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Controls on Long-term Saltmarsh Accretion and Erosion in the Wash, Eastern England

K. Pye

Postgraduate Research Institute for Sedimentology
University of Reading
Whiteknights
Reading RG6 2AB, England

ABSTRACT

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The Wash is a macrotidal embayment in eastern England which forms part of a once much larger tidal basin which is now largely infilled by silts and peats of Holocene age. Sediment transport within the Wash is dominated by tidal processes, although waves are significant in shaping the detailed morphology along its margins. Much of the coastline has experienced significant accretion of intertidal flats and saltmarshes since Roman times, mainly induced by natural processes but enhanced by human activities which have included drainage diversion, marsh reclamation and construction of training walls. The sediment which has accreted within the intertidal zone during the past two centuries is predominantly sandy and has been derived from below low water mark within the Wash itself. However, most of the mud present on the higher mudflats and saltmarshes is derived from coastal and offshore sources outside the Wash. The rate of coastal accretion appears to have declined progressively since Roman times, possibly in response to a reduction in sediment supply. At present some of the Wash saltmarshes are in a state of dynamic equilibrium or are experiencing marginal erosion, but the majority are still accreting vertically and laterally. Since 1950 there has been a major seaward movement of both high and low water mark along the western shore, accompanied by seaward extension of saltmarsh. However, the rate of seaward progradation has slowed down in the last 15 years. Along the southwestern and southern shores, which are most exposed to storm waves from the northeast, there has been relatively little net change in the position of low watermark since 1950. This shore has not been significantly affected by reclamation in the past 40 years, and there has been only limited seaward growth of saltmarsh at the expense of intertidal flats. In recent years the seaward edge of these marshes has suffered erosion. In the more sheltered southeastern corner of the Wash there has been rapid seaward accretion of marshes since 1950, but the position of low water mark has remained fixed or has even moved landwards slightly. Significant land claim occurred after 1950, and although the area of saltmarsh has been maintained there has been a net loss of intertidal flat area. Vertical accretion of the saltmarshes is quite capable of keeping up with the current rate of sea-level rise in the area, estimated to be about 1.5 mm a^{-1}. Recent patterns of accretion and erosion appear to be controlled principally by movements in the position of the deep water channels and by variations in storm wave frequency and approach direction.

ADDITIONAL INDEX WORDS: *The Wash, England, saltmarsh, accretion, reclamation, seabanks.*

INTRODUCTION

The Wash embayment in eastern England (Figure 1) contains the largest single area of active saltmarsh in the British Isles (4,199 ha, representing more than 9% of the total national area of active saltmarsh (BURD, 1989; PYE and FRENCH, 1993). The active marshes form a fringe, in many places 1–2 km wide, around the western, southern and southeastern shores of the Wash, and are backed by seabanks which protect a much larger area of low-lying reclaimed marsh from tidal inundation. At the northwestern margin of the Wash, and locally on the eastern shore, small back-barrier marshes are developed behind shingle and sand spits. To seaward lie extensive intertidal mudflats and sandflats which, together with the marshes, are of high environmental value, particularly as feeding grounds for birds. The entire area was notified as a Site of Special Scientific Interest in 1949 and declared a Ramsar site and Special Protection Area in 1988.

The saltmarshes presently show a predominant trend for both lateral and vertical accretion, although in the past twenty years some sites have experienced lateral erosion and sections of seawall have suffered wave damage. The authorities responsible for managing the sea defences and the nature conservation interests have therefore become concerned that the accretional regime of the intertidal zone of the Wash could be reversed, particularly if there is a significant increase in the rate of sea level rise or the frequency of severe storms during the next 50 years. Against this

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background, this paper presents a summary of the current accretion/erosion status of saltmarshes in the Wash, reviews their age and evolutionary development, and considers the geological and wider environmental factors which govern the pattern of saltmarsh accretion and erosion. It draws on previously published literature and on data from primary sources gathered in connection with the Wash Management Strategy (PYE, 1992) and a national survey of saltmarsh accretion and erosion trends in Great Britain (PYE and FRENCH, 1993).

GEOLOGICAL BACKGROUND

The Wash is a remnant of a once much larger tidal basin which is now largely infilled by Flandrian-age peats and silts (Figure 1). The four principal river systems (Witham, Welland, Nene and Ouse) which flow into the Wash drain an area of 12,500 km^2, of which the lowland plain of Fenland comprises about 3,500 km^2. The seaward limits of the Wash, which has a present day area of 610 km^2, are defined as Gibraltar Point on the Lincolnshire coast and St. Edmund's Point on the Norfolk coast (Figure 2). The intertidal zone comprises approximately 45% of the total area (DAVIDSON *et al.*, 1991). The total length of shoreline (excluding tidal rivers) is approximately 107 km, of which more than three quarters is fronted by saltmarshes and mudflats. The entrance to the Wash is some 16 km wide and the maximum depth is more than 30 m in the Lynn Deeps channel (Figure 3).

The origins of the Wash are probably fluvial, but the embayment was widened and deepened by ice during the Anglian and Wolstonian glaciations and by marine processes during the Ipswichian and possibly earlier interglacials (STRAW and CLAYTON, 1979). During the Devensian glaciation, ice advanced only as far as a line between Boston and just to the north of King's Lynn, and much of the Fenland basin was occupied by a large proglacial lake with marginal gravel and sand beaches and deltas. As the Devensian ice retreated, meltout till and outwash deposits were deposited across the area now occupied by the northern Wash and adjacent North Sea. Rising sea level partially reworked these deposits and flooded much of the Wash and Fenland basin during the early to mid-Flandrian, initiating the deposition of a thick sequence of marine deposits, estuarine silts and freshwater peats which has continued in an episodic manner until the present (SKERTCHLEY, 1877; GODWIN, 1940, 1978; GODWIN and CLIFFORD, 1938; SHENNAN, 1986a,b, 1987a,b). The bedrock surface below the Wash now lies at −20 to −40 m relative to Ordnance Datum (O.D.) Newlyn., although there are a number of deeper channels which were cut by river at times of lower sea level (WINGFIELD *et al.*, 1978; GALLOIS, 1979).

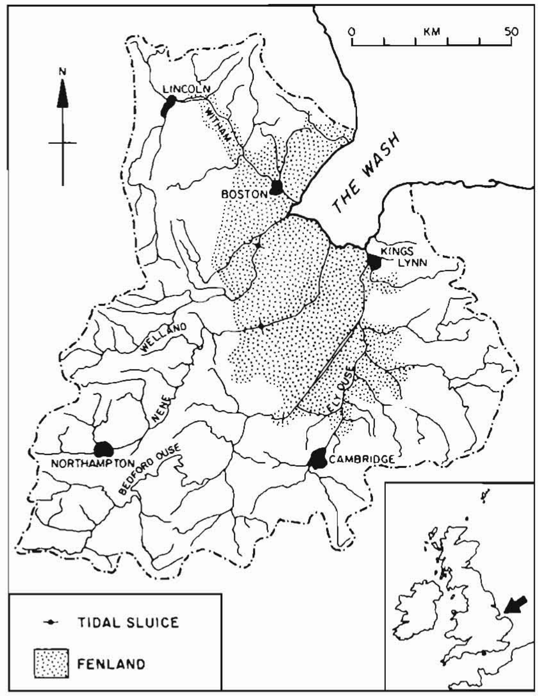

Figure 1. Location of the Wash and Fenland.

