Appendix C

Baseline processes

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C1 Introduction

This appendix reports on the coastal processes and evolution task and aims to provide a review of coastal behaviour and dynamics. The information collated and assessed during this task was subsequently used as a basis for developing the baseline scenarios, as reported in appendix F. It was also used to identify the risks and test the response and implications of different management policy scenarios over the different timescales.

Section 2.1 of the main document summarises the key information about the coastal processes and its relevance to the SMP, based on this appendix. The contents of this appendix have also played an important role in informing the development of the baseline scenarios as reported in appendix F.

C2 Review of information

The first Shoreline Management Plan (SMP1) was produced in 1996. This used a considerable number of studies for the north Norfolk area, dating back to work carried out by J.A.Steers, initially in 1927. However, it was recognised that, despite this information, because of the complex nature of the coast, the often local nature of processes and how coastal behaviour varies over time, there was a lot of uncertainty associated with coastal processes. This uncertainty was highlighted in the work done by the University of East Anglia long-term project team, with work extending over the period from 1979 (Vincent) to 1983 (Clayton, McCave and Vincent). The work in 1983 re-interpreted the initial determination of sediment transport.

Since developing SMP1, further work has been done to look at the detailed behaviour of the coast[1]. However, three studies in particular have been completed, attempting to provide a more strategic view relevant to the north Norfolk coast:

- Futurecoast (Halcrow 2003) setting a national and regional geomorphological framework for developing second generation SMPs.
- Southern North Sea Sediment Transport Study (SNS2) (HR Wallingford et al 2002), developing an understanding of sediment pathways, particularly within the nearshore and offshore areas of the southern North Sea but also examining previous analysis of longshore sediment transport, including that for north Norfolk.

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[1] Such work includes analysis of Environment Agency beach profile monitoring (ongoing since 1991) by Leggett et al (1998) and Schans et al (2001), together with work by Andrews (2000). Also more local studies at the sites of Brancaster West Marshes (EA 2000), Blakeney (EA 2001), Cley and Salthouse (EA 2006) and further east at Cromer (HR Wallingford 2002).

- North Norfolk Coastal Habitat Management Plan (CHaMP) (Royal Haskoning & Pethick 2003)[2] aimed at providing advice to the SMP2 about managing Natura 2000 sites.

Although in each of these projects new data and information were identified, their main aim has been to gather together and re-interpret information, providing a better overall understanding of the area, each with a slightly different purpose and emphasis.

This geomorphological review draws directly from these strategic level reports, providing an overview of that emerging understanding about the needs of the SMP2 analysis and adding any further information to confirm or clarify areas of continued uncertainty. The format of each of these reports is broadly similar, starting by considering the general structure and context of the coastline, following this down to collate information about individual sections of the coast. This review follows a similar structure. It also incorporates information from the CFMP for the area and provides specific information about water levels, tidal flow and wave analysis.

C3 General overview

C3.1 General description

The SMP covers the area between St Edmunds point, the hard cliff outcrop to the north of Hunstanton (within the entrance to the Wash), through to Kelling Hard and the rising cliffs at Weybourne in the east. The coastal area is characterised by low-lying land of one to three kilometres wide occupied by extensive salt and grazing marsh, mudflats, generally fronted by dunes, shingle and sand spits, beaches and barrier islands.

The land inland of this coastal fringe rises relatively steeply to the edge of the Norfolk plateau. This rising land is cut by the valleys of the four main rivers:

- the Hun, to the north of Holme running to the sea north of Thornham
- the Burn, exiting at Burnham behind Scolt Head Island
- the Stiffkey to the west of Blakeney Point
- the Glaven, flowing to the coast through Blakeney and behind Blakeney Spit.

Other creeks develop at the back of the saltmarshes and flow out through the marshes, sandbanks and mudflats along the coast. The most obvious of these are the various creeks flowing to the west of Scolt Head Island, through Brancaster harbour, the various creeks of the Wells saltmarsh, feeding both east (through Cabbage Creek) and west (through the Wells channel) and the

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[2] As part of the English Nature/Defra/EA/NERC project “Living with the Sea”.

drainage channel to the Cley marshes. This basic hinterland structure and coastal fringe is shown in figure C3.1 (taken from the North Norfolk CFMP).

Towards the sea, the low water contour follows in a series of soft, effective headlands and bays:

- in the west with the open beaches running north from Hunstanton to Gore Point
- within the entrance of the Wash, Brancaster bay
- between Gore Point and Scolt Head, Holkham bay
- between Scolt and Bob Hall's Sand, Stiffkey bay
- between Bob Hall's Sand and Blakeney Point
- at the soft coastal fringe then running out to the more linear beach/cliff system typified by the Weybourne to Cromer frontages

It appears that this advanced sedimentary shoreline is associated with the topography of the underlying chalk (discussed further in the following sections) with the presence of a possible east/west palaeo-valley within the nearshore area. This is indicated in the existing sea bed bathymetry along the frontage, shown in figure C3.2 (taken from figure 4.1 of the CHaMP). The blue lines are bed elevation contours.

To the west of the frontage, along the eastern shoulder of the Wash, are a series of drying sand banks: the Sunk Sand and the Middle and Gore, flanking the main channel and running parallel with the Lincolnshire coast from offshore into the Wash. This is illustrated in the plot of the offshore bathymetry in figure C3.3. This bird's eye view from the north east into the Wash shows the deepest channels in grey and the shallower reaches in blue, ranging to purple and red for the saltmarshes in the Wash that are around mean high water level.

The Sunk Sand effectively links to the shore with a very shallow channel between the bank and the wide beach. The Middle and Gore banks are separated from the Sunk Sands and from the shore by a more distinct channel (The Bays) reaching depths typically of three to four metres below chart datum (CD). Further east, offshore of the western end of Scolt and in general line with the position of the Gore Bank, is a hollow (the Brancaster Road) with depths typically of five to six metres below CD. These features, together with other generally deeper areas (such as the Sledway) and shoaling areas (such as the Woolpack) lie within, or over, the large expanse of shallow sea bed making up the Burnham Flats and beyond that the Docking Shoal.

Figure C3.1 General hinterland and coastal fringe topography

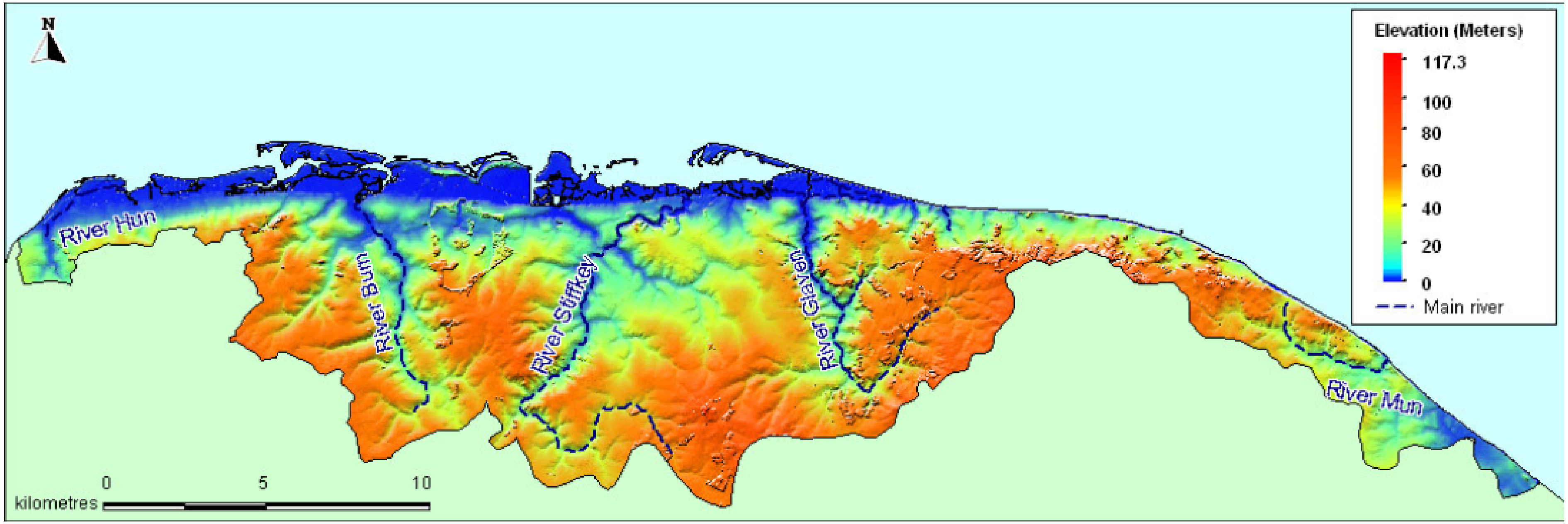


Figure C3.2 Nearshore bathymetry indicating an east-west trough

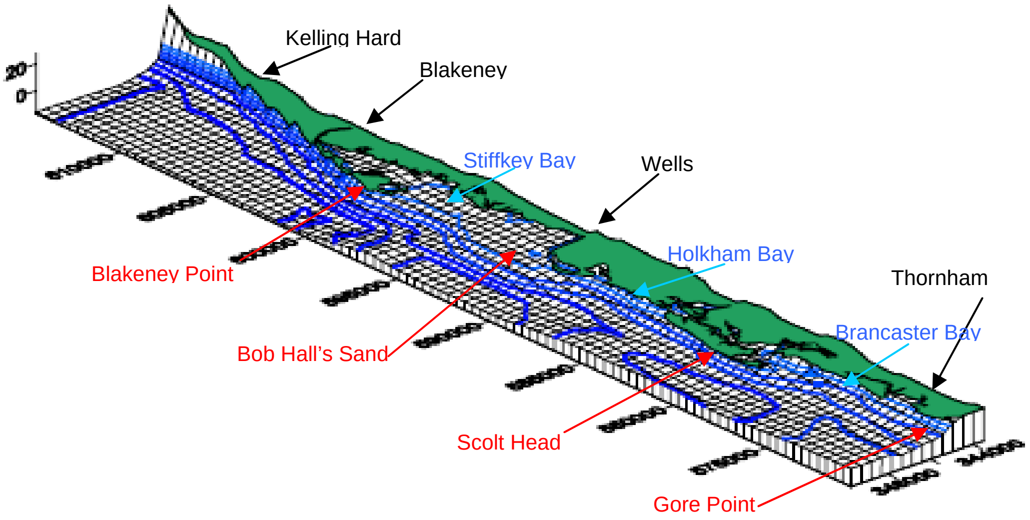
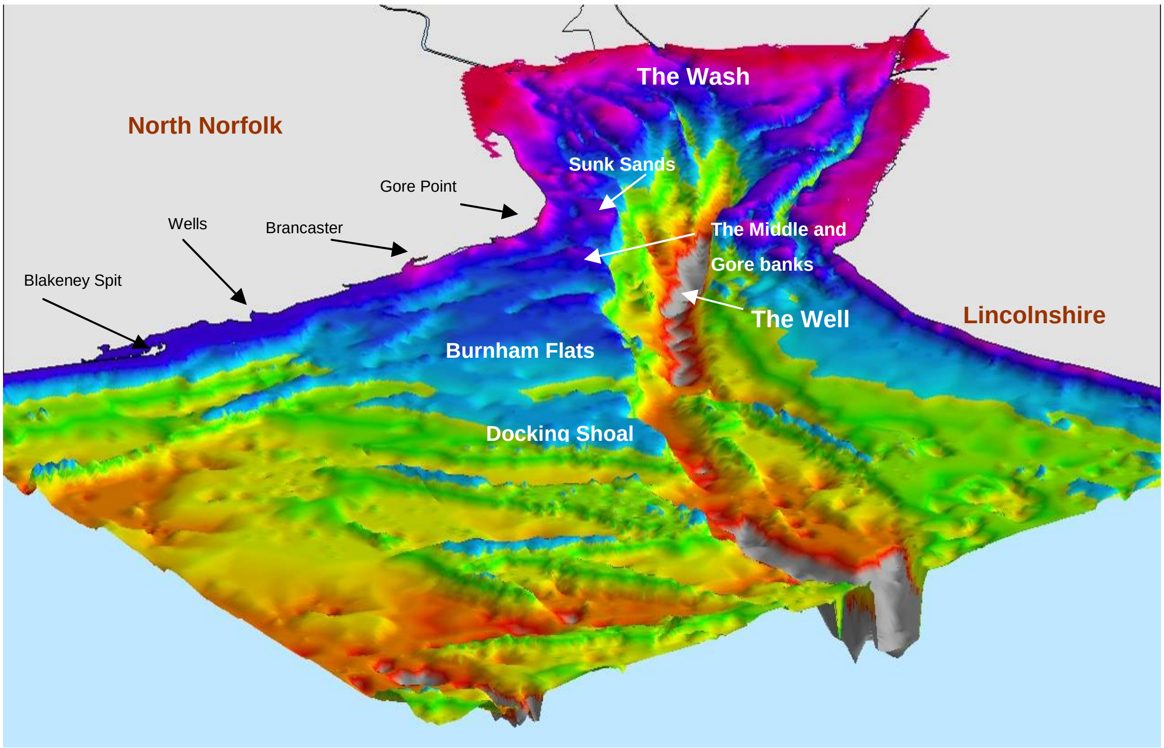


