British Saltmarshes

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Saltmarsh erosion in southeast England: mechanisms, causes and implications

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CONTENTS

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ABSTRACT

Rapid erosion of saltmarshes in southeast England during the past 150 years, and particularly in the past 25-30 years, has created serious concerns related to habitat conservation and flood defence. The mechanisms of erosion vary from area to area, but include landward recession of the marsh edge, wave erosion of the marsh surface, internal dissection due to the enlargement and coalescence of tidal creeks and mud basins, and direct removal due to human activities. Evaluation of the available evidence leads to the conclusion that several factors have contributed to erosion, but the apparent acceleration of erosion since 1970 is due primarily to an increase in wind/wave energy. Erosion of saltmarshes on

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formerly reclaimed land which have been rejuvenated following storm breaching of the enclosing sea walls is also a major factor which reflects the high erodibility of sediments which have accreted at such sites in the last 80-120 years. Increases in mean sea level and tidal range are underlying factors leading to coastal 'squeeze', and human activities such as dredging, navigation and mud digging are contributory factors of significance in some areas. Net saltmarsh loss is likely to continue and may accelerate in the next century if predictions of enhanced sea level rise and further increased storminess are correct. While managed retreat potentially provides a means of recreating saltmarsh habitat, political pressures mean that it is unlikely to be possible to implement such a policy on a large scale. In this event, construction of artificial shore-parallel barriers on sections of open coast, such as the Dengie Peninsula and Mersea Island, combined with sediment recharge using dredged material, may provide the only alternative means of recreating significant and sustainable areas of saltmarsh and associated tidal flats.

INTRODUCTION

Southeast England contains about 700 ha of active saltmarsh, representing about 15% of the national total area (Burd, 1989; Pye & French, 1993). The region also contains extensive areas of reclaimed marsh which have been enclosed mainly since Medieval times. Much of this reclaimed land now lies below high spring tide level and is protected from flooding by earth embankments or concrete defences. The area of active saltmarsh has declined significantly in the past 30 years (Burd, 1992; Pye & French, 1993; Carpenter & Pye, 1996), creating considerable concern from both conservation and flood defence points of view. In view of predictions of accelerated sea level rise and increased storminess in the next century, further loss of intertidal area through 'coastal squeeze' is likely (English Nature, 1992; Pye & French, 1992), and a policy of 'no net habitat loss', as specified under the European Habitats Directive, will be increasingly difficult to sustain. Choice of the most appropriate management strategy under this scenario requires an adequate understanding of the underlying causes of coastal and estuarine change, including the timing and controls on previous erosional and accretional episodes. A number of investigations have been undertaken in the last few years in order to throw more light on the causes of marsh erosion and to identify options for future management (e.g. Pye & French, 1993; Carpenter & Pye, 1996). The purpose of this paper is to summarise some of the main findings of these studies, and to highlight outstanding questions.

PATTERNS AND MECHANISMS OF SALTMARSH EROSION

The principal areas of saltmarsh in southeast England occur within the estuaries of the Swale, Medway, Thames, Roach/Crouch, Blackwater, Colne, Hamford Water, Stour, Orwell, Deben and Ore/Alde; this paper is concerned principally with marshes between the Blackwater and the Swale (Figure 1).

Several different marsh morphological types have been recognised in the UK, based on physiographic setting and plan morphology (Figure 2). Marshes in southeast England are predominantly of the estuarine fringing type, although