The basic Flandrian stratigraphy of Fenland was established by SKERTCHLEY (1877) and has subsequently been refined by GODWIN and CLIFFORD (1938), GODWIN (1940), SMITH (1970), CHURCHILL (1970), GALLOIS (1978) and SHENNAN (1982, 1986a,b, 1987a,b). At the base of the sequence, overlying former terrace gravels, glacial deposits and weathered Jurassic clays are the Lower Peat, containing the stumps of 'bog oaks' which are mainly rooted in the underlying sediments. Pollen evidence indicates a vegetation succession from oak through pine forest to sphagnum moss bog, reflecting rising water tables and a change from alkaline to acid groundwater conditions. The Lower Peat is a diachronous deposit which thickens towards the Wash. It had begun to form in the north and east 7,700 years ago, but near the southwestern margin of Fenland accumulation

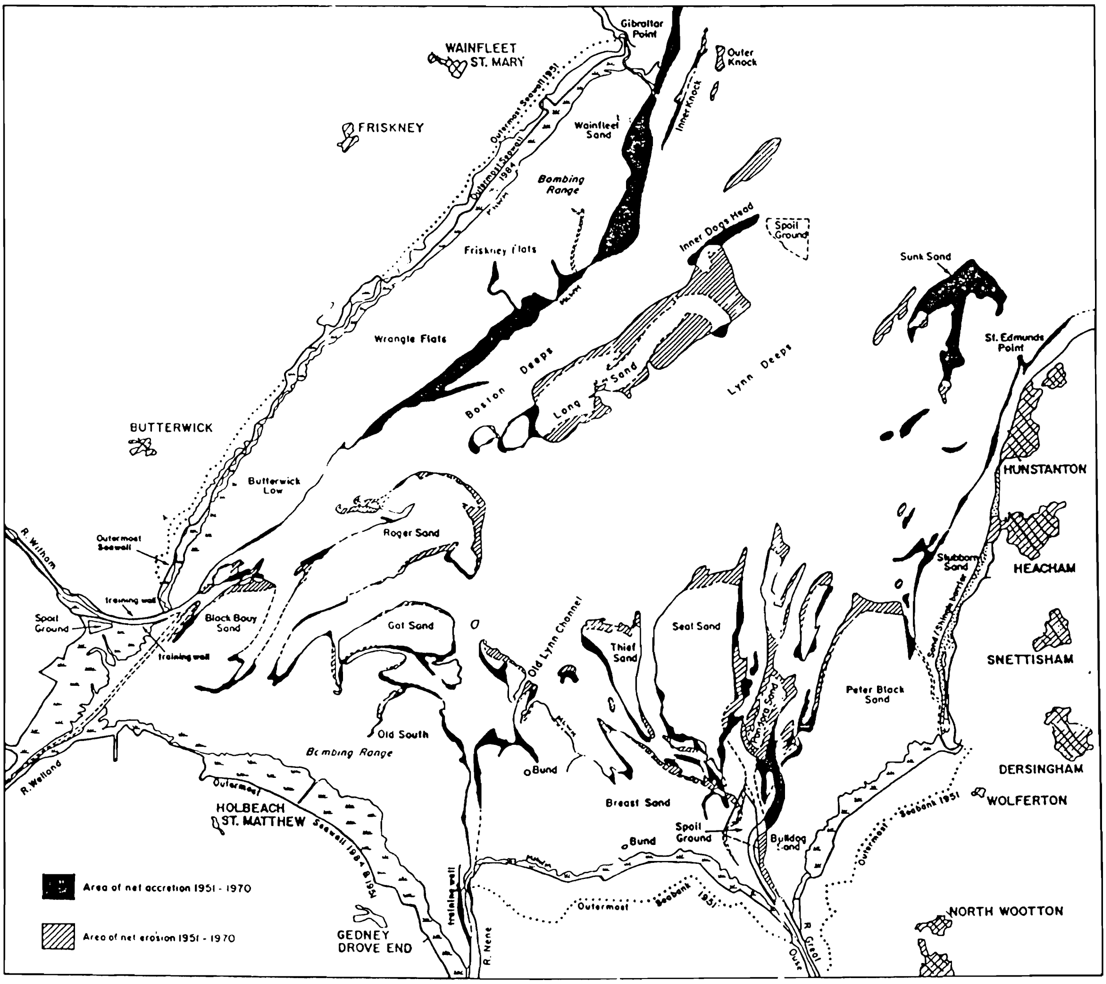

Figure 2. Major morphological features of the Wash, showing changes in the intertidal area between 1951 and 1969–1970, based on Ordnance Survey maps.

began only 3,400 years ago (GALLOIS, 1978; HORTON, 1989). Above the Lower Peat lie the Barroway Drove Beds (the "Fen Clay" of GODWIN, 1940) which consist mainly of dark grey, very soft, slightly humic and silty clays. They contain numerous root traces including the remains of *Phragmites* reeds which grew as the clay was being deposited. The clays are cut by networks of sinuous channels filled with silt and fine sand. Due to differential shrinkage and compaction, the channels now form low ridges known as 'roddons' (FOWLER, 1934; GODWIN, 1938). The base of the Borroway Drove Beds is also diachronous, rising gently and becoming younger towards the south-western Fen margin. Palaeoecological evidence suggests the Beds represent estuarine mudflat, saltmarsh and brackish to freshwater marsh environments. The upper part of the Borroway Drove Beds in the Peterborough area is more silty than the lower part and may represent open mudflat rather than saltmarsh environments. Marine molluscs, notably *Cerastoderma edule* and *Macoma balthica,* occur occasionally throughout the formation. MACFADYEN (1933, 1938, 1970) identified both marine and brackish estuarine foraminfera, and GODWIN and CLIFFORD (1938) recorded dia-

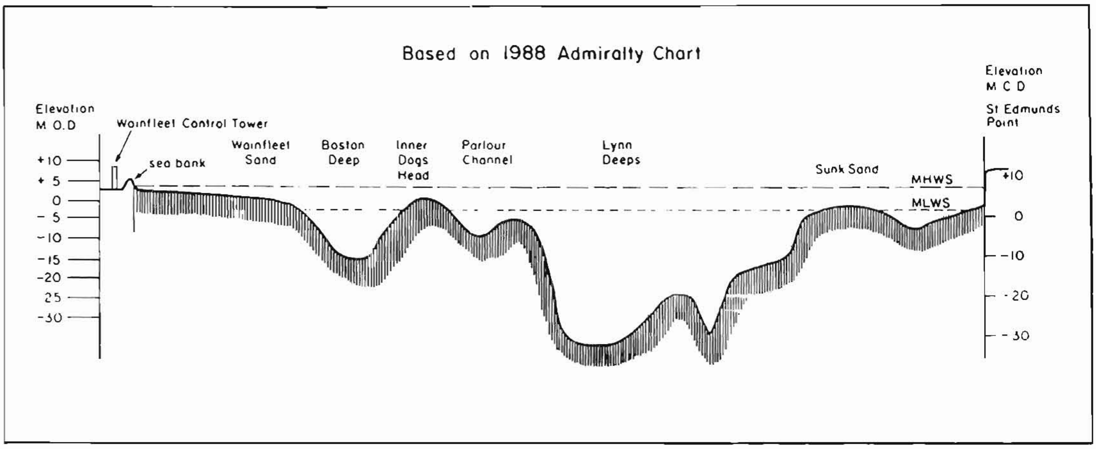

Figure 3. Section across the mouth of the Wash, based on the 1988 edition of Admiralty Chart 108.