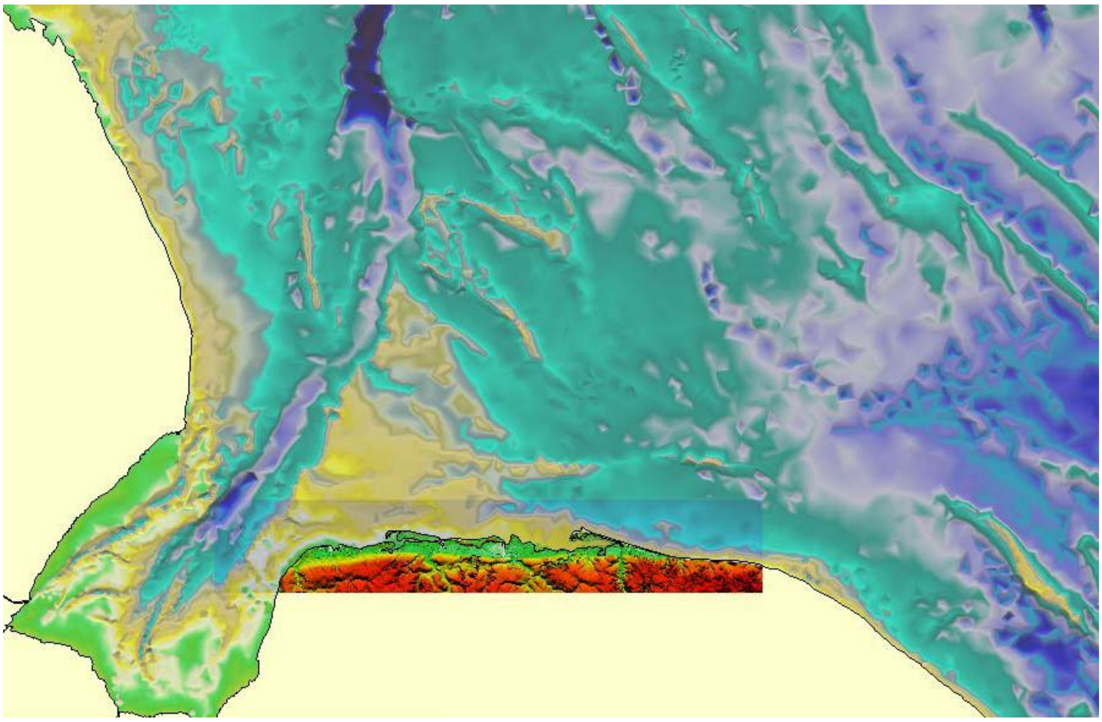
Figure C3.3 Bird's eye view illustration of general bathymetry



The Burnham Flats and Docking Shoal merge northwards into the sandbanks of the Race Bank, The Ridge and Dudgeon Shoal. While these sandbanks have the typically elongated shape of banks in this area of the southern North Sea, together with evidence of sand waves, the Burnham Flats and Docking

Shoal do not. However, they do represent a large reservoir of sediment that can release sand towards the east. This broader distribution of the shoals and banks is illustrated in figure C3.4. Though not cored as yet, from geophysical evidence there are up to 10 metres of sediment within these features.

Figure C3.4 Illustration of bathymetry of the general area (blue = deep, yellow/green = shallow)



Elsewhere in the North Sea there are extensive deposits of peats, saltmarsh and intertidal sands and muds that were deposited during the early phases of the recent sea level rise between 9,000 and 7,500 before present (BP) (Eisma et al.1981). In areas immediately to the east of the SMP frontage there were such areas where tidal flat and saltmarsh sediments were deposited, confirmed by peat and intertidal bivalves found within cores (Balson 1999). It is very likely that the Burnham Flats and Docking Shoal are remnants of such an intertidal sedimentary environment, deposited on the eastern border of the southern part of The Well / Inner Silver Pit channel and to a receding coastline to the south where these sedimentary environments still exist.

It may be seen, in broad descriptive terms, that the SMP area acts as a single geomorphological system formed as a triangular wedge of sediment extending north across the Burnham and Docking Shoal flats, with a base of marsh and barrier islands pinned up against the rising land of the north Norfolk plateau. To the west, this unit is contained against the shore by the main Wash channel and, to the east, tailing out against the more open coast of the Weybourne to Cromer coastline. Within this shoreline attachment of sediment, the more local barrier features are compressed against the coast by wave energy and water level, but responding to specific events in terms of sediment movement and worked by the tidal flows along the nearshore area.

Internally, this marine barrier is influencing and responding to the various fluvial and entrapped drainage pathways.

This general description provides the overall framework within which to consider the coastal development and processes discussed below.

C3.2 Geology and geomorphological development

The text in this section has been extracted from CHaMP 2003.

C3.2.1 The sedimentary environments

The north Norfolk coast is made up of a discontinuous series of beach barriers fronting extensive back-marsh areas, some of which have been reclaimed. The barriers are made of sand and gravels and vary from relatively high sand dune ridges to low shell and gravel cheniers. Most notable of the barriers are Scolt Head Island and the Blakeney Ridge. The dune ridge running between Holme-next-the-Sea and Brancaster, and the low sand and gravel ridge running between Warham and Morston (the Meols/Meals), are also very important in providing the framework within which the extensive mudflats and saltmarshes of the coast have developed. To the north (seaward) of the barriers are extensive sand flats up to two kilometres wide that form a crucial wave energy dissipation surface. The modern coast therefore comprises the following sedimentary environments:

- intertidal sand flats with mega-ripples and beach bars
- barrier and spit systems composed of gravel and coarse sand
- aeolian sand dunes located on the barrier systems
- back-barrier saltmarsh and intertidal muds
- sandy tidal channel deposits with small amounts of gravel.

C3.2.2 The chalk surface

Recent research (Andrews 2000; Funnel 1992 and Chroston 1999) has shown that the distribution of these sedimentary environments is closely related to a geological framework provided by the underlying chalk and the glacial tills that overlie the chalk foundations of the area. Chalk lies below the whole of the north Norfolk coast area although, due to the covering of glacial till, it is exposed only in the cliffs at Hunstanton and on the wave-cut platform in front of the Weybourne to Cromer cliff section. The upper surface of the chalk shows a long west to east trough running parallel to the shore and located along the line of the back-marsh area of the present coast (figure C3.2). The trend of this trough, which is interpreted as a palaeo-valley (Chroston 1999), may have been determined by faulting within the chalk. The palaeo-valley dips gently from Holme in the west to Salthouse in the east, where it runs offshore.

C3.2.3 Interglacial shoreline

In several places along the coast the rising ground south of the present day high water mark (HWM) is formed by a low cliff that marks the probable higher sea level during the last interglacial period, the Ipswichian[3]. This cliff line is particularly well marked at Stiffkey, where it forms the inland edge of the saltmarshes and effectively prevents these marshes moving inland in response to sea level rise.

C3.2.4 Devensian tills

Between the overlying Holocene deposits and the chalk are the glacial tills, of varying thickness but mainly between two and five metres. They were mostly laid down during the last glacial period when the front of the Devensian ice sheet lay along the coast. The tills extend seaward beyond the present day barriers and have been, and perhaps still are, an important source of coarse-grained sediment for the Holocene coastal deposits. Although in general the Holocene barriers and marshes cover the glacial deposits of the intertidal zone, in places the glacial till topography emerges from the Holocene covering forming till islands known locally as ‘eyes’ (Cley Eye, Blakeney Eye, Little Eye and Gramborough Hill).

C3.2.5 Holocene sediments

The Holocene sediments resting on this glacial till consist mainly of sands and gravels and fine-grained silts and clays. However, in places, particularly in the west-east trough described above, the basal Holocene deposits are freshwater peats laid down just before the incursion of the sea at around 8,000 years BP. Freshwater peats have also been exposed in the intertidal area north of the beach barrier at Thornham and Brancaster Staithe. These appear to be much younger than elsewhere (3,000 years BP) and suggest that here a freshwater lagoon had formed inland of a barrier system that prevented sea water access. The recent (1999) exposure of the Seahenge archaeological site here is of the same age and may also be associated with this impermeable barrier.

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[3] It has been suggested that this cliff line was formed by marine action during a previous high sea level, possibly that of the Ipswichian (130,000 to 125,000 years BP). However, Andrews et al (2000) suggest that it was the southern margin of an eastward-trending ice front channel (SNS2 2002).

The existing line of the barriers and back-marshes appears, at first sight, to be controlled by this west-east trough, with the barriers, including Scolt and the Blakeney ridge, located on the northern lip of the valley and the marshes occupying the trough itself. The gravel barrier ridge between Blakeney Point and Kelling, for example, lies over a pronounced ridge in the chalk, while the intertidal sand and muds of Blakeney harbour are formed in the valley to the south of the chalk ridge (figure C3.2). However, although the extreme eastern end of Blakeney ridge is grounded on a high point in the underlying chalk, most of the gravel barrier appears to be only coincidentally associated with the underlying chalk ridge. This is because a thickness of till that effectively buries the chalk topography lies between the chalk and the Holocene gravels.

This may be a crucial issue to future management of the north Norfolk coast. If the present barriers are only associated with the underlying chalk topography due to a coincidence in time, and they have in fact been moving towards land over the Holocene period across a planar till surface, they may be expected to continue to move towards land in the foreseeable future. On the other hand, if the location of the barrier is determined by the underlying chalk ridge and valley sequence, their location may be more permanent.

In contrast with the Blakeney barrier ridge, evidence from Holkham and Burnham Overy suggests that here the barriers have already transgressed across the chalk valley. It also appears probable that the Blakeney barrier has not yet done so due to the pinning of its eastern end on the higher chalk surface. However, even here at Salthouse-Cley the modern barrier ridge has moved towards land over the Holocene saltmarsh deposits that fill the palaeo-valley. These are often exposed on the seaward flank of the shingle ridge indicating that the location of this barrier is by no means static.

C3.3 Holocene history

C3.3.1 Past sea level rise

The Holocene sea level curve for the north Norfolk coast indicates a rapid rise in sea level, at an average rate of four millimetres a year, during the period 8,000 to 6,000 years BP. This was followed by a sharp fall in the rate at around 6,000 BP to 1.5 millimetres a year, an average rate that has persisted until now.

C3.3.2 Holocene geomorphology

In the early Holocene period, while sea level was below -16 metres ordnance datum, the coast was characterised by fluvial processes that caused basal freshwater peats to form in some places. These peats have upper surfaces that lie at around -6 metres ODN. This level appears to be associated with the onset of marine conditions around 7,000 to 6,000 years BP. As the sea level rose after this period, the modern Holocene marine sequence was laid down inland of the outer barrier. An initial layer of mudflat sediment, up to 15 metres thick, was formed between 7,000 and 6,500 BP. At this stage lower saltmarsh began to form succeeded by upper saltmarsh at around 5,000 to 4,000 years BP.

The barrier beaches that protected these mudflat and saltmarsh deposits appear to have moved towards land during the last 6,000 years at rates of around one metre a year. This landward movement of the barrier seems to be a response to sea level rise, which has averaged 0.0015 metres a year for 6,500 years. Assuming that the intertidal slope has remained at its present gradient of 1:600 over this period, landward movement of the barrier would have occurred at 0.9 metres a year. Since the pre-Holocene surface slope gradient is between 1:500 and 1:1000, the landward movement of the entire Holocene sedimentary prism seems to have been at the same rate as the movement of the barriers. A tidal range of five metres on a slope of 1:600 would result in an intertidal width of three kilometres, roughly the average width of the modern intertidal zone. It is not until the high water mark reached the rising ground of the Ipswichian shore that any sediment would have been lost due to landward movement. The width of the existing intertidal zone suggests that this loss has been relatively small so far.

