Appendix C

Baseline processes

Contents

C1 Introduction

This appendix reports on task 2.1a - coastal processes and evolution - and aims to provide a review of coastal behaviour and dynamics. The information collated and assessed during task 2.1a was later used as a basis for developing the baseline scenarios (task 2.2) and identifying the risks and testing the response and implications of different management policy scenarios over the different timescales (task 3.2), as reported in appendix F.

An appreciation of the potential wider impacts of policies on the coastal processes throughout the SMP frontage is essential at various time and spatial scales. So that robust decisions can be made, a detailed review of existing information is important so that any uncertainties are clearly defined.

In the current study area, much relevant information was collated while preparing SMP1 and during Defra’s Futurecoast research and development (R&D) study. Key findings from these studies are included here, together with important findings from other studies such as strategies, analytical reports and R&D outputs that have been completed since the original SMP.

Appendix D of the SMP2 guidance (Defra, 2006) advocates a ‘behaviour systems approach’ to understanding coastal behaviour and dynamics. This focuses on identifying and understanding the components, interactions and linkages within a system to develop an overall framework of coastal system functioning.

Figure C1.1 provides a site plan of the Wash to allow easy reference to locations referred to in the main body of this report.

C2 General overview

The Wash is a large (approximately 615km^2), relatively low-energy embayment open to the North Sea in which tides are the main (but not exclusive) factor controlling sedimentary processes. It is a marine basin carved out of the Jurassic clays of eastern England by fluvial processes and glacial action.

After the last ice age, sea levels rose and flooded the forested fenland to produce an embayment. For at least 6,500 years, sedimentation has generally out-paced the rate of sea level rise, causing the position of the coastline to move seaward or ‘prograde’.

Tidal flood embankments separate the Wash from the land-claimed coastal plain of the fenland over much of its length. Seaward of these embankments are a series of sand banks and low water channels and large inter-tidal areas made of sand and mud flats and salt marshes. There is a shingle ridge between Wolfterton Creek and Hunstanton and there are sea cliffs at Hunstanton.

Four small tidal rivers, namely the Witham, Welland, Nene and Great Ouse, drain into the embayment. Each is trained at its mouth, with the Witham and Welland trained to a common outfall.

Figure C2.1 presents an overview of the Wash study area as a Landsat image.

Figure C1.1 Map of the Wash

Figure C2.1 Landsat image of the Wash

C3 Geological framework

C3.1 Jurassic and Cretaceous

During the Jurassic period, limestones were formed that now outcrop along the western margin of the fenland. These were followed by the formation of Jurassic mudstones, which underlie much of the central part of the fenland and the Wash. Lower Cretaceous chalk, outcropping along the eastern edge of the fenland, was then deposited out of sequence on the Jurassic mudrocks. The rocks have a general eastward dip caused by uplift of the western margin of the North Sea basin during the late Cretaceous and Tertiary. Erosion of the bedrock during this time removed the softer mudrocks relative to the harder more resistant chalk beds. The Wash-Fenland basin was therefore created as part of a large clay valley stretching from Humberside to Cambridgeshire. The easterly dip of the rocks has produced westward-facing chalk scarps, forming the eastern edge of the fenland, and a shallower-sloping western edge.

C3.2 Pleistocene

Over the Pleistocene (two million to 10,000 years ago) the climate of the United Kingdom has varied, with periods of temperate climate interrupted by repeated advances and retreats of glaciers and ice sheets. Collectively these periods have become known as ice ages and the actions of the ice sheets have been instrumental in forming the modern Wash landscape.

Ice originating in the North Sea widened and deepened the embayment during the Anglian glaciation (Rose, 1987; Clayton, 2000a, b). The ice sheet extended as far south as a line between the rivers Thames and Severn (Bowen et al., 1986; Boulton, 1992) depositing till, sands and gravels (Perrin et al., 1979) over a wide area of East Anglia and the Midlands. After the ice sheet withdrew a drainage system became established with rivers such as the proto-Trent, proto-Great Ouse and proto-Nene flowing into the newly-formed Wash-Fenland lowland (Rose, 1994). The Anglian glaciation was followed by the Hoxnian interglacial, Wolstonian glacial and Ipswichian interglacial. Deposits from these periods are preserved around the edge of the Wash-Fenland, providing evidence for alternate marine and periglacial conditions.

The Ipswichian interglacial was followed by the Devensian glaciation, when ice flowed south into the embayment with the ice maximum located along a line between Boston and Hunstanton (Bowen et al., 1986; Boulton, 1992). The catchments of the rivers draining into the embayment were subject to intense periglacial activity and large quantities of gravel were deposited, either as terraces in confined valleys or low gradient fans at the margins. In the southern Fenland, the valleys of the rivers Great Ouse, Nene and Welland contain large outcrops of these gravels. The evolution of the Devensian landscape caused lowering of the fenland surface, independent of the course of the rivers, leaving the Devensian gravels isolated in the southern fenland as “islands” such as March-Wimblington, Chatteris and Ely.

C3.3 Holocene

Before the extensive land claim and associated building of tidal flood embankments, the Wash embayment was even greater than today and included much of the modern fenland.

In its natural state, between 8,000 and 2,000 years ago, the embayment partly filled with sediment in response to post-glacial relative sea level rise and local and regional marine and estuary processes.

The general trend of relative sea level in the Wash describes an initial rise at an average rate of 4.5 metres every 1,000 years between 8,000 and 6,000 years ago. Because of this early rapid sea level rise, the shorelines of the North Sea migrated landward. In the Wash, due to the low gradient of the area offshore, the lateral rates of shoreline movement associated with this were high initially, estimated between 30 and 60 metre a year (Balson, 1999). More recently than 6,000 years ago, the rate of sea level rise slowed to less than 1.3 metres every 1,000 years (Shennan et al., 2000).

Brew et al. (2000) contend that the rising sea entered the embayment around 8,000 years ago, quickly flooding the central and eastern sectors, while the western and southern sectors only became flooded around 4,400 years ago. During this period the embayment was gradually filling in with sediment. This sedimentary infilling, together with a slowing rate of sea level rise, finally led (post-4,000 years ago) to advancing of the shoreline. At first, this was local but, by around 3,000 years ago, it was happening on a more embayment-wide scale.

After 3,000 years ago, however, a second phase of landward shoreline movement happened with renewed expansion of inter-tidal areas further into the embayment. This was prompted by a deficit in sediment supply relative to sea level rise, leading to tidal processes re-working previously-deposited sediments.

C4 Recent historic development

C4.1 Land claim

In more recent historic times, the shoreline has moved as much in response to the land claim of fringing salt marsh and fen as to natural processes. This history of land claim really started in the 13th century when farmers were eager to exploit the fertile land formed from siltation of estuary deposits. Consequently, the great Sea Bank (Roman Bank) was built to form a continuous barrier to the tides and stretched along the majority of the embayment, stopping only at the Tofts ridge, a significant topographical feature located between Wainfleet and Friskney. This embankment and the Tofts ridge formed the landward limit of tidal flooding and defined the new position of the shoreline. The origin of the Tofts ridge is uncertain and has been widely disputed. The majority of the theories agree that the ridge is associated with salt making activities, which began in the Iron Age and were an important industry for the area. Salt making involved extracting salt from sediment collected from the intertidal zone. One theory for the origin of the ridge is that waste sediment from the salt making process was discarded in one location and this artificially elevated the natural topography. This formed the mound now known as the Tofts ridge. Other theories are based on the belief that the ridge feature is too large to have been formed artificially (as a result of salt making) and therefore there must have also been some natural processes at work (and the dumping of waste from the salt making activities simply added to the already raised elevation of the land in the area). (Brew et al 2000, Brew and Williams 2002).

Also in the 13th century, serious and repeated fluvial flooding of areas upstream of the Wash forced inhabitants to alter the drainage of the fenland. As a result, most of the freshwater that used to flow to the Wash was diverted along its eastern side, causing increased siltation in the embayment due to the reduction in fluvial flushing. This led to extensive salt marsh development in the western section of the embayment which later spread until an extensive strip of around four kilometres wide had built up in front of the earth embankment. The most major phase of land claim in the Wash initially focused on this area of salt marsh. Land claim started in the lee of Gibraltar Point towards the end of the 16^{th} century. The most noticeable phase of land claim was in the 17^{th} century, when it was extended out from the 16^{th} century reclamation and then in a southerly direction towards Friskney. Since that time, some $320km^2$ of the Wash has been turned into agricultural land, continually changing the position of the shoreline in the process (Brew et al 2000, Brew and Williams 2002).

The effects of land claim have been many:

- The shoreline position of the Wash has changed artificially and significantly over time.
- The land claim process has tended to promote build up of the fronting salt marsh (Kestner, 1962; 1963). This has led to a net reduction in overall inter-tidal mud flat and sand flat area, compressing the succession of salt marsh, mud flat and sand flat into a narrower zone.
- The former inter-tidal area claimed by the embankment stops benefiting from the deposition of marine sediment, while this process continues on the seaward side. This has led over time to a quite substantial, topographic differential in places between seaward and landward sides of the embankment.

- The material used to build the land-claiming embankments usually came from 'borrow-pits' on the seaward side of the embankment (Osborne and French, undated).

A ban on further land claim in the Wash has been established in a moratorium in Lincolnshire's 1978 Structure Plan. The last land claim in the Wash was therefore in the early 1980s at Wash Banks. In reversal of the historic trend of land claim, a section of embankment near North Sea Prison Camp at Freiston shore was breached in August 2002 and returned to tidal flooding as a Managed Realignment scheme.

C4.2 Shoreline changes

The large-scale land-claims have reduced the tidal prism of the Wash causing a loss of tidal energy within the embayment, and potentially creating a situation where salt marsh accretion increases. Historical evidence indicates that the salt marshes have, in general, advanced seawards around most of the Wash, associated with a seaward movement of the high water mark (Inglis and Kestner, 1958; Hill and Randerson, 1987; Hill, 1988; Pye, 1995). Lateral accretion is often very rapid, and, according to Inglis and Kestner (1958) and Kestner (1962, 1975, 1979), is greatly increased by land-claim. They argued that when a new embankment is built, the sedimentary environment is no longer in balance. The mean current velocity across the inter-tidal flats to seaward and in salt marsh creeks is reduced, either by reduction of the volume of tidal water or dissipation of energy caused by interfering with the natural flow. This leads to rapid seaward migration of the boundary between the salt marsh and mud flat through increased deposition of fine-grained sediment. The expansion of salt marsh continues until the balance is re-established. The rate of lateral accretion will depend on the sediment supply, shape of the inter-tidal profile and the proximity of the low water mark (Hill, 1988). Kestner (1975, 1979) showed that lateral accretion occurs in a cuspate fashion with the seaward-pointing cusps centred on the creeks that supply water and sediment to the marsh. He concluded that the lateral accretion of the Wash shoreline over the last few centuries had resulted from phases of salt marsh growth, triggered by repeated embankment construction. In contrast, Stoddart et al. (1987) suggested that salt marsh development in the Wash is controlled by the physical processes of speed variation and sediment flux on the marshes themselves and could find no support for the hypothesis of Inglis and Kestner (1958) and Kestner (1962).

C4.3 Salt marsh edge between 1971/74 and 1982/85

Hill (1988) calculated that, between 1971/74 and 1982/85, the net area of active salt marsh in the Wash decreased by two per cent (from 42.41 km^2 to 41.58 km^2). However, this decrease is largely due to enclosure of 8.64 km^2 (20 per cent of the original area). If land-claim is excluded from the calculation, then active salt marsh area increased by 18 per cent.

Table C2.1 Total areas of salt marsh (km^2) in 1971/74 and 1982/85 subdivided by shoreline section (Hill 1988)

Figures (sq km)	Area 1971/74	Area enclosed	Area 1982/85	Net change	Gain outside enclosure
Gibraltar Point–Witham	11.12	5.27	9.28	-1.84	3.43
Witham-Welland	8.26	0.00	8.44	+0.18	0.18
Welland–Nene	12.04	0.59	14.73	+2.69	3.28
Nene–Ouse	6.76	2.78	4.48	-2.28	0.50
Ouse-Hunstanton	4.22	0.00	4.66	+0.44	0.44
Total	42.41	8.64	41.58	-0.83	7.81

Table C2.1 shows a net loss of salt marsh along the sections of the Wash coast where large land claims have occurred. A net loss of 1.84 km^2 was recorded along the Gibraltar Point-River Witham shore and 2.28 km^2 between the rivers Nene and Great Ouse. Along sections of coast where no land claim has taken place since 1971/74, the area of salt marsh has remained relatively stable, increasing by 0.44 km^2 on the east coast and by 0.18 km^2 around the rivers Witham and Welland outfalls.

Changes in the position of the seaward edge of salt marsh at 46 points around the Wash between 1971/74 and 1982/85, in front of embankments of various ages, are shown in table C2.2 (Hill and Randerson, 1987; Hill, 1988). Movement of salt marsh edge is calculated from the difference in marsh width between 1971/74 and 1982/85 vegetation maps, taking into account the width of any land claims between those dates. Positive numbers denote seaward movement of the salt marsh edge and negative numbers denote retreat of salt marsh edge.

The highest rates of lateral accretion have taken place along the north-western shore between Wainfleet and Friskney. A rate of 42 metres a year was calculated in front of a 1966 embankment, 10-25 metres a year seaward of a 1973 structure and 14-27 metres a year in front of a 1976/77 land claim. In contrast, (and not normal for the Wash as a whole) the salt marshes at Freiston Low and Butterwick Low (also along the north-western shore) in front of 1952 and 1979/80 embankments have retreated by two to three and 15 metres a year, respectively. By comparison, Inglis and Kestner (1958) and Kestner (1962) calculated a mean seaward advance of about eight metres a year between 1828 and 1952 for the salt marshes in the same area. Before the River Witham training wall was built, the salt marsh advanced at an average rate of 1.4 metres a year (1828-1871) whereas between 1887 and 1903 the average rate was 4.2 metres a year, peaking at 10.7 metres a year between 1903 and 1918. According to Pye (1992, 1995), the recent retreat was due to an insufficient inter-tidal mud flat height at the time of embankment construction. This meant that vegetation was not able to become established. Progressive land claims may have advanced too far onto the existing salt marsh and left not enough width and height in front of the embankment to form new salt marsh (University of Newcastle, 1998a).

Along the southern shore, lateral salt marsh accretion rates of between five and 11 metres a year were recorded at Terrington and Wingland Marshes where the last land claims took place in 1955 and 1974, respectively. Coles (1978) recorded a 100 to150 metre seaward advance of the mud flats two years after completing the 1974 embankment. These figures compare with lateral accretion rates of over 20 metres a year for similar areas between 1917 and 1952 (Inglis and Kestner, 1958). Even earlier, building of the River Nene outfall in the 19th century changed tidal and current patterns such that the rate of extension of the Wingland salt marsh was as high as 50 metres a year (Kestner, 1962). Between Wolferton and Wootton along the east coast of the Wash a two to12 metres a year seaward extension of the salt marsh occurred in front of 1960/67 embankments.