toms and ostracods which they interpreted as indicating a brackish environment penetrated by high tides. In places near the Fen edge, the Borroway Drove Beds overstep the Lower Peat and rest directly upon older drift or solid rocks. Radiocarbon dates suggest that these silts were deposited in the east simultaneously with peat accumulation further west. Silt deposition began at least 7,500 years ago and continued locally until about 2250 B.P. In places the Borroway Drove Beds are divided into lower and upper units by a Middle Peat, which represents a short-lived phase of relative emergence. The landward maximum of the transgression in the Peterborough Geological Sheet area was probably attained about 3,000 years ago (HORTON, 1989). Deposition of the Borroway Drove Beds was finally brought to an end by a significant regression of the shoreline, possibly in response to a fall in relative sea level. Formation of an Upper Peat (the Nordelph Peat) began near the Fen margins around 3,250 years ago and continued until very recent times (SHENNAN, 1982).

In the northern and eastern parts of the Fen basin the Nordelph Peat is overlain disconformably by the Terrington Beds (GALLOIS, 1978). Two facies have been recognized; (1) pale brown silty clays and silts which represent tidal flat and saltmarsh deposits; and (2) pale brown silts and fine sands which represent tidal channel fill deposits cross-cutting the tidal flat deposits. Channels of Terrington Beds age extend landwards into the outcrop of Borroway Drove Beds where they form distinct roddons or form secondary infills in existing channels. These deposits were formed during a period of marine transgression which probably began some time after 2500 BP and may have ended before the Roman occupation of the silt Fens around 1900 BP (SALWAY, 1970).

Based on sedimentological and biostratigraphic evidence, SHENNAN (1986a,b) recognized seven "positive tendencies" separated by six "negative tendencies" during the last 6,500 years. Positive tendencies were equated by Shennan with transgressive overlap, in which the terrestrial peat deposits were buried by littoral and marine clastic sediment while he equated negative tendencies with 'regressive overlap' in which the reverse occurred. Shennan considered these tendencies to be regional in extent, and inferred that movements in sea level were the major driving factor. However, changes in sediment regime, coastal morphology and rates of consolidation could be important in producing the apparent stratigraphic changes (*e.g.*, WALLER and HALL, 1991).

Much of Fenland has been artificially drained and widely reclaimed since Roman times (DARBY, 1940). Owing to shrinkage and compaction, large areas of reclaimed land now lie below the level of mean high water spring tides (3.6–3.9 m O.D.). The rivers have very low gradients (typically 1:10,000) and flow in embanked channels which rise above the level of the surrounding land. The outfalls of these rivers are controlled by sluices

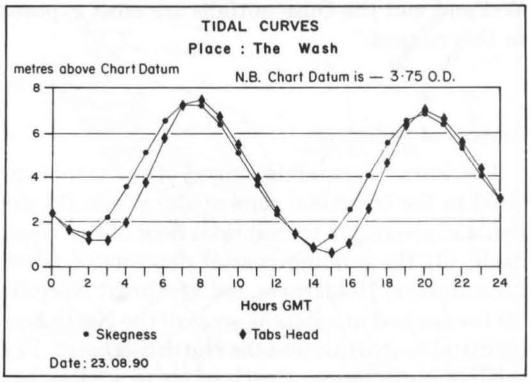

Figure 4. Tidal curves for Skegness and Tabs Head (Witham Outfall), 23rd August 1990 (modified after Dugdale and Evans, 1990).

which allow freshwater discharge at low tide. Tidal incursion extends up the lower reaches and is limited by sluices. The tidal defences are currently maintained to a minimum level of 6.0 m O.D.

The average annual rainfall in the Wash catchment is approximately 570 mm, with maxima occuring in June–August and November–January. However, owing to variations in evapotranspiration and water abstraction, the largest discharges of freshwater into the Wash occur during February and fall to a minimum in September. Annual runoff, averaged over the Wash catchment, is approximately 185 mm (Wilmot and Collins, 1981). As a result of drainage diversion in the thirteenth century, most of the flow now enters the Wash by way of the Great Ouse at King's Lynn.

ENVIRONMENTAL CONTROLS ON INTERTIDAL SEDIMENTATION

Tides and Tidal Currents

The Wash experiences semi-diurnal tides with an approximate half-hour progression in the time of each succeeding high water. The spring tidal range is 6.5 m at Hunstanton, 6.8 m at Tabs Head (located at the mouth of the River Witham) and 5.8 m at King's Lynn. The respective neap tidal ranges are 3.1 m, 3.2 m and 3.2 m. The tidal curves show flood-dominated asymmetry with a relatively steeply rising flood tidal limb and a more gently falling ebb limb (Figure 4). The tidal wave becomes progressively modified as it moves into the Wash, accentuating the asymmetry and leading to a slight increase in the height of high water. Mean High Water Springs 3.1 m O.D. at Skegness, 3.6 m at Hunstanton, 3.8 m at Tabs Head and 3.9 m at Boston, while the respective heights for Mean High Water Neaps are 1.5 m, 1.8 m, 1.9 m and 1.9 m O.D. At Tabs Head the spring tides flood for approximately four hours and ebb for approximately six hours.

Differences between predicted and observed tidal levels are common due to the influence of surges. Postive surges which raise predicted spring high tide levels by more than 1 m are most significant in terms of flood defence and coastal erosion. The storm of 31st January–1st February 1953 caused a surge of 2 m in the Wash and produced a resultant high tide of 5.25 m O.D. at Boston Dock, 5.4 m at Boston Grand Sluice, 5.4 m at Fosdyke, and 5.65 m at King's Lynn (Robinson, 1953). Even higher resultant levels were attained in January 1978, when a smaller surge was added to a higher predicted spring tide. On this occasion the maximum levels attained were 5.5 m at Boston Dock, 5.63 m at Boston Grand Sluice, 5.9 m at Fosdyke and 5.92 m at King's Lynn (Steers *et al.*, 1979).

Because of the large tidal range, high tidal current velocities are experienced in the major tidal channels of the Wash. In the Old Lynn Channel (Figure 2) the maximum flood velocities are typically 2.3 knots at spring tides and 1.1 knots at neap tides, while maximum ebb velocities are 2.0 knots at springs and 1.0 at neaps. Peak velocities are somewhat lower in the Lower Road channel off Butterwick Low and the Cork Hole channel off Snettisham. Analysis of the channel and sandbank morphology, combined with tidal current measurements (Dugdale and King, 1978), suggests the existence of flood residual currents along the Wainfleet Swatchway, the western side of the Boston Deep and along the western side of Lynn Deeps, while ebb residual currents occur along the eastern side of Boston Deep and the eastern side of Lynn Deeps. A tendency for residual flood flow along the western side of the Wash and residual ebb flow along the eastern side is favoured by the Coriolis effect and by freshwater discharge from the Great Ouse and Nene rivers. A plume of lower than average salinity extends northeast from the Ouse outfall towards Hunstanton. Close to the Great Ouse estuary, density differences due to salinity variations are a significant influence on the tidal flow structure, particularly during the ebb (West *et al.*, 1986). Ebb tidal scour and low stage freshwater discharges are important in maintaining the channels across the tidal flats.

