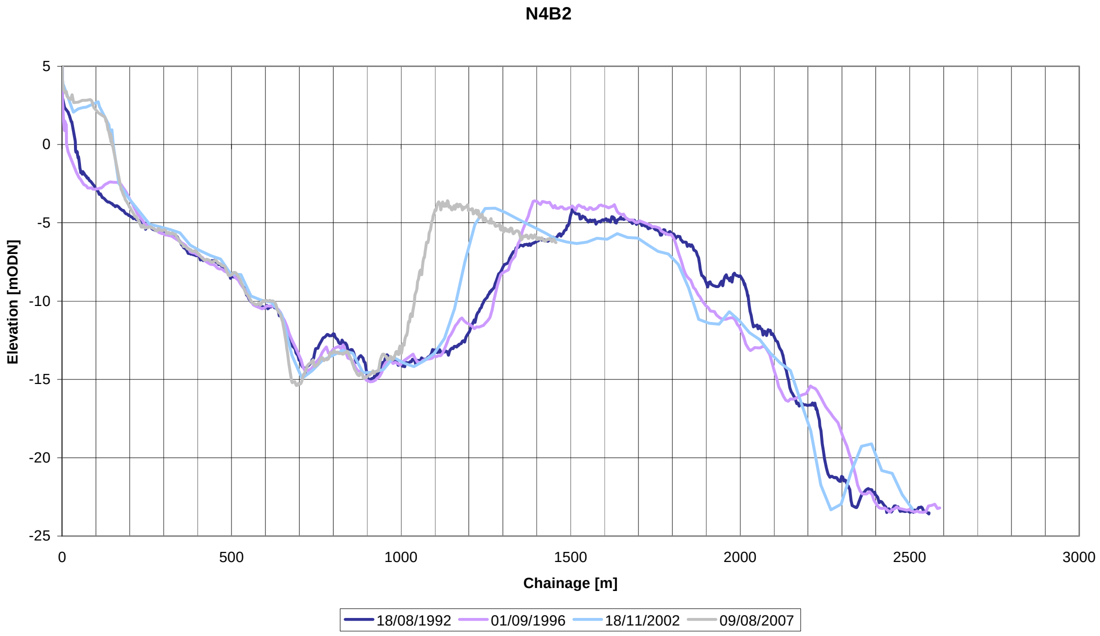


Figure 3.10 Profile N4B2: North Caister-on-Sea

(source: Environment Agency)

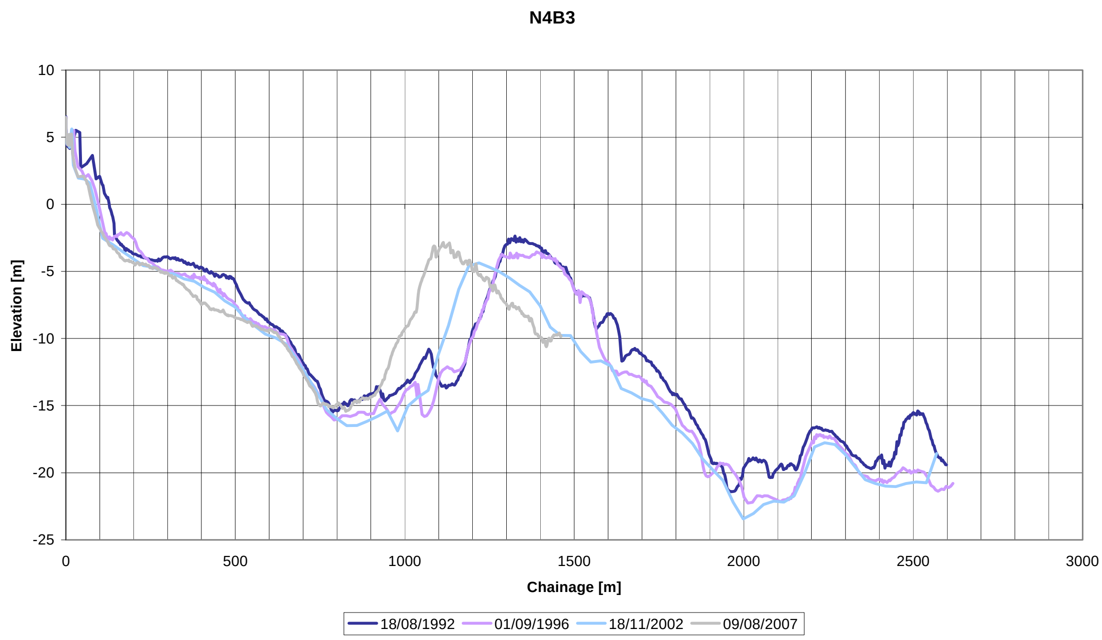


Figure 3.11 Profile N4B3:Caister-on-Sea

(source: Environment Agency)

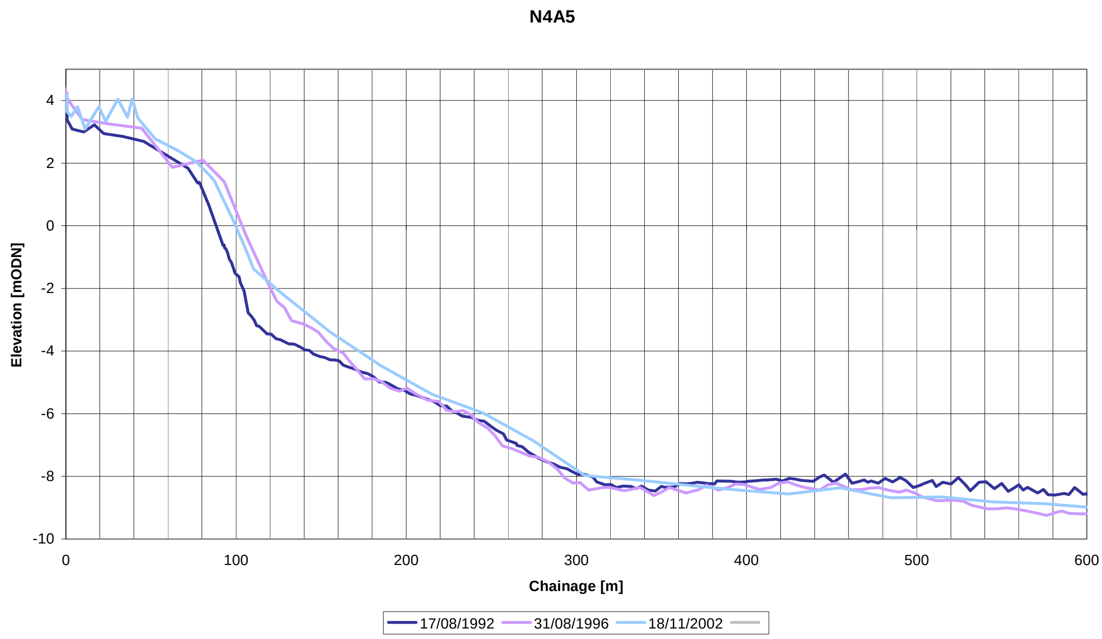


Figure 3.12 Profile N4A5: Great Yarmouth

(source: Environment Agency)