Inglis and Kestner (1958) and Hill (1988) showed that, in the absence of land-claim or large-scale engineering works, the salt marsh edge is relatively stationary. Hill (1988) showed little movement of the salt marsh edge between 1971/74 and 1982/85 in front of 19th century embankments. At Leverton the salt marsh edge retreated at a rate of two metres a year in front of the 1809 embankment. Around Holbeach, retreats of 0.5 to four metres a year took place in front of an 1838 embankment. Near the rivers Witham and Welland outfalls, movement varies between a one metre a year advance and a two metre a year retreat in front of 1865/70 embankments.

University of Newcastle (1998a) compared the width of the inter-tidal zone with the movement of the salt marsh boundary (1971/74-1982/85) between Gibraltar Point and the River Witham (figure C2.2). They showed that, as the inter-tidal flat width decreased towards the south, the rate of advance of the salt marsh boundary decreased until, at a point nine kilometres north of the River Witham outfall, it reverses from advance to retreat. North of this point the salt marsh advanced seaward at gradually increasing rates in a northward direction, averaging around 18.5 metres a year. South of this point the salt marsh boundary receded at an annual rate of 1.4 metres. They showed that salt marsh erosion begins when the inter-tidal flat width is about 3.5 kilometres. Any decrease in the width of the inter-tidal flat means that wave dissipation is reduced to a level at which erosion of the salt marsh begins. With sea-level rise, the point at which salt marsh begins to erode will move further north along this coast. Assuming sea-level rises of three and six millimetres a year, this point (or “node”) will move northwards at nine and 18 metres a year respectively (University of Newcastle, 1998a).

Table C2.2 Changes in salt marsh width between 1971/74 and 1982/85 to seaward of land claims of various ages (Hill 1988)

Point	NGR	Last land claim date	Extension 1971/74-1982/85
1	550578	1966	+460
2	541573	1973	+270
3	534566	1973	+110
4	523555	1976/77	+215
5	518551	1976/77	+295
6	509542	1976/77	+230
7	497528	1976/77	+155
8	473507	1976/77	+245
9	470508	1809	+100
10	458497	1962	+60
11	447486	1809	+110
12	439476	1809	-25
13	430459	1972	+5
14	425452	1972	-5
15	418445	1972	+60
16	406433	1979/80	-165
17	406423	1976	+60
18	399414	1952/65	-30
19	393399	1952	-20
20	369388(E)	1865	+15
21	369388(W)	1865	-25
22	362379	1870	-20
23	355365	1870	+65
24	351357	1870	-10
25	372352	1949	+75
26	388354	1950	+170
27	412339	1838	-5
28	423337	1838	-40
29	438329	1838	-20
30	453320	1840	+110
31	464303	1875	+90
32	477293	1875	+25
33	482283	1978	-105
34	486275	1865	+85
35	501267	1974	+50
36	504266	1974	+120
37	513263	1974	+110
38	528260	1974	+125
39	546264	1955	+120
40	567262	1955	+50
41	584253	1974	+85
42	601256	1967	+20

Point	NGR	Last land claim date	Extension 1971/74-1982/85
43	611268	1960/66	+35
44	617279	1966	+100
45	632289	1966	+130
46	643297	1966	+25

Figure C2.2 Inter-tidal width and salt marsh boundary changes (University of Newcastle 1998a)

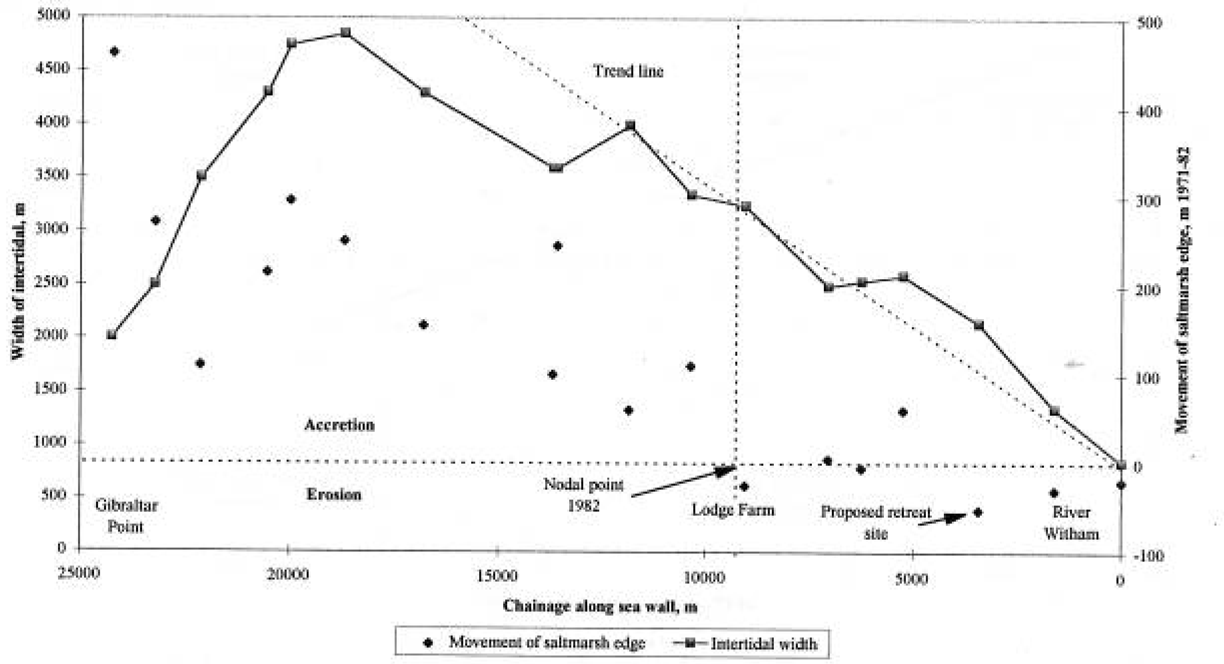


Figure C2.3 Salt marsh boundary changes between 1994 and 2000 along Breast Sand (Pethick 2002)

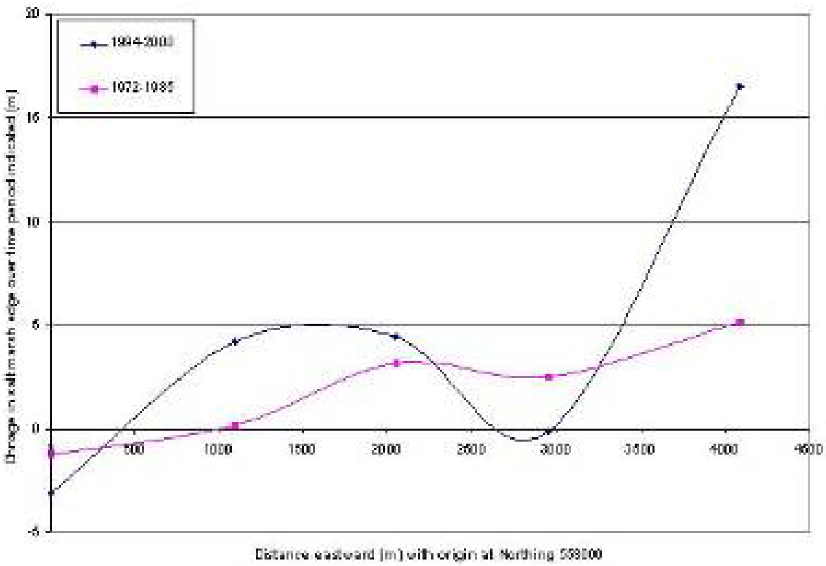
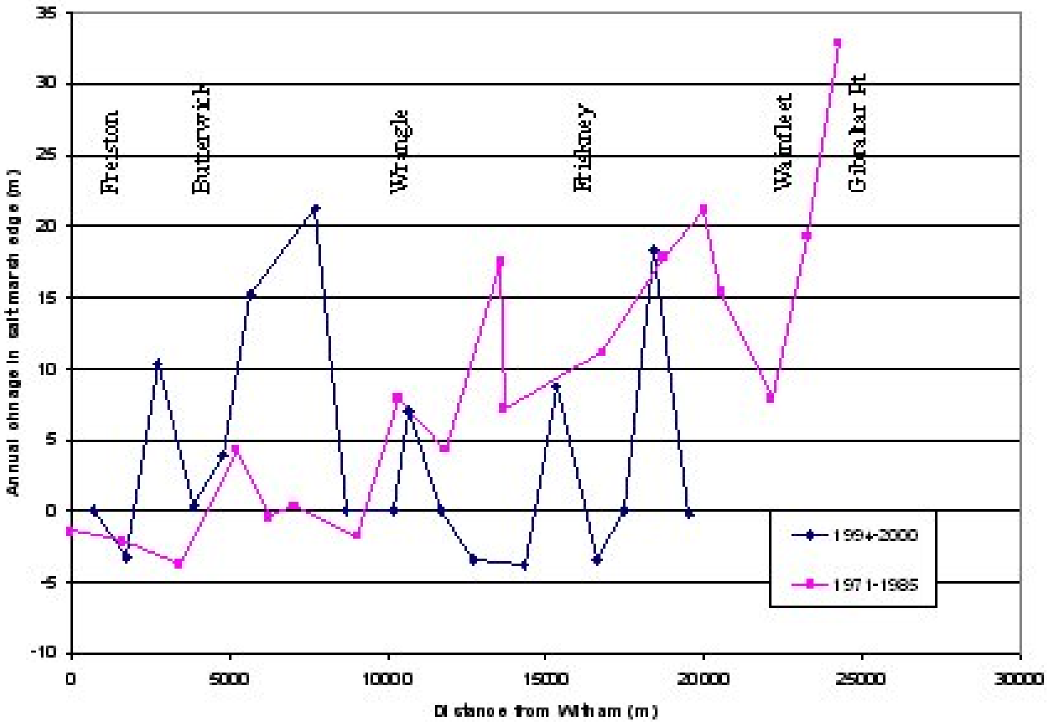


Figure C2.4 Salt marsh boundary changes between 1994 and 2000 along the north-western shore (Pethick 2002)



C4.4 Salt marsh and mud flats between 1994 and 2000

Pethick (2002) extended the analyses of Hill (1988) to investigate the position of the salt marsh-mud flat boundary between 1994 and 2000 along the north-western shore and at Breast Sand (Terrington, south-eastern shore). Along the north-western shore, most of the salt marsh advanced at an average rate of 5.6 metres a year, apart from the southernmost 1.5 kilometres and areas 12-16 kilometres north of the River Witham outfall where retreat took place (figure C2.4). Over most of the Breast Sand area, the salt marsh edge advanced seaward at three metres a year between 1994 and 2000. However, an advance of 16 metres a year and a retreat of one to two metres a year were recorded at the eastern and western ends respectively (figure C2.3).

Beach profiles at Butterwick Low (figure C2.5) show that, between 1994 and 2000, the salt marsh increased in height by eight millimetres a year. In contrast, the inter-tidal flats experienced erosion from zero at the salt marsh boundary to 64 millimetres a year, around 1.5 kilometres from the embankment (average rate of 20 millimetres a year). Wrangle Flats shows similar trends (figure C2.6) where the salt marsh increased in height at nine millimetres a year and the inter-tidal flats eroded at an average rate of 36 millimetres a year. The erosion rate of the inter-tidal flats decreased landward to zero at the salt marsh boundary. The salt marsh at Breast Sand increased in height by 20 millimetres a year between 1994 and 2000.

Pethick (2002) argued that salt marsh accretion rates, both vertically and horizontally, are positively related to the distance from the adjacent subtidal channel, that is the width of the inter-tidal zone. They suggested that a wider inter-tidal zone was capable of more effective attenuation of wave energy than a narrower one (Cooper, 2001) so salt marsh backing a wide inter-tidal zone is impinged by lower wave energies.

Figure C2.5 Comparison of 1994 and 2000 beach profile data from Butterwick Low showing changes in height of salt marsh and inter-tidal flats (Pethick 2002)

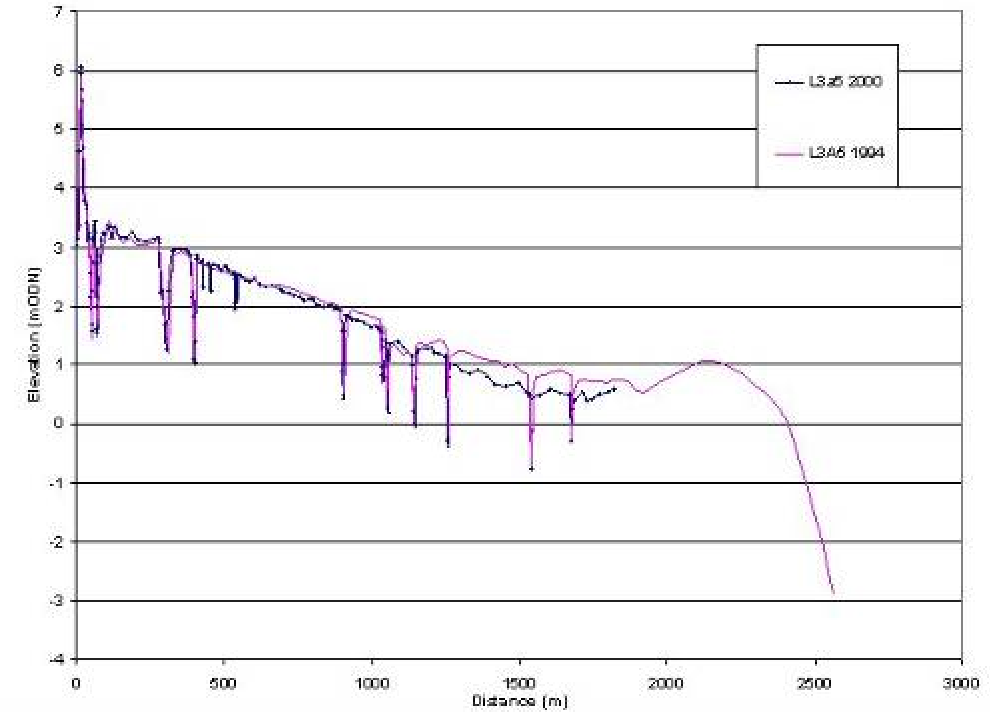
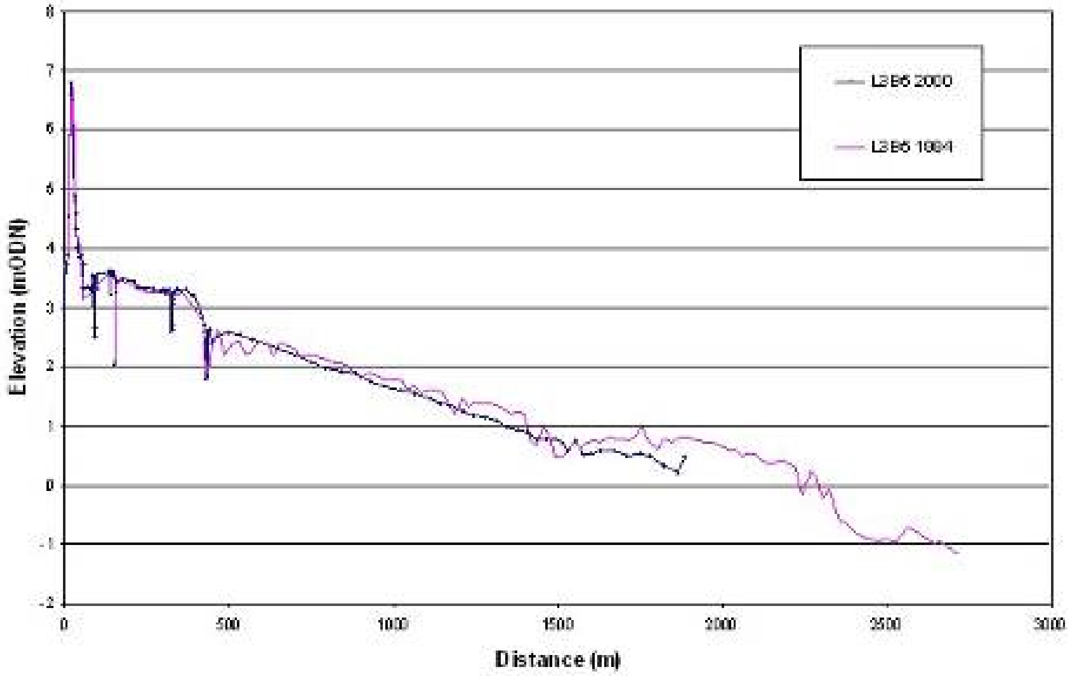