Tidal currents over the Freiston intertidal sandflats north of the Witham outfall have a strong onshore–offshore component, but there is a residual component directed alongshore towards the northeast (Amos and Collins, 1978; Collins *et al.*, 1981). The speed of tidal currents measured 10 cm above the bed were found by Evans and Collins (1975) to diminish landward in a linear manner from 0.9–1.0 m sec^{-1} on the outer sand flats to 0.3–0.4 m sec^{-1} over the inner sandflats and to less than 0.1 m sec^{-1} over the upper mudflats. Maximum current velocities occur during the first stage of the flood tide and during the last stage of the ebb. Velocities within creeks on the lower marshes may, however, be as high as those in the deeper channels. Stoddart *et al.* (1987) reported maximum flood current velocities of 1.0 m sec^{-1} in a creek on the lower marsh at Terrington, although maximum flood velocities at a creek station near the landward limit of the marsh were only 0.4 m sec^{-1} during the same overmarsh tide. The maximum ebb velocity at the most seaward station also reached 1.0 m sec^{-1}.

Waves

The prevailing winds across England blow from the southwest, but the direction of greatest wave fetch in the Wash is northeasterly. Waves generated with the Wash by winds blowing from other directions are fetch-limited and relatively small. Wave model calculations predict a mean inshore wave height in the Wash of <0.1 m, while the predicted 1 in 100 year wave height is <4.0 m except along the coast between Snettisham and Hunstanton, where it is just over 4.0 m (Anglian Water, 1988a,b), owing to the higher exposure to northerly winds and the maximum fetch (30 km) for waves generated by southwesterly and westerly winds.

Wave data collected in the southern Wash (Driver and Pitt, 1974; Collins *et al.*, 1981) confirm that under most conditions waves are relatively small and their energy is dissipated across the full width of the intertidal flats. However, under conditions of exceptionally high spring tides and strong northeasterly winds, long period waves can reach the saltings and their energy may not be fully dissipated before they hit the sea banks. The southern shores of the Wash between the Welland and the Ouse outfalls are most exposed in this respect.

Sources of Sediment

There are five possible sources of sediment supplied to the intertidal zone of the Wash: (1) the Fenland rivers; (2) the subtidal floor of the Wash itself; (3) the eroding coastal deposits of north Lincolnshire, Holderness and northeast Norfolk; (4) the sea bed in adjacent areas of the North Sea; (5) distal sources around the North Sea basin. The relative importance of each of these sources has long been debated (Wheeler, 1875–1876; Kestner, 1961, 1963; Evans, 1965; Shaw, 1973; Wilmot and Collins, 1981; Dugdale *et al.*, 1987; Evans and Collins, 1987), but is still not fully resolved. The Crown Estate Commissioners (1969) concluded that no more than 200,000 t a^{-1} of sediment is currently supplied to the Wash by Fenland rivers, a figure which agrees with Wilmot and Collins' (1981) estimated maximum of 173,000 t a^{-1}. By comparison, the amount of sediment transported over the intertidal flats of the Wash during each spring tide is approximately 120,000 t a^{-1}, and the current rate of intertidal sediment accretion in the Wash is about 1,600,000 t a^{-1} (Evans and Collins, 1975). Although the Fenland rivers are now highly regulated, and are able to carry only silt and clay size material, it is unlikely that they ever carried large quantities of sand. Suspended sediment loads may have been somewhat higher during the Iron- and Bronze Age vegetation clearances, but stratigraphic and archaeological evidence indicates that much of the sediment was deposited within the alluvial floodplains before it reached the sea. Considering the large volume of sediment which has accumulated in the Wash during the Flandrian period, 80% of which consists of sand, it is unlikely that more than a few percent of the total sediment volume, and perhaps 10% of the silt and clay fraction, has been supplied by the Fenland rivers.

Kestner (1962) calculated that the volume of intertidal sediment accumulation in the Wash between 1828 and 1917 was almost exactly matched by an increase in the water volume below low water mark. He therefore suggested that most of the new intertidal sediment was derived from within the Wash by deepening of the subtidal channels. Wingfield *et al.* (1978) also concluded

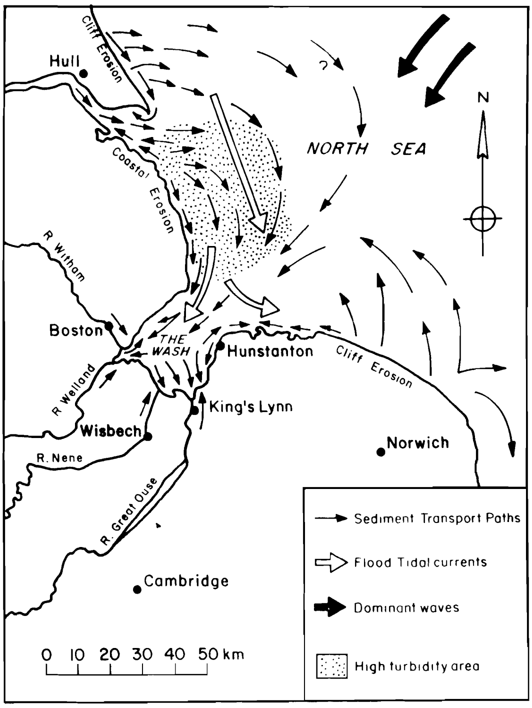

Figure 5. Major sediment sources and transport paths in the Wash and adjacent North Sea, based on various sources and lines of evidence.

that the channels of the central and outer Wash are areas of net sediment erosion while the intervening banks and intertidal flats are areas of net accretion. It is unlikely that much of the intertidal mud is derived from the floor of the Wash which is predominantly sandy or gravelly. The sand fraction of the Wash sediments is coarsest in Lynn Deeps and Boston Deeps where tidal currents are strongest. The mean size of sand on most of the offshore banks lies in the range 0.25–0.375 mm, while on the intertidal flats it typically lies in the range 0.125–0.18 mm (WINGFIELD *et al.*, 1978). The proportion of mud increases towards the inner Wash margins. Temporary deposits of silts occur just above and below low water mark, but long-term silt and clay deposition is mainly restricted to the high intertidal zone. The principal constituent of the sands is quartz, with subsidiary chert, feldspar, calcite and heavy minerals. The fine silt and clay fractions are principally composed on kaolinite, illite, illite-smectite, chlorite and quartz (SHAW, 1973; WILMOT, 1985).

Erosion of the Chalk, Greensand and glacial till cliffs near Hunstanton can yield only a very small amount of fine sediment, and while there is undoubtedly some redistribution of existing intertidal mud within the Wash (KESTNER, 1962; EVANS and COLLINS, 1975), there are no large-scale areas of net erosion. Consequently the balance of evidence indicates that the principal sources of fine sediment supplied to the saltmarshes are external to the Wash (Figure 5).

The glacial deposits which form the cliffs of Holderness and northeast Norfolk have been eroding at a rate of several metres per year for centuries, and contribute an estimated 1,400,000 t a^{-1} to the pool of suspended sediment in the southern North Sea (MCCAVE, 1987). However, evidence from satellite observations and water sampling suggests that the sediment eroded from the Holdnerness cliffs is carried eastwards into the central North Sea by strong tidal currents leaving the Humber estuary. Very little sediment appears to find its way directly onto the Lincolnshire shore, although some may do so after being dispersed and mixed by tidal currents.