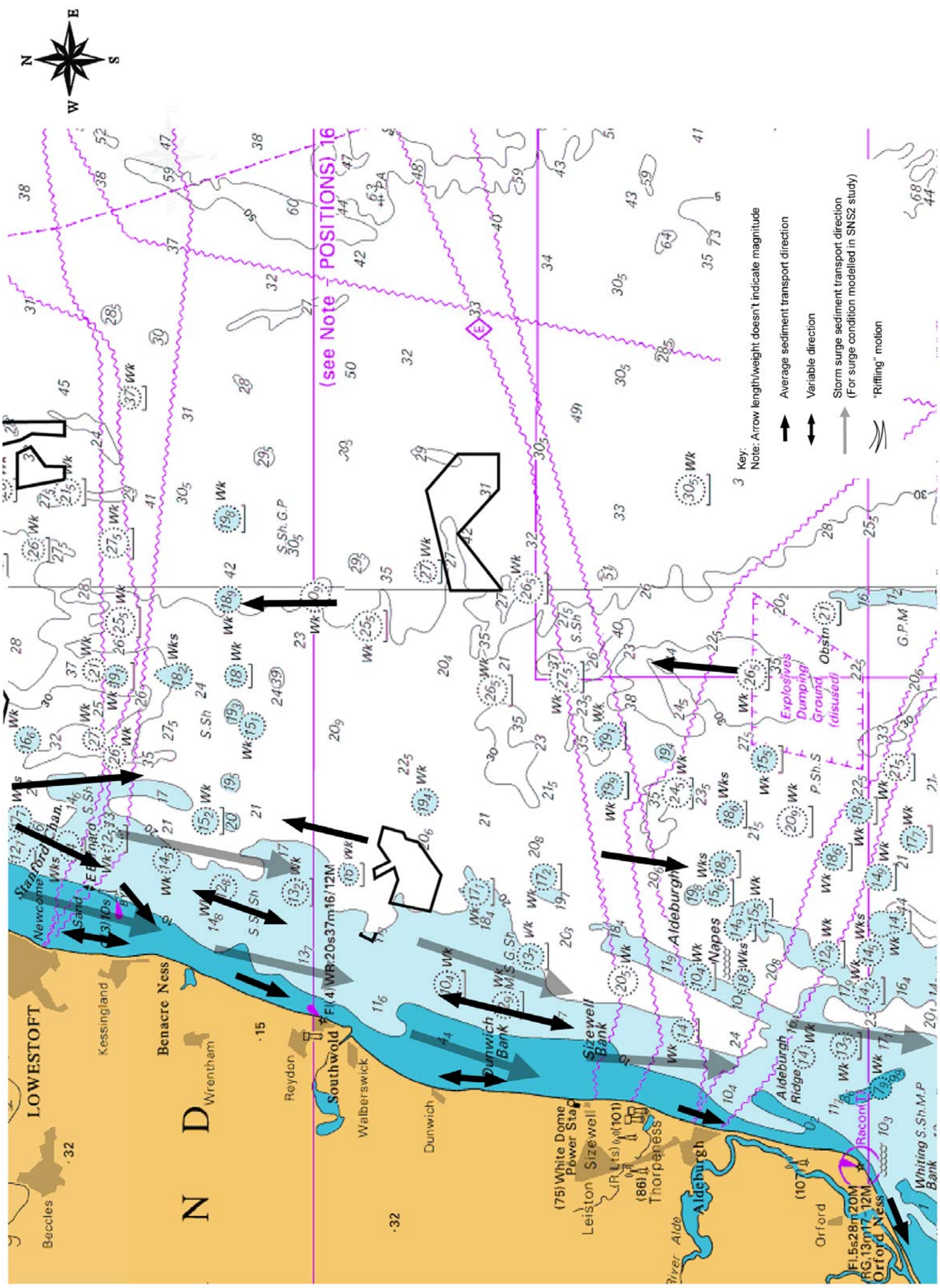


Figure 3.13 North Suffolk schematic sediment transport pathways

(source: SNSSTS2 HR Wallingford et al., 2002)

Figure 3.14 Profile SWG2: Gorleston-on-Sea

(source: Environment Agency)

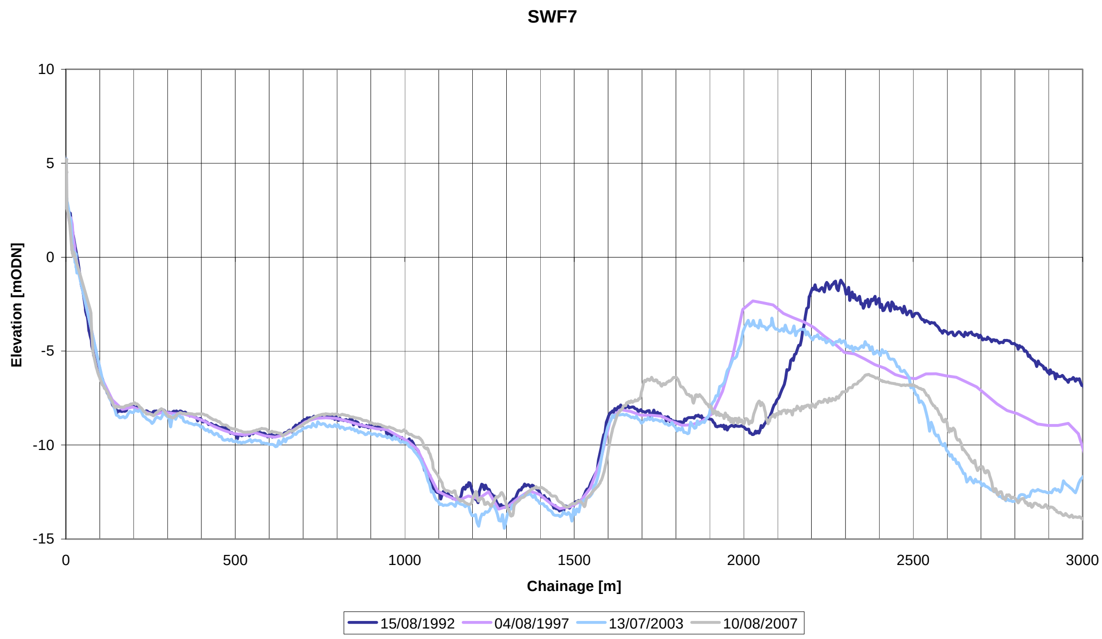


Figure 3.15 Profile SWF7:Lowestoft

(source: Environment Agency)

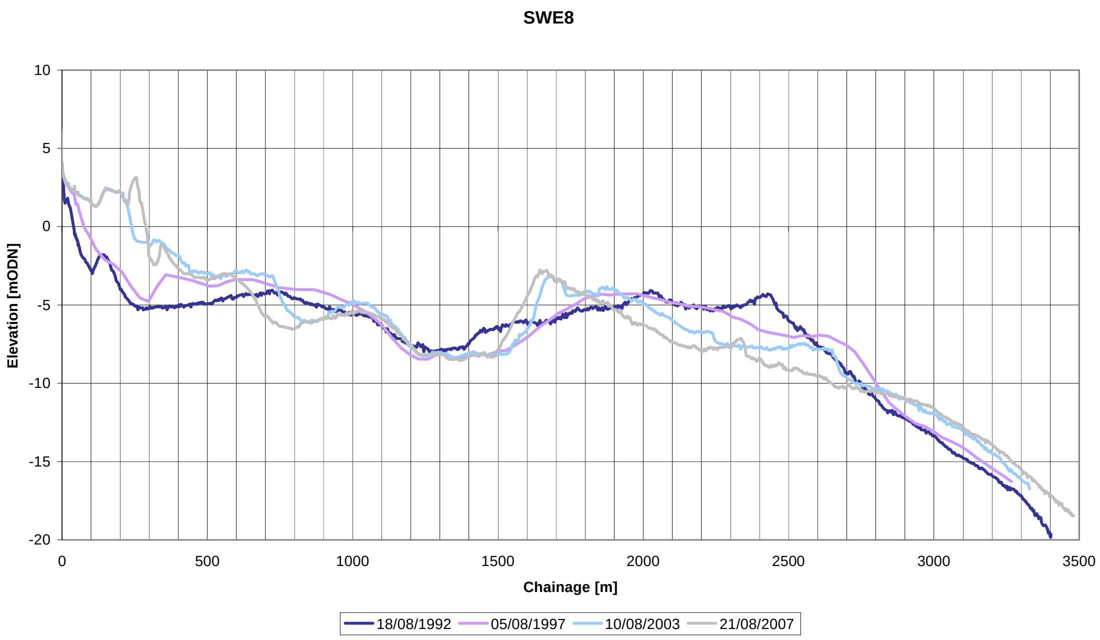


Figure 3.16 Profile SWE8: Kessingland

(source: Environment Agency)