Figure C2.6 Comparison of 1994 and 2000 beach profile data from Wrangle Flats showing changes in height of salt marsh and inter-tidal flats (Pethick 2002)



C4.5 Low water mark between 1828 and 1995

The Wash Extended Shoreline Evolution Analysis undertaken for the Environment Agency (Posford Duvivier 1997) analysed the changing position of the low water mark (mean low water spring tide) of the Wash between 1828 and 1995 and between 1971 and 1995. They divided the coastline into 17 shore normal transects with transect 1 at Gibraltar Point and transect 17 at Hunstanton (table C2.3). The movement of the low water mark was mapped at each of these transects. It illustrates a high degree of spatial variability with areas of local advance and retreat occurring at the same time (figure C2.7).

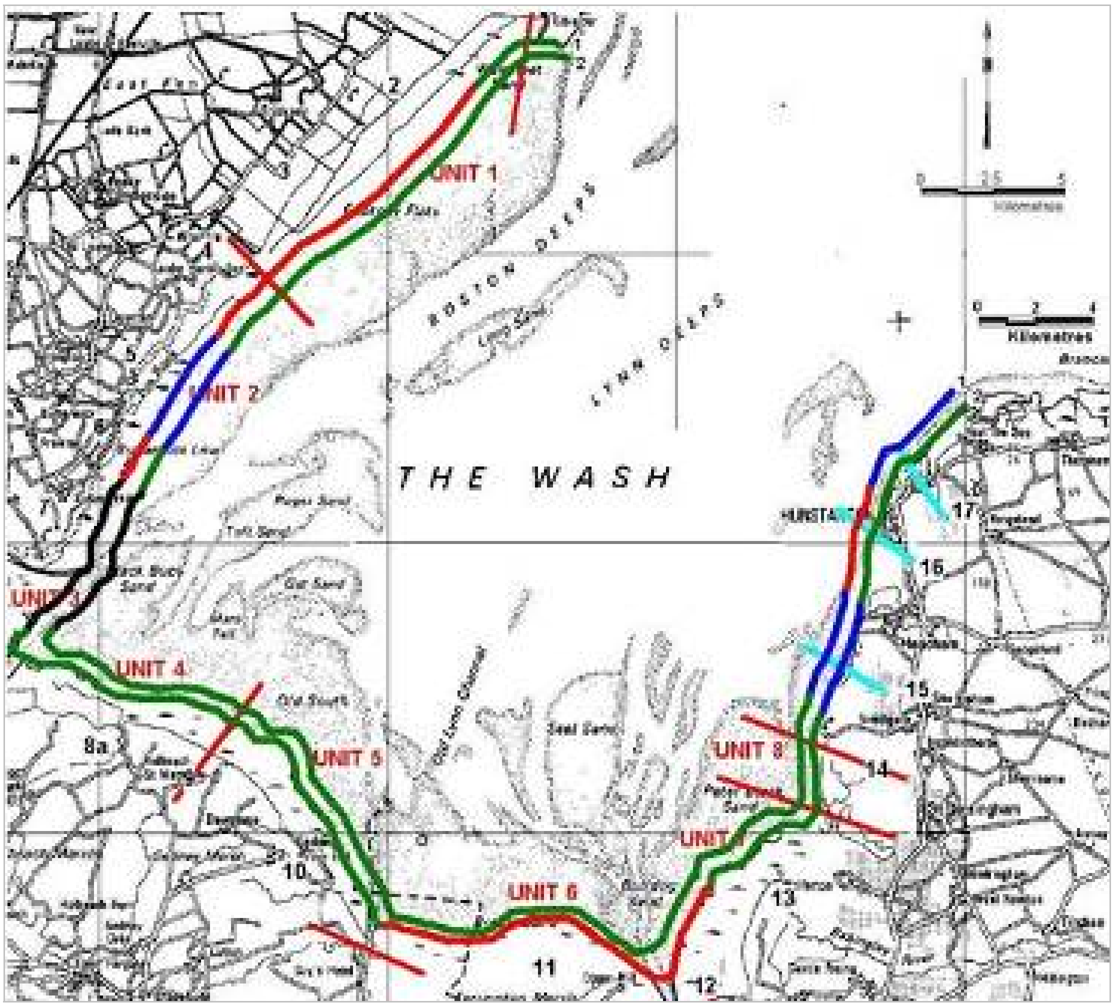
Over the period 1828 to 1995 the low water mark of the Wash has advanced in a seaward direction (or remained stable) apart from a short stretch at Heacham that has retreated landward. The Heacham shoreline is exposed to the most extreme wind and wave conditions in the Wash (Posford Duvivier 1996a). Over more recent times (1971-1995) the pattern of movement has been more complicated with areas of landward movement (for example Wainfleet to Butterwick Low, River Nene to Bulldog Sand), seaward movement (for example River Welland to River Nene and Bulldog Sand to Dersingham) and stability (Leverton and Snettisham).

The general trend of historic (1828-1995) movement of the Wash low water mark is seaward. However, this general trend masks more recent (last 30 years) local fluctuations with significant lengths of the low water mark moving landward. Also, the movement of the Wash low water mark is affected by the movement of offshore sand banks. Although a seaward advancing low water mark is observed on the south-western shore between the rivers Welland and Nene, it is possible that the landward migration of sand banks to join the shore produces an apparent seaward advance (Posford Duvivier, 1997a).

Table C2.3 Historical evolution of the low water mark at transects around the Wash coast. (Posford Duvivier 1997a)

Transect	Location	1828-1995	1971-1995
1	Gibraltar Point	Seaward	Seaward
2	Friskney Flats	Seaward	Landward
3	Friskney Flats	Seaward	Landward
4	Wrangle	Seaward	Landward
5	Leverton	Stable	Stable
6	Butterwick Low	Seaward	Landward
7	Black Buoy Sand	Insufficient data	Insufficient data
7A	Black Buoy Sand	Insufficient data	Insufficient data
8	River Welland	Seaward	Seaward
8A	Mare Tail Sand	Seaward	Seaward
9	Holbeach St Matthew	Seaward	Seaward
10	Gedney Drove	Seaward	Seaward
11	Breast Sand	Seaward	Landward
12	Bulldog Sand	Seaward	Landward
13	Peter Black Sand	Seaward	Seaward
14	Dersingham	Seaward	Seaward
15	Snettisham	Stable	Stable
16	Heacham	Landward	Seaward
17	Hunstanton	Stable	Seaward

Figure C2.7 Historical evolution of the low water mark (Posford Duvivier, 1997a).



Line 1 (most seaward line) shows 1828 – 1995 evolution and line 2 (most landward line) shows 1971 – 1995 evolution. Red line = retreat, blue line = stable, green line = advance and black line = insufficient data

C4.6 Mean high water spring horizontal position and mean sea level between 1991 and 2000

Environment Agency (2003a, b, c) analysed beach profile data from around the coast of the Wash to determine changes in the horizontal position of mean high water spring and mean sea level (the same distance between high water and low water) between 1991 and 2000 (figures C2.8, C2.9, C2.10, C2.11 and C2.12). The data analysed were collected every six months (in summer and winter).

Figure C2.8 Mean annual retreat or advance rate of mean high water spring (Gibraltar Point to River Nene outfall) between 1991 and 2000 (Environment Agency 2003a)

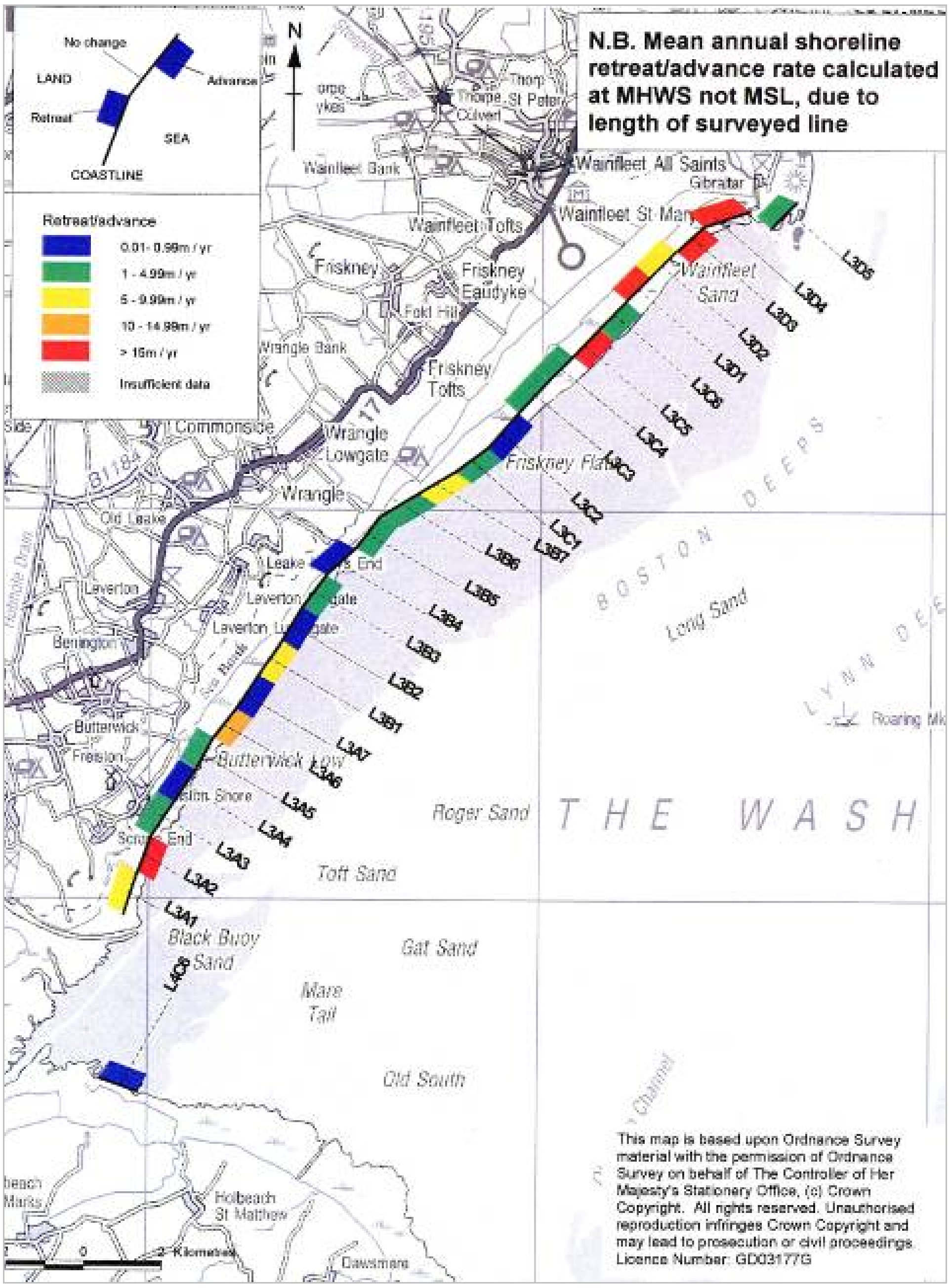


Figure C2.9 Mean annual retreat or advance rate of mean sea level (Gibraltar Point to River Nene outfall) between 1991 and 2000 (Environment Agency 2003a)

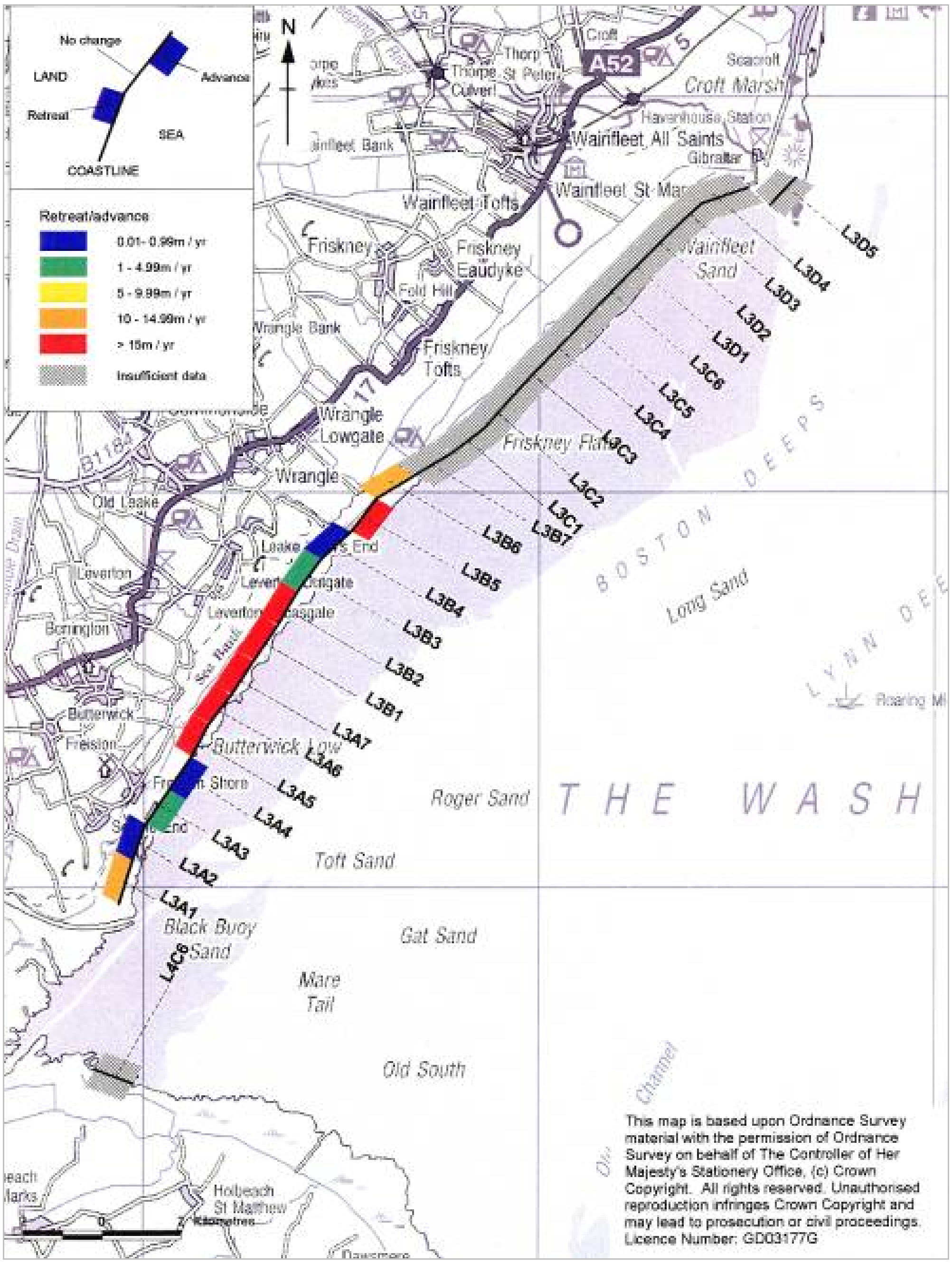


Figure C2.10 Mean annual retreat or advance rate of mean high water spring (River Witham outfall to River Great Ouse outfall) between 1991 and 2000 (Environment Agency 2003b)