There is direct observational evidence of mud transport from the eroding coast and sea bed off Mablethorpe in a southerly direction towards the Wash. Plumes of turbid water extending south from Mablethorpe have been documented by ARANUVACHAPUN and BRIMBLECOMBE (1979) and EVANS and COLLINS (1987). The amount of sediment from this source is difficult to estimate, since much of the erosion occurs sub-tidally. However, based on the area of outcrop and apparent rate of erosion, it may be as high as 400,000 t a^{-1}. Some of this material is transported towards the Humber estuary, but most appears to be moved southwards. Accumulation on the marshes of North Lincolnshire and the mudflats of the Humber amounts to approximately 129,000 t a^{-1} (MCCAVE, 1987), leaving a surplus of at least 250,000 t a^{-1} available for deposition in the Wash.

There is good evidence of a southerly drift of sand along the beach and nearshore zone between Mablethorpe and Gibraltar Point, and there is also exchange of sand between the offshore banks and the mainland south of Skegness (ROBINSON, 1964; KING, 1964, 1973; DUGDALE and KING, 1978; DUGDALE *et al.*, 1978; FOX, 1978; CHANG SHIH-CHIAO and EVANS, 1992). This southerly movement of material inshore is favoured both by littoral drift under the influence of dominant northeasterly waves and by flood residual currents landward of the innermost banks. However, little of the sand appears to pass southwards beyond Gibraltar Point, where there has been rapid lateral accretion during this century (BARNES and KING, 1957; KING, 1968, 1970, 1978).

Only a relatively small proportion of sandy material appears to enter the Wash from the North Norfolk coast at present due to the residual tidal circulation pattern and easterly littoral drift on the upper foreshore near Gore Point. The net drift direction on the lower foreshore south of Hunstanton is northeasterly, out of the Wash, although the amounts involved are relatively small (ANGLIAN WATER, 1988a,b). Erosion of soft cliffs in northeast Norfolk yields about 665,000 t a^{-1} of fine sediment (McCAVE, 1987), and some of this may reach the Wash in suspension. An estimated 104,000 t a^{-1} of fine sediment is deposited on the marshes of north Norfolk, and a further 100,000 t a^{-1} in the estuaries of Suffolk and north Essex, leaving more than 400,000 t a^{-1} available for retention in North Sea waters or sedimentation elsewhere. In addition, an unknown quantity of mud may be supplied by wave and current reworking of glacial deposits on the sea bed off north Norfolk, including Burnham Flats, where gravelly sand forms only a relatively thin veneer over glacial till.

Only limited data are available concerning suspended sediment concentrations within the Wash itself. INGLIS and KESTNER (1958) reported concentrations of 0–30 ppm in the approaches to King's Lynn under calm water neap tide conditions and typical values of 150–200 ppm during periods of rough weather and spring tides. Measurements at several stations across the tidal flats at Freiston under a range of conditions indicated average concentrations of 100–200 ppm, with exceptional values of 1,200 ppm (COLLINS *et al.*, 1981). Average concentrations were found to be highest during the early stages of the flood tide (100–200 ppm), falling to 50 ppm during the later stages of the flood and to 25 ppm during much of the ebb. The measurements showed that the suspended sediment concentration on the flood generally increases in a landward direction, probably due to temporary resuspension of previously deposited material. Measurements by STODDART *et al.* (1987) in saltmarsh creeks at Terrington indicated much higher values (1,000–5,000 ppm) but confirmed that concentrations are higher on the flood than on the ebb, implying net intertidal deposition.

MORPHOLOGY AND SEDIMENTS OF THE SALTMARSHES AND INTERTIDAL FLATS

The outer Wash is characterized by two major channels (Lynn Deeps and Boston Deeps) on either side of which there are major linear sand banks oriented parrallel to the direction of tidal flow. At the entrance to the Wash the maximum channel depth is 30–35 m (Figure 3). Chart evidence suggests that the major banks and channels have been in existence for at least the previous 150 years, although their size and position has been rather variable (KESTNER, 1962). Comparison of Ordnance Survey Maps and Admiralty Charts shows that between 1950 and 1970 many of the banks and channels moved to the east and south, and there was a net reduction in the drying area of the offshore banks in the western Wash and an increase in the drying area of banks in the eastern Wash (Figure 2). However, it is uncertain to what extent this trend has continued since 1970, since more recent survey maps are not available.

Intertidal flats and saltmarshes are the dominant coastal features in the Wash south of Gibraltar Point. EVANS (1965, 1975) recognized five main sedimentary environments in the intertidal zone: (1) lower sandflats; (2) lower mudflats; (3) *Arenicola* sandflats; (4) higher mudflats; and (5) saltmarsh. In many places, however, there is no lower mudflat zone and a distinction between lower sandflats and *Arenicola* sandflats cannot easily be made (McCAVE and GEISER, 1979).

The sandflats generally occur between low tide mark and 1.7 m O.D., dipping seawards at 1–4°. Mud begins to accumulate above 1.7 m O.D. and extends up to the limit of pioneer marsh vegetation at about 2.1–2.4 m O.D. The sediment is mostly medium to fine, well to moderately sorted sand, but near the landward transition from sandflats to mudflats, the silt content increases and the sands are heavily bioturbated by *Corophium* sp. and various annelids. Further seawards, the sands are cleaner and the surface is often covered by current ripples. Dense populations of *Arenicola marina* and *Cerstoderma edule* occur within the sands. Near low water mark, the sand surface may be characterized by the development of dune-scale transverse bedforms which are principally formed by the flood tidal currents (McCAVE and GEISER, 1979; VAN SMIRREN and COLLINS, 1982). Thin coverings of mud are not uncommon but are usually transient. Similar deposits are found on

Figure 6. Grazed high marsh at Frampton, in the southwestern corner of the Wash. A water-filled borrow pit can be seen in the foreground.

the margins of the sand banks in the centre of the Wash.

The inner mudflats consist mainly of well-laminated layers of silt and sandy silt. The sand content is generally higher along the western shore of the Wash than in the southeast. At Butterwick (Figure 2) the muds on average contain 37% sand, 47% silt and 16% clay, with a median size of 0.045 mm (EVANS, 1965). The mineralogical composition of muds around the Wash is relatively uniform, with quartz comprising 55–80% of the bulk sediment, calcite 5–25% clay, minerals 10–20% and with traces of feldspar, mica and dolomite (SHAW, 1973). Small differences can be detected in the composition of sediments found in the lower reaches of the Witham, Welland, Nene and Ouse rivers, reflecting differences in source areas (WILMOT, 1985), but the deposits within the Wash are well mixed.

In some places (*e.g.*, Wrangle and Gedney) the higher mudflat surface is presently characterized by irregular topography with ridges and scoured depressions. These features are ephemeral and are formed by differential erosion of a surface partially stabilized by algal mats. Once the surface mat has been breached, a depression is rapidly formed by turbulent scouring processes associated with waves and currents. Some depressions retain standing water at low tide, while the surfaces of the adjoining ridges may dry out and experience shrinkage cracking during the summer.