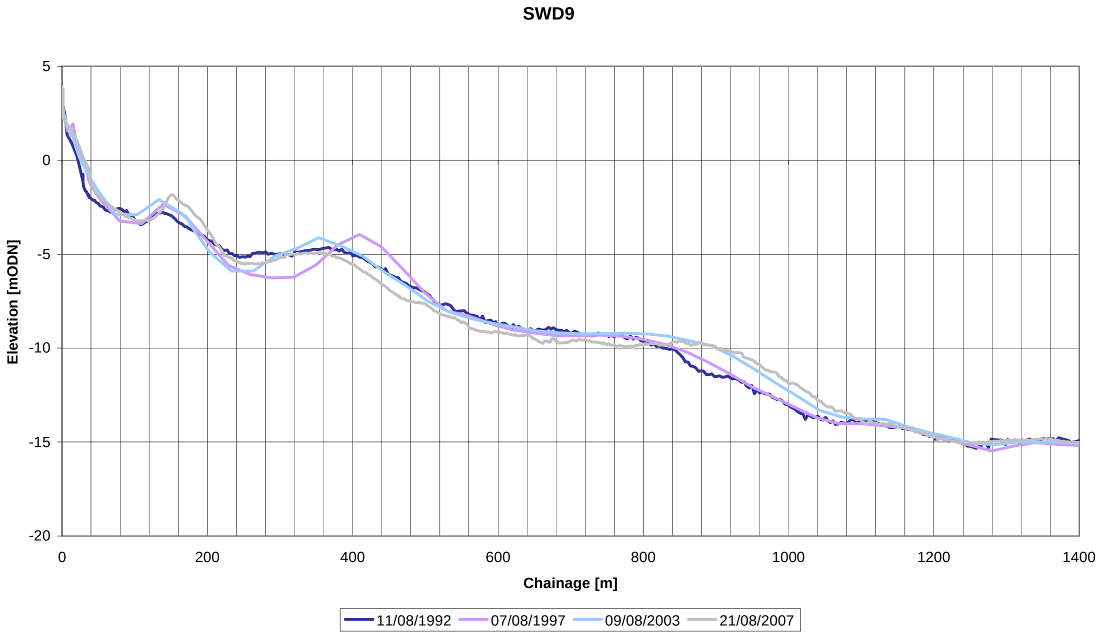


Figure 3.17 Profile SWD9: Southwold

(source: Environment Agency)

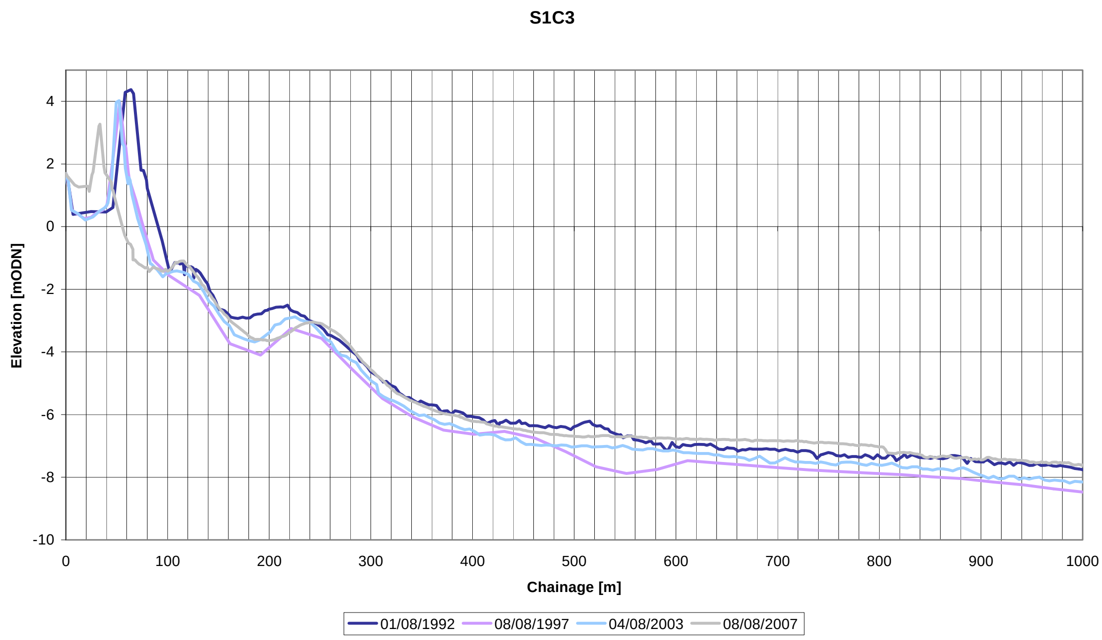


Figure 3.18 Profile S1C3: Alberswick

(source: Environment Agency)

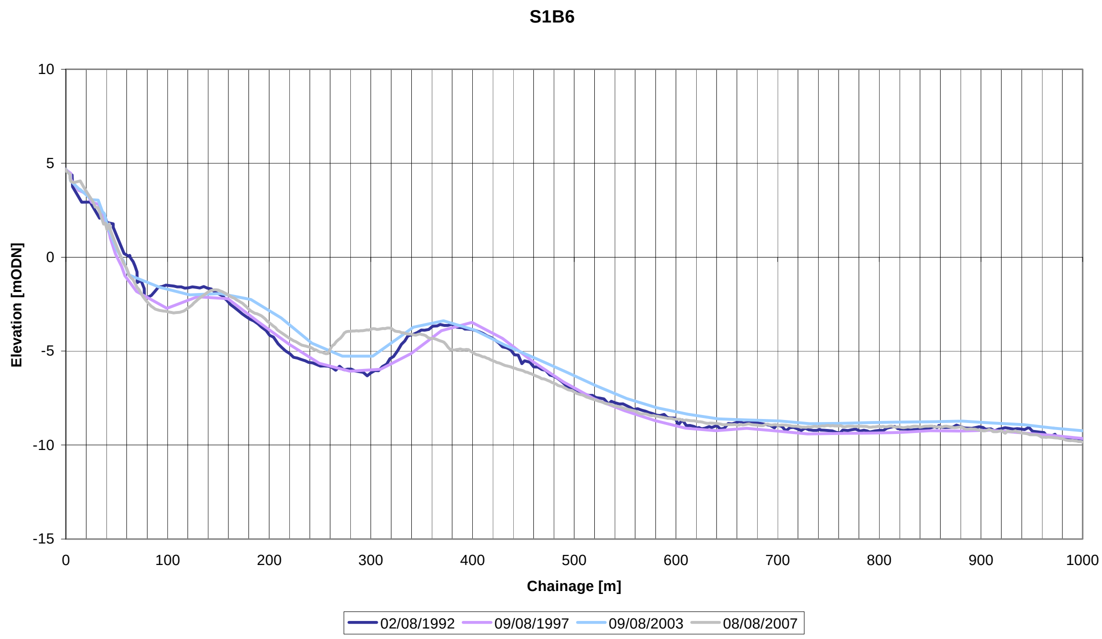


Figure 3.19 Profile S1B6:Sizewell

(source: Environment Agency)

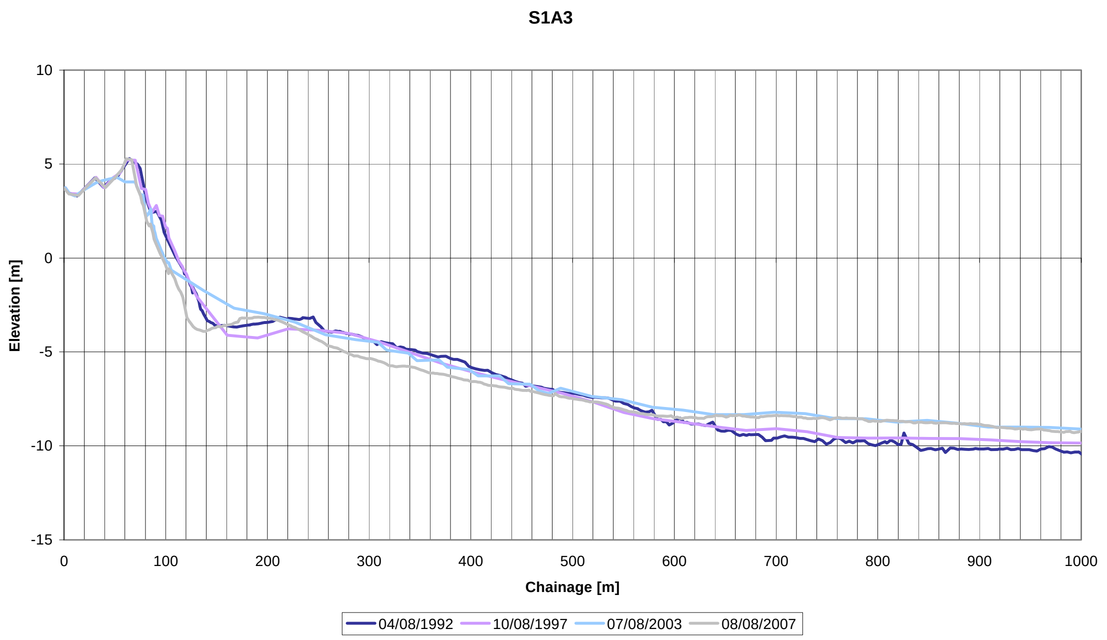


Figure 3.20 Profile S1A3: Thorpeness

(source: Environment Agency)