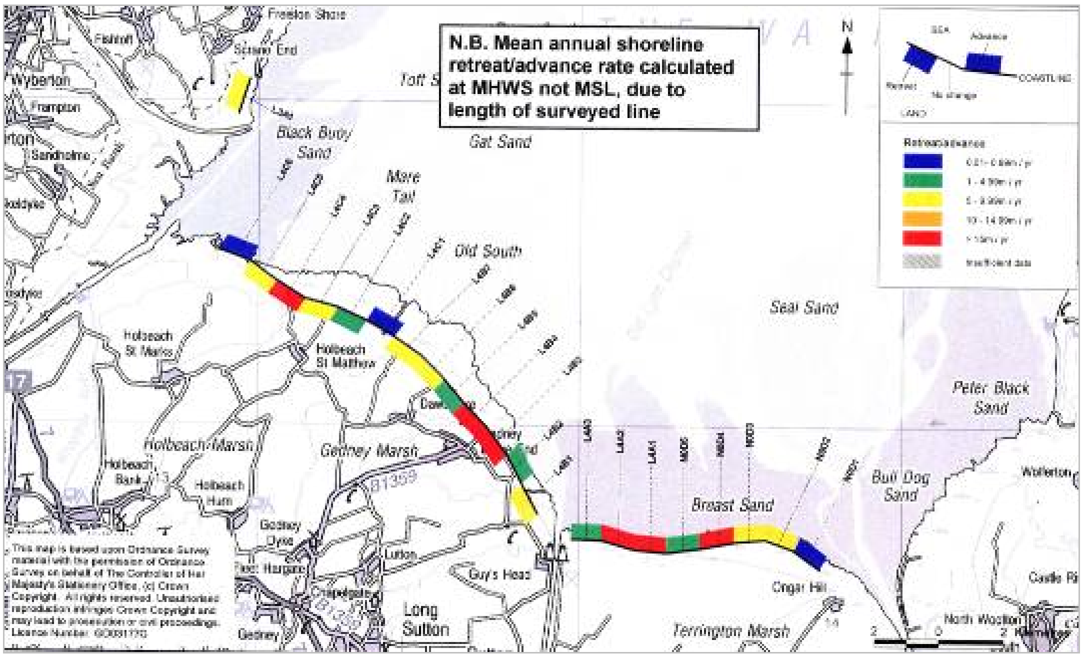


Figure C2.11 Mean annual retreat or advance rate of mean high water spring (River Nene outfall to Hunstanton) between 1991 and 2000 (Environment Agency 2003c)

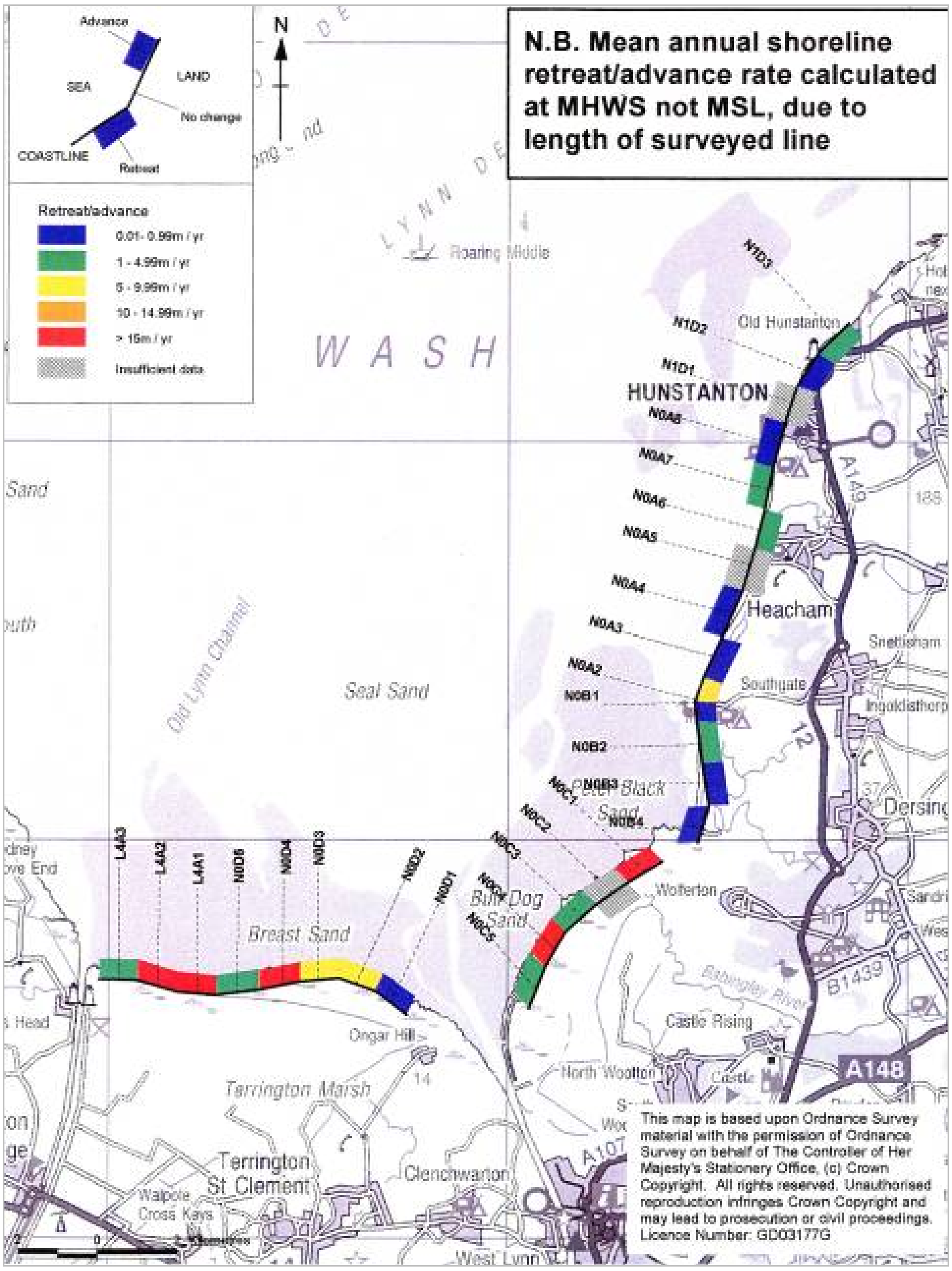
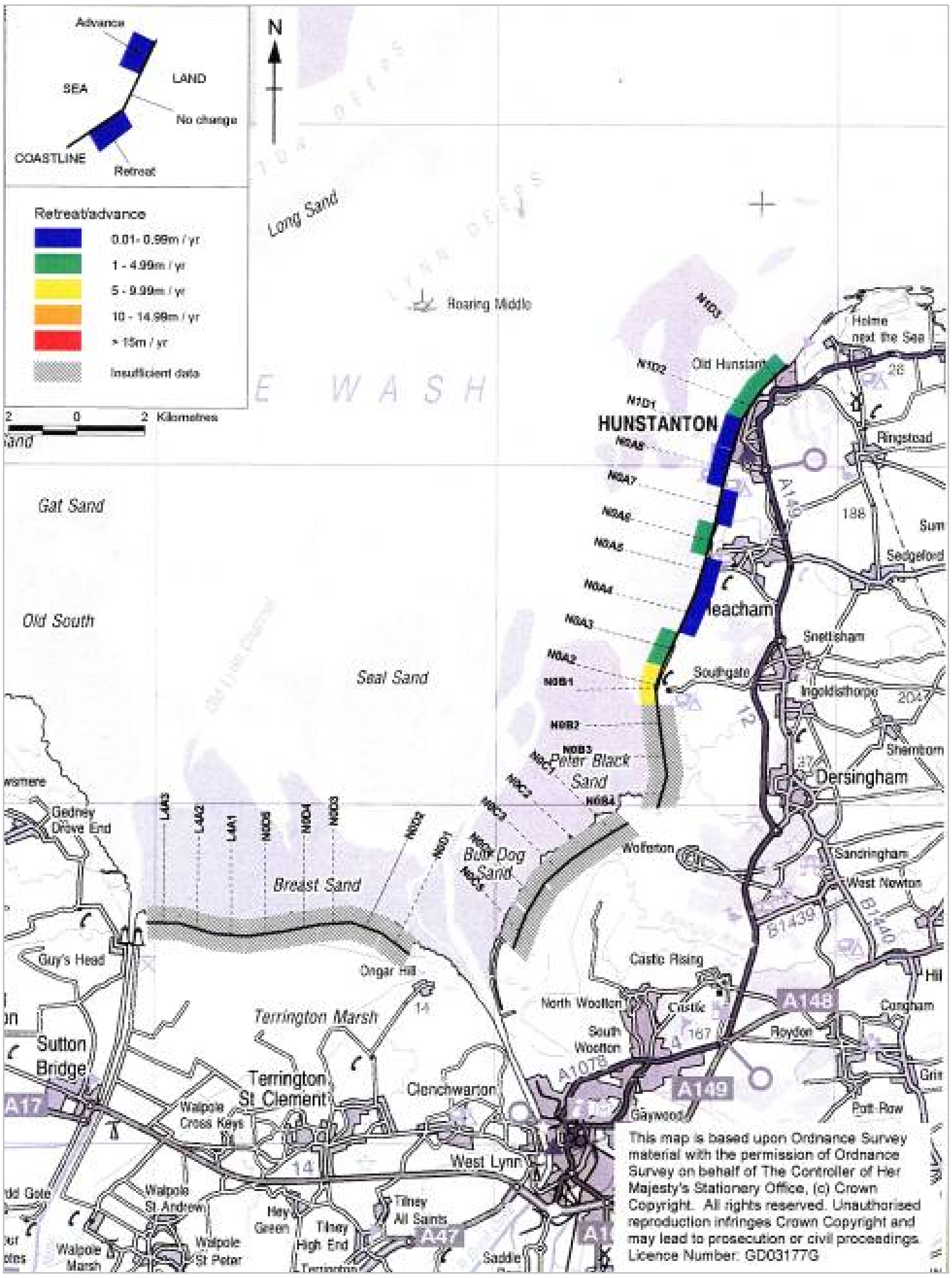


Figure C2.12 Mean annual retreat or advance rate of mean sea level (River Nene outfall to Hunstanton) between 1991 and 2000 (Environment Agency 2003c)



Between Gibraltar Point and Holbeach, the position of mean high water spring has varied (Environment Agency, 2003a). The northern section between Gibraltar Point and Friskney has retreated (one to 27 metres year) and advanced (one to 64 metres a year). Between Friskney and Butterwick, mean high water spring has generally advanced (0 to13 metres a year), but south of this, the Freiston shore has generally retreated between 0 and eight metres a year (with an unusual advance of 25 metres a year). Between

Holbeach and the River Nene outfall the position of mean high water spring is characterised by general retreat at rates between one and 36 metres a year, whereas between the River Nene outfall and Dersingham it is characterised by advance at rates between 0 and 20 metres a year (Environment Agency, 2003b, c). North of Dersingham to Hunstanton a general retreat of mean high water spring occurred with rates ranging from 0 to six metres a year. The Hunstanton and Old Hunstanton frontages have generally advanced up to 1.5 metres a year (Environment Agency, 2003c).

The results for mean sea level between Wrangle and Butterwick contrast strongly with those for mean high water spring. Apart from a short section at Wrangle, mean sea level has retreated between 0 and 56 metres a year. South of Butterwick, mean sea level has been reasonably static (advance up to 1.6 metres a year and retreat up to 0.2 metres a year) to the River Witham outfall when a higher retreat rate occurs (eight metres a year). Between Snettisham and Hunstanton, there has been a general advance of mean sea level. This compares to the general retreat of mean high water spring at Snettisham and lower advances at Hunstanton. The comparative movements at Snettisham may be due in part to regular beach recharge activities here between 1991 and 1999 (Environment Agency, 2003c).