Pioneer marsh vegetation first becomes established when the height of the mudflat reaches 2.3–2.4 m O.D., although scattered vegetation may be found as low as 2.1 m O.D. *Salicornia* is the most common pioneer species, and may be associated with algae such as *Vaucheria* and *Enteromorpha* (HOBBS and SHENNAN, 1986). In some areas *Spartina anglica* is also important in the pioneer zone, and this species is dominant in the southeastern corner of the Wash between the Ouse outfall and Wolferton, and south of the Steeping River at Wainfleet. Elsewhere the lower marsh vegetation communities, at elevations up to about 2.8 m O.D., are dominated by *Salicornia* spp., *Aster tripolium, Suaeda maritima* and *Puccinellia maritima* (HILL and RANDERSON, 1987; HILL, 1988; BURD, 1989). Mid-marsh communities (2.8–3.4 m O.D.) include *Halimione potulacoides, Puccinellia maritima* and (on creek bank levees) *Agropyron pungens*. On the ungrazed upper marshes (above 3.4 m O.D.) the dominant species are *Puccinellia maritima, Plantago maritima, Festuca rubra, Halimione potulacoides, Agropyron pungens* and *Artemesia maritima*. Most of the mature unreclaimed marshes in the Wash have an elevation of 3.6–3.8 m O.D., although the oldest marshes

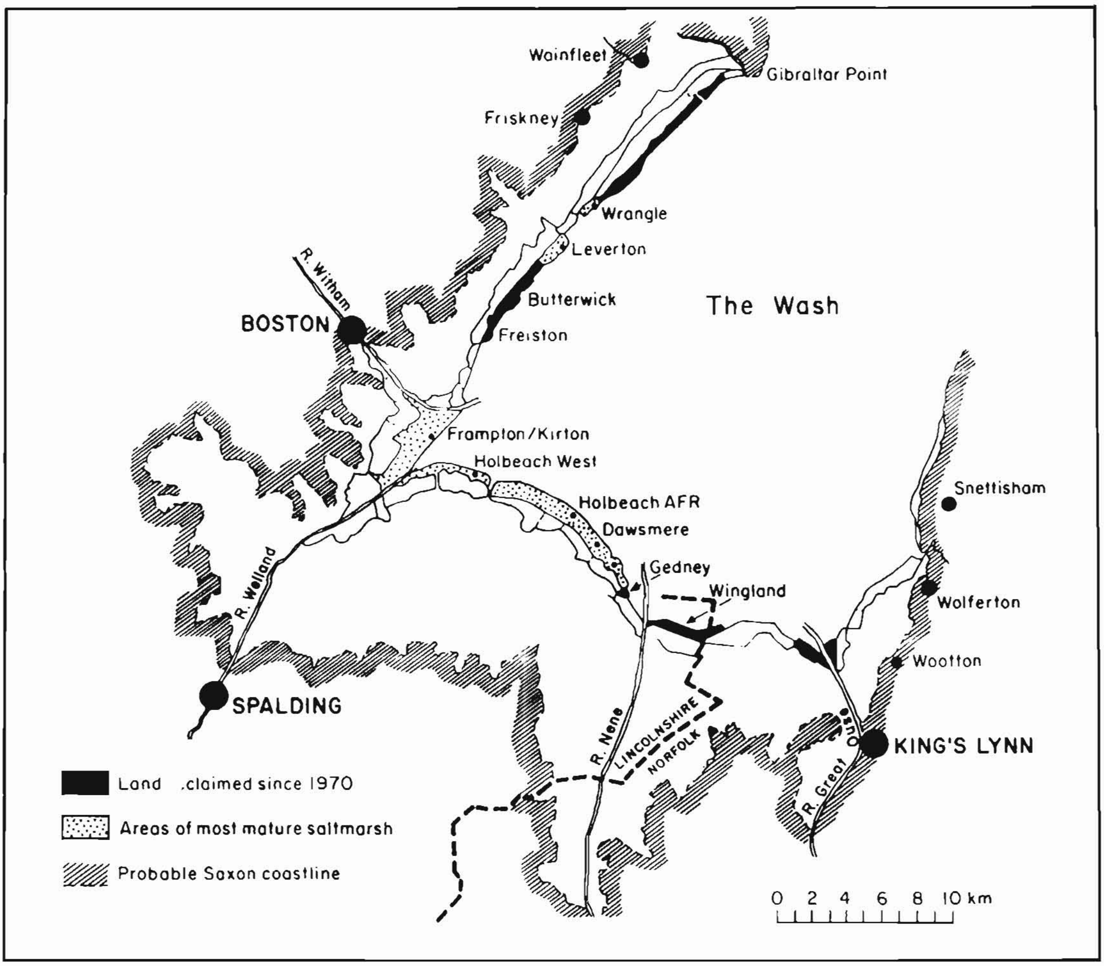

Figure 7. Changes in the shoreline of the Wash since Saxon times, showing areas of land claim since 1970 and remaining areas of the most mature saltmarsh (based on Lincolnshire County Council, 1982) and other sources.

reach elevations up to 4.0 m O.D. (Figure 6). Since, in the past, marshes have generally been judged to be ripe for reclamation when they reached 3.4–3.5 m O.D. (DALBY, 1957; BUCHNER, 1979), high marshes are relatively rare.

The particle size of the saltmarshes decreases with increasing elevation, since only the finest particles can be carried onto high marsh surfaces by relatively low velocity flows. EVANS (1965) reported that the near-surface sediments of the relatively young marshes at Butterwick contain an average of 5% sand, 53% silt and 42% clay, with the average median size being 0.01 mm.

SALTMARSH ACCRETION AND EROSION

Accretion and Reclamation

Significant net accretion has taken place around the margins of the Wash in the last two thousand years and continues at the present day. Major drainage works, involving the creation of new channels and straightening of others, were undertaken by the Romans, who probably also constructed earth embankments and reclaimed some areas of marshand. In Saxon times, the shoreline probably lay roughly along the line of the so-called 'Roman Bank' between Boston, Spalding, Wisbech and King's Lynn (Figure 7). On the western side of the Wash and north along the Lincolnshire coast, the shoreline lay well inland of Boston, Skegness and Mablethorpe (ROBINSON, 1981, 1987).

There were also early medieval land claims, but the greatest changes have occurred since the late sixteenth century. Numerous new sea banks were constructed and marshes enclosed on the Lincolnshire side of the Wash in the 16th and 17th centuries, and similar works were undertaken on the southern shores seaward of the 'Roman Bank' beginning in the 17th century (RUXTON, 1979; ROBINSON, 1981). The belt of saltmarsh seaward of the Roman Bank by this time had become more than 4 km wide. The total area of landclaim since Saxon times exceeds 47,000 ha (PRATER, 1981), of which 32,000 ha has been claimed since the seventeenth century (BORER, 1939; KESTNER, 1962; DOODY, 1987; ROBINSON, 1987). A number of reclamations were undertaken between 1970 and 1981, when a moratorium was imposed (LINCOLNSHIRE COUNTY COUNCIL, 1982). These reclamations included Wainfleet St. Mary (1873, 80 ha), Friskney Jubilee Bank (1976, 350 ha), Freiston (1976–1979, 45 ha; 1979–1980, 47 ha), Gedney Drove End (1978, 17 ha), Wingland (1974, 177 ha), Ongar (1974, 101 ha), Fosdyke, Duck Point and East Welland (1970–1980, 41 ha).