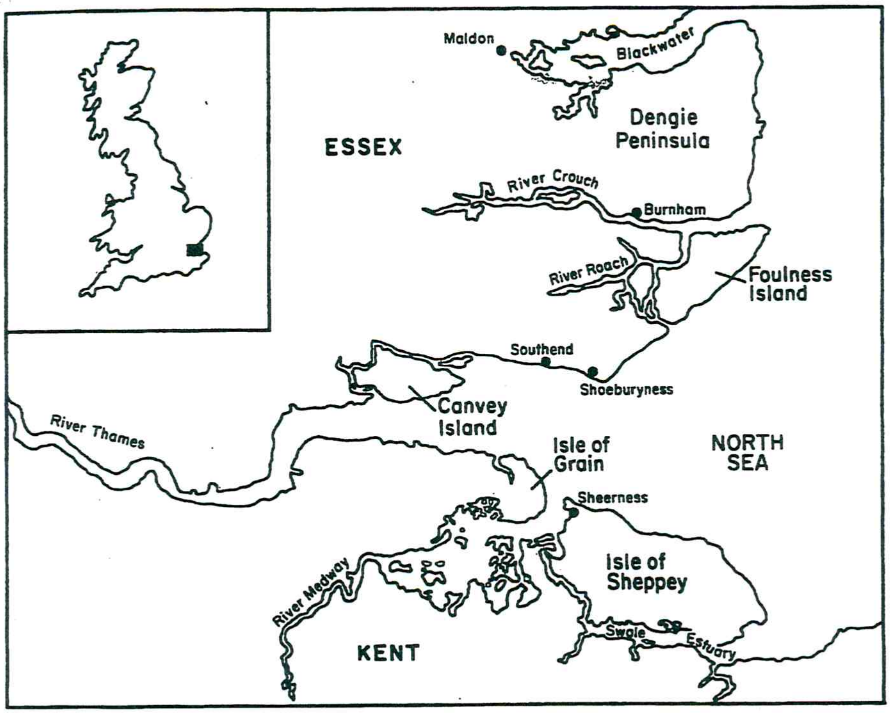

Figure 1 Study area and principal localities mentioned in the text

examples of open coast, open embayment, open coast back-barrier and estuarine back-barrier marsh can be identified. The marshes are predominantly muddy; those within the middle and inner parts of estuaries generally overlie quite thick sequences of estuarine muds and peats, while those towards the mouths of the larger estuaries and on the open coast frequently overlie sands or mixed mud-sand sequences.

The surface morphology of the marshes shows considerable variation, in large part governed by differences in the plan geometry of marsh tidal creek systems. A number of creek system types can be identified, ranging from simple linear and linear-dendritic systems to complex and superimposed systems (Figure 3). The precise nature of the morphology on any given marsh is governed by the interaction of several factors, including sediment erodibility, tidal range, marsh elevation within the tidal frame, and the history of marsh development, both natural and anthropogenically-modified (Crooks & Pye, in press). Many of the estuarine marshes in the region have a complex morphology compared with that in some other parts of the country; in part this reflects their considerable age and long history of human influence.

Almost all active saltmarsh areas in southeast England have experienced net erosion in the past 30 years, with the loss of area between 1973 and 1985/8 ranging from 10% to 44% (Burd, 1992). Based on a comparison of aerial photographs,