Table C2.4 Mean annual shoreline retreat/advance rate of mean high water spring and mean sea level (in brackets). Compiled from Environment Agency 2003a, b and c

Location	Profile	Retreat	Advance
Gibraltar Point	L3D5	1.02	
Wainfleet	L3D4	27.04	
Wainfleet	L3D3		64.14
Wainfleet	L3D2	6.81	
Wainfleet	L3D1	15.41	
Wainfleet	L3C6		3.85
Friskney	L3C5		19.64
Friskney	L3C4	4.65	
Friskney	L3C3	1.01	
Friskney	L3C2		0.73
Friskney	L3C1		4.54
Wrangle Lowgate	L3B7		7.19
Wrangle Lowgate	L3B6	(11.1)	3.28
Wrangle	L3B5		3.81 (18.2)
Wrangle	L3B4	0.27 (0.2)	
Old Leake	L3B3	(2.2)	1.37
Old Leake	L3B2	(17.3)	0.14
Leverton	L3B1	(26.7)	9.92

Location	Profile	Retreat	Advance
Bennington	L3A7	(21.0)	0.24
Butterwick	L3A6	(56.2)	13.47
Butterwick	L3A5	1.31 (47.6)	
Freiston	L3A4	0.09	(0.2)
Freiston	L3A3	4.15	(1.6)
Freiston	L3A2	(0.2)	24.97
Witham Outfall	L3A1	7.77 (11.1)	
Holbeach	L4C6		1.0
Holbeach	L4C5	5.7	
Holbeach	L4C4	25.5	
Holbeach	L4C3	6.1	
Holbeach	L4C2	1.4	
Holbeach	L4C1		0.8
Gedney	L4B7	6.9	
Gedney	L4B6	6.6	
Gedney	L4B5	2.2	
Gedney	L4B4	15.7	
Gedney	L4B3	36.0	
Nene outfall	L4B2		4.0
Nene outfall	L4B1	7.8	
Nene outfall	L4A3		1.8
Nene outfall	L4A2		16.4
Terrington	L4A1		20.3
Terrington	N0D5		3.6
Terrington	N0D4		30.4
Terrington	N0D3		5.9
Great Ouse outfall	N0D2		5.4
Great Ouse outfall	N0D1		1.0
North Wootton	N0C5		1.8
North Wootton	N0C4		15.3
North Wootton	N0C3		3.3
Wolferton	N0C2		
Wolferton	N0C1		18.9
Dersingham	N0B4		0.7
Dersingham	N0B3	0.3	
Snettisham	N0B2	1.4	
Snettisham	N0B1	0.7	(9.53)
Snettisham	N0A2	5.6	(9.53)
Snettisham	N0A3	0.3	(2.92)
Heacham	N0A4	(0.52)	0.9
Heacham	N0A5	(0.18)	

Location	Profile	Retreat	Advance
Heacham	N0A6	1.0	(2.19)
Hunstanton	N0A7	1.2 (0.59)	
Hunstanton	N0A8	0.3	(0.28)
Hunstanton	N1D1		1.6 (0.86)
Hunstanton	N1D2		0.3 (1.86)
Old Hunstanton	N1D3		1.5 (2.56)

C4.7 Bathymetry between 1828 and 1971

Hydraulics Research Station (1975a) described changes in the bathymetry (measurement of water depth) of the Wash, and the positions of the outfall channels of the rivers Nene and Great Ouse, between 1828 and 1971. They indicated that the major banks of the Wash have generally not changed position over the 143 year period, but changes in size occurred. For example, Sunk Sand off Hunstanton, increased significantly in size in south-west and south-east directions and Thief Sand, Sunk Sand and Ferrier Sand all suffered erosion (about 1.5 kilometres) of their northern ends. The seaward positions of the main channels in the south-east Wash were also fairly stable between 1828 and 1971. However, towards their landward ends the channels changed greatly with regular switching and meander shifts. The channel of the River Great Ouse has switched twice from one channel to another, whereas the outfall channel of the River Nene has remained relatively stable.

C4.8 Recent observed trends

The Environment Agency's Shoreline Management Group has produced a draft report to inform the SMP2 process. This details the findings of the Anglian Coastal Monitoring Programme (the Wash – Gibraltar Point to Old Hunstanton) that involved the regular strategic coastal monitoring of the East Anglian coast since 1991 (Environment Agency 2007). This programme collected a variety of data including annual aerial photographs, annual topographic beach surveys (winter and summer) at one kilometre intervals, bathymetric surveys and continuous wave and tide recording (nearshore and offshore).

The report summarises two separate types of analysis. Firstly, vertical changes were measured on the saltmarshes and mudflats. Secondly, horizontal changes were measured along the sand/shingle ridge on the eastern shore. Also, orthorectified aerial photographs were analysed to establish the extent of saltmarsh horizontal growth or loss between 1992 and 2006. The 1992 and 2006 photographs were both taken in July which allows a direct comparison between the two datasets and allows seasonality to be dismissed as a cause of saltmarsh growth.

C4.8.1 Horizontal accretion

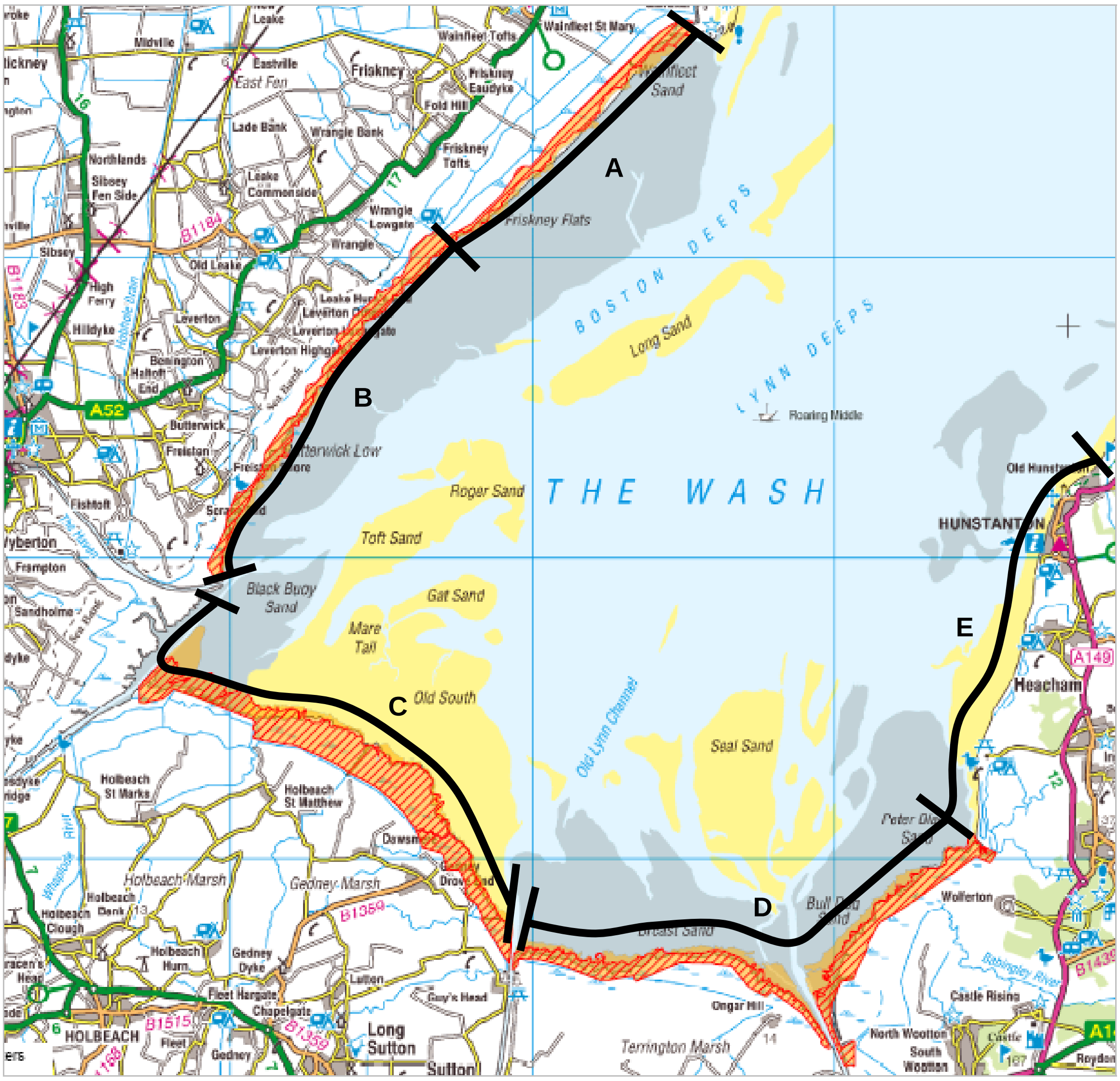
Table C2.5 and figure C2.13 show the total area of saltmarsh in 1992 and 2006. For this purpose the Wash has been split into five sub-cells, as indicated on figure C2.13. Sub-cell E is characterised by sandy beaches so saltmarsh change does not apply to this stretch of coastline. The red cross-hatching on figure C2.13 indicates 1992 saltmarsh area and the orange shading represents the 2006 area.

Table C2.5 clearly shows that overall saltmarsh area has increased horizontally so the saltmarshes have been characterised by a general trend of growth. The highest rates of growth have been seen in sub-cell D, which is generally the southern shoreline of the Wash.

Table C2.5 Saltmarsh comparison between 1992 and 2006

Location	Saltmarsh area 1992	Saltmarsh area 2006	Saltmarsh area change 1992-2006 (hectares)
Sub-cell A	381.52	523.93	+142.41
Sub-cell B	540.80	683.45	+142.66
Sub-cell C	1431.82	1722.97	+291.15
Sub-cell D	1003.08	1448.09	+445.01
Sub-cell E	N/A	N/A	N/A
Totals	3357.22	4378.44	+1021.23

Figure C2.13 Salt marsh area comparison between 1992 and 2006 (After Environment Agency 2007)



C4.8.2 Vertical accretion

It is also important to consider the vertical growth along the profiles. In general most of the profiles have shown some degree of vertical growth over the last 13 years. Growth rates appear to be highest where new marsh has formed between 1993 and 2006. Growth appears to stop or become variable on more mature marsh where the vertical height approaches roughly 3.5 mOD. This is particularly obvious near the Holbeach St Matthew area (profiles L4B5 to L4C3) where the upper landward ends of the profiles show a minor erosion trend. However, here the saltmarsh/mudflat boundary has grown by between 150 and 400 metres.

There is also a local trend of mudflat erosion and saltmarsh growth at a number of profiles. Profiles L3B1, L3A7 and L3A6 (figure C2.14), L3B4 and

L3B3 (figure C2.15), L3B7 and L3B6 (figure C2.16), L3C6 (profile 2.17) and L3D4 (figure C2.18) all show this trend. These profiles are confined to sub-cells A and B, particularly on the Wrangle and Leverton marshes and at local points on Wainfleet marsh. This trend could be explained by the fact that, possibly due to sea level rise, sediment is eroded from the lower profile (mudflat) and then transported up-profile and deposited on the upper profile (saltmarsh).

C4.8.3 Summary

The western shore of the Wash is characterised by significantly lower horizontal saltmarsh growth than the southern shore. Between The Horseshoe and Butterwick Low (sub-cell B) most of the profiles show a trend of horizontal erosion.

The lower sand flats between Shepherd's Port and Heacham (contained within sub-cell E) also show a trend of horizontal erosion, whereas the sand/shingle ridge on the upper beach at these locations shows a trend of stability. However, these profiles have been heavily modified through sediment reprofiling, recycling and nourishment.

Figure C2.14 Profiles L3B1, L3A7 and L3A6 show erosion of the lower profile (mudflat) and growth of the upper profile (salt marsh). Green lines represent a vertical accretion trend and red lines indicate vertical lowering or erosion (Environment Agency 2007)

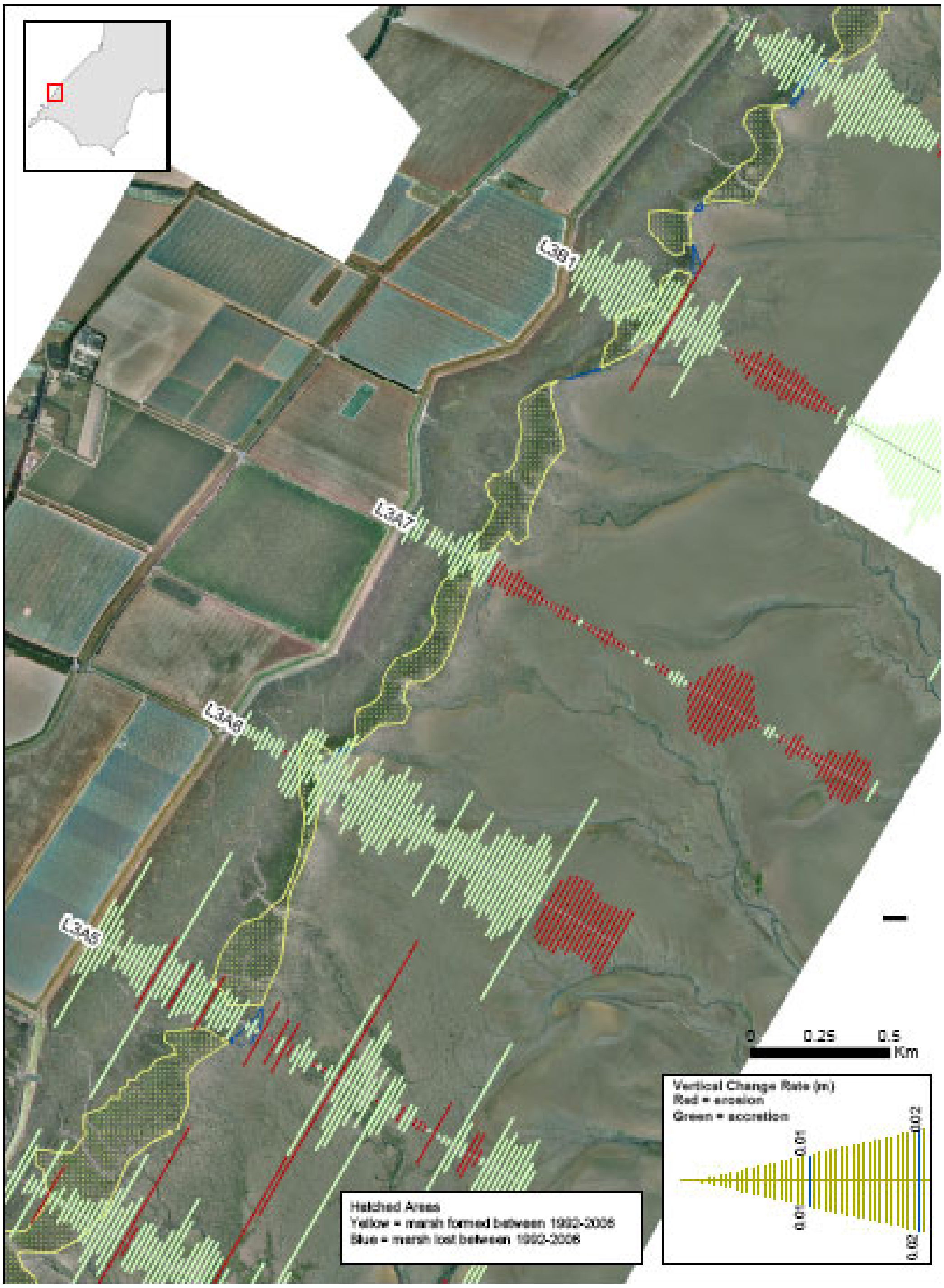


Figure C2.15 Profiles L3B4 and L3B3 show erosion of the lower profile (mudflat) and growth of the upper profile (salt marsh). Green lines represent a vertical accretion trend and red lines indicate vertical lowering or erosion (Environment Agency 2007)