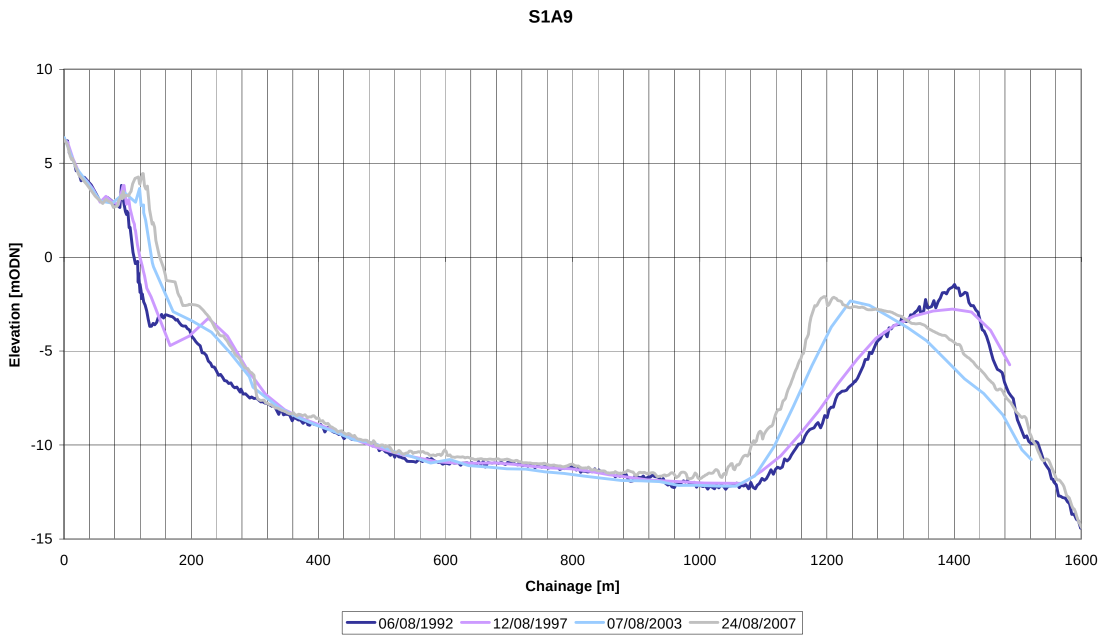
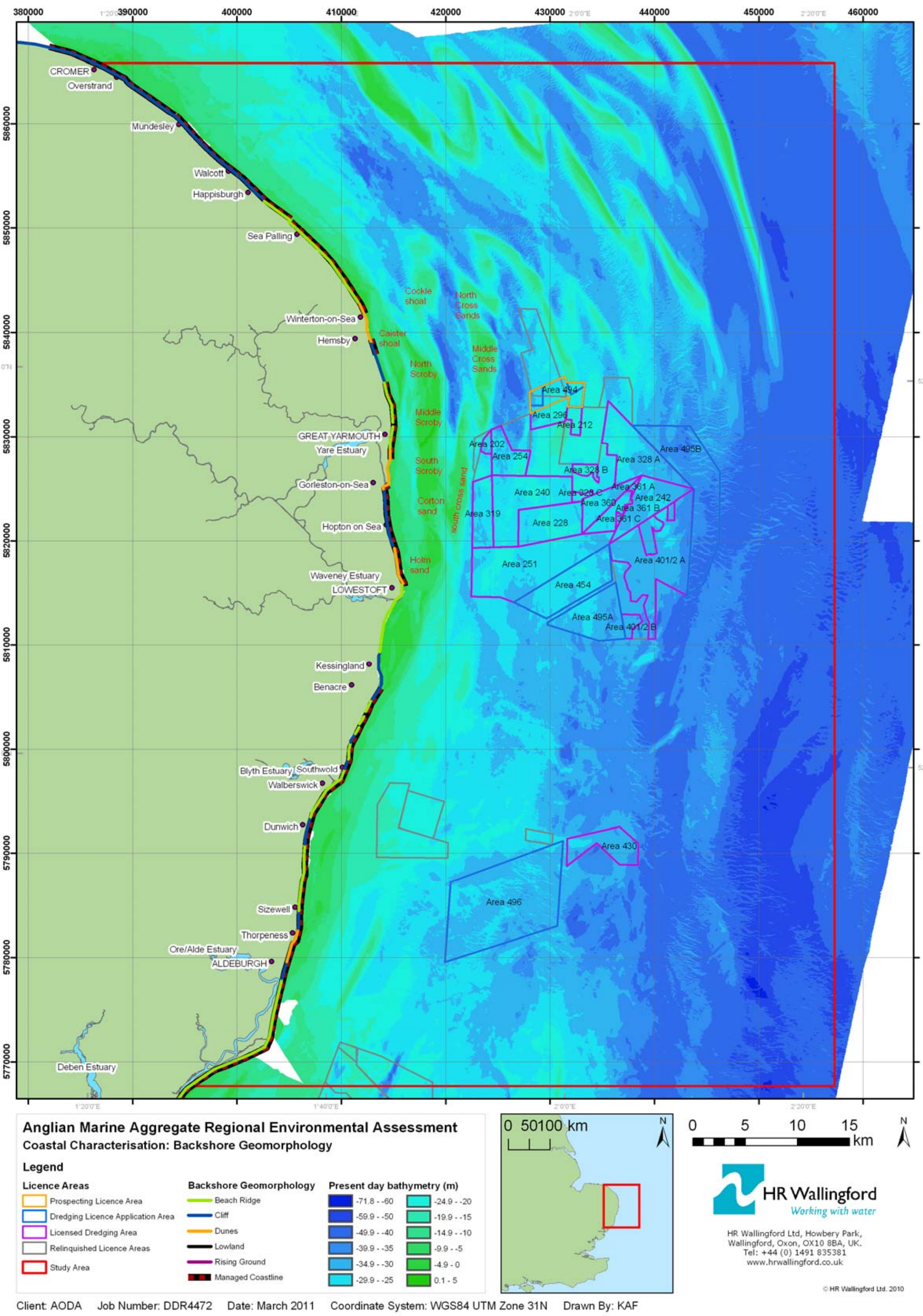


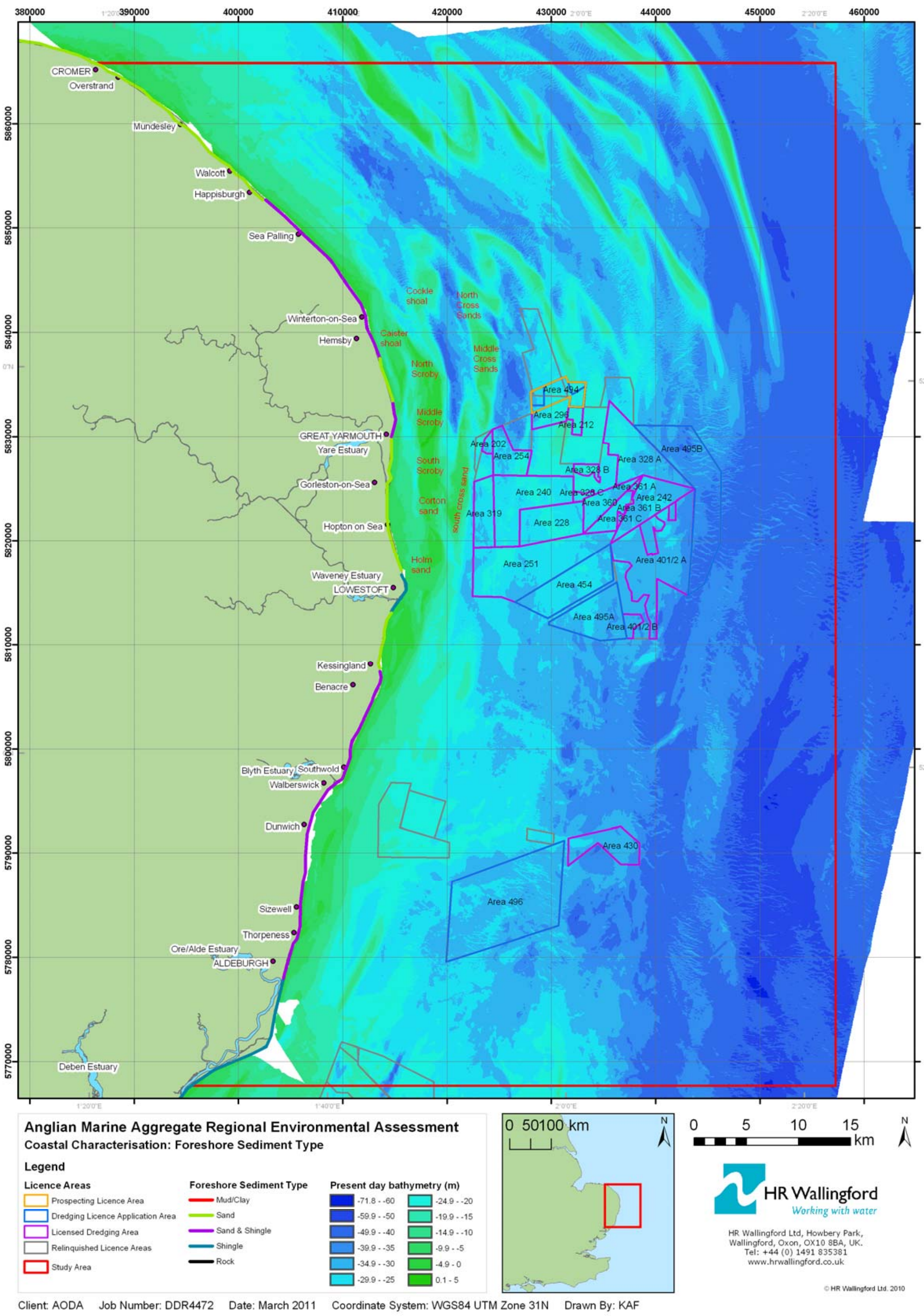
Figure 3.21 Profile S1A9 (out to 1600m): Aldeburgh