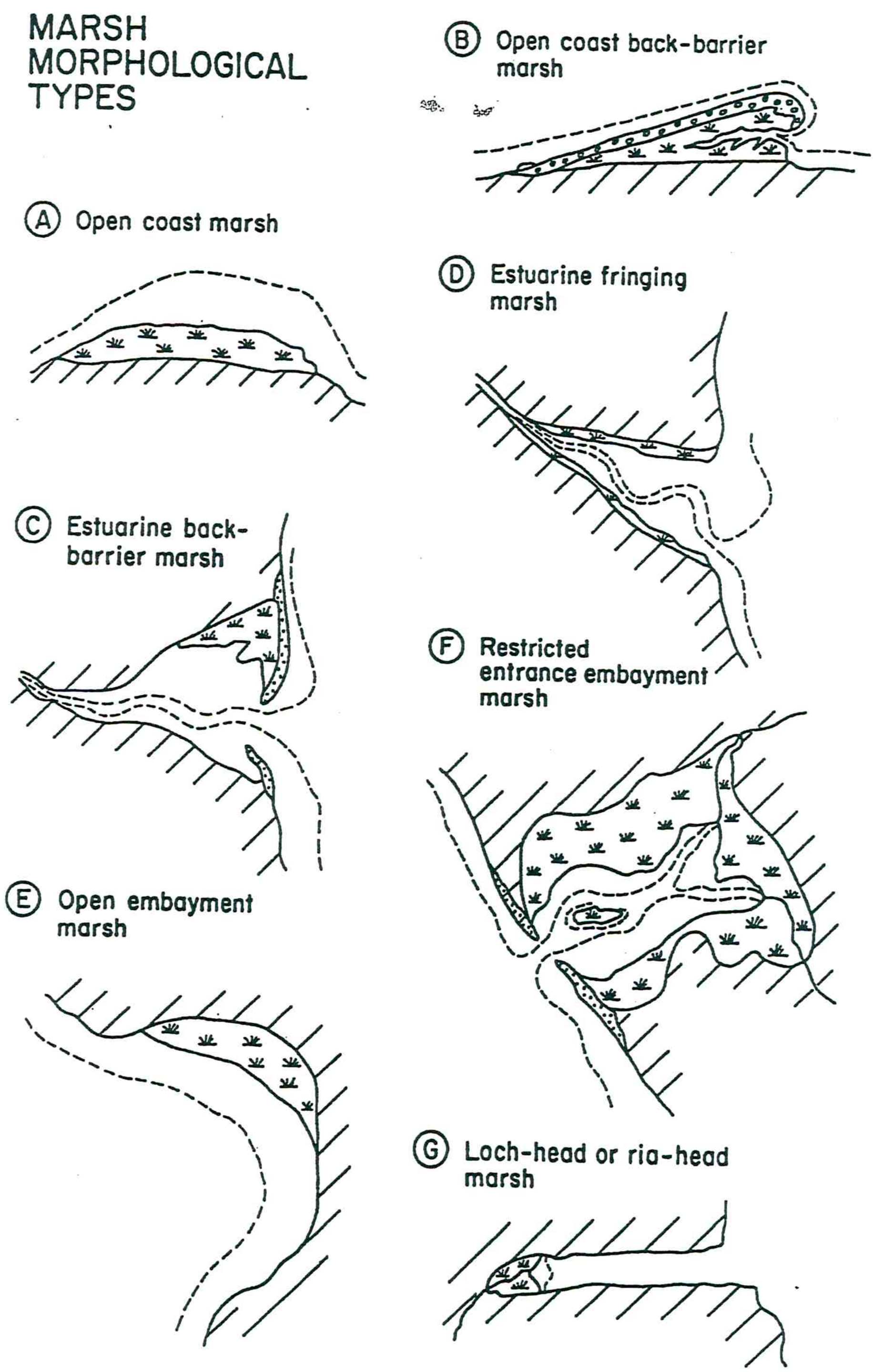

Figure 2 Classification of saltmarshes based on geomorphological setting (after Pye & French, 1993)