This analysis contrasts with that of Andrews et al (1999) who propose that the entire Holocene sediment prism is now only half its original width. They suggest that, although there is now no trace of a wider shore zone, the sediments derived from its progressive thinning have been extensively reworked and re-deposited towards land. These transgression rates may not apply in some areas of the north Norfolk coast. At Scolt for example, there are two sets of barriers - the inner barrier, comprised of the Ramsay Ridges and the Nod, and the present day Scolt Island. Andrews (1999) proposes that the Scolt Island barrier is relatively young, possibly less than 3,000 years old, and developed as a spit emanating from Holkham and seaward of the older inner barriers. Similarly the western, distal, end of Blakeney Ridge was formed relatively recently, probably in the 16th century as a response to intertidal reclamation. This may explain why both these barriers, Scolt and Blakeney, lie much further out to sea than the other barriers on the coast.

C3.4 Present day processes

C3.4.1 Tide and water levels

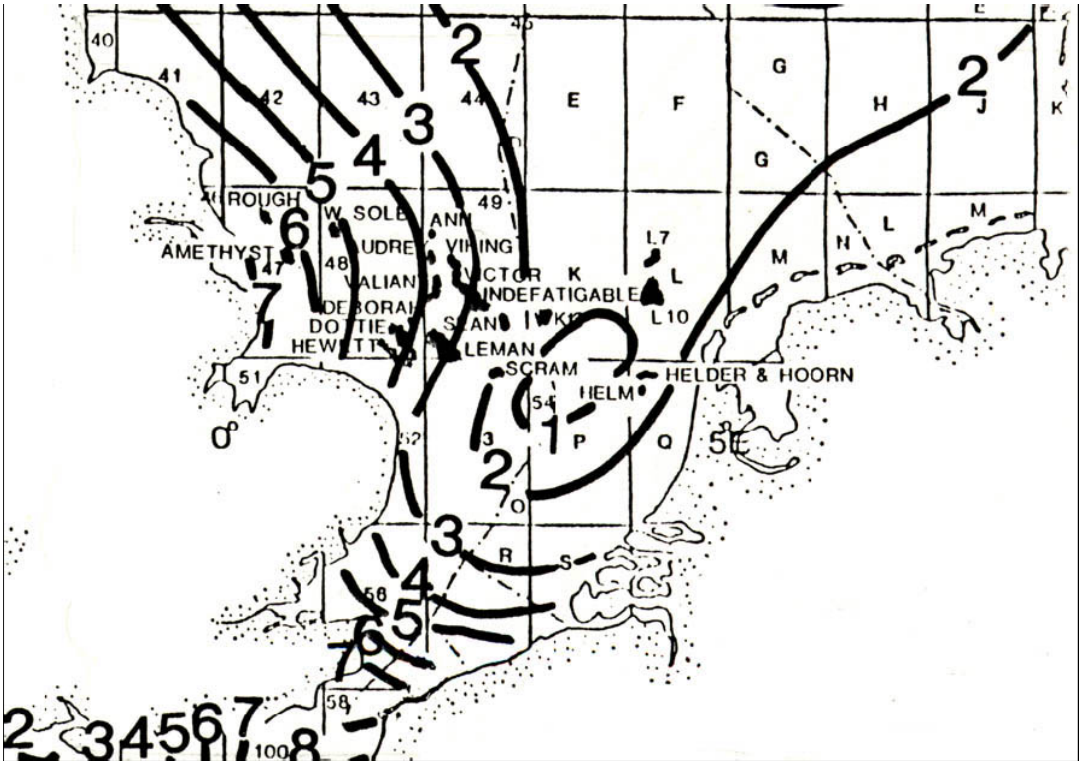
Water levels across the frontage result from a combination of predicted astronomical tide levels and surge caused by meteorological effects of wind and pressure.

Astronomical tides

The propagation of tides across the north Norfolk area is affected by the enclosure of the North Sea with tidal influence from the north and south. The effect is that the net tidal wave travels in an anti-clockwise direction around a null point situated between the Anglian coast and the coast of Holland, as shown in figure C3.5. This gives rise to a significant variation in tidal range and levels across the frontage.

Predicted water levels taken from the Admiralty tide tables are presented in table C3.1. These levels are given for secondary ports with reference to tidal levels at Immingham in the Humber estuary.

Figure C3.5 Propagation of tides



This variation in water level is significant, resulting in a difference in water level across the frontage at both high water and low water. This is discussed further in relation to water movement in subsequent sections below.

Table C3.1 Tide levels (m ODN)

Port	MHWS	MHWN	MLWN	MLWS	LAT	Time relative to MHWS Immingham	Range on springs (m)
Hunstanton	3.65	1.85	-1.25	-2.85		+ 20 min	6.5
Burnham	2.90	1.50	Dries			+ 55 min	
Wells	2.75	1.25				+ 45 min	
Blakeney	2.60	1.20				+ 55 min	
Cromer[4]	2.15	1.05	-0.95	-2.25		+ 30 min	4.4

Surge and water levels

Extreme water levels for the frontage have been taken from the Environment Agency report on Extreme Tide Levels (Royal Haskoning 2007). Extreme water levels are set out in table C3.2.

Table C3.2 Extreme water levels

Location	Return period (years)							
	1:1	1:5	1:10	1:25	1:50	1:100	1:250	1:500
Hunstanton	4.73	5.09	5.24	5.45	5.60	5.76	5.96	6.11
Holme	4.46	4.83	4.99	5.20	5.36	5.52	5.73	5.89
Brancaster	4.16	4.54	4.70	4.92	5.08	5.24	5.46	5.62
Burnham Overy Staithe	3.96	4.35	4.52	4.75	4.92	5.09	5.31	5.48
Wells	3.87	4.29	4.47	4.70	4.88	5.06	5.30	5.48
Blakeney	3.67	4.07	4.24	4.47	4.64	4.82	5.05	5.22
Weybourne	3.32	3.70	3.86	4.07	4.23	4.39	4.61	4.77
Cromer	3.05	3.42	3.58	3.79	3.95	4.11	4.32	4.48

This distribution of water levels is shown in figure C3.6. It reflects the typical nature of surge in the North Sea, being generated to the north and progressing as a wave to the south. This propagation of the surge will tend to be higher as it sets against the north Norfolk coast, being lower further offshore, but then increasing further south in the southern North Sea as the surge is funnelled.

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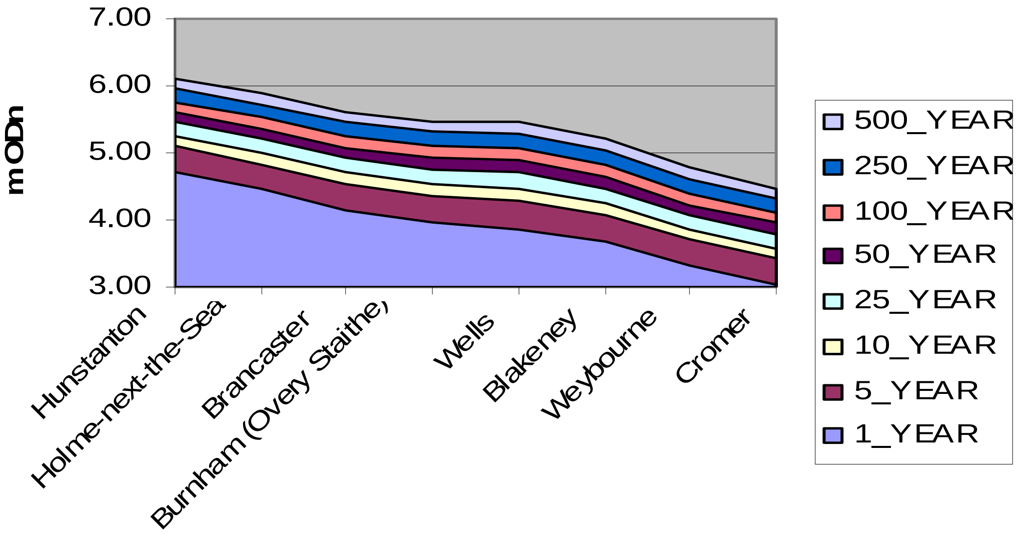
[4] The datum correction between ODN and CD given in the Admiralty tide tables has been found to be incorrect. Previously recorded MHWS levels for Cromer of 2.45 metres ODN have now been corrected in line with the findings of the EA Eastern and Central Area Report on Extreme Tide Levels (Royal Haskoning 2007).

Figure C3.6 Distribution of extreme water levels



C3.4.2 Hydrodynamics

Tidal flow

With the variation in tidal level across the area, tidal flows also tend to be complex. Reference to Admiralty tidal diamonds shows that, to the west of the frontage, there is a division of flow on the flood between the entrance to the Wash and flow across the north Norfolk coastline.

At a location on the eastern side of the main Wash channel, flood flows reach a maximum of 2.4 knots in towards the Wash (SSW) some three hours before high water, decreasing over high water. These flows are lower approaching Hunstanton at mid-tide (1.6 knots), again decreasing over high water.

In the offshore area, over the Burnham Flats, flow at mid-tide on the flood is lower (0.6 knots) towards the Wash, increasing (1.3 knots) over high water and backing to flow towards the east. This pattern is also seen off Blakeney Spit, with low westerly flow two hours before high water, increasing and backing sharply to the east (2.1 knots) over high water.

In effect, the flow pattern over much of the rising tide is relatively weak over mid-tide and towards the west, increasing to give a strong easterly flow over high water. This reflects the difference in water levels across the frontage seen in the section on tide levels.

On the ebb, the pattern is effectively reversed, with strong westerly flows over low water between Blakeney and the Burnham Flats, flowing into the ebb tide from the Wash.

While these flow patterns are lower inshore against the coast, they may influence sediment transport[5]. In combination with waves, tidal currents may strongly affect beach sediment transport. Clearly, with strong currents occurring over high water to the east and over low water to the west, it is suggested that there may be distinct transport pathways under typical wave conditions affecting different levels of the beach and nearshore areas in different ways, depending on depth.

Surge conditions, especially more infrequent high energy surge conditions with strong wave action, may create sudden increased patterns of sediment movement. This was highlighted from the modelling undertaken in SNS2, suggesting that material across the Burnham Flats may be significantly mobilised with changing normal sediment pathways and delivery, or moving substantial quantities of sediment in single events.

C3.4.3 Wave climate

Various wave studies have been undertaken for the area, mainly to assess sediment drift (UEA 1979 to 1983). Further wave data were determined during the Anglian Region Sea Defences Management Study (SDMS) (Halcrow 1988b) and this formed the basis for analysis of the SMP1. The distribution of wave climate from SMP1 is shown in figure C3.7.

More recent wave measurements were undertaken as part of the Norfolk Area monitoring programme. Figure C3.8 shows the locations at which measurements were taken, together with the places where data were obtained from hindcast modelling for the offshore area.

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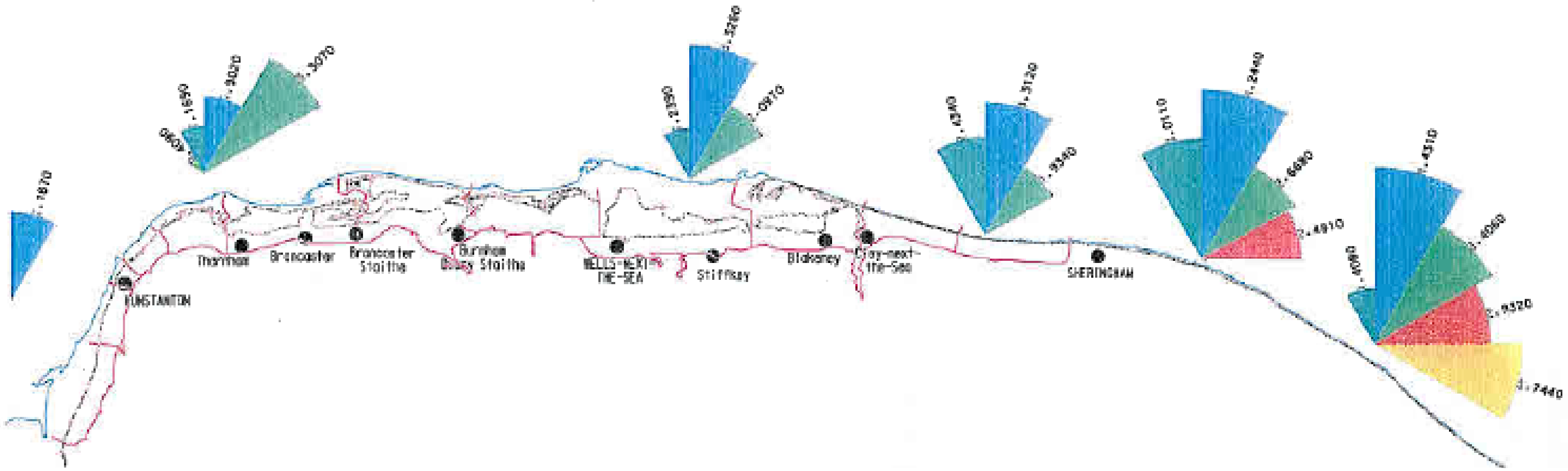
[5] SNS2 indicates low residual transport due to tidal action in the nearshore area.
The Cromer Study (HR Wallingford 2002) records that current speeds of 1.2 to 1.5 knots are capable of mobilising and transporting seabed sediments up to the size of small gravel.