(source: Environment Agency)

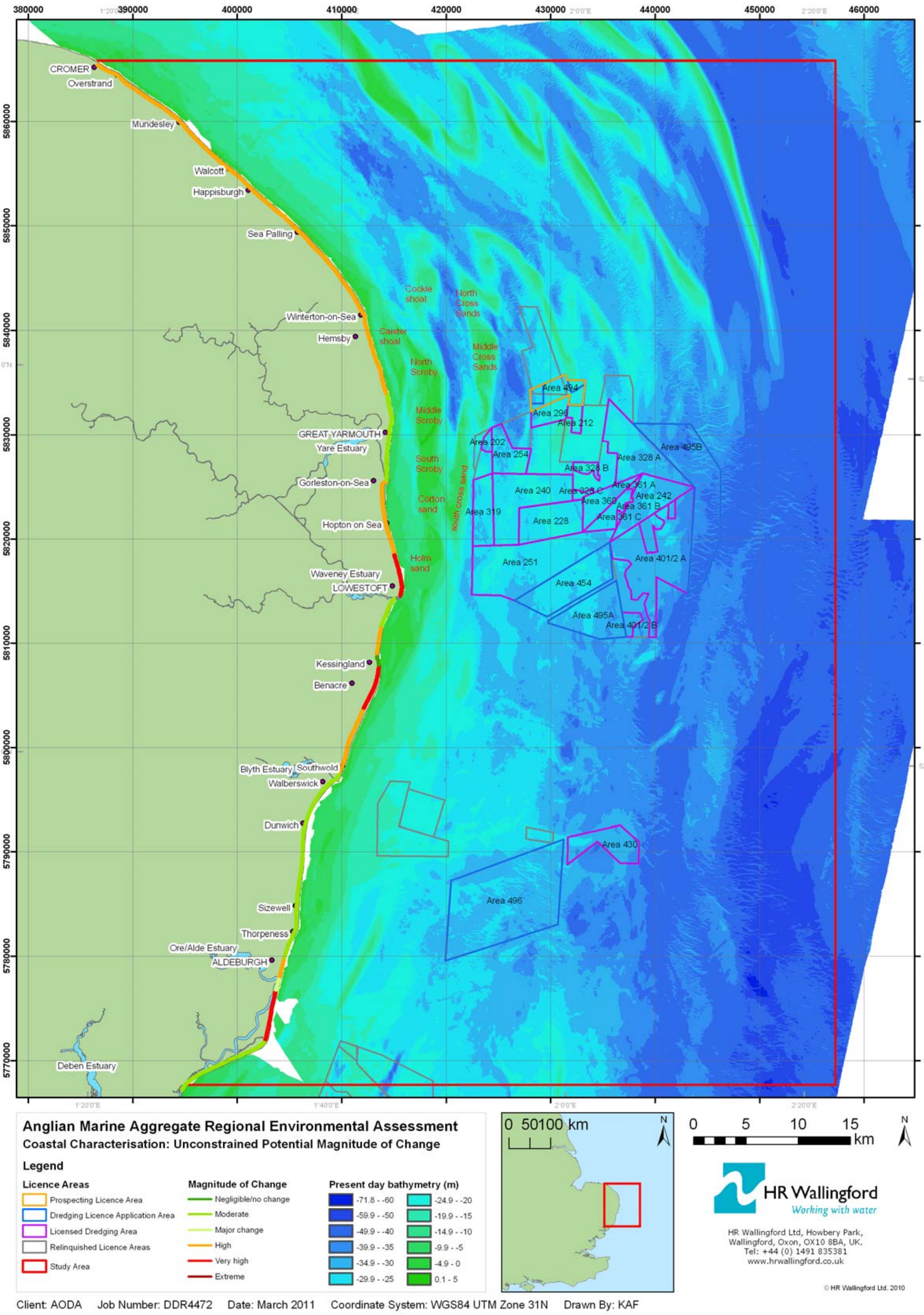
Maps



Map 1 Backshore geomorphology and managed coastline



Map 2 Foreshore geomorphology



Map 3 Unconstrained potential magnitude of change

Plates

Plate 1 Timber revetment west of Overstrand

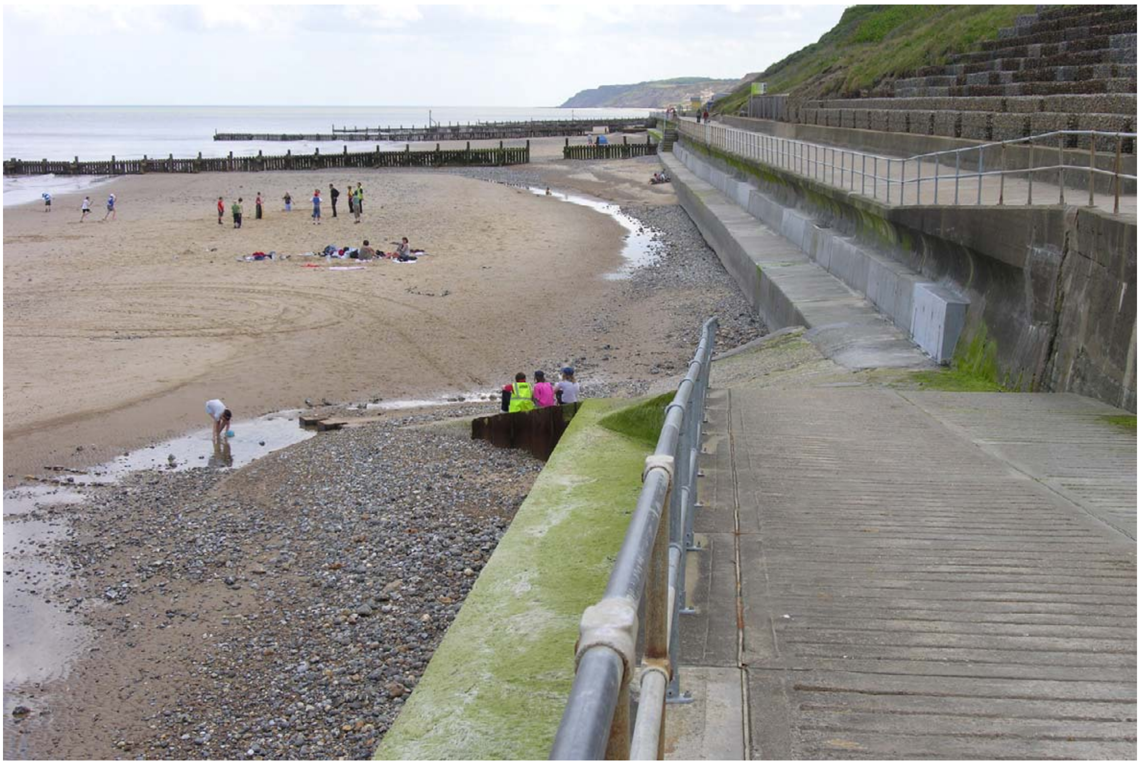


Plate 2 Seawall and gabion cliff protection at Overstrand

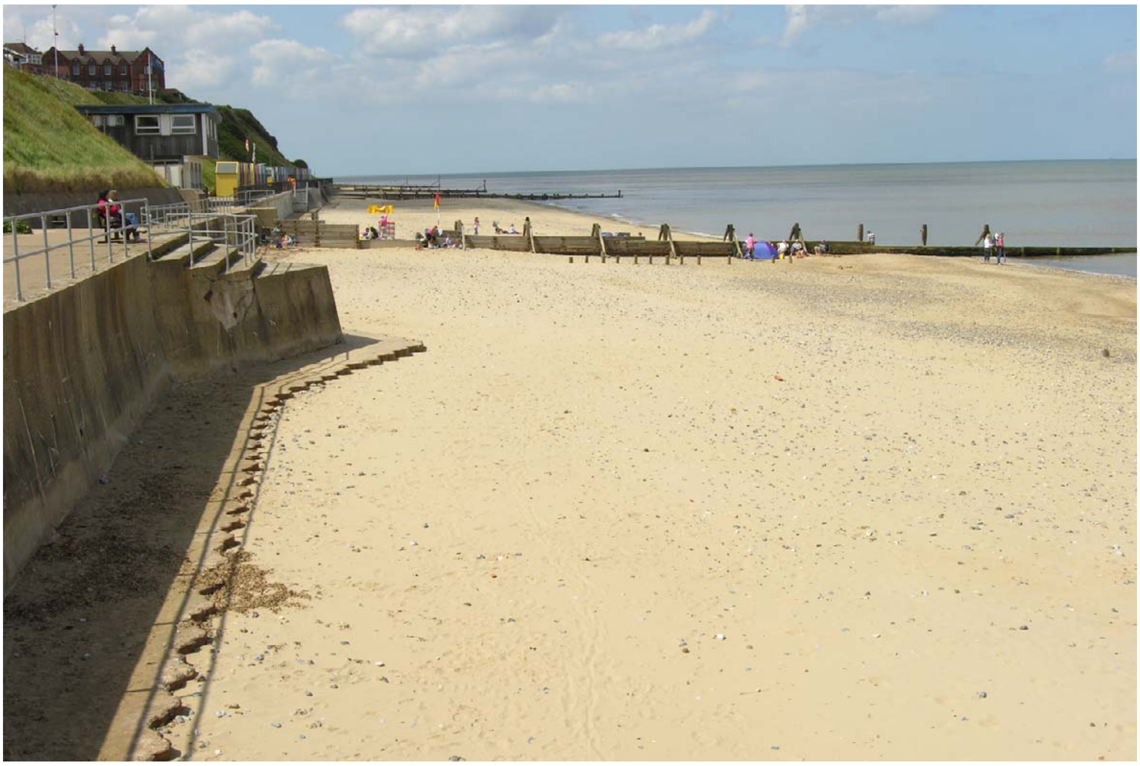


Plate 3 Seawall at Mundesley

Plate 4 Rock armour protection at Paston

Plate 5 Seawall at Walcott

Plate 6 Destroyed sea defences at Happisburgh

Plate 7 Seawall at Cart Gap, Eccles

Plate 8 Beach between reefs 3 and 4 at Sea Palling

Plate 9 Accreting beach at Winterton

Plate 10 Eroding sand cliffs at Hemsby Hole

Plate 11 Rock berm in front of cliffs at California

Plate 12 Accretion at Caister-on-Sea

Plate 13 Mixture of defences at Beach Road, Hopton

Plate 14 Low beach levels at Corton

Plate 15 Lowestoft Ness

Plate 16 Pakefield Beach in 1967

Plate 17 Pakefield beach in 1996

Plate 18 Accretion north of Kessingland village

Plate 19 Protection to outfall at Benacre Pumping Station

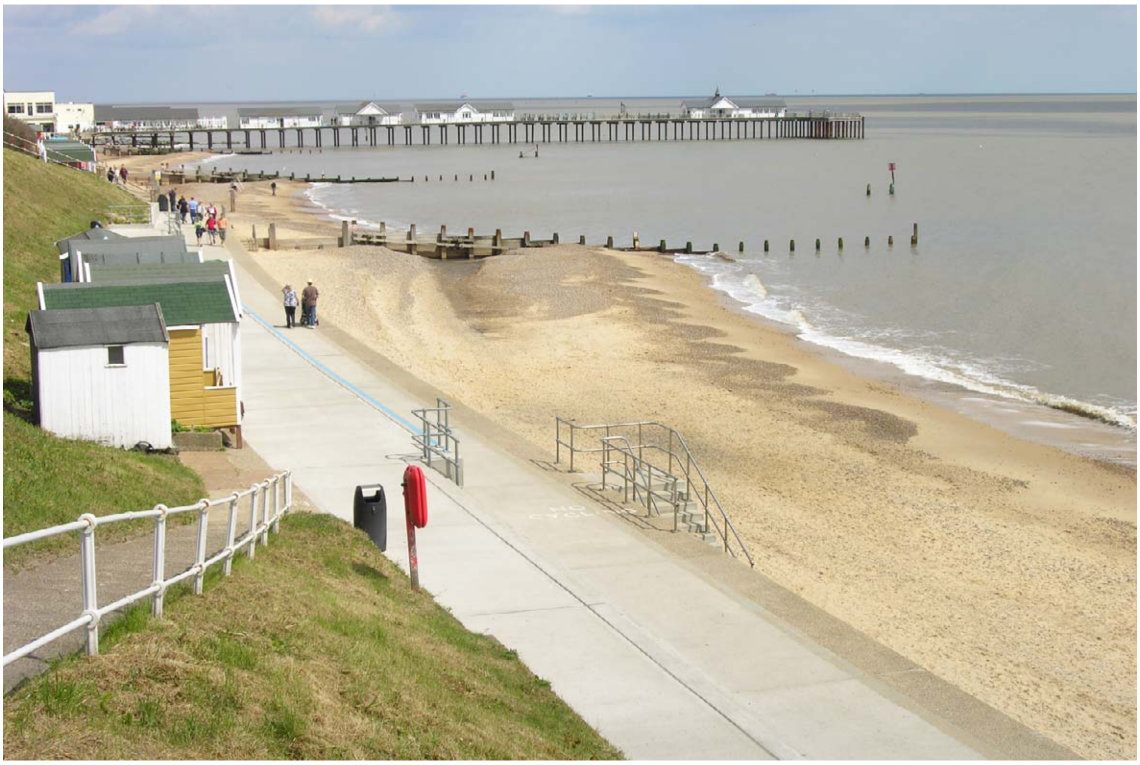


Plate 20 Sea defences at Southwold

Plate 21 Dunwich Cliffs low cost protection works

Plate 22 Healthy beach fronting Sizewell power station

Plate 23 Relatively stable cliffs south of Sizewell

Plate 24 Beach at Thorpeness village

Plate 25 Aldeburgh beach in 1960s

Plate 26 Aldeburgh beach in 2008

Plate 27 South end of Slaughden seawall in 1983

Plate 28 South end of Slaughden seawall in 2008

Appendices

Appendix 1 Beach draw-down and seaward limit

A common concern of coastal residents is that beaches could also be affected by their sediment being lost into the depressions in the seabed caused by dredging. This potential danger is known as "beach draw-down". In the UK, restrictions on aggregate dredging have been in place for longer than the last 40 years to avoid this possible problem. In addition, Coastal Impact Studies carried out for every aggregate extraction licence application explicitly consider and ensure that beach draw-down into the proposed dredging area will not occur.