Although there has clearly been a natural long-term trend towards accretion, the process has been enhanced by various human activities which include the draining of the Fens (DARBY, 1940; GODWIN, 1978), embankment construction and reclamation. The digging of a new channel in the 13th century to alleviate flooding in Fenland diverted much of the water which formerly entered the Wash via the Nene at Wisbech into the Ouse. This was followed by extremely rapid accretion in the Wisbech estuary, possibly because of the reduced scour in the low tide channel (KESTNER, 1976). Construction of the Welland training walls, begun in 1838 and extended in 1849, and those of the Witham, commenced in 1884, also led to accelerated accretion of muddy sediment on either side of the trained channel and to seaward of it (INGLIS and KESTNER, 1958). More recently, dumping of dredge spoil from Boston has enhanced accretion on the south side of the Witham Cut and on the east side of the Welland outfall. Similarly, the rapid accretion which has taken place since 1950 at Vinegar Middle and Bulldog Sand has been enhanced by the combined effects of embanking, training wall construction and dredging in the approach channel to King's Lynn.

KESTNER (1975) argued that the effect of embankment construction was to reduce the mean flow velocity across the tidal flats to seaward, since a smaller volume of tidal water must cross a given point on the foreshore after land claim, thereby enhancing the rate of accretion. He also argued that the beheading of tidal creeks reduces the volume of water passing a given point on both flood and ebb tides, thereby reducing average velocities and promoting infilling of the creeks. Since creeks are the principal routes by which sediment is supplied to the higher mudflats and saltmarshes, coastal progradation has often occurred in a spatially irregular manner, with 'cusps' of slightly higher ground projecting from the seabanks in the vicinity of creeks (Figure 8; KESTNER, 1975, 1979).

The traditional method of reclamation in the Wash has involved the construction of an earth embankment close to the seaward limit of a marsh considered 'ripe' for enclosure, usually using material excavated from the marsh in front of the embankment (DALBY, 1957). In some instances attempts were made to enhance the rate of accretion in front of the wall by placing rows of stakes or brushwood parallel to the embankment, or by placing cut turfs (usually *Puccinellia*) on the upper mudflats (WHEELER, 1875–1876). Straight channels, known as 'grips', were also sometimes dug at right angles on the marsh outside the new embankment to improve drainage and to facilitate management following enclosure.

The short-term effects of embankment construction on mudflat accretion and growth of new marsh were analyzed by KESTNER (1975) following an enclosure at Wingland in the 1950's. The vertical accretion rate immediately following completion of the embankment was rapid, averaging 3.3 cm a^{-1} between 1956 and 1962, but it slowed during the period 1962–1968 to 1.4 cm a^{-1} as the level of the mudflat rose and it became covered by fewer tides. However, the accretion rate accelerated again to 2.9 cm a^{-1} between 1968 and 1972, apparently in response to colonization by marsh plants which trap mud more efficiently.

KESTNER (1975, 1976) concluded that new marshes in the Wash approach an equilibrium height and width approximately 30 years after embankment construction. He suggested that the equilibrium marsh height is approached asymptotically, with the asympote lying some 0.6–0.9 m below the level of HWMOST, and that 92% of

Figure 8. Vertical air photograph of accreting saltmarshes and mudflats on the western shore of the Wash, taken in 1989. Note the serrated edge of the marsh front related to the distribution of tidal creeks which introduce sediment to the higher intertidal areas. Scale 1:10,000. Reproduced by permission of the Aerial Photography Unit, Cambridge University.

the vertical growth is accomplished with the first 18 years following land claim. Following WHEELER (1875–1876), Kestner also suggested that the equilibrium marsh width in the Wash is 500–900 metres and that further seaward growth is only possible if a new embankment is constructed to seaward. However, several lines of evidence throw doubt on these conclusions. First, levelling data indicate that the surfaces of the oldest active marshes around the Wash extend up to 4.0 m O.D., which is slightly higher than the level of MHWS. Vertical marsh growth slows down as the surface level rises, but the asymptote is apparently governed by the level of extreme high water spring tides. Second, marshes in the Wash can grow to a width exceeding 500–900 m in the absence of further embankment construction, as shown by the great width (> 4 km) of marsh which developed in front of the 'Roman Bank' at Sutton and Gedney before reclamation in the 17th century and by the growth of marshes more than 1.0 km wide at Wootton since the late 1970's. If the sediment budget is favourable, the level of the mudflats in front of a saltmarsh continues to rise, allowing further seaward movement of the vegetation limit. Due to enhanced accretion rates on the vegetated surface relative to the mudflat, a discontinuity between the two may develop into a small cliff. In more exposed areas, wave reflection from such a cliff can prevent settling of mud on the fronting mudflat until such time as there is a sudden onshore movement of sediment and a rapid rise in mudflat level. Following such an event, a new marsh may become established, separated from the higher marsh by a residual clifflet. However, since accretion rates are higher on the lower marsh, the height differential between the two marshes is progressively reduced and may in time disappear.

There is no evidence to support Kestner's hypothesis that the increased volume or velocity of water ebbing from a wide belt of marsh onto the mudflats limits the equilibrium marsh width. Indeed, observational evidence suggests that the ebb tidal prism over the marsh declines with increasing marsh maturity, leading to a reduction in average velocities and a reduction in the capacity of the tidal creek network, thereby possibly encouraging accretion on the fronting mudflats (PYE and FRENCH, 1993).

Recent Changes in Saltmarsh Extent

Air photographs and field surveys have provided clear evidence of major changes in the extent of sand spits and associated saltmarshes in the Gibraltar Point area during the last 70 years (Figure 9; BARNES and KING, 1953, 1957, 1961; KING, 1968, 1970, 1973, 1978; DUGDALE and KING, 1978; DUGDALE and EVANS, 1990; HARPER, 1978; HARTNALL, 1984). The spit complex has shown a tendency to grow eastward and slightly southward over this period as sand has moved down the coast towards the mouth of the Steeping River, at the northwestern extremity of the Wash. The sandy intertidal areas between successive ridges have developed into saltmarshes which become progressively younger towards the east. At the present time, parts of the most seaward back-barrier marshes are being destroyed by overwash and burial by windblown sand transported through a breach in the outermost dune ridge (Figure 9). Elsewhere, however, the marshes are in a healthy condition and continue to accrete vertically.

A survey by HILL (1988), using air photographs and ground surveys to assess changes in the extent and nature of marsh vegetation communities within the Wash between 1971–1974 and 1982–1985, showed that the total area of active saltmarsh in the Wash decreased during this period by 83 ha (2%). This decrease was largely a result of land claim which led to the enclosure of 864 ha; excluding this factor, the area of active saltmarsh increased by 781 ha (16%). Most of the accretion occurred on the western shore between Gibraltar Point and Butterwick and on the southern shore between the River Welland and the River Nene. However, significant net erosion occurred along the southwestern shore between Butterwick and the River Witham. Measurements of changes in the marsh width by HILL (1988) showed considerable variations, with the highest rate of lateral spread (460 m) being recorded in the *Spartina* marsh near the Steeping River, where the last land claim occurred in 1966. Rapid seaward growth also occurred at Wainfleet and Friskney (110–295 m) in front of the embankments constructed in 1973 and 1977. In front of the 1974 embankment at Wingland, the marsh edge moved 50–120 m seaward between 1971–1974 and 1982–1985 (average rate 6 m a^{-1}). At Terrington, the marsh edge moved 85 m seawards between 1971–1974 and 1982–1985 (7 m a^{-1}). These figures compare with lateral accretion rates of 51 m a^{-1} following embankment construction at Wingland, 17 m a^{-1} near the River Ouse and 21 m a^{-1} near the River Nene between 1917 and 1952 (INGLIS and KESTNER, 1958).