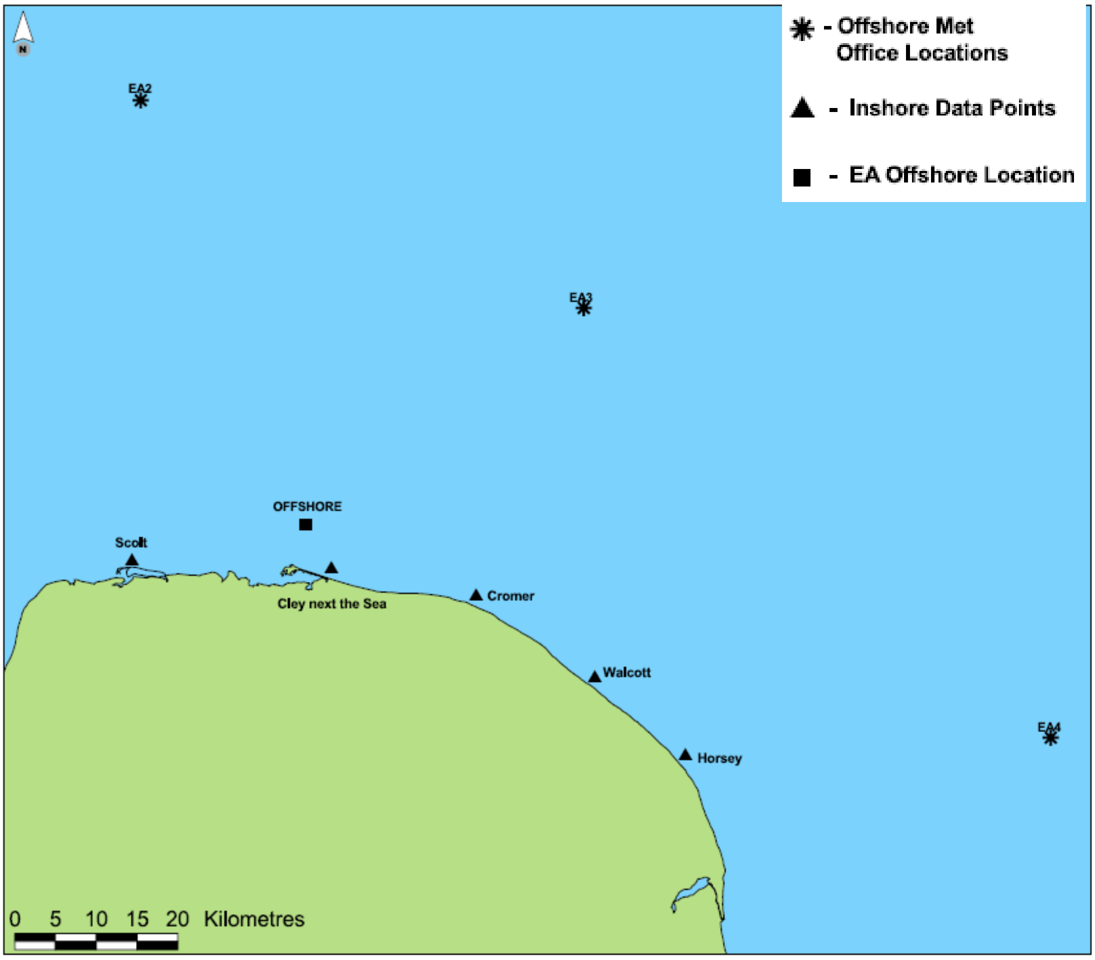
Figure C3.7 Wave climate (taken from SMP1)



Wave roses are for the season January to March and are expressed in metres.

This illustrates extreme wave heights at measured locations around the north Norfolk coast.

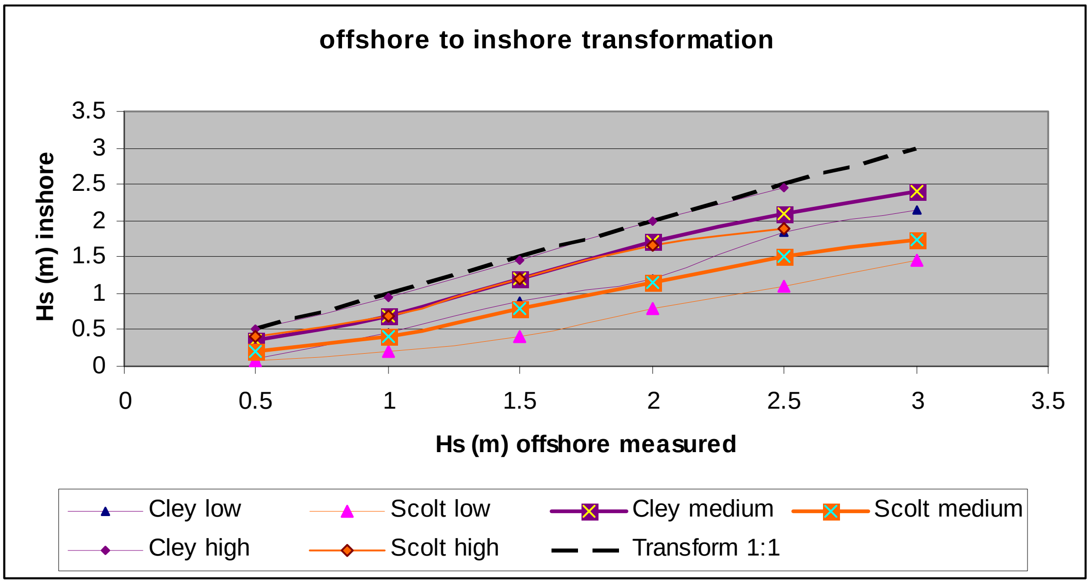
Figure C3.8 Wave data locations for Norfolk wave and tide analysis



Comparison of wave heights at Scolt and at Cley with respect to the measured data offshore of Cley (figure C3.9) showed that wave heights at Cley tend to be larger than at Scolt. This might be anticipated given the relative location of each measurement station, but also that there was considerable variation in comparison.

Figure C3.9 presents the lowest, medium and highest wave height measured for the inshore stations for a given wave height measured offshore. At Cley the maximum wave height tends to be very similar to the actual offshore wave height. At Scolt, the maximum wave height tends to be about 0.8 of the offshore wave height and between 0.6 and 0.8 of the wave height at Cley.

Figure C3.9 Comparison of wave height at Scolt and at Cley



The report, although acknowledged to be an analysis of only one year of data, also showed that there was a relatively weak correlation between individual offshore and inshore storm events, with a large spread of both direction and wave heights. Notwithstanding the general pattern that wave heights at Scolt were lower than at Cley, specific events were identified when the wave height at Scolt could be greater. Clearly direction was a major influence in both these findings and it was found that for different directions there was better correlation between the various offshore data and those recorded inshore. There was also some indication that, while generally for storms from a north to east quadrant there was reasonable correlation in terms of direction between the four offshore datasets, outside this quadrant very different directions were observed for each station.

It was also noted that, for a specific north north east wave direction there was, on more major storms, a quite wide spread of offshore directions recorded. This meant that, with the most southerly of the offshore data points (EA4) showing directions between 20 and 30 degrees, station EA3 and the offshore measurement site recorded directions of 0 degrees. The most northerly point, and possibly the most relevant to the frontage under this direction, gave a wave direction west of north.

These various observations highlighted the difficulty and caution needed in directly interpreting wave climate information at the shore for this section of the coast. The further difficulty is in using such information to determine sediment drift, as well as the value of monitoring.

Against this general assessment, wave modelling has been undertaken as part of the Cromer study. Outside the SMP frontage this information gives useful wave climate analysis for the offshore area and an indication of wave climate at the eastern boundary of the SMP.

C3.4.4 Sediment transport (edited from SNS2)

Longshore transport rates around East Anglia were modelled in the pioneering studies by the University of East Anglia in the late 1970s and early 1980s (Vincent, 1979; Clayton et al., 1983; Onyett and Simonds, 1983). They developed a model for longshore transport that was applied to the whole of East Anglia and part of Essex. Many of the regions were not modelled again for several years. However, following the requirement for Shoreline Management Plans, some areas have been modelled in more detail using more up-to-date techniques and site-specific model settings. These transport rate predictions are described below and the results are shown in table C3.3.

Table C3.3 Longshore transport rates in north Norfolk (as collated by SNS2)

mE	mN	Location	Dir	Q[m^3/yr]	Type	Source
577050	345150	Royal West Norfolk GC	270	0	Observation	HR Wallingford
584500	346700	Scolt Head Island	270	190,000	Wave	Vincent (1977)
597000	346400	Stiffkey	270	290,000	Wave	Vincent (1979)
600000	347000	Blakeney	270	350,000	Wave	Onyett & Simmonds (1983)
602500	346300	Blakeney	288	600,000	Wave	Vincent (1979)
609500	344200	Weybourne	283	160,000	Wave	Vincent (1979)
611300	343800	Weybourne	274	200,000	Wave	Onyett & Simmonds (1983)
615000	343550	Sheringham (west)	87	6,900	Wv, Sh	HR Wallingford(1994)
616000	343500	Sheringham (centre)	94	18,800	Wv, Sh	HR Wallingford (1994)
617000	343400	Sheringham (east)	100	28,100	Wv, Sh	HR Wallingford (1994)
617750	343400	Sheringham	278	87,000	Wave	Vincent (1979)
		Cromer west	90	95,000	Wave	HR Wallingford 2002[6]
		Cromer west	90	6,800	Wave	HR Wallingford 2002[6]
		Cromer east	90	230,000	Wave	HR Wallingford 2002[6]
		Cromer east	90	16,400	Wave	HR Wallingford 2002[6]

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[6] Drift rates added subsequent to those collated by SNS2.

The following provides a brief summary of the techniques applied, as described by SNS2.

Vincent, 1977 and 1979

The longshore sand transport rate was calculated using daily vector-averaged wind data from a single site, input into empirical equations to calculate the offshore wave heights. Wave refraction diagrams with the offshore topography provided the angle of incidence of waves on the beach and the ratio of the incident wave's energy for each unit crest length to the offshore wave energy for each unit crest length. Six-second period waves were considered, with the cosine-squared directional spread of energy about the average wind direction. Wind data for 1964 to1976 inclusive were put into the model. The longshore transport rate was calculated using the CERC formula. Results were averaged over not less than five kilometres of coast.

Onyett and Simmonds, 1983

The longshore sand transport rate was calculated using daily vector-averaged wind data from a single site input into empirical equations to calculate the offshore wave heights. Wave refraction diagrams with the offshore topography provided the angle of incidence of waves on the beach and the ratio of the incident wave's energy for each unit crest length to the offshore wave energy for each unit crest length. The longshore transport rate was calculated for the 20 years from 1961 to 1980 inclusive. Note that Onyett and Simmonds provided the results used by Clayton McCave and Vincent (1983) and that these results came from the same University of East Anglia project as Vincent’s.

HR Wallingford, 1994

HR Wallingford (1994) modelled the longshore drift of shingle above the 0 metre CD contour at Sheringham. The values for potential longshore transport of shingle are given in table C3.3. There was a net transport potential towards the east that increases on going east. The net drift direction was confirmed by observations of the Sheringham frontage. Analysis of differential cliff change also showed that cliff and beach recession was nearly four times higher on the east side of Sheringham compared to the west, indicating downdrift scour to the east. Moreover, the amount of shingle on the frontage reduced towards the east. This was explained in terms of the increasing transport potential towards the east. The results suggested that the drift null point was to the west of Sheringham. However, the location of the drift divide may be different for shingle and sand and will vary in time as the wave climate exhibits inter-annual variability. Indeed Vincent [private communication] has shown that decadal averages of net longshore transport rates at Cromer have different directions. Comparisons are only strictly valid if generated in similar ways using the same wind data. The potential sediment transport was influenced by a number of factors:

- The supply of sediment was restricted.

- Beach control structures and discontinuities modify the drift.
- Tidal current will favour shingle transport to the east.