In considering beach draw-down, it is important to know the depth below the lowest tidal level at which a beach ends and the seabed begins. During storms, sediment, i.e. sand or gravel, is eroded from the upper part of beaches and deposited further offshore/seawards, before being brought back onshore/landwards during calmer weather. These predominantly seasonal changes in beach profiles can be detected at some depth below the low water mark. A previous study of East Coast of England by Sir William Halcrow & Partners (1991) suggested a maximum limit of 7 metres below lowest tidal level for such seasonal beach fluctuations. Within the boundaries of the present MAREA region, the aggregate dredging areas are at least 5km offshore, and often much further, and the minimum water depth within them is greater than 15m below the lowest tidal level.

As part of this study, further analysis of beach and nearshore seabed profiles has been undertaken for the coastline between Cromer and Orford Ness. The aim of this has been to estimate the maximum depth at which seasonal changes in beaches can be detected, in each of the four coastal units considered in this study. For this analysis, we have obtained, from the Environment Agency, cross-sectional survey data gathered using both topographic and bathymetric surveys undertaken in 1991/2, 1996, 2002 and 2007. These repeated surveys have been carried out at 119 designated cross-sections, approximately 1km apart, and generally extend from landward of the beaches to a point at least 2,000m offshore, although some of the surveys have been extended further offshore to cover nearshore sandbanks.