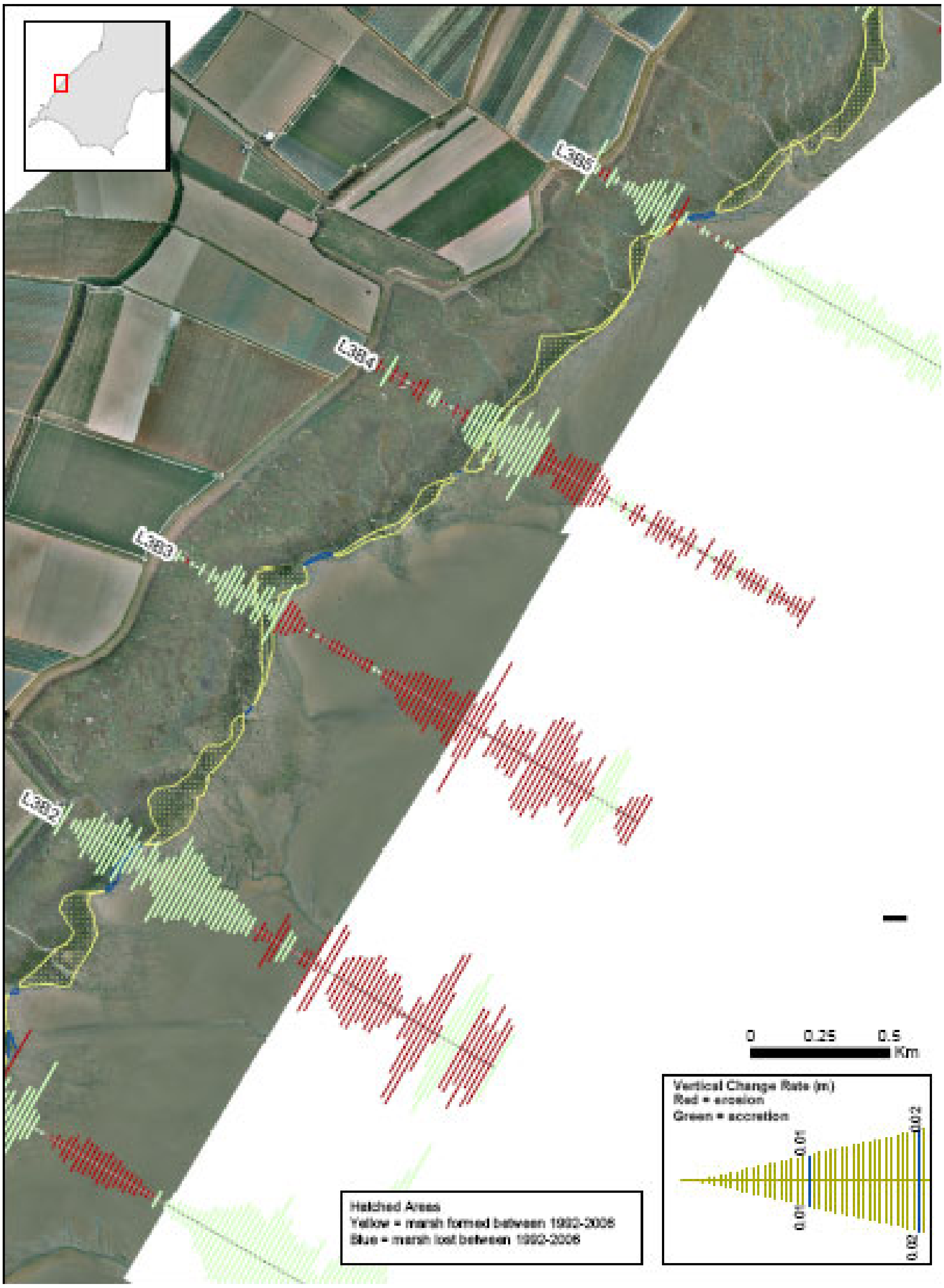


Figure C2.16 Profiles L3B7 and L3B6 show erosion of the lower profile (mudflat) and growth of the upper profile (salt marsh). Green lines represent a vertical accretion trend and red lines indicate vertical lowering or erosion (Environment Agency 2007)

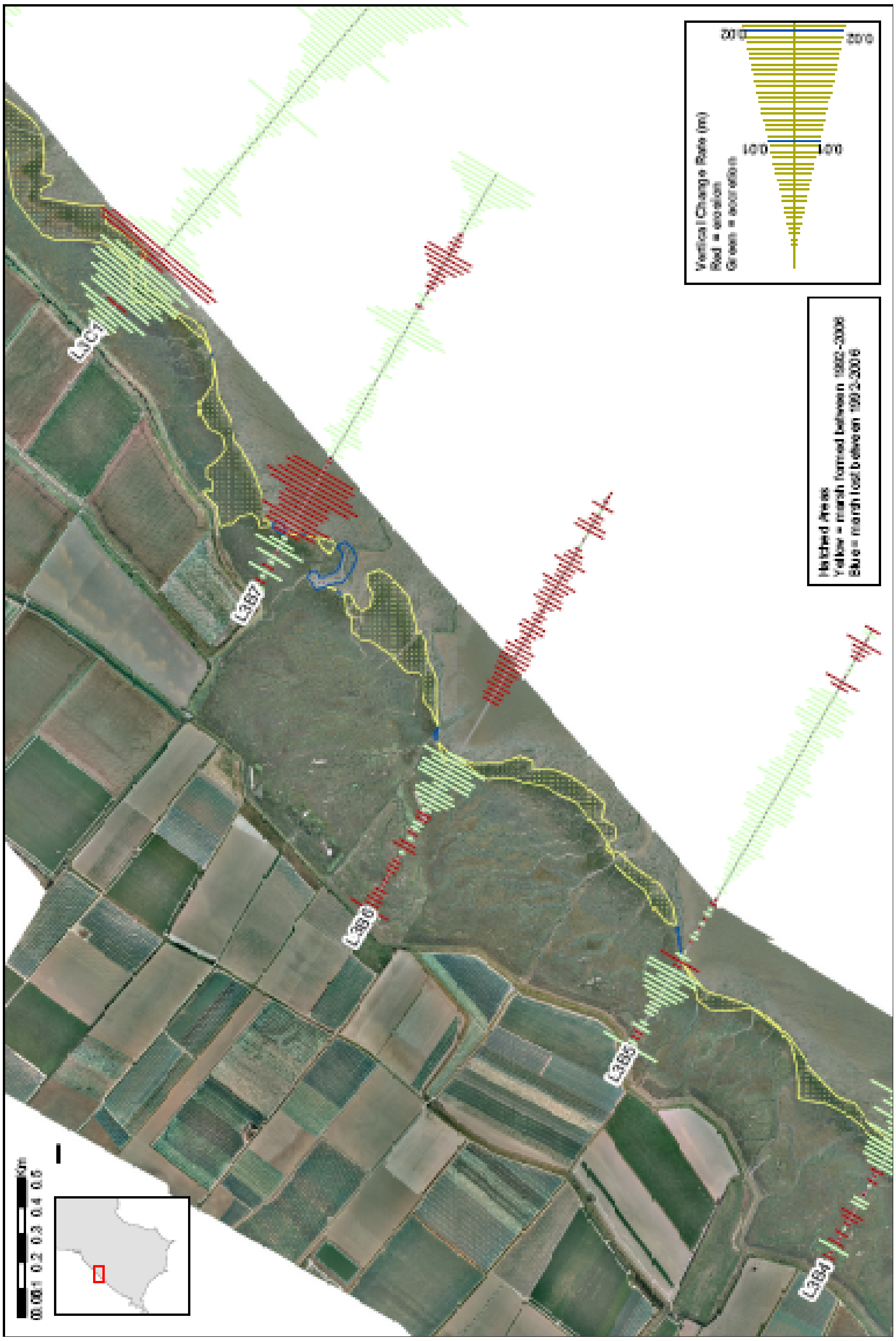


Figure C2.17 Profile L3C6 shows erosion of the lower profile (mudflat) and growth of the upper profile (salt marsh). Green lines represent a vertical growth trend and red lines indicate vertical lowering or erosion (Environment Agency 2007)

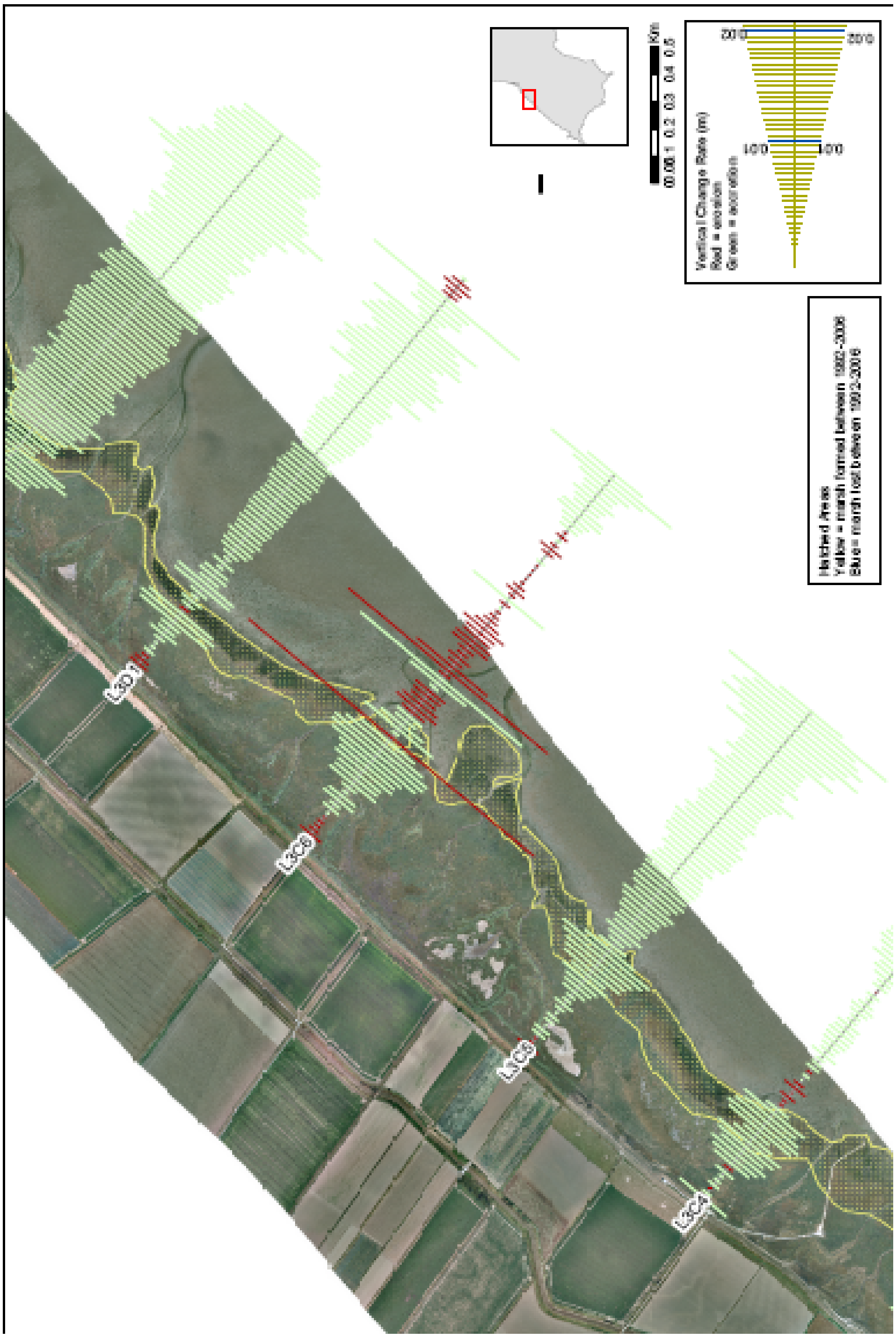
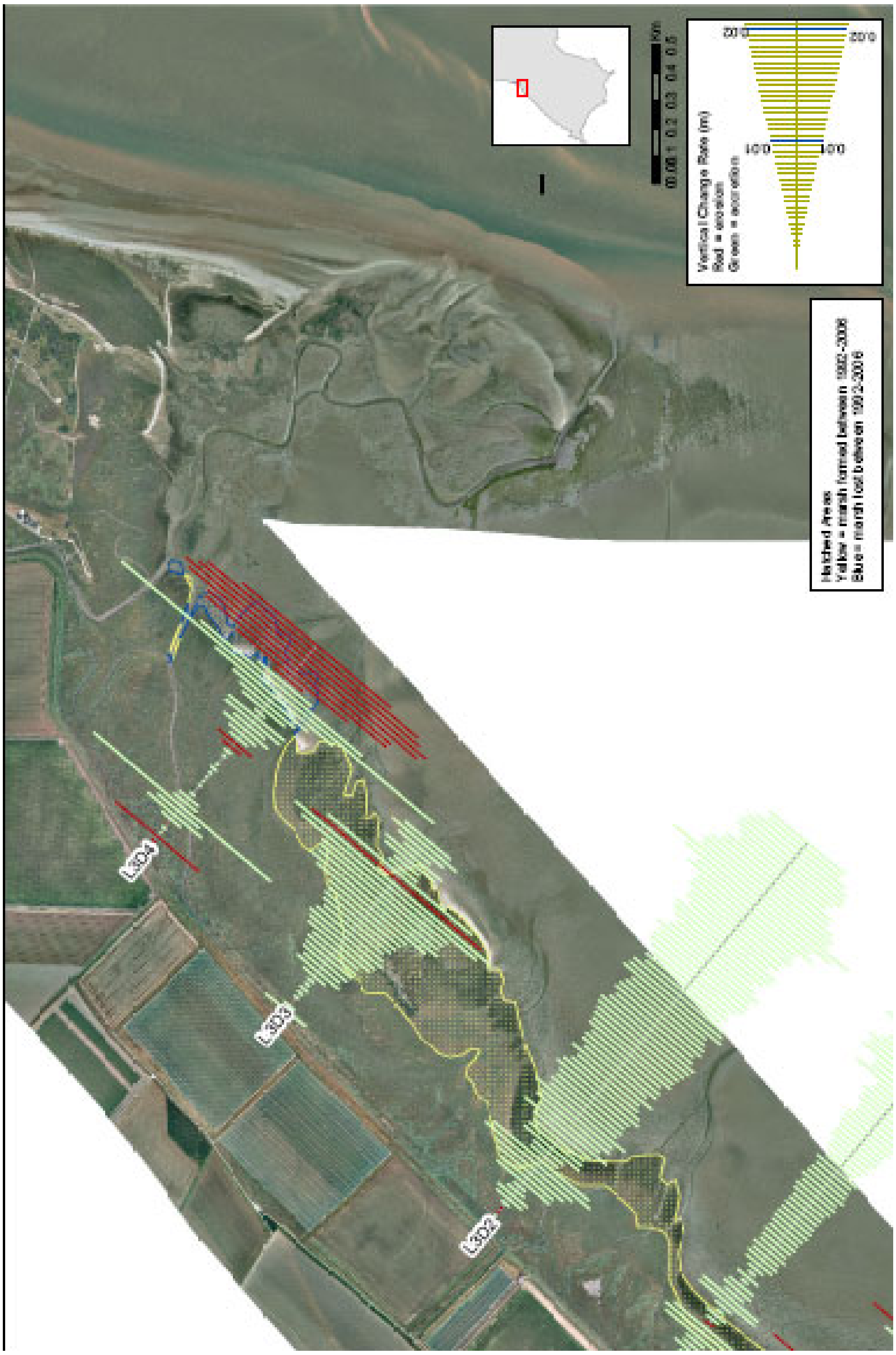


Figure C2.18 Profile L3D4 shows erosion of the lower profile (mudflat) and growth of the upper profile (salt marsh). Green lines represent a vertical growth trend and red lines indicate vertical lowering or erosion (Environment Agency 2007)



C5 Contemporary processes

The contemporary Wash has a plan area of about 615 km^2 and a total length of shoreline of about 110 kilometres (excluding the tidal estuary outfalls). Most of this is fronted by salt marsh and inter-tidal mud flats and sand flats. The Wash has an average bathymetric depth of less than 10 metres, although the deepest sections of the main central channel extend to some 40 to 50 metres below ordnance datum.