Shingle supply is almost all from the west. The shingle beaches to the west of Sheringham were healthy (in 1994) while discontinuities in the plan beach shape to the east of Sheringham means there was very little possibility of shingle being transported from east of the frontage to the west. At high tide, recorded peak tidal flows are 0.44 metres a second to the east. There was little reverse transport at low water as the shingle beach was dry. The fact that a higher rate of potential transport existed to the east of the frontage, but there was much less shingle there, may imply that the actual transport rate was limited by supply from the west.

HR Wallingford 2001a (Cromer)

HR Wallingford (2001a) also calculated net longshore drift rates at Cromer along the "natural" coastline (that is, ignoring the presence of groynes). The longshore transport rate at Cromer was therefore calculated using 22 years' of wave data covering the period from 1979 to 2000. These calculations were made for two places along the seafront, west and east of Cromer pier. These estimates of drift rates were made using the standard CERC formula, as used by previous researchers. This allowed a straightforward comparison with the results of the earlier studies mentioned above.

The sea walls along the sea front at Cromer now effectively prevent any additional sediment being added to the beaches to compensate for losses. Sand and shingle beaches were modelled separately and the results were combined, giving values of 24,500m^3 a year west of the pier and 53,900m^3 a year east of the pier, in both cases from west to east. Between 1979 and 1987 the annual drift direction was towards the east in some years and towards the west in others. From 1988 onwards however, the drift was mainly towards the east. Comparing the mean annual drift for the period 1979 to 1987 with that for the period 1988 to 2000, it was found that the drift rate has roughly doubled in the latter period. Although outside the SMP area, this analysis has been included in the review, highlighting the variation between sand and shingle movement, but also highlighting the observation made about the variation of drift rates found depending on time periods analysed.

Discussion of sediment drift rates provided by SNS2

Some early estimates of the net annual longshore drift rate along the coastline of Norfolk were made by research workers at the University of East Anglia (UEA) in the 1970s (Vincent 1979, Clayton et al, 1983). The basic method had three main steps:

1. A time series of wave heights, periods and directions close to the coast was modelled.
2. Longshore transport rate was calculated for each wave condition.

3. The drift rates were averaged to produce a mean annual net drift rate.

As normal in such studies, the longshore drift rate was calculated by a simple formula that estimates the instantaneous rate of sediment transport caused by any wave condition. By repeated use of this formula for the whole wave climate, as predicted for a chosen location at the coast, the total volume of longshore drift at that location was estimated. This approach is still widely used, but it is important to realise that the longshore drift rates calculated by this numerical method are subject to a lot of uncertainty unless a site-specific validation can be carried out. Also, estimates made using information about waves over one period can vary dramatically from subsequent estimates made using wave information for a different period. Moreover, although many studies estimating drift rates along the north Norfolk coast have been carried out, there is no way of physically measuring the rates of sand transport along the coastline. Any drift rates quoted must therefore be treated as estimates rather than absolute values. The early work by the University of East Anglia, however, developed the following picture:

- estimated longshore drift rates along some parts of the Norfolk coast are very large (indeed as high as, or higher than, anywhere else in the UK)
- there are large potential drift rates towards the west between Cromer and Blakeney Point
- there is an increase in the longshore drift rate going along the coastline from the Cromer area, where the rate is very low, to an area near Happisburgh where it has a maximum value. From that area southward, there is a decrease in the rate until it is nearly zero again south of Great Yarmouth.

Subsequent studies have modified the picture presented by the UEA results somewhat (as discussed below) but refining the modelling does not reduce the pioneering nature of the studies. In all cases, the potential sediment transport rate for sand was calculated and, if the beach had less than that potential volume of sand available for transport, the calculated transport rate could not have occurred. Moreover, the transport rate will have been wrong if the sediment present was not medium sand. Typically, the transport rate for sand is about 15 to 20 times greater than the transport rate for shingle. Vincent (1979, figure 5) showed the fraction of shingle and sand present at each site. In some cases (such as Blakeney Point), the beach sediment was essentially shingle and the calculated rates must be considered to be significantly greater than the actual transport rate of shingle. So the rates quoted in Vincent (1979) should be interpreted with caution (as the author himself has stated).

Clayton et al. (1983) reviewed the work of Vincent and suggested there was very little longshore drift between Gore Point and Blakeney village (inshore of Blakeney Point). There must, however, be some longshore littoral drift from east to west in this area as the western end of Scolt Head Island continues to accrete. Vincent's potential sand transport rate of 190,000m^3 a year on Scolt Head Island is rather high for a beach that contains pebbles and gravel as well as sand. The actual transport rate would depend on the beach size distribution. For example, if the beach were half sand and half shingle, the potential transport rate would drop to around 100,000m^3 a year (assuming that the transport rate for shingle is about 1/15 that for sand). However, if the beach was only 25 per cent sand, the total potential transport rate might drop below 60,000m^3 a year.

A BGS survey of seabed sediments and facies shows that the transport direction for sand offshore of Scolt Head Island is from west to east, at least below the seven metre contour. This agrees with the other facies data (shown in HR Wallingford, 2002a) that show west to east transport further offshore. The seven metre contour is not far offshore of Scolt Head Island and the littoral drift is east to west. This suggests that sand and shingle is being transported to the west on the beach face, but that sand is transported to the east if it is carried offshore of the steep beach face onto Burnham Flats, perhaps during a storm.

At Blakeney Point, Vincent (1979) calculated a potential sand transport rate of 600,000m^3 a year westwards towards the spit. This was a lot greater than his calculated sediment yield from cliff erosion to the east of 150,000 ± 50,000m^3 a year. Moreover, the cliff erosion included silts, sands and gravel, while Blakeney Point contains mainly gravel. As a rough estimate, the 600,000m^3 a year of potential sand transport reduces to 60,000m^3 a year of sand combined with 36,000m^3 a year of shingle transport (using the 15:1 transport ratio and assuming 90 per cent shingle). When there is a clear break between the shingle and sand parts of a beach (such as at Blakeney Point), it would be better to calculate separate cross-shore distributions of sand and shingle potential transport. These could be combined by taking shingle on the upper beach and sand on the lower beach, using the measured change in sediment in the modelling.

The sorts of reduced rates determined above could be achieved in rough balance with the sediment yields from the cliffs. Onyett and Simmonds (1983) suggest a lower figure of 350,000m^3 a year of longshore transport along Blakeney Point, while Vincent (1979) calculated a drift rate of 160,000m^3 a year just west of Weybourne, in the region that supplies Blakeney Point with its new material. Vincent's value is again for sand in a region that is about 90 per cent shingle. Vincent states that the increase in drift rates from Weybourne towards Blakeney (from 160,000m^3 to 600,000m^3 each year) is due to the decreasing fetches for westerly winds. He therefore suggests that the actual drift rate along the frontage is limited by the drift rate at Weybourne. The increase in potential drift along Blakeney Point may serve to push the point back towards the south (and west) as suggested by Andrews et al. (2000). The increase in potential drift rates along Blakeney Point may not be reliable due to the difficulties in applying the type of wave model used over the wide shallow area of Burnham Flats (as the wave model ignores bottom friction).

There is no obvious pathway for shingle to move west from Blakeney Point. There are small shingle ridges to the west, but they may have been formed by local supplies of shingle being pushed onshore by wave action, not fed by Blakeney Point. The sand that is released to the beach by erosion around Weybourne is likely to travel west towards and along Blakeney Point. It may be possible for some sand to be transported to the west, from Blakeney, below the level of the shingle beach. However, there are no obvious signs of such a supply arriving further west along the coast. Any sand that moves significantly offshore will almost certainly be transported to the east by tidal action (HR Wallingford, 2002a).

The lower estimates of longshore drift (produced by estimating the combined sand and shingle transport rate from the potential sand transport) lead to correspondingly lower combined sand and shingle drift rates. The net transport direction along Blakeney Point is clearly from east to west[7]. Clayton et al. (1983) also suggested a revised value of around 60,000m^3 a year from east to west for the sediment transport roughly between Cromer and Blakeney. The location of this estimate is unclear, although it appears reasonable if it applies between Weybourne and Blakeney.

The differences in the results deserve some comment. The results from Vincent (1979), Onyett and Simmonds (1983) and Clayton, McCave and Vincent (1983) were all from the same study. The differences between their results come from using different methods and then developing these through the programme and from re-interpreting and re-analysing different effects. Vincent (1979) published two sets of figures from the same data. He had calculated longshore drift rates at a large number of points then averaged over a length of coastline. His specific rates were averaged over stretches of, typically, five kilometres, while his average rates were calculated by averaging over around 25 kilometres of coastline. The average rates give a broad overview of sediment transport around East Anglia. Averaging over such a long length of coast can also be slightly misleading, particularly in areas of rapid variation, such as around the drift null point near Weybourne and Cromer. Figure 1 of Clayton, McCave and Vincent (1983) produced two illustrations of transport rates and sources. The first is based on Vincent's average rates, while the second is their estimate of the most probable drift rates, taking supply and other factors into account. It is an improvement on Vincent's (1979) average results, but is also at a broad regional scale and also calculates the potential sand transport rate at all locations, irrespective of sand content. The specific rates in Vincent (1979) and Onyett and

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[7] Although this may be a simplification of a more complex system as discussed in subsequent sections of this review based on the CHaMP

Simmonds (1983) were calculated using similar techniques and so are broadly compatible, generally within 50 per cent of each other when calculations were made relatively close together. Onyett and Simmonds used a longer time series of wind vectors to derive their waves and transport rates than Vincent. This can have an important effect on the magnitudes of transport calculated, so may be the main difference between the two sets of data. The main difference between their results and later results around Cromer and Sheringham are that Vincent and Clayton et al. calculated potential sand transport rates, while HR Wallingford (1994, 2001a) estimated a transport rate for shingle or a combination of sand and shingle. There are problems in determining the position of the drift divide, which was originally estimated to be near Cromer, but is probably closer to Weybourne. However, this may be due to the length of coastline averaged over, changes in modelling techniques and changes in wave conditions over time.

As mentioned previously, there are substantial uncertainties in these theoretical calculations. One of the most important of these potential sources of error is whether there is enough sediment to “satisfy” this calculated drift rate. The source of sand on the beaches of this coastline is largely from the eroding cliffs of north Norfolk, while the shingle probably comes mainly from the chalk exposed on the nearshore seabed.

Further inaccuracies will result from the numerical modelling of the waves and the neglect of tidal currents.

C3.5 Present day geomorphology

The text in this section has been extracted from CHaMP 2003 with other information included.

C3.5.1 Barrier beaches

The barrier beaches of the north Norfolk coast show a diverse morphology ranging from gravel ridges to sand dunes. In general, these ridges appear to be moving towards land at a rate of around one metre a year. In some cases new ridges are developing seaward of these older barriers implying a more complex process than a simple onshore movement accompanied by progressive narrowing of the shore zone.

Movement of the barriers towards land is by sediment rollover, where storm waves cause wash-over fans to develop on the landward flank of the beach ridge. As well as these shore-normal movements, the barrier beaches are also developing in the shore-normal direction. Both Scolt and Blakeney have been experiencing accretion on their western edges at a rate of around 3.5 metres a year, over periods of between 400 years (Blakeney) and 1,100 years (Scolt), although evidence from early maps suggests that the Blakeney

Ridge extended more rapidly in the 16th century, probably by an average rate of five metres a year.

This westward growth of the two barriers has been attributed to longshore sediment movement from east to west along the coast (Vincent 1979), forming recurved laterals to the end of each barrier. This classic model fails to explain, however, the abrupt change from shingle to sand on Blakeney. According to map evidence, this occurred in the early 17th century and at the same time as the reclamation of the Salthouse-Cley saltmarshes.

An alternative model may be proposed that coarse-grained sediment transport (mainly sand) is from west to east and that this sediment movement by-passes each of the major tidal channels along the coast (for example at Brancaster Staithe, Wells and Morston) as episodic sand waves. These easterly-moving sand waves then weld to the western extremities of the barriers forming the characteristic fulls and lows and recurved laterals of Scolt and Blakeney, but also to a lesser extent at Lodge Marsh to the east of Wells harbour. The rapid extension of the Blakeney Ridge following the reclamation of Cley marshes may therefore be explained by the reduction in tidal flow across the mouth of the Glaven estuary allowing more rapid transit of sand waves which followed a more inland pathway than previously[8].

C3.5.2 Sand dunes

Although there are sand dunes along much of the coast, there are few examples of sand dune fields with multiple dune ridges. For the most part the dunes are single ridges colonised by *Ammophila* with occasional fore-dune and embryo-dune development. However, the Gun Hill dunes at Burnham Overy, and parts of the Blakeney and Scolt dune ridges, are more extensive, with mature dune ridges colonised by a diverse dune flora.