These surveys have been compared and analysed to better understand how the beach profiles change along this coastline and, specifically, to estimate how far seawards beaches extend before becoming "seabed", i.e. where changes in the seasons and wave conditions do not cause any significant changes in bed levels.

Rather than merging imperceptibly with the offshore seabed, it is not uncommon around the UK to find that beaches terminate rather abruptly where they meet a nearly horizontal shore-platform of exposed bed-rock. Good examples of this can be found at both the northern and southern ends of the coastline described in this report, for example at Cromer (see Figure A1 – profile N3E2) and Orford Ness (see Figure A2 – profile SA10).

Along the East Anglian coastline, the nearshore bedrock is usually the same type of glacial drift that forms the cliffs. As sea levels have risen over the centuries, waves have slowly eroded this rather soft rock to form wide shore-platforms. Occasionally however, for example offshore of Cromer seafront, the shore platform is chalk, which is rather less easily eroded. While some sediment travels across these platforms, and may temporarily settle in any depressions in their surfaces, there will rarely be any significant depths of sand or shingle covering them but only a thin veneer, less than a centimetre or two deep. As a result, repeated surveys of a shore-platform over several decades will typically show little change in levels, at least once the inaccuracies in bathymetric surveys have been taken into account.

Above the beach toe, much more substantial changes in level from survey to survey can be expected, reflecting both the greater thickness of the sediment deposits and the effects of varying wave conditions on transporting the sediments, particularly in the shallowest water depths. Along the coastline of East Anglia, beach sediments can range from rather coarse shingle to fine sand, and these different types of sediment result in different beach profile gradients.

In Figure A2, for example, the upper part of the beach profile near Orford Ness is shingle and has a gradient of approximately 1 in 7. Quite abruptly beyond the -6m ODN depth contour, the gradient of this cross-section becomes much shallower (at about 1 in 45), probably reflecting the presence of sand on the lower part of the beach. The profiles then become virtually horizontal at a level of about -9.5m ODN. This is deduced to be the location of the beach toe at this location, and from here the shore-platform extends some 500m further seawards before meeting the landward flank of Aldeburgh Ridge, and large bank that runs roughly parallel to this part of the Orford Ness shingle ridge.

This cross-section and that shown in Figure A1 at Cromer both show the general characteristic of beach profiles becoming gentler the further seawards one travels down them. If the beach meets a shore-platform that itself has a similarly shallow gradient, then it can be difficult using simple bathymetric surveys to discern where the beach profile ends and the shore-platform begins. This difficulty can be made greater if there are doubts about the accuracy of the survey data. As an example, Figure A3 shows the surveys of a coastal cross-section for a location between Walcott and Happisburgh. This shows the coastal cliffs, rising to above 15m ODN, a persistent nearshore sand bar, often known as a breakpoint bar, about 250m offshore, and a gently sloping beach face (about 1 in 30) further seaward that eventually meets a near horizontal platform about 725m offshore. The deduced beach toe at this location may be as deep as 14.5m below ODN (or about 12.2m below lowest tidal level at this location). The apparent increase in bed levels between 1991 and 1996 followed by a nearly equal lowering in the next four years is presumed to be a result of inaccuracies in the bathymetric surveys rather than genuine accretion/erosion.

Were all the cross-sections as simple as those shown in Figures A1 to A3, then it would have been a relatively straightforward exercise to provide an estimated depth, or range of depths, at the toe of the beaches along this coastline. However, in the central third of the coastline being considered, extending from Winterton Ness in Norfolk southwards to Lowestoft, the situation is more complicated. Here there are numerous nearshore sandbanks and channels, and the lower part of the beach profile may also act as the upper part of the side-slope of a nearshore channel. As an example, Figure A4 (profile N4B2) shows surveys of a cross-section just to the south of California, to the north of Caister on Sea. The surveys taken show clear changes in beach level landwards of the -5m ODN contour at about chainage 250m. Beyond this to about the -15m contour, there is little sign of change despite the major changes in the position of the sandbank further offshore. At this location, it is not possible from these surveys to be sure whether the bed between chainages 250m and 600m is exposed bedrock or mobile sand.

At this location, beach sand could not be drawn down into any aggregate dredging area offshore of the sandbank, i.e. further than 2500m offshore, since for this to occur it would have to travel first down into the tidal channel and then up and over the sandbank crest. There would however be a possible concern that dredging too close to the seaward face of the sandbank could cause a draw-down of sediment from that bank into the dredging area, which in turn cold lower the crest of that bank and thus increase wave heights reaching the beach. This possible danger can be conveniently referred to as “bank draw-down”, and also needs to be considered when assessing the possible effects on the coast of offshore aggregate dredging.

It should be noted, however, that the mechanisms that cause the movement of sand up or down the seaward face of the nearshore sandbanks are different to those acting on beach faces. The gradient of the seaward face of the sandbank shown in Figure A4, for example, is about 1 in 20 near the toe of the bank. This is much steeper than would occur in water depths of 20m to 25m on a beach face where the gradient is dominated by wave action. The morphology of the nearshore sandbanks off this part of the coastline is very largely governed by tidal currents rather than by wave action. It is therefore necessary to investigate whether proposed aggregate dredging will alter tidal flows along the outer faces of these banks as well as considering any changes in wave conditions.

For the sections of the coastline between Eccles and Lowestoft which have nearshore tidal channels and banks, we have still estimated the level of the beach toe, but numerical modelling will need to be undertaken to assess whether the cumulative effects on the seabed of past and future dredging could alter waves, tidal current and sediment transport along the outer edges of the sandbanks, and hence lead to a risk of draw-down of the most seaward bank.

Figures

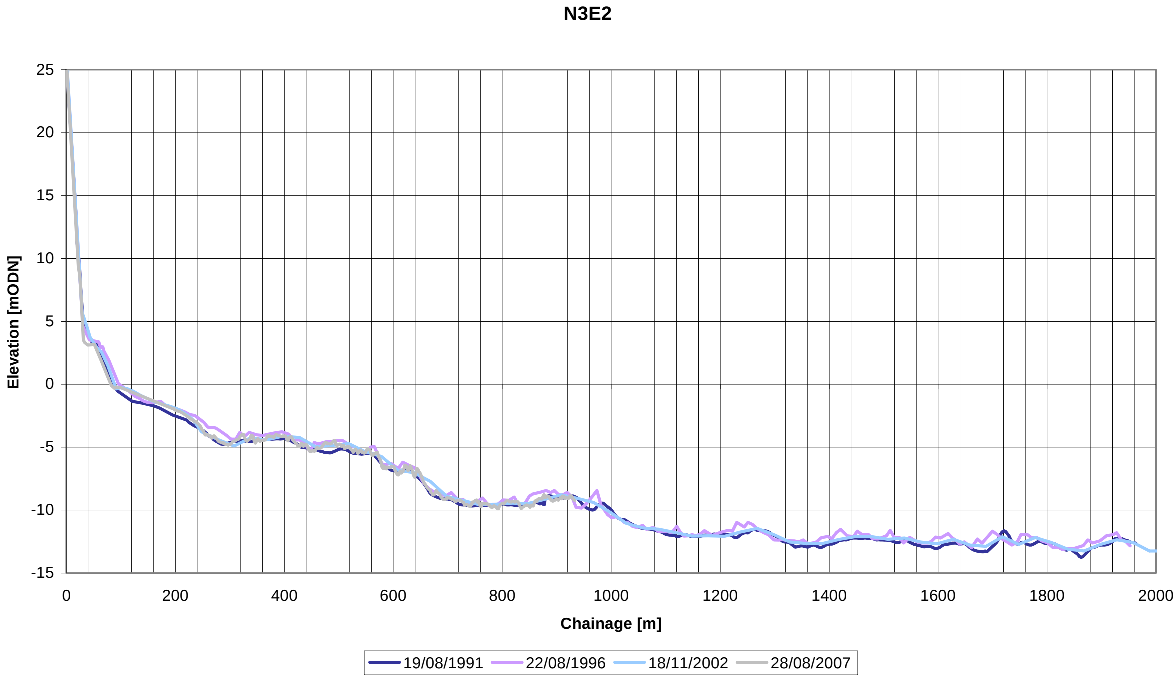


Figure A1 Cross-sectional profile at Cromer (profile N3E2)