C5.1 Tidal regime

C5.1.1 Astronomical tides

The Wash is characterised by a macro-tidal semi-diurnal tidal regime, with a spring tide range of about 6.3 metres and a neap tide range of around 3.0 metres.

Astronomical tidal levels stated in Admiralty tide tables for standard and secondary ports are shown in table C2.6.

Table C2.6 Tidal levels for Admiralty ports in the Wash

Location	Tidal level (mODN)			
	MHWS	MHWN	MLWN	MLWS
Hunstanton	3.65	1.85	-1.25	-2.85
King's Lynn	3.77	1.97	-1.23	-2.03
Wisbech Cut	3.80	1.90	-1.00	no data
Port Sutton Bridge	3.80	2.00	-1.20	-2.0
Tabs Head	3.30	1.90	-1.30	-3.0
Boston	3.93	2.83	-1.17	-2.47

The flooding tide lasts longer than the ebbing tide so there is tidal asymmetry which increases as the tidal wave moves towards land. This asymmetry in the tidal curve influences the flood and ebb tidal currents.

C5.1.2 Tidal currents

Tidal currents can be relatively strong in the Wash, especially in the main channels during spring tides. This is because of its large tidal range.

Typical current speeds recorded at various places across the Wash are shown in table C2.7.

Table C2.7 Observed tidal currents from previous literature sources

Location	Current velocity (m/s)	Comments	Literature source
Old Lynn Channel	1.20	Peak flood, spring tide	Admiralty chart
	1.02	Peak ebb, spring tide	
	0.56	Peak flood, neap tide	
	0.51	Peak ebb, neap tide	
River outfalls	≈ 1.50	-	HR Wallingford, 1972
General Wash	≈ 0.8 – 1.0	-	
Outer sand flats	1.00	-	Evans & Collins, 1975
Inner sand/mud flats	0.35	-	
Upper salt marsh	0.10	-	
Central body	Not stated	Flood-dominated	Ke, Evans & Collins, 1996
Margins	Not stated	Ebb-dominated	

C5.1.3 Extreme water levels

Astronomical water levels, presented in table C2.6, can be changed by meteorological effects such as wind set-up and atmospheric pressure that cause positive or negative surges to occur. In terms of flood and erosion risk management, it is positive surges, where astronomical tidal levels increase beyond the predictable astronomical tidal levels, which have the greatest effects. In the 1953 flooding event, a positive surge of up to two metres was observed at Boston, Fosdyke and King's Lynn.

In 2006, Mott MacDonald produced a tidal analysis report for the Environment Agency Anglian Region Northern Area coast that extended between Whitton in the Humber and Terrington in the Wash. This report included an investigation into the extreme tidal levels at the coasts and estuaries. The Spatial Revised Joint Probability Method (SRJPM) set out by Dixon and Tawn from the Proudman Oceanic Laboratory (POL) was used to determine the extreme still water levels along coasts and estuaries. This method gives more reliable results than a single-site analysis as the latter approach can lead to misleading answers in some cases.

Table C2.8 presents the results of this extreme tidal analysis. The one-year levels have been derived from the r-largest method, the extreme return periods have been interpolated using the POL growth values and the King's Lynn values are from the GEV analysis.

Table C2.8 Extreme water levels – coast and estuary (Mott MacDonald 2006)

Location	Return period extreme tide levels (mODN)							
	1:1	1:10	1:25	1:50	1:100	1:200	1:500	1:1000
Burgh sluice	4.26	4.45	4.63	4.76	4.90	5.03	5.21	5.34
Witham – Hobhole	4.82	5.30	5.49	5.64	5.78	5.93	6.12	6.27
Welland - Lawyers	4.84	5.32	5.51	5.66	5.80	5.95	6.14	6.29
Nene – W. lighthouse	4.88	5.37	5.57	5.71	5.86	6.01	6.21	6.35
King's Lynn	4.93	5.43	5.63	5.78	5.93	6.08	6.28	6.43

Extreme tidal levels along the tidal rivers (Nene, Welland and Witham) for various return periods are also presented in table C2.9. These stations are the base gauges as they are the closest to the mouth of each tidal river.

Table C2.9 Extreme tide levels – tidal rivers (Mott MacDonald 2006)

River	Return period extreme tide levels (mODN)							
	1:1	1:10	1:25	1:50	1:100	1:200	1:500	1:1000
Witham (Hobhole)	4.85	5.23	5.39	5.49	5.64	5.74	5.88	5.99
Welland (Lawyers)	4.55	4.95	5.12	5.22	5.37	5.48	5.63	5.74
Nene (W. Lighthouse)	4.49	4.91	5.09	5.18	5.35	5.46	5.61	5.73

Royal Haskoning (2007) also completed a study on the extreme tide levels at a number of sites on the southern side of the Wash embayment and into north Norfolk. The same method was used as for the Mott MacDonald study and MHWS was also included for reference. Peak tide level results are shown in table C2.10.

Table C2.10 Extreme tidal level results – coastline (Royal Haskoning 2007)

Site	1:1	1:10	1:25	1:50	1:100	1:200	1:500	1:1000
Hunstanton	4.73	5.24	5.45	5.60	5.76	5.91	6.11	6.27
Heacham	4.81	5.31	5.52	5.67	5.82	5.97	6.18	6.33
Snettisham Scalp	4.86	5.36	5.56	5.71	5.86	6.02	6.22	6.37
Mouth Great Ouse*	4.93	5.43	5.63	5.78	5.93	6.08	6.28	6.43
Mouth Nene*	4.88	5.37	5.57	5.71	5.86	6.01	6.21	6.35

* Sites from which tide level data were used in the assessment

Table C2.11 Summary of extreme tidal level results. Black numbers indicate Mott MacDonald's (2006) results and red numbers indicate Royal Haskoning's (2007) results

Site	1:1	1:10	1:25	1:50	1:100	1:200	1:500	1:1000
Burgh sluice	4.26	4.45	4.63	4.76	4.90	5.03	5.21	5.34
Mouth Witham	4.82	5.30	5.49	5.64	5.78	5.93	6.12	6.27
Mouth Welland	4.84	5.32	5.51	5.66	5.80	5.95	6.14	6.29
Mouth Nene	4.88	5.37	5.57	5.71	5.86	6.01	6.21	6.35
Mouth Nene	4.88	5.37	5.57	5.71	5.86	6.01	6.21	6.35
Mouth Great Ouse*	4.93	5.43	5.63	5.78	5.93	6.08	6.28	6.43
Snettisham Scalp	4.86	5.36	5.56	5.71	5.86	6.02	6.22	6.37
Heacham	4.81	5.31	5.52	5.67	5.82	5.97	6.18	6.33
Hunstanton	4.73	5.24	5.45	5.60	5.76	5.91	6.11	6.27

To provide a list of extreme water levels for the Wash SMP study area, we need to combine these two studies. Mott MacDonald was commissioned to undertake tide level analysis from the Nene running westwards towards Gibraltar Point. However, a number of more easterly sites were also included in their final report. Royal Haskoning was commissioned to undertake tide level analysis from the Nene running north-eastwards along the coast towards Hunstanton. So the distinct geographical boundary of the mouth of the River Nene will be used to define the places that will need Royal Haskoning or Mott MacDonald analysis results. Table C2.11 summarises the final tide levels to be used.

C5.1.4 Sea level rise

Climate change (natural and man-made) is causing sea levels to rise. This rate has been between one and two millimetres a year since 1900. There is, however, great uncertainty about the future rate. One definite fact is that global temperatures are rising and this is leading to the thermal expansion of water and the melting of land ice. Combined, these two effects are likely to lead to an increasing rise in global sea levels (see figure C2.18). Rates of this sea level rise are uncertain, but it is essential that this SMP takes into account the possibility of increasing sea level, regardless of the reason. This is known as applying the precautionary principle. The Defra guidance provides values for sea level rise for the three epochs. These are the values that have been used for all SMPs in assessing future shoreline response and in the more quantitative assessments of intertidal habitat loss. These Defra guidance values are provided in table C2.12. These values suggest a total sea level rise of 1.1 metres by the end of epoch 3 (2105).

Figure C2.18 Recorded sea level rise (Proudman Oceanographic Laboratory)

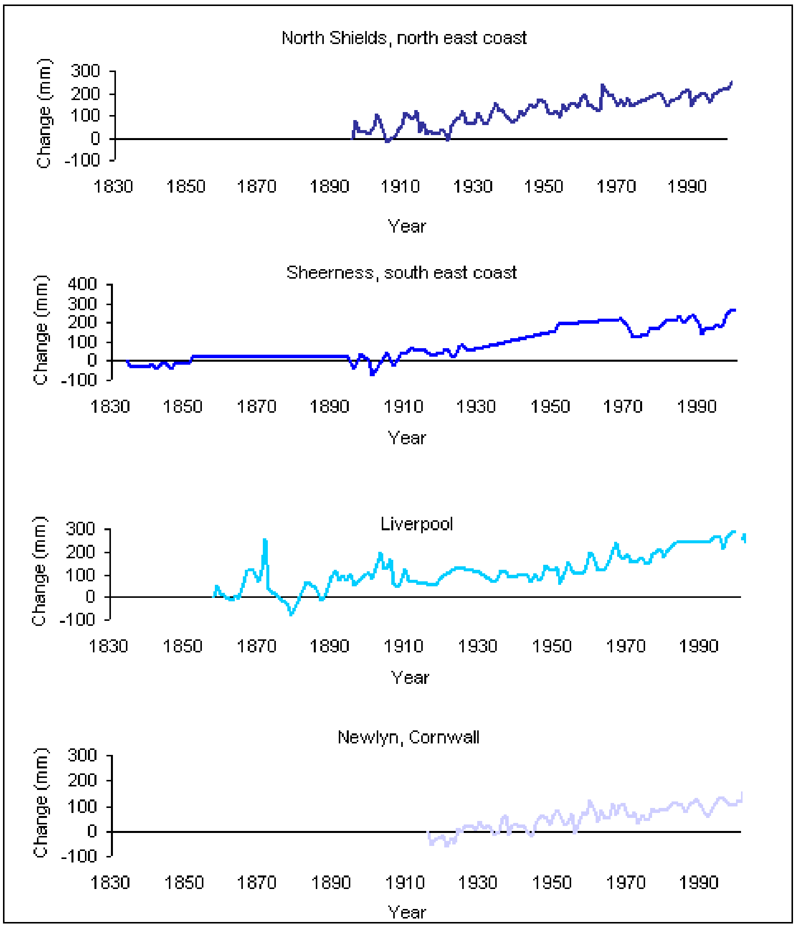


Table C2.12 Latest sea level rise allowances for the east coast (Defra 2006)

Time period	Net sea level rise (mm a year)	Total sea level rise (mm)	Cumulative sea level rise (mm)
Epoch 1 (2009 to 2025)	4.0	64	64
Epoch 2 (2025 to 2055)	8.5	255	319
Epoch 3a (2055 to 2085)	12.0	360	679
Epoch 3b (2085 to 2105)	15.0	450	1,129

C5.2 Wave regime

Although the Wash is a very tidally-dominated environment, the effects of waves and their interactions and feedbacks with the physical features are important.

Waves generated in, or propagating from, the North Sea will enter the Wash through its mouth. They will travel along the length of the main channels before being dissipated by the shallow bed profiles and surface roughness of the inter-tidal sand and mud flats and, particularly, salt marshes. Such waves will have greatest effect on the Wash when propagating from the north-east as this is in line with the entrance and the main channels along which the tide will flood the Wash. Annual significant wave heights of around three metres have been noted at the entrance to the Wash, reducing to around one metre further inshore (Posford Duvivier, 1996).

Between May 1999 and May 2000, the Environment Agency deployed a directional wave-rider buoy in the mouth of the Wash, moored in a water depth of 24 metres CD, to measure incoming wave conditions. During this period the maximum recorded value of the significant wave height (Hs) was 2.81 metres, with a mean Hs value of 0.61 metres. Wave periods were typically in the range 2.5 to 4.0 seconds and wave direction was most commonly along a north-east to south-west axis, with conditions being either directly onshore of directly offshore.

Waves can also be generated internally in the Wash by winds blowing across the water surface. These will be most pronounced when strong winds combine with times of high water spring tides, when the water surface area is greatest and the local fetch is at a maximum. The ‘internal’ wind-generated waves typically will have shorter periods and be smaller than those travelling into the Wash from the North Sea.

The sand flat, mud flat and salt marsh features of the Wash are important in reducing the incoming energy as waves are transformed from the deeper water channels across the shallower inter-tidal zones. The Environment Agency measured wave conditions at ‘upper’, ‘mid’ and ‘lower’ locations along three shore-perpendicular transects, Wrangle Flats, Butterwick Low and Breast Sand, between May 1999 and May 2000 to observe such transformation processes. Results showed that, across the entire inter-tidal profile, wave energy could be reduced from the lower station to the upper station by between 69 and 97 per cent, with most of this attenuation observed across the salt marsh areas (Cooper, date unknown). This increased attenuation across the upper profile is due to both the higher land and increased surface roughness presented by the vegetated areas.

C6 Sediment regime

C6.1 Sediment character

The central main channel of the Wash has a relatively high percentage of gravel. This originates from the deposition of glacial till that was carried by the Devensian ice sheet. The material was deposited in the North Sea and northern parts of the Wash embayment as the ice melted and was then re-distributed by rising sea levels. There is also gravel in areas subject to harsher wave climate, such as the mussel scalps and Gibraltar Point and south of Hunstanton.

Further from the main channels, the sand element dominates the bed in the form of sand flats. Higher up the foreshore still, muddy sediments dominate in the form of mud flats and salt marshes.

The sediment character is controlled by the differences in energy, with coarser sediment in the zones of higher energy (wave or tidal) and finer material in zones of lower energy.

C6.2 Sedimentary processes

The basic sedimentary process operating in the Wash is that sediments in the North Sea are transported in suspension and as bedload by the tidal currents as the tide floods through the entrance. As these currents start to reduce progressively further from the main channels as water levels increase and spill across the inter-tidal zone, first the coarser materials (for example sands) are deposited on the lower inter-tidal areas (sand flats) and then, as the currents reduce even further, the finer materials (for example muds) are deposited on the mid and upper inter-tidal mud flats and salt marshes.