Fore-dune ridges are experiencing erosion along much of this coast at the present time with the exception of those between Wells and Holkham. Holme and Brancaster bays have been rapidly eroded over the past decade, although, as shown below, this dune erosion has been balanced by foreshore accretion. The dunes of both Scolt and Blakeney are experiencing erosion as these barriers roll towards land. However, unlike the gravel barriers, the dunes do not reform by rollover processes and the dune ridges are progressively narrowing as the barriers move towards land.

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[8] SNS2 also indicated from analysis, particularly of storm surge events, that they resulted in episodic movement of large quantities of material west to east along the shore. The SNS2 interpretation, however, is that this is also associated with shoreline east to west movement in areas such as Blakeney spit. This may then act to consolidate episodic delivery of material to this feature's western end.

C3.5.3 Tidal deltas

Discharges from tidal inlets across the intertidal and nearshore zones cause the longshore pathway of sediment to be pushed seaward and its movement to become intermittent. The resulting sediment lobe with accompanying sand waves and a marked ebb tide bar make up the tidal delta. There are seven such deltas along the coast at:

- Gore Point
- Thornham
- Titchwell
- Brancaster Staithe
- Burnham Overy
- Wells harbour
- Morston to Blakeney Far Point.

Each delta forms a pronounced lobe in the lower intertidal that is associated with a reduction in wave energy at the upper shore and the formation of sand dunes. The size of these deltas, and therefore their effect on the upper shore, depends on the strength of the tidal currents from the inlets relative to the longshore sediment transport rate.

Reduction in the tidal prism of an inlet due to reclamation, or increase due to managed realignment, can therefore have an effect on both the tidal delta and the adjacent shoreline. This effect was clearly illustrated by the breaching of a reclaimed marsh at Titchwell during a storm in 1949. The subsequent growth of the tidal delta, and the prograding of the dunes on the adjacent shore, has locally reversed the erosion of this section of Brancaster bay.

C3.5.4 Saltmarshes

The saltmarshes of the north Norfolk coast are among the most extensive in Europe (2,127 hectares, Lambley 1999) and are of extremely high geomorphological and ecological value. Although no detailed mapping of changes in saltmarsh extent has been undertaken, it is clear that the progressive movement towards land of the barrier beaches, coupled with the rising ground inland often marked by the Ipswichian cliff, is resulting in a form of natural coastal squeeze by which the area of saltmarsh is being reduced.

This reduction in saltmarsh area is to some extent offset by new marsh areas developing inland of several recently-formed barriers. So, saltmarsh development within Holkham Gap, which took place as recently as 1990, has resulted in some 20 hectares of *Puccinellia* marsh while a larger area of *Spartina* marsh has developed since 1950 in the shelter of Stiffkey Meols.

The horizontal loss of saltmarsh due to barrier migration has not been offset by movement of the inland edge of the marshes towards land because of the presence of rising ground, as discussed above, despite rapid vertical accretion of the marsh surfaces. Work by Andrews et al (1999) using caesium isotopes as a sediment marker, showed that vertical accretion of the marshes averaged 4.55 millimetres a year over the past decade (see table C3.4). This rate is three times that of long-term sea level rise and suggests that fine-grained sediment supply would be adequate to keep pace with predicted sea level rise in the future (French & Spencer 1993).

Table C3.4 Vertical accretion rates on north Norfolk saltmarshes (data from Andrews et al 1999)

Location	Vertical sedimentation rate (mma^{-1})
Stiffkey: *Spartina* marsh	6.4
Stiffkey: Mid marsh	3.6
Stiffkey: Upper marsh	2.1
Scolt: Great Aster marsh	5.4
Scolt: *Plantago* marsh	3.9
Scolt: Plover marsh	3.2
Scolt: Hut marsh	3.9
Scolt: Missel marsh	7.9

C3.5.5 Reclaimed marshes

Despite a widely-held impression that the north Norfolk coast is a natural system untouched by human interference, over 50 per cent of its saltmarsh area has been reclaimed over the past 300 years (Pye, 1992). The total area of grazing marshes is put at 867 hectares (Lambley 1999) which is 41 per cent of the current saltmarsh area. The main areas of reclaimed grazing marsh on the coast are shown in table C3.5.

Table C3.5 Main areas of reclaimed marsh on the north Norfolk coast (data from Lambley 1999)

Location	Area (ha)
Cley to Salthouse	171
Blakeney Freshes	142
Holkham	295
Burnham Norton	121
Thornham to Brancaster	54
Holme	84

These grazing marshes show a complex hydrology, with saline seepage and freshwater springs resulting in a range of salinities in both soil and drainage ditches that are central to their ecological importance. Nevertheless, a lowering of local water tables, coupled with the increase in sea level, means that these hydrological conditions are changing rapidly.

The reclaimed marshes today are between 1.1 and 2.5 metres ODN. This is between 0.6 and 2.0 metres below the current upper saltmarshes, which have surface elevations of between 1.7 and 3.1 metres ODN (Pye 1992; IECS 1993). This means that these marshes have a sediment deficit of around 9×10^6 m^3 and this will increase rapidly as sea level rise accelerates. Moreover, the grazing marsh surface height lies on average 2.5 metres below the level of the 10-year flood and about 3.5 metres below embankment crest heights protecting these marshes that are typically at 5.5 metres ODN (IECS 1993). The grazing marshes therefore appear to be one of the most susceptible and fragile of the habitats along the north Norfolk coast.

C3.6 Sediment budgets (based on interpretation within CHaMP)

C3.6.1 Shore profile analysis

Work by Newcastle University (1999) on Environment Agency beach survey data in 12 sediment cells along the north Norfolk coast has been reviewed and extended as part of this report. Time series analysis of the sediment volumes in each of the cells 3 to 8 (Kelling to Holme) has been undertaken for the period 1992 to 2002. The results are shown in figure C3.10. Using the regression coefficient as an indication of the trend in sediment volumes has allowed the compilation of a figure (see figure C3.11, taken from the CHaMP) showing the spatial distribution of sediment trends along the entire north Norfolk coast.

Figure C3.10 Time series of volume change, with regression coefficients for sediment cells.

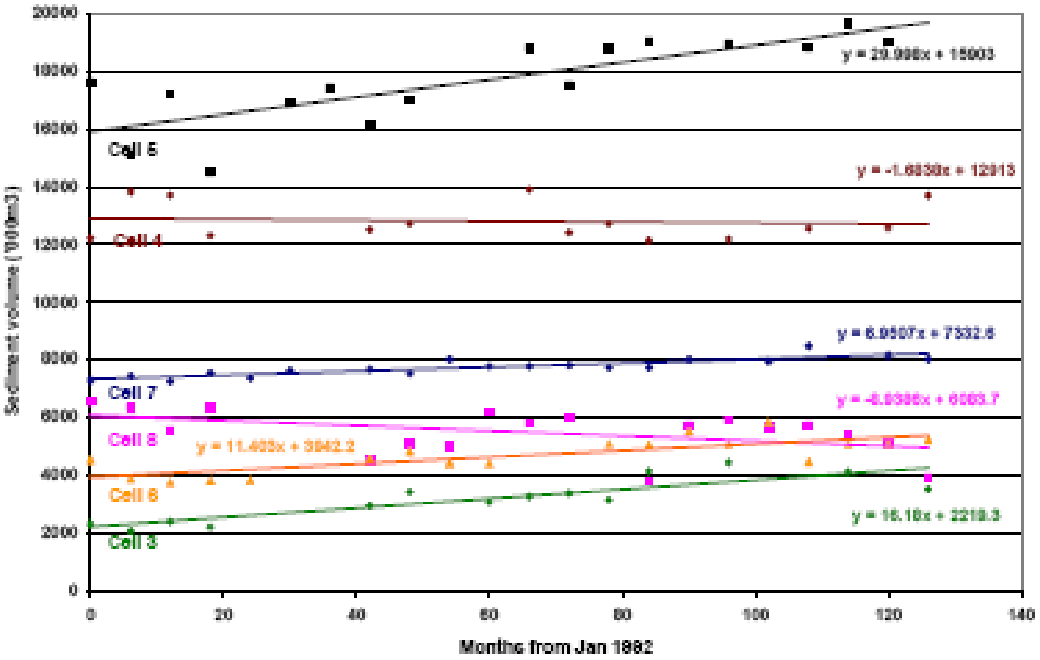
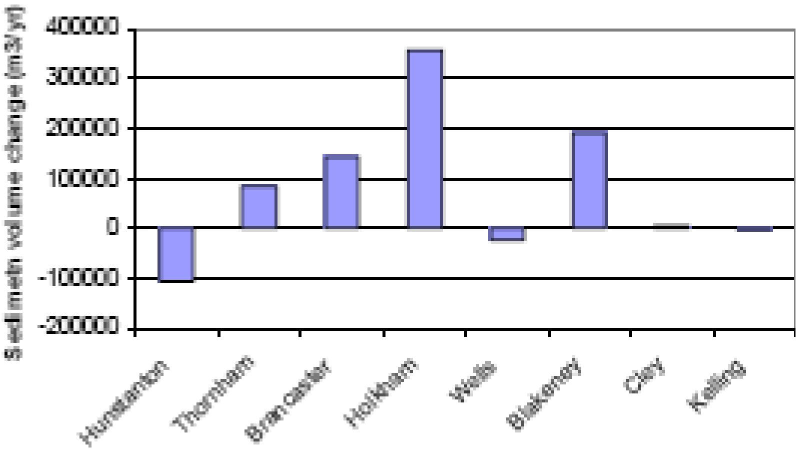


Figure C3.11 Spatial distribution of sediment volume trends over the past decade (cells 3 to 8)



The results of this analysis of the Environment Agency datasets are:

- Figure C3.11 shows that the centre of the north Norfolk coast (at Holkham) gained sediment over the past decade at the rate of about 300,000m^3 a year. Moving away from this central location, the figure shows that sediment gains reduced to both the east and west. Cell 8 (Holme) experienced a net loss (-100,000 m^3 a year).

- The behaviour of cells 4 and 3 (Stiffkey and western Blakeney Spit) is crucial. The evidence suggests that the Stiffkey shore was extremely volatile (rapid shifts from positive to negative sediment budgets) with a net trend that is indistinguishable from zero. Cell 3 in contrast shows a strong positive signal and here the individual profile analyses (Newcastle University 1999) show that these gains were due to the onshore movement of discrete sand bars that welded to the distal end of Blakeney ridge.
- It appears, therefore, that cells 3 and 4 may be linked so that losses in 4 are reflected by gains in 3 and that over the decade 1992 to 2002 the balance lies towards cell 3. This may be a reflection of the data series rather than a long-term trend.
- If these figures are accepted, the north Norfolk coast shows a positive sediment budget over the past decade. The source of the sediment appears to be from the nearshore north of Holkham[9] and is therefore possibly associated with the Docking shoal.
- The conclusion must be that the north Norfolk coastal system looks extremely healthy at the present time with abundant sediment input and an accretionary trend. The implications of these conclusions for the sediment budget are considered in section 3.6.2.

Analysis of recent Environment Agency beach survey data (1991 to 2006) largely agrees with the work undertaken by University of Newcastle (1999). Figure C3.12 presents the total cumulative volume change (m^3) for each profile between 1991 and 2006. This agrees with the data presented in figure C3.10 and suggests that two areas of the coast experience annual accretion: around Scolt Head Island and along the Wells and Stiffkey frontages, particularly near Bob Hall's Sands.

From this updated information, it is also possible to conclude that the north Norfolk coast is still showing a positive sediment budget, very much in line with the findings of the CHaMP. There is some indication that the main area of sediment gain to the shore is derived from the nearshore area at Brancaster Staithe. This again supports the influence and interaction between the nearshore bathymetry, discussed in section C3.1, and the coastline, where the nearshore channel identified in figures C3.2 and C3.3 virtually disappears, allowing direct input to the coast.

The latest analysis reinforces the conclusions drawn from earlier work that the north Norfolk coastal system looks extremely healthy at the present time.