At Freiston, near Butterwick, the marsh edge

Figure 9. Vertical air photograph of the Gibraltar Point area taken in 1989, showing accreting sand ridges (A, B, C), mudflats (D) and saltmarsh (E). A breach in the outermost dune ridge can be seen near the top of the photograph (F). Scale 1:10,000. Reproduced by permission of the Aerial Photography Unit, Cambridge University.

Figure 10. Vertical air photograph taken in 1989 showing erosion of the saltmarsh and mudflats (arrowed) in front of the 1979 embankment at Butterwick in the southwestern part of the Wash. Scale 1:10,000. Reproduced by permission of the Aerial Photography Unit, Cambridge University.

retreated by 165 m at one point and advanced seaward by only 60 m at another, despite the reclamations of 1976–1979 and 1979–1980 (HILL, 1988). Air photographs taken in 1989 show that vegetation has still not become fully established on the upper foreshore at the southern end of the 1979 embankment, which is currently subject to toe erosion (Figures 10 and 11). The problems at this point arise from the fact that the marsh level was not sufficiently high at the time of embankment construction, and there was too much disturbance to the foreshore during excavation of the borrow pits which were wider and shallower than normal. The embankment suffered a partial breach soon after construction and was then rebuilt landward of its original position.

Problems with erosion were also encountered at the southern end of the Friskney embankment, where a short section of bank was originally built beyond the limit of the consolidated marsh, but was later moved back, following the marsh edge (HILL, 1988). Recent air photographs and ground survey in 1992 showed that erosion is still affecting parts of the upper foreshore in this area, and a privately maintained section of sea bank is threatened with destruction.

HILL (1988) reported variable progradation rates for marshes where no embankment construction had taken place. Relatively little seaward movement occurred between 1971–1974 and 1982–1985 at Leverton, Holbeach west, Kirton/Frampton and Gedney/Lutton, but extension of about 100 m occurred on the east side of Holbeach Range and at Horseshoe South, to the south of the Friskney land claim. At Terrington the marsh edge advanced 120 m, although this may have been enhanced by construction of a trial bank and approach causeway for the Wash Water Storage

Figure 11. Erosion damage to the 1979–1980 embankment at Frinskney where the fronting saltmarsh between two former creeks is slightly lower than on either side. Photograph taken in July 1992.

Scheme. In the southeastern corner of the Wash on the Wootton and Wolferton marshes, seaward growth of 20–130 m occurred. Since the time of the second survey there has been further rapid accretion in this area.

Comparison of profiles surveyed in 1973 and 1986 showed a general increase in marsh surface elevation of 20 cm at Wainfleet (HILL, 1988). At Gedney the two profiles showed little change between 150 m and 450 m seaward of the new seabank; beyond 450 m the 1986 profile was clearly lower than in 1973, indicating net erosion. The seaward limit of colonization was also lower (2.12 m O.D) compared with 1973, although at a similar distance from the sea bank. The edge of the consolidated marsh had also retreated by 105 m at this point since the previous survey (HILL, 1988). Field surveys by the author in 1991 and 1992 confirmed that the marsh edge and upper mudflat in this locality is eroding. Parts of the established marsh are also undergoing erosion due to deepening and widening of the creeks whose heads are connected to borrow pits. The pits create a reservoir of water which increases the ebb tidal velocities in the creeks, leading to bed scour and bank collapse. The borrow pits themselves show only limited evidence of infilling, suggesting a possible shortage of sediment and dominant ebb transport in the creeks. Similar creek entrenchment related to borrow pits is seen to the east of the Welland outfall.

At the Nene transect, HILL (1988) recorded an increase in marsh elevation since 1973 in the upper 300 m of the transect but little difference below this point, resulting in a steepening of the marsh profile. The edge of the pioneer zone had, however, moved approximately 100 m seawards, being at a lower elevation (2.49 m O.D) in 1986 than in 1973 (2.62 m O.D.).

Field surveys carried out in 1992 by PYE and FRENCH (1993) suggest that the majority of saltmarshes in the Wash are still accreting, notably in the northwest and southeast; on the southwestern and southern shores, field evidence indicates further localized steepening of the upper intertidal profile and erosion of the marsh edge. The ending of embanking and reclamation in 1980 does not provide an adequate explanation for this tendency, since some of the sites where accretion has been slowest and where there is localized erosion occur in front of the most recent embankments. The concentration of sites of low accretion and erosion on the south western and southern shores of the Wash suggests that exposure to larger or more frequent waves from the northeast is an important factor. The late 1970's and 1980's saw a higher than average frequency of severe storms on the east coast of England which have been responsible for initiating or increasing the rate of saltmarsh erosion in many localities (PYE and FRENCH, 1993). However, as yet there is no conclusive evidence that this change is part of a longer term climatic deterioration.

There is also no firm evidence that sea-level rise has had a significant effect on the pattern of saltmarsh accretion and erosion in the Wash. The nearest Class 'A' tide gauge stations are Immingham and Cromer, but the latter has only been included in the network for a few years and the record at Immingham is only reliable as far back as 1960. Data from Immingham suggest an average rate of relative rise of 3–4 mm a^{-1}, but there is a marked cyclicity in the record (WOODWORTH, 1987). Data for Lowestoft show a net rise of only about 1 mm a^{-1} over the same period, while the Southend record suggests an average rise of 2–3 mm a^{-1} since 1930. SHENNAN (1989) calculated that net crustal movement in the Wash area has averaged about -1 mm a^{-1} in the Holocene. Levelling of marsh surface height differences across seabanks of different ages at Butterwick suggests an average rate of sea-level rise of 1.41 mm a^{-1} between 1809 and 1972 (SHENNAN, 1992). It is probable that relative sea level is currently rising around the Wash at a rate of approximately 1.5 mm a^{-1}. Given the availability of sediment in the Wash, vertical accretion of marshes can easily keep pace with rates of sea-level rise of this magnitude, which are considerably lower than those which prevailed during much of the Holocene. There is also no evidence that the present rate of sea-level rise is causing a steepening of the intertidal flats and widespread erosion of the marsh edge.

CONCLUSIONS

The Wash embayment has acted as a long-term sink for sediment supplied from neighbouring coastal and offshore areas in the southern North Sea. Extensive saltmarshes have existed in the area for much of the later Flandrian period and have gradually extended seaward, encouraged by embankment construction and land reclamation but principally due to net landward movement of sediment into the embayment by tidal action.

Although the rate of sediment supply declined progressively during the Holocene, due partly to a declining average rate of sea-level rise, partly to exhaustion of seabed sediment sources, and partly to the extension of coastal protection works in the last 150 years, the Wash continues to act as a sediment sink. During the last 20 years, there has been very rapid lateral accretion of marshes along the northwestern and southern shores of the Wash, associated with a seaward movement of both the low and high water marks. However, net stability or slow erosion of the marsh edge has dominated along the southwestern and southern shores which are more exposed to the largest storm waves from the northeast. Localized erosion of the marsh surface has also arisen due to wave reflection from the most recently constructed seabanks and due to the linking of some borrow pits, from which clay is extracted to build the seabanks, to marsh creeks. There is as yet no evidence that this localized erosion represents the beginning of a more general response to climate change or an increase in the rate of sea-level rise.

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