(source: Environment Agency)

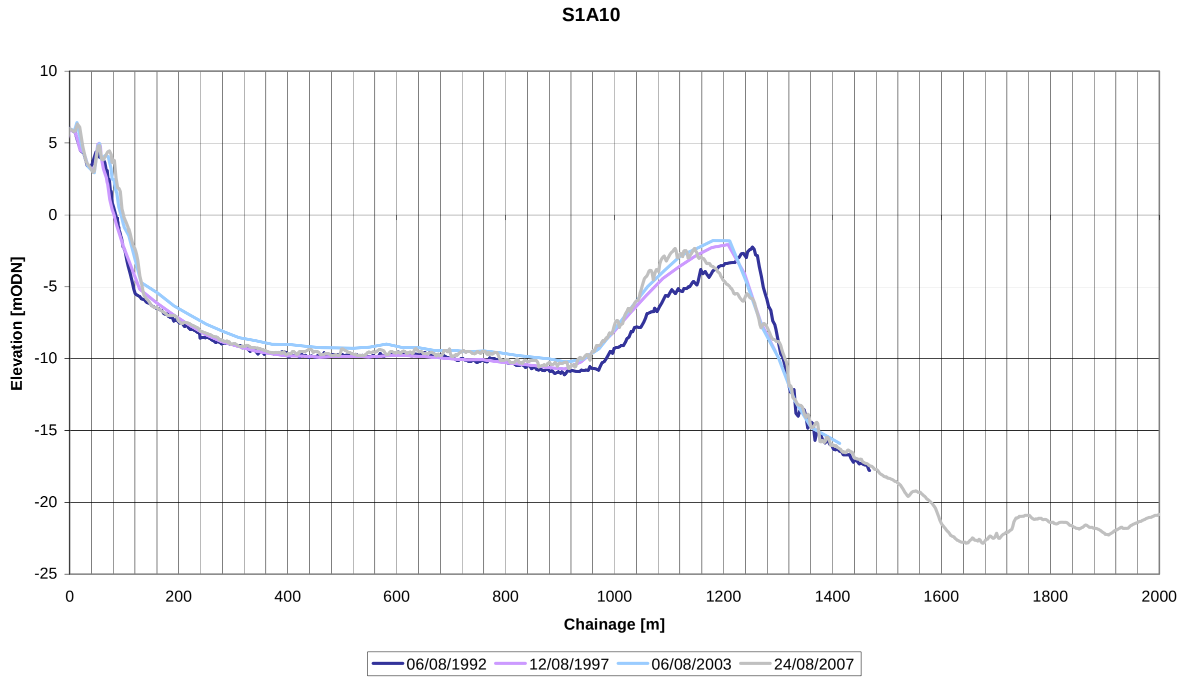


Figure A2 Cross-sectional profile at Orford Ness (profile SA10)

(source: Environment Agency)

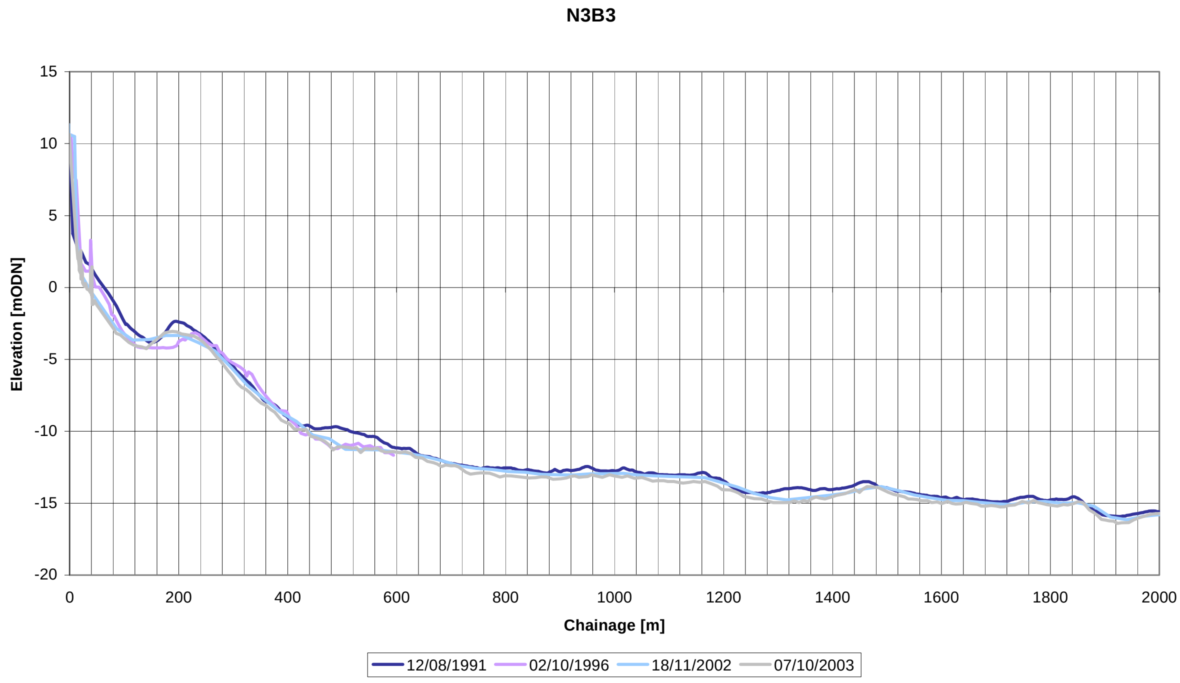


Figure A3 Cross-sectional profile between Walcott and Happisburgh (profile N3B3)

(source: Environment Agency)

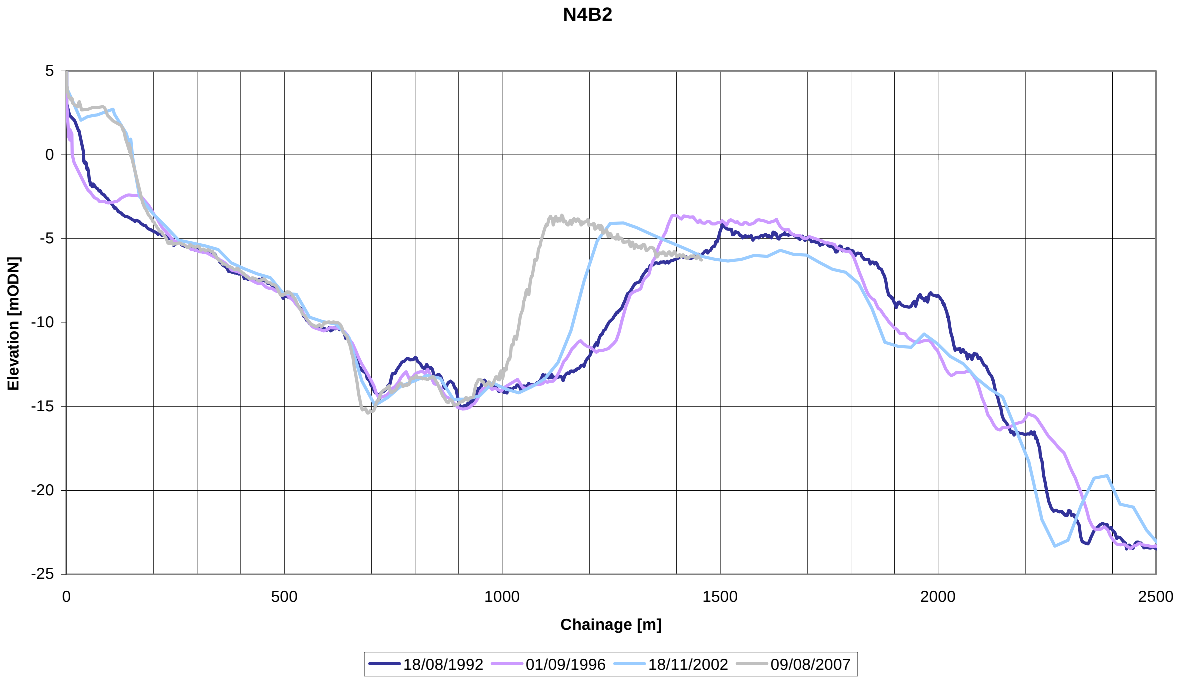


Figure A4 Cross-sectional profile at (profile N4B2)

(source: Environment Agency)

References

Sir William Halcrow & Partners, 1991. "The Anglian Sea Defence Management Study – Stage III", Study Report prepared for NRA (Anglian Region), April 1991.