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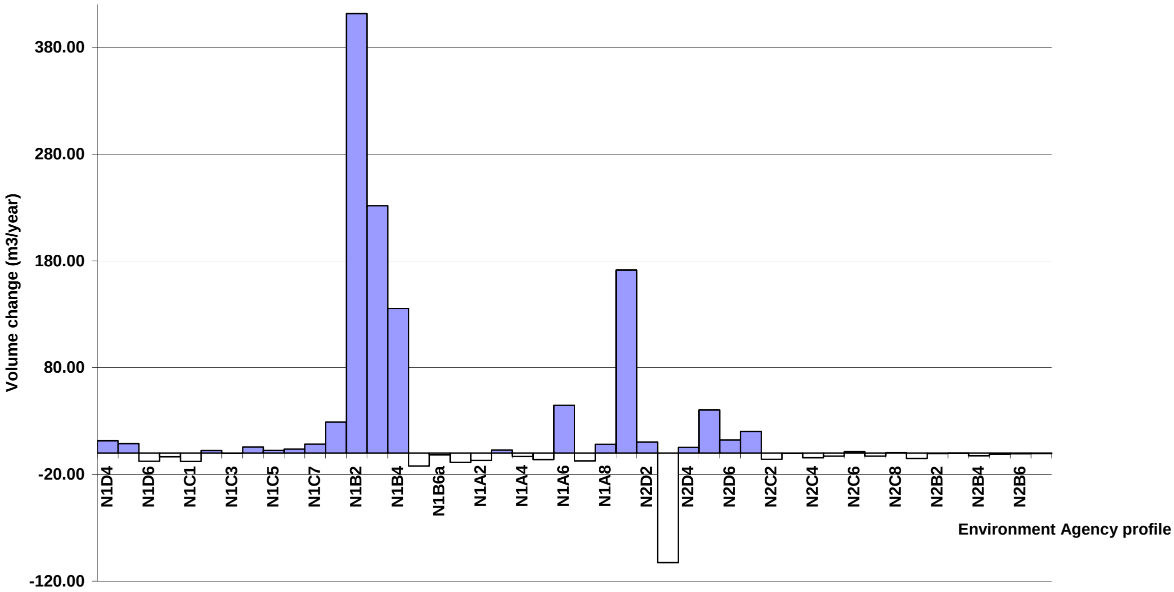
[9] This seems to accord well with, and may relate to, an apparent closure at the point of the east-west running channel discussed earlier and as indicated on the representation of bathymetry shown in figure 2.3.

The volume change differences between profiles highlighted by the recent Environment Agency monitoring data show the benefits of a continued programme of monitoring along this stretch of coastline. This will allow any assumptions made about geomorphological development to be re-assessed drawing on an increasing dataset.

Figure C3.12 Total cumulative volume change (m^3) 1991 to 2006



C3.6.2 Sediment demand

The north Norfolk coast is characterised by two distinct sediment types: a coarse-grained sand and gravel suite that makes up the outer sand flats, barrier beaches and sand dunes and a fine-grained silt and clay suite that makes up the inner saltmarshes and associated mudflats. The total Holocene sediment prism was calculated by Andrews (1999) to be 685 x 106 m^3. Of this total the coarse sediment suite made up 48 per cent or 329 x 106 m^3 while back-barrier fine sediment made up the remaining 356 x 106 m^3. The coarse sediments come from several sources, including the nearshore seabed, cliff erosion and recycling of intertidal sediments. Fine-grained sediments are derived ultimately from erosion of the cliffs along the Holderness coast (McCave 1978), although some of this material will be recycled through the Wash as well as moving directly to the north Norfolk coast. A small amount of fine-grained sediment is derived from the erosion of cliffs along the Norfolk coast.

The sediment demand for coarse-grained sediment is difficult to calculate with any accuracy. The spatial variability of accretion and erosion processes mean that estimates for the whole coastal zone must be treated, at best, as rough approximations. The long-term average for sediment demand on the north Norfolk coast can be calculated from the data provided by Andrews et al (1999). They estimate that a total of 685 x 106 m^3 of sediment has accreted on the coast during the last 7,000 years of the Holocene. The long-term annual mean is therefore 97,857m^3 a year.

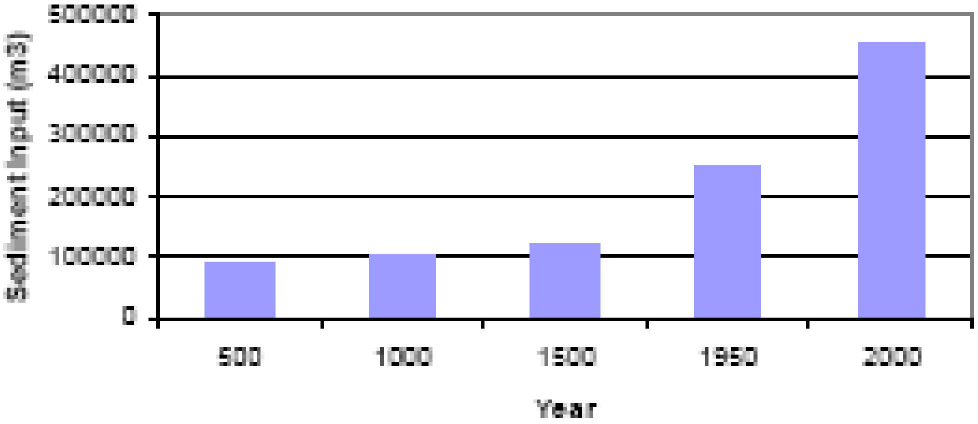
The intertidal area of the north Norfolk coast is around 5,500 hectares. If the long-term annual mean is averaged over this area, the annual vertical accretion rate is 0.0018 metres a year, which is similar to the long-term rate of sea level rise of 0.0015 metres a year.

If the data provided by Andrews et al (1999) for saltmarsh accretion over the past 40 years are examined, however, a different annual mean value is produced. Table C3.4 shows the variation in saltmarsh accretion derived from caesium isotope profiles. The mean vertical accretion rate derived from these data is 0.00455 metres a year, which is three times greater than the long-term rate of sea level rise.

The total area of saltmarsh on the coast is 2,127 hectares (Lambley 1999). This means that the annual volume of fine-grained sediment accumulating on the marshes is 96,778 m^3 a year. This total sediment volume for saltmarsh alone is equivalent to the long-term average for the entire north Norfolk coast intertidal area, including both saltmarsh and intertidal sand flats, barrier islands and sand dunes. If the vertical accretion rate of 0.00455 metres a year were to be applied to the entire intertidal area, the total annual volume accumulation would be 250,250 m^3 a year. This apparent increase in the annual volume of sediment accreting on the coast over the past few decades is supported by calculations derived from the Environment Agency shore profiles as reported in the previous section.

These data suggest that an annual total of 600,000m^3 of coarse-grained sediment has accreted on the north Norfolk coast during the past decade while around 150,000m^3 a year has been eroded. It is not possible to find out whether the eroded sediment is re-deposited in nearby accreting areas so a minimum estimate for net accretion will be 450,000m^3 a year (figure C3.13). This represents an average vertical accretion rate of 0.0018 metres a year over the entire intertidal area of the coast, a figure that is five times greater than the long-term rate of sea level rise.

Figure C3.13 Long-term sediment input rates to the north Norfolk coastal zone



The conclusions that may be drawn from this analysis of the sediment demand are:

- there seems to have been an exponential increase in the rate of sediment accumulation on the north Norfolk coast over the past 50 years
- the long-term (Holocene) annual sediment input of around 100,000 metres a year had apparently risen to 250,000 metres a year in the period 1950 to 1999 and to 450,000 metres a year in the period 1992 to 2000 (figure C3.13)
- this increase in the spatially-averaged vertical sediment accretion derived from these recent data is much higher than the long-term rate of sea level rise
- no data are available for the period before 1950, so the abrupt increase shown by these data may have been part of a much longer-term increase in sediment accumulation.

Explanations for the apparent increase in sediment accumulation include:

- some or all of the data are wrong
- the rate of sea level rise on the coast has accelerated over the recent past and the increased sediment accumulation rate is keeping pace with this rise
- the recent data are unduly influenced by episodic storm events that are averaged out in the long-term Holocene data.

Despite the potentially controversial nature of these results, there seem to be two conclusions that can be drawn with some certainty:

- the north Norfolk coast sediment budget is positive
- sediment is currently available to the coastal system.

C3.6.3 Sources of sediment (based on CHaMP)

Identifying sources of sediment to the north Norfolk coast has been, and remains, a major problem. The Southern North Sea Sediment Transport Study (SNS2) highlights 'conflicting evidence', although its general conclusion for the eastern end of the frontage is that sediment is derived from the erosion of the Weybourne to Cromer cliffs and is transported westwards along the coast.

This conclusion is difficult to reconcile with other evidence presented in the CHaMP, both from seabed indicators and from modelling studies. All such evidence points to a west to east movement of sediment and a source area defined by the Burnham Flats and the Docking Shoal. Indeed, SNS2 states that 'Offshore seabed indicators show both nearshore and offshore (over the Burnham Flats and Docking Shoal) movement in an easterly direction'. The report includes evidence from the British Geological Survey (BGS) that states that '…although sand and shingle is being transported to the west on the beach face, sand is transported to the east if it is carried offshore of the steep beach face onto Burnham Flats, perhaps during storms'.

The morphological evidence presented above (section C3.6.2), based on annual surveys of the shore profiles by the Environment Agency, indicates an annual accretion rate on this coast of around 400,000m^3. This represents the net accretion and so, presumably, underestimates the gross movement of sediment along the coast. The estimates presented in SNS2 (2002) for longshore drift towards the west are, in contrast, relatively small. They cannot be compared with the present day accretion rates of 450,000m^3 a year or, for that matter, with the long-term accretion rates shown by Andrews et al (1999) to average 100,000m^3 a year throughout the Holocene.

It may be concluded that the conflicting evidence presented here could be resolved by assuming that a sediment transport pathway is developed towards the west on this coast during low magnitude, high frequency events involving relatively small volumes of sediment. This movement therefore probably represents a redistribution of sediment already present within the north Norfolk system and does not imply a major source to the east. Although some sediment derived from cliff erosion to the east of Weybourne may enter the system during these low magnitude events this is not, and indeed cannot be, seen as the main source of sediment for the north Norfolk coast.

In contrast, during high magnitude, low frequency events, a strong north to south movement develops across the Burnham Flats and Docking Shoal, as shown in all the model predictions of the SNS2. This moves large volumes of sediment onshore.

Nearshore sediment movement during such events is from west to east, mainly between -5 and -15 metres with accretion occurring as this material moves into the tidal deltas along the coast. From these accretionary centres, sediment is then redistributed to the inshore regions during the low magnitude events outlined above.

Such a model is clearly shown in the summary diagram produced by SNS2. This diagram shows the contrast between sediment movements during low and high magnitude events. It is clear from this diagram that the major source of sediment is the extensive fine sand deposits within the Burnham Flats and Docking Shoal, extending north to the Race Bank. A secondary source may be the sand deposits within the Wash embayment although, as shown in the SNS2 figure, these deposits are themselves ultimately derived from the Burnham/Docking Shoals.

The analysis of sediment movement and present day geomorphology re-emphasises the need to consider the north Norfolk coast as a single geomorphological system, as stated earlier. It also highlights, however, that within this system there are local dynamics influencing and responding to natural and man-made defences and landforms at a variety of interdependent scales.

C4 Local overview

C4.1 Discussion of division of coast.

This section will provide a discussion of the division of the North Norfolk SMP frontage. It is important to note here that this division of the coast was mainly used for a number of stage 2 tasks, such as ‘baseline scenarios assessment’ and ‘flood risk’. These divisions are **not** the final frontages for which the SMP will define policies. These so-called SMP policy units were decided during stage 3 and discussed with the Client Steering Group and Elected Members’ Forum to allow their comments to be incorporated.

From the above general description, it is clear that any division of the SMP frontage is difficult. This is less from a point of view that there are major interactions affecting the whole length of the coast, but rather that there is difficulty in identifying specific break-points in the interlocking chain of local features. It may be understood that, for example, the behaviour or management of Blakeney Spit may have relatively limited direct implications for Wells or the development of Bob Hall’s Sands. However, both the management and behaviour of the spit, the management of the Wells saltmarsh and the development of the sands seaward of these marshes, both affect the behaviour of Stiffkey bay. The management of the Cley frontage, and that of the Cley marshes and the River Glaven, affects the behaviour of

Blakeney Spit. The management of the Holkham marshes may affect physical development in the Wells area.

This difficulty is obvious in the divisions and considerations of local frontages undertaken by previous studies. Table C4.1 defines these previous divisions.