The asymmetry in the tidal regime generates net residual currents that lead to the preferential import of suspended sediment through the central parts of the entrance and export along the flanking areas. The net trend, however, is for more sediment to be deposited than is removed, so a pattern of growth is generally observed.

This basic pattern can, however, be influenced by both high river flows and by wave activity, as described below:

- During times of high freshwater flow in any of the tidal rivers that discharge into the Wash, the effect of the ebb currents relative to the flood currents is increased, leading to higher potential for the export of sediment.
- Wave activity can move sediments from the bed that otherwise would not be influenced by tidal currents alone. Once suspended in the water column, the eroded material could then be transported by the residual tidal currents.

There have been problems of siltation in and around the outfalls of the tidal rivers that flow into the Wash (Kestner, date unknown). This has mainly been caused by the reduction in tidal prism, and hence ebb-tide flushing potential, caused by land claim and canalisation of these outfalls. The Wash River Outfalls Strategic Studies (WROSS) investigated the issues at each outfall and made recommendations about whether or not training walls should be raised to counter the siltation effects.

WROSS Part 1 (Posford Duvivier 1995) focussed on the rivers Witham, Welland and Nene. It concluded that, without some sort of control or mitigation of siltation, there would be serious adverse effects on land drainage, flood defence and navigation. The report also highly recommends a self-sustaining means of siltation control.

General conclusions about the effects of not maintaining the training walls are as follows:

- Growth at and near the tidal limit sluice would impede flood discharge through the sluice, reducing upstream flood defence standard.
- Siltation at land drainage outfalls would impede discharges, to the detriment of land drainage standards within large areas of highly productive agricultural land.
- Build-up of mud at the side of the tidal channel around high water mark ("warp") would lead to over-steepening and random slip failure of the bank, endangering tidal flood defences.
- Failure to maintain the training walls would eventually lead to their deterioration, with collapse in some parts.
- Stopping dredging would rapidly lead to reduced navigation depth and likely serious decline in trade to ports on the rivers.

The WROSS Summary Report (Posford Haskoning 2002) gives further findings and specific recommendations for the river outfalls, as listed in table C2.13. This summary report does not discuss recommendations for the River Witham, so information about this river was taken from the WROSS Part 1 report (Posford Duvivier 1995).

Table C2.13 Main findings and recommendations from the WROSS studies

River	Recommendations
Welland	• Do not raise or elongate the training walls. • Maintain integrity of the training walls. • Annual aerial photography of the study area. • Annual current velocity and direction profiles. • Annual river bed level survey. • Two yearly conditions survey. • Monitor fluvial discharge from main drainage system. • Undertake profile on current velocity and turbidity along three sections within the cut every three years. • Investigate the effects of disposing dredged material from Boston harbour.
Nene	• Dredging every five years to lower bed levels. • Bed level survey twice a year. • Monitor fluvial discharge entering tidal river. • Undertake particle size analysis between dog-in-a-doublet sluice and Wisbech. • Take cross-sections along the entire estuary length at one kilometre intervals every five years.
Great Ouse	• Do not raise or elongate the west training wall. • Rain Creek outfall accommodated over west training wall. • Continue to dredge west training wall. • Continue to dredge dock shoal. • Undertaken aerial photographs biannually. • Continue transect lines annually and extend further into the Wash. • Monitor fluvial flows and siltation.
Witham	• Removal of "warp" that accumulates at the side of the tidal channel around high water mark is not needed.

C6.2.1 Sediment sources

Collins (1972) and Collins et al (1981) estimated the following sediment sources in the Wash:

- Input from adjacent marine areas = 6.8 x 106 tonnes a year
- Input from fluvial sources = 0.15 x 106 tonnes a year
- Material re-worked due to erosion of bed material = un-quantified.

C7 Geomorphological functioning

The physical (geomorphological) functioning of the Wash may be understood by looking at the key physical features and process, the controls that these have on behaviour and the linkages between different parts of the system.

The effect of human intervention on these controls and linkages also needs to be considered.

Key **physical features** of the Wash are:

- Gibraltar Point – this is a curved sand spit that is fed by alongshore transport of material carried southwards along the Lincolnshire coast. The spit comprises a series of beach ridges.
- Deep water channels – Lynn Deep, Boston Deep, the Well, Inner Silver Pit, etc. influence tidal flow patterns in the Wash. The position of some of these marks the position of the low water line along the shoreline.
- Offshore sand bars / sand banks – these have a major influence on the physical processes and sediment flow patterns and therefore erosion and growth of materials at the shoreline. The banks are parallel to the axis of main tidal flow and tend to separate flood and ebb dominant sediment transport pathways.
- Tidal deltas and channels - at each of the tidal river outfalls, there are a series of deltaic deposits and flow channels. The outfall of the Welland/Witham links with the Boston Deep but, at the mouth of the Great Ouse, there is a 'bird's foot' type delta. The deposits and channels at the river mouths show periodic changes in configuration, with some channels closing and others opening. This is usually triggered by short-term storm events rather than being governed by a long-term persistent trend.
- Inter-tidal sand and mud flats and salt marshes – these are important in moderating incoming wave energy before it reaches the upper shoreline and causes erosion or flooding.
- Snettisham Scalp – a mussel bed at the change between the sand and shingle beaches to the north and the muddy foreshores to the south. The scalp accentuates the sheltering effect of the inter-tidal.
- Shingle ridge - between Wolferton Creek (Heacham) and Hunstanton there is a beach ridge. This ridge extends along 11 kilometres of frontage and reaches a maximum crest height of six metres. It encloses an area of low-lying ground between it and rising ground.
- Hunstanton – simple sea cliffs reaching a maximum height of 60 metres in places. These cliffs are composed of weak rock (chalk and sandstone) and are largely undefended. Erosion of the cliffs is dominated by toe erosion, with the major failure mechanism deemed to be stress induced failure as a result of deep undercutting. The presence of relatively weak rock materials at the toe of the cliff makes them prone to wave attack. Material then erodes by undercutting, which propagates up to the cliff face by a series of small slab or block failures. In addition 'minor failures' can be caused by kinematic feasibility of movement along existing discontinuities. The most prevalent of these is thought to be planar sliding failures within the Grey Chalk along the inclined joint. This toe erosion releases some generally fine material to the fronting beach. The cliffs are fronted by a shore platform of jointed sandstone. Offshore is a

bank called Sunk Sand that extends over four kilometres and dries at low tide.

Key **physical processes** operating in the Wash are:

- The large tidal range generates tidal currents that can move and transport sediments in most places.
- Despite the tidally-dominated regime, wave action is also important and can locally lead to erosion and initiate sediment movement.
- Sediment deposition has historically outstripped or maintained pace with sea level rise, leading to general infilling of sediment.

The **controls** on behaviour are:

- Gibraltar Point acts as a ‘soft’ headland at the north-west side of the entrance. It imposes a constraint on the mouth width but also provides shelter against wave attack for the inter-tidal areas on much of the north-west margin of the Wash. This sheltering effect is enhanced by the presence of sand banks lying just offshore from the Point.
- The sandstone and chalk geology imposes a constraint on the entrance to the Wash at its north-eastern limit. Here the geology is exposed in sea cliffs at Hunstanton.
- Large sand banks in the Wash have a significant effect on patterns of wave energy and tidal flow.
- The main deep water channels at the mouth are incised into the underlying geology and reflect the historic topography of fluvial channels that would have formerly drained the Wash-Fenland embayment.
- Boston Deeps has a major influence on where the shore is between Gibraltar Point and North Sea prison camp. Due to its alignment in relation to the shoreline, the inter-tidal width decreases south-westwards along this margin.
- The inter-tidal flats and salt marshes control the amount of wave and tidal energy reaching the upper profile because of their in-built energy dissipation properties, both through their height and the surface roughness of the salt marsh vegetation.
- Flood embankments are a key control on shoreline evolution.

The key **linkages** between elements are:

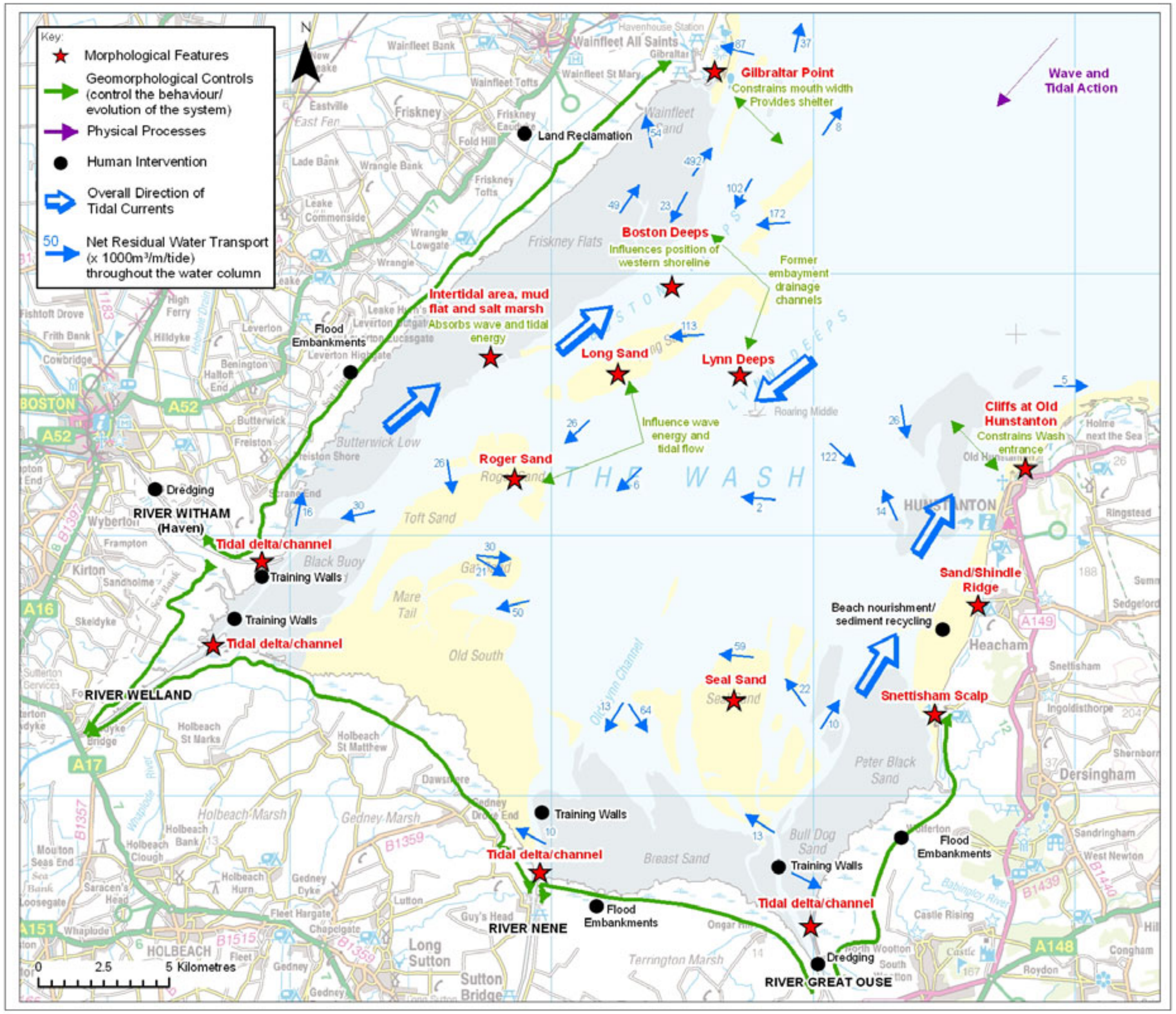
- The Wash as a whole acts as a sink for sediment transported along the coastlines of Lincolnshire (southwards transport into the Wash) and north Norfolk (westwards transport into the Wash) and in suspension within the North Sea.
- The fluvial flow (and associated sediment input) from the tidal rivers that outfall into the Wash is small compared with the tidal range and sediment behaviour in the wider embayment.

The main effects of **human intervention** on behaviour are:

- Most of the shoreline is protected against tidal flooding by earth embankments. In some places, the front-line embankments are backed by older secondary or tertiary embankments that are usually relict features and generally not maintained. The current location of the shoreline is almost entirely the result of land and river management practices. It is not, therefore, the result of natural shoreline evolution, although the location of reclamations did tend to follow the pattern of areas experiencing the most rapid growth in height and/or area.
- Reclamation of the Wash and, on a smaller scale, reclamation of each of its tributary rivers, has reduced the tidal prism of the embayment (or the tidal river) increasing its effectiveness as a sediment sink.
- The ports of Boston and King's Lynn dredge deposited material to maintain navigable channel depths in the river and approach channels.
- Training walls along the river outfalls have had local effects on tidal flow and sediment circulation.
- Beach nourishment along the Lincolnshire coast has helped to maintain a supply of sediment to Gibraltar Point and the sand banks just offshore.
- Eroding cliffs at Hunstanton have been partly defended in places, reducing the small sediment source that feeds the beach further south of the town.
- Beach nourishment and sediment recycling have been used since 1990 to maintain the beach ridge between Hunstanton and Heacham. An embankment backs the beach near Wolferton Creek and this reduces the degree of overwashing of the ridge and limits its ability to move landwards in response to sea level rise.

The key physical features are summarised in figure C2.20.

Figure C2.20 The Wash key physical features



C8 Other issues

C8.1 Climate change

Climate change and associated sea level rise is an important factor to consider in terms of how they affect the coastal processes operating in the Wash embayment. Historically, sea level rise has led to salt marsh growth. This is likely to continue if the rate of future sea level rise continues to be less than the rate of sediment infilling. However, there may come a time when this process is reversed and sea level rise reaches a threshold where is it greater than the rate of sediment infilling. This could cause potential large-scale erosion of the salt marsh and therefore increased pressure on the existing defences.

Climate change could also lead to increased storminess, which could, in turn, cause increased erosion rates along both the Holderness and Lincolnshire coasts. There is uncertainty as to whether this release of sediment would reach the Wash embayment, or whether it would be transferred offshore into offshore sediment stores (sand banks) or into the wider sediment transport system of the North Sea.

These will be important processes to consider when identifying the future scenarios, but will be a source of doubt as the occurrence, extent and timing of this change is uncertain.

C8.2 Wind farm cables

With the increasing drive for renewable energy and the current building of large wind farms, it is also important to consider the effect of the cables associated with these structures on the physical coast. These cables should be buried under the sea bed and inter-tidal areas and so will only have short-term local effects. Installing these cables is likely to cause disturbance - in particular direct damage to the inter-tidal area and release of suspended sediments into the water column. However, it is believed that this would not have a long-term effect on the physical functioning of the system.

C8.3 Salt marsh grazing

Grazing of livestock on the salt marsh areas has been a widely-discussed and long-running debate. Grazing will shorten vegetation blades and this has the potential to reduce marginally the frictional effects on wave and tidal energy. However, as this is a local practice, this issue will be marginal for the Wash system as a whole. Salt marsh widths are generally large throughout the study area so there is a high degree of wave energy dissipation before the grazing areas are reached.