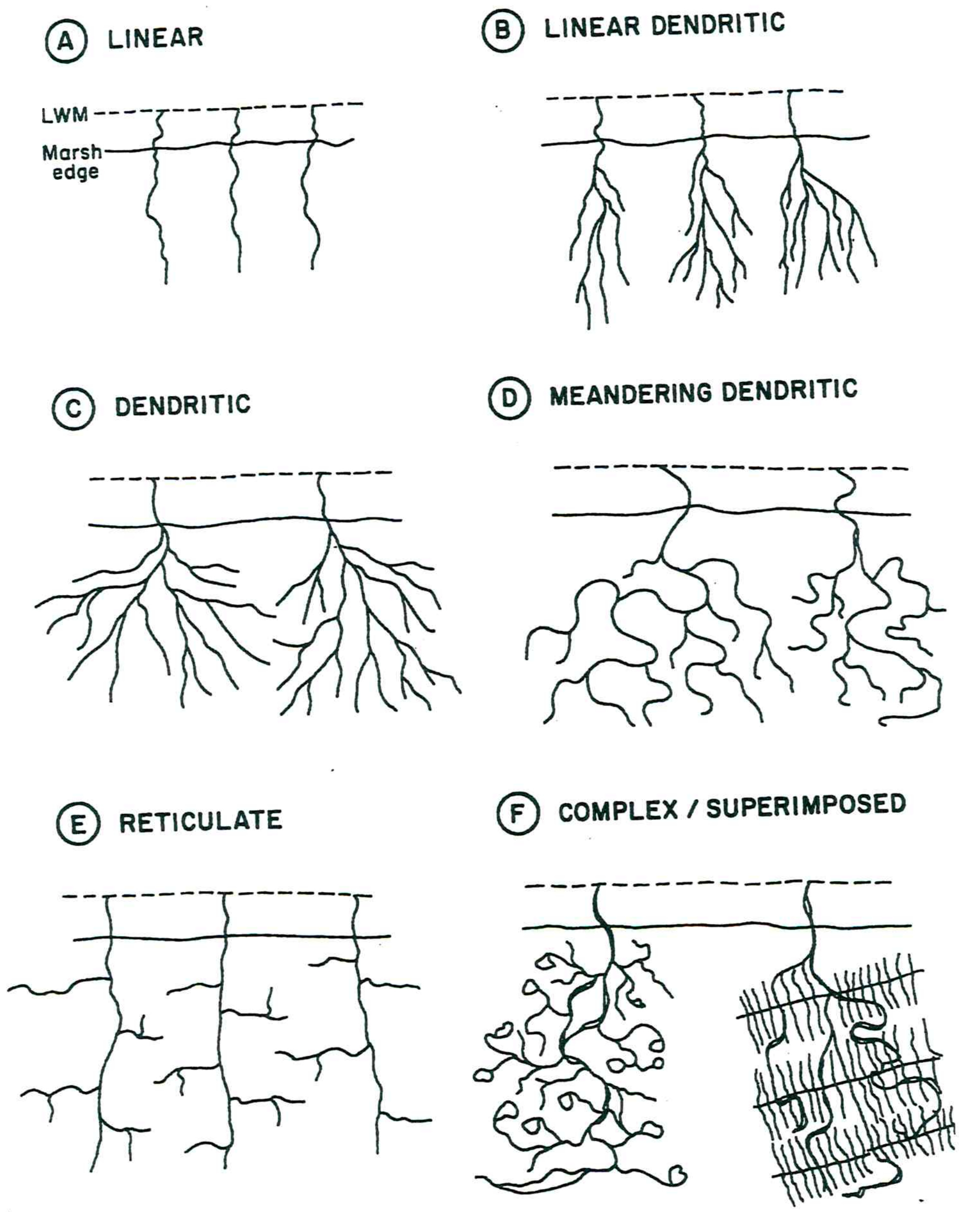

Figure 3 End member types of marsh tidal creek network (after Pye & French, 1993)

Burd (1992) estimated 58 ha of net marsh loss in the Swale estuary, 180 ha in the Medway, 98 ha in the Thames, 124 ha in the Courch, 200 ha in the Blackwater, 93 ha in the Colne, 169 ha in Hamford Water, 116 ha in the Stour, and 32 ha in the Orwell estuary, mostly due to erosion. Since 1988 there has been further erosion in many areas, although the additional reduction in area has not been accurately quantified. Some areas have exhibited apparent net stability, but areas of marsh progradation are very localised (Pye & French, 1993).

Short to medium term trends of marsh edge progradation or retreat can often be inferred by examination of the marsh edge morphology. Accreting and stable marsh edges are usually typified by an accretional ramp upon which pioneer and low-marsh vegetation communities become established (A and B in Figure 4). Erosional margins, on the other hand, are characterised either by the presence of mud-mound topography or by marsh-edge cliffs fronted by toppled blocks (Figure 4, C and D; Figures 5 and 6). Terraced marsh margins (case E, Figure 4) indicate episodic erosion and accretion on timescales of decades to centuries.

Four main modes of saltmarsh erosion can be distinguished:

- lateral retreat of the seaward edge;
- erosional lowering of parts of the marsh surface, usually involving partial or complete destruction of the vegetation (Figure 7);
- internal dissection and enlargement of the drainage network, ultimately leading to the creation of mud basins (Figure 8);
- direct removal (mud digging).

Marsh cliff formation is commonplace within the narrower estuaries where intertidal profiles are relatively steep and where there are periodic shifts in channel position, or on the more exposed open coast where muds overlie sandier deposits. Mud-mounds occur mainly in the outer parts of the wider estuaries and on exposed sections of open coast (e.g. northern Foulness and Dengie Peninsula) where the intertidal zone has a low gradient and exposure to wave action is relatively high. Retreating marsh cliffs and erosional mud-mound ramps are, in many places, capped by shell and/or gravel-rich ridges, known as cheniers (e.g. Greensmith & Tucker, 1967), which are driven landwards as the marsh edge recedes and the fronting tidal flats are reworked by wave action.

In more exposed marsh settings, the marsh surface for up to 50 m landward of the marsh edge may show evidence of wave erosion (Figure 7) in the form of damaged vegetation and circular or linear scour pits. Localised destruction of vegetation also sometimes occurs further landward, in front of the sea walls where drainage is poor, sediment supply restricted, and surface sediments poorly aerated. Waterlogging and build-up of toxic compounds eventually leads to death of the vegetation and subsequent scouring of the surface sediments by waves at high tide.

The history of marsh accretion and erosion has been studied in detail at a number of locations, utilising old maps, charts, air photographs and documentary evidence. For example, the Dengie Peninsula is currently fronted by a zone of

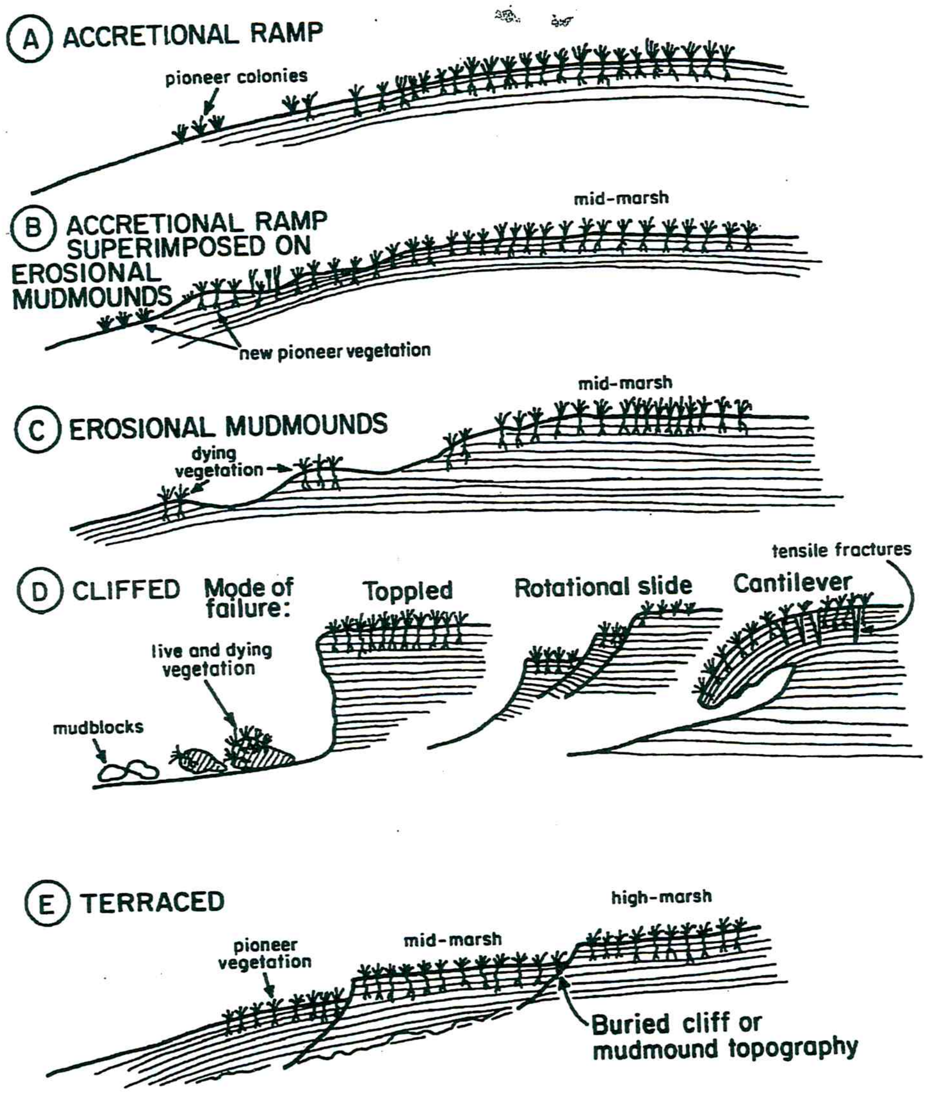

Figure 4 Variations in marsh edge morphology in relation to formational processes (after Pye & French, 1993)

fringing marshes which attains a maximum width of 700 m between Grange Outfall and Howe Outfall (Figure 9). The marsh edge has been eroding since ca. 1955 and for much of its length is cliffed or characterised by mud-mound topography. In several places, including Sales Point and Marsh House, shell ridges and washover fans occur along the marsh edge (Greensmith & Tucker, 1965, 1967; Harmsworth & Long, 1986). At the landward limit of the active marsh is a concrete-faced sea wall which encloses a large area of reclaimed marshland.Most of the reclamation took place after 1774, and much of it after 1840 (Gramolt, 1960). Archival evidence suggests that the active marshes prograded

Figure 5 Erosional mud-mounds, Dengie Peninsula

Figure 6 Marsh edge cliff, toppled blocks, and erosional cliff-foot platform, Higham Saltings, Thames estuary

Figure 7 Wave eroded marsh surface, Orwell estuary

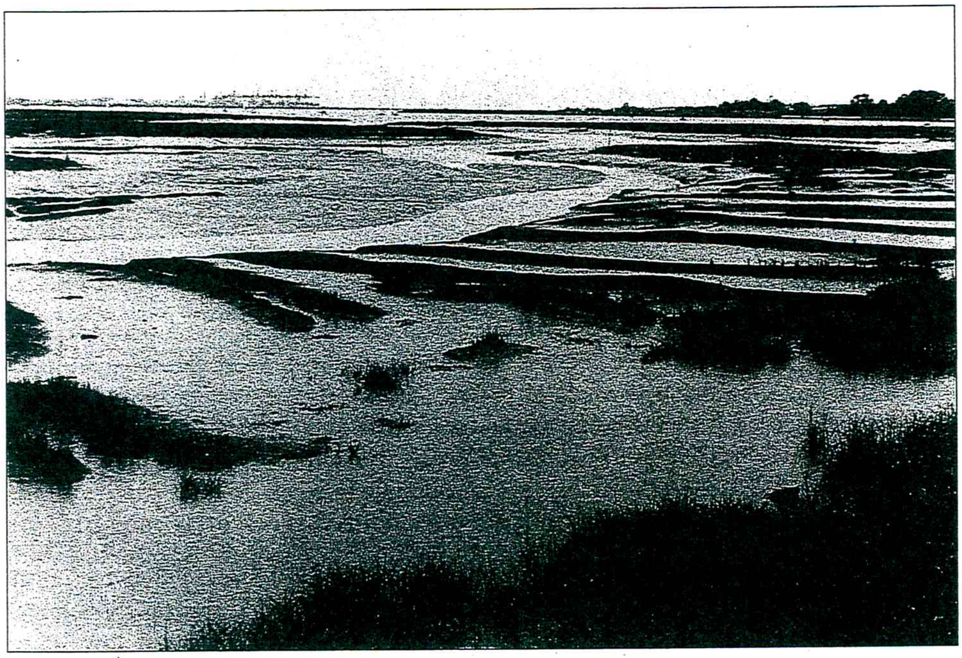

Figure 8 Large-scale destruction of marsh vegetation and internal dissection, Orwell estuary

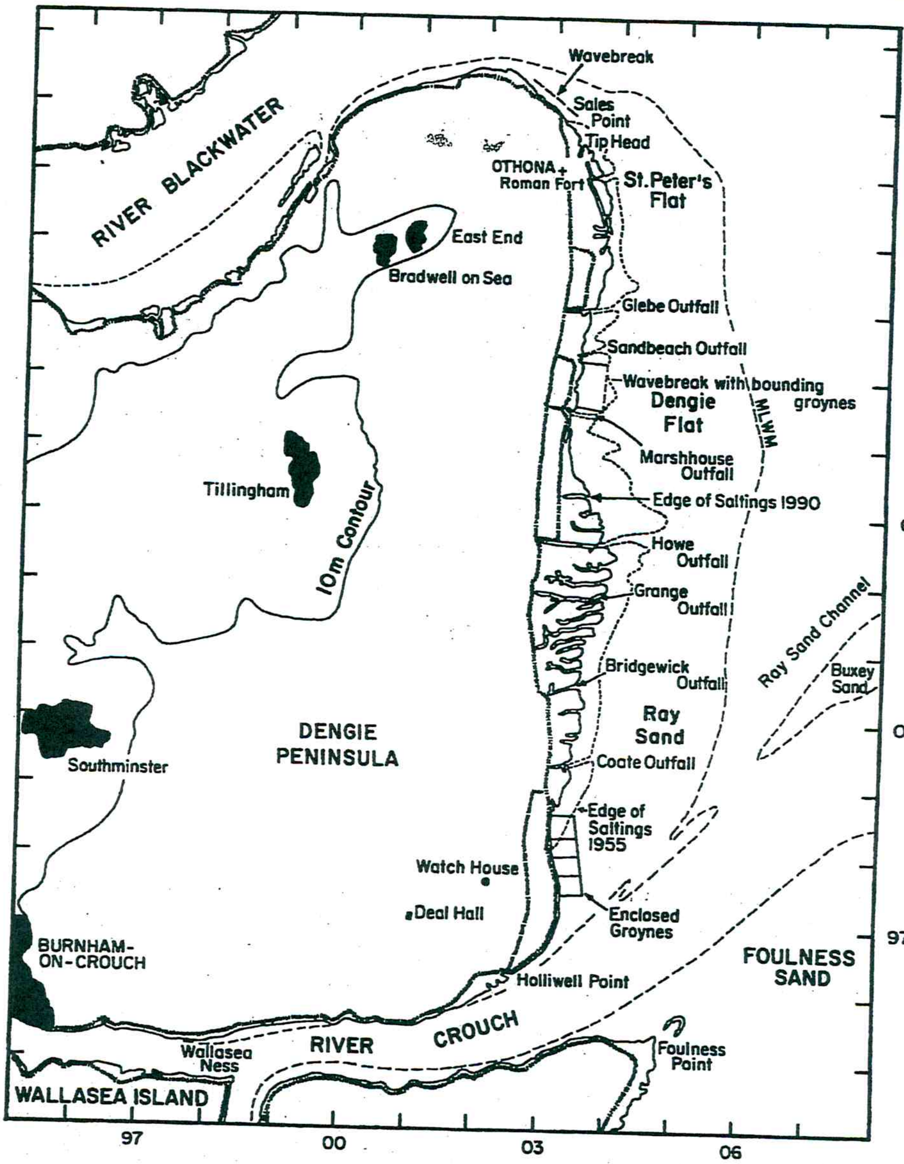

Figure 9 Changes in the position of the marsh edge along the Dengie Peninsula between 1955 and 1990, based on Ordnance Survey maps and air photographs (after Pye & French, 1993)

rapidly between 1870 and 1955 and particularly after 1891-5. The rate of progradation was highest near Howe Outfall where it averaged 9.7 m/yr between 1873 and 1955 (Pye & French, 1993). No lateral accretion occurred during this period on St. Peter's Flat, or south of Watch House. Coincidentally, mean low water mark moved landwards at an average rate of 8.7 m/yr at St. Peter's Flat and 13.3 m/yr at Watch House, leading to a steepening of the foreshore. North of Sandbeach Outfall, marsh progradation occurred mainly after 1940. The marsh edge along the northern half of the Peninsula retreated by up to 270 m between 1953 and 1960, while virtually the entire marsh frontage receded between 1960 and 1981. There was net stability and even some accretion between 1960 and 1970, and again between 1973 and 1978, with episodes of rapid erosion between 1970 and 73 and again after 1978. Maximum lateral retreat, of almost 1,000 m, has occurred near Howe Outfall since 1955. However, lateral erosion has been accompanied by continued vertical accretion, with short term average rates of up to 7.5 mm/yr (Reed, 1988).

Since the late 1970s a variety of attempts have been made to stop erosion and to rejuvenate eroding marshes along the Dengie frontage and elsewhere in Essex (Pethick & Reed, 1987; Holder & Burd, 1990). The methods tried include the construction of wooden groynes and polders, as used extensively in northern Germany and western Denmark (Figure 10), construction of wavebreaks using old Thames barges, planting of *Spartina*, tidal creek diversion and obstruction, and artificial sediment recharge. While these experiments have brought some benefits at the local level, they have not had a significant impact on the overall erosion problem. Much of the Dengie marsh frontage continues to erode, although the Sales Point spit and back-barrier marsh complex has stabilised since 1990.

To the south of the Crouch estuary, around Foulness Point, there has also been significant marsh erosion during the past century. In 1897 there was a continuous fringe of saltmarsh around Foulness Point (Figure 11), but by 1938 the marsh had been totally eroded on the northern side. Between 1938 and 1990 there was large scale wave reworking of the tidal flats to the north and east of Foulness Point, resulting in landward reworking of very large numbers of shells to form a series of dynamic shell banks and chenier ridges. These ridges provided shelter for the development of new saltmarsh to the northeast of Foulness Point, but further erosion since 1978 has led to landward migration of the shell ridges and exposure of eroded saltmarsh on the seaward side. On the northern side of Foulness Point the integrity of the concrete sea wall is now threatened (Figure 12). Material eroded from the northern end of Foulness is to some extent being compensated by the seaward growth of new marsh between Northern Corner and Havengore at the southern end of the island.

A further example of the rapidity of saltmarsh loss is provided at Higham Saltings near Gravesend, on the southern side of the Thames estuary. A map of 1874 shows that an embayment in the sea wall at Higham was almost totally infilled by saltmarsh (Figure 13). Erosion of the seaward margin, by 35-65 m, occurred between 1873 and 1923, and there was significant disintegration of the marshes at the northern end of the embayment before 1909. Between 1923 and 1983 the seaward edge retreated a further 50-85 m, and marsh in the northern half of the embayment was almost totally destroyed, partly by natural disintegration and partly by mud digging. Since 1983 a 2 m high marsh-edge cliff has continued to retreat at an average rate of 1-2 m/yr.

After 1880 many sea walls in Essex and Kent ceased to be maintained, largely as a result of economic factors. A series of high tides resulted in breaching of the walls and reversion of extensive areas of reclaimed land to mudflat and saltmarsh.