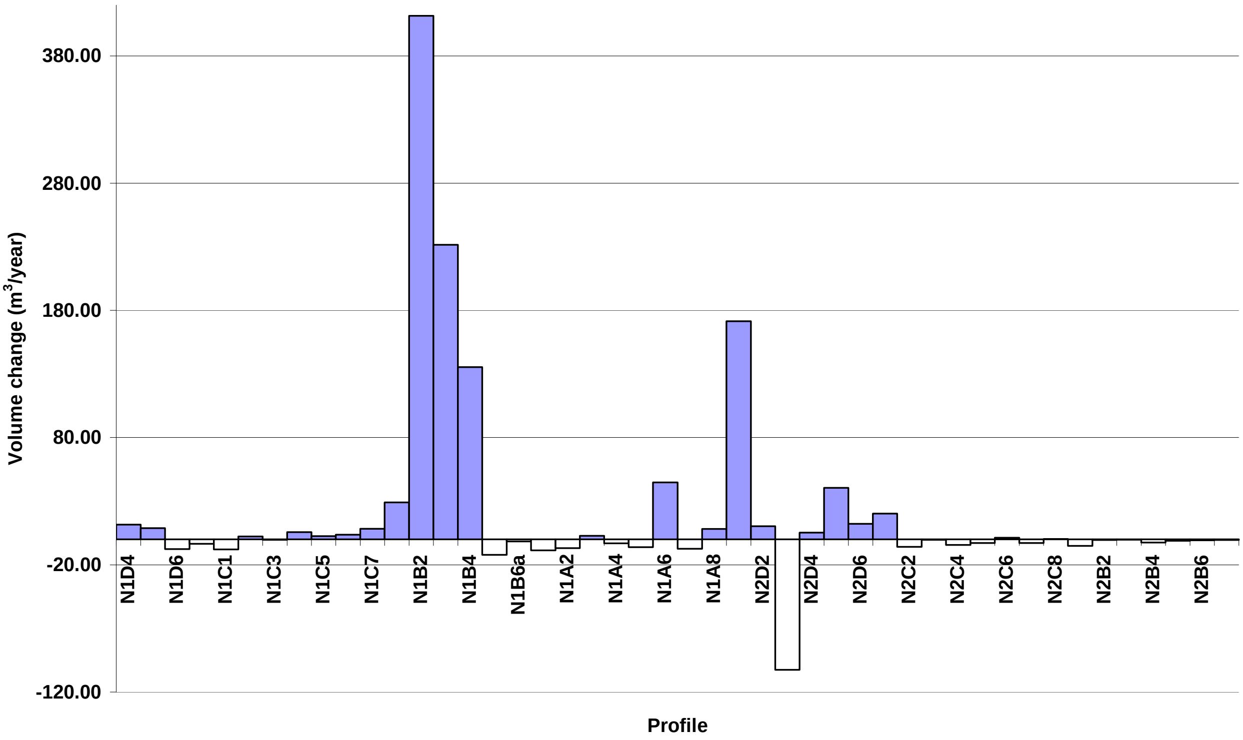
Table C4.1 Previous definitions of the north Norfolk frontage

Location	SMP1 management units	CHaMP behavioural units in relation to habitat	SNS2 sediment transport	SMP2 local physical description of frontages
St Edmunds Point				
Eastern extent of cliffs	9			A
Gore Point	8	7	Gore Point to Weybourne	B
Thornham	7			C
Brancaster Staithe	6			
Scolt Head Island		6		D
Gun Hill	5	5		E
Holkham Gap				
Wells harbour	4	4		
Stiffkey marshes		2 and 3		F
Blakeney Point	3			G
Cley coastguards / Cley Eye	2			H
Kelling Hard (Quag)				
Weybourne				

Any division at this stage of developing the SMP2 has to be seen more as a convenience of description rather than suggesting clear division by coastal processes. To assist this process, however, a number of the datasets derived from the Environment Agency's beach profile monitoring were manipulated and plotted to try to identify obvious frontage characteristics in assessing and developing baseline scenarios.

Figure C4.1 presents the total volume change (m^3) each year for each profile, as calculated from beach profile data between 1991 and 2006. This reflects possible divisions based on processes and longshore interaction. In contrast, figure C4.2 illustrates the percentage of the beach lying between the HAT and MHWS, MHWS and MHWN, MHWN and MSL, MSL and MLWN and the MLWN and MLWS marks. This reflects the cross-shore behavioural units along the coast. This latter diagram is based on the calculation for each profile from an average of the various water level positions measured between 1991 and 2006.

Figure C4.1 North Norfolk total volume change (m^3/year)



Finally, figure C4.3 provides a more general plot showing where there has been either erosion (red) or accretion (green) for each year between 1991 and 2006 for all profiles. This is focused on the upper beach only (between the HAT and MSL marks). Missing data are illustrated by a blank cell. In this plot each year was divided into two periods. For example '199101' represents end of winter 1990 to end of summer 1991 and '199102' represents end of summer 1991 to end of winter 1991. The top line of the figure (titled 'Average change') illustrates the average volume change for each profile (between 1991 and 2006).

Figure C4.2 North Norfolk average beach profiles (1991 to 2006)

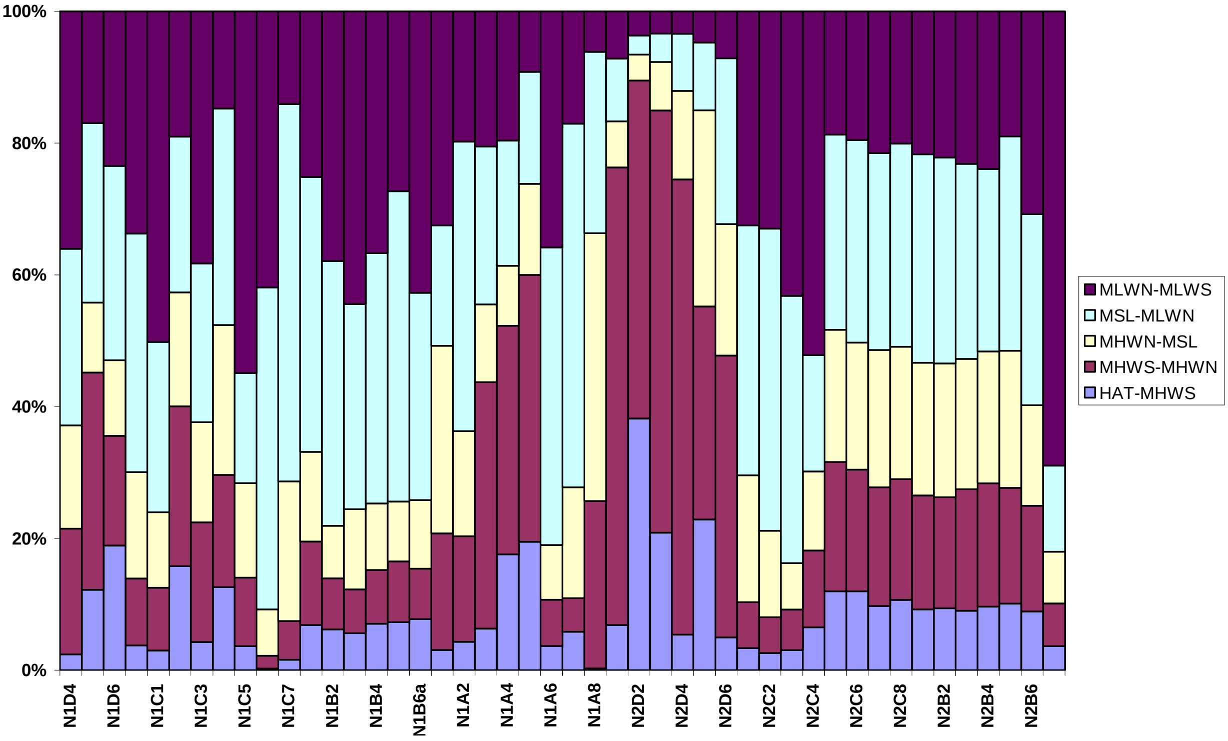
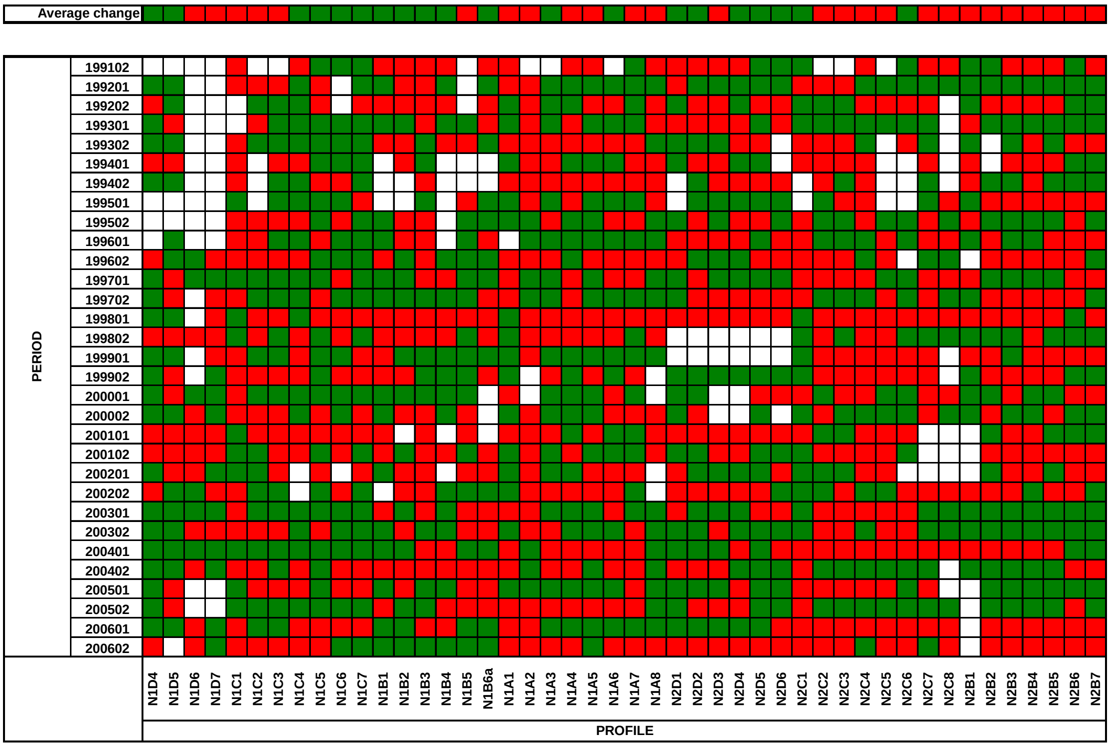


Figure C4.3 Overall volume change upper beach (HAT – MSL) 1991 to 2006 (red = erosion, green = accretion, blank = no data)



The plots represent different aspects of behaviour and, as may be seen, then suggest different divisions of the coast. Using these in combination, eight units are very loosely defined for the North Norfolk SMP study area. These are listed in table C4.2, along with a brief characterisation of each frontage.

While developing the SMP further, these eight frontages have continued to be used, but in parallel a higher level has been used. The eight frontages have been combined into three ‘super-frontages’ for which shoreline management has negligible or limited longshore effects. This means they can be treated as policy development zones. These super-frontages are:

- Super-frontage 1: frontages A and B (Old Hunstanton to Thornham).
- Super-frontage 2: frontages C, D, E and F (Titchwell to Stiffkey).
- Super-frontage 3: frontages G and H (Blakeney to Kelling Hard).

Further background and analysis of the super-frontages is in appendix F, section 3.1.2.

Table C4.2 North Norfolk SMP2 deduced geomorphological frontages

SMP2 frontage reference	Location	Environment Agency profiles
A	**Old Hunstanton -** start of dunes at Old Hunstanton to north-eastern extent of Old Hunstanton golf course	N1D5
B	**Holme-next-the-Sea and Thornham** - north-eastern end of Old Hunstanton golf course to western end of Brancaster bay (just to the east of Thornham)	N1D6, N1D7, N1C1, N1C2, N1C3
C	**Titchwell and Brancaster** - western end of Brancaster bay to western end of Scolt Head Island	N1C4, N1C5, N1C6, N1C7, N1B1
D	**Scolt Head Island** – western extent of Brancaster bay to Norton Hills	N1B2, N1B3, N1B4, N1B5, N1B6a
E	**Holkham Bay** - Norton Hills to Bob Hall's Sands	N1A1, N1A2, N1A3, N1A4, N1A5, N1A6, N1A7, N1A8
F	**Stiffkey marshes** - Bob Hall's Sands to western end of Blakeney Spit	N2D1, N2D2, N2D3, N2D4, N2D5, N2D6, N2C1
G	**Blakeney Spit** - western end of Blakeney Spit to Blakeney Eye	N2C3, N2C4, N2C5
H	**Cley and Salthouse** - Blakeney Eye to Kelling Hard (eastern boundary of SMP study area)	N2C6, N2C7, N2C8, N2B1, N2B2, N2B3, N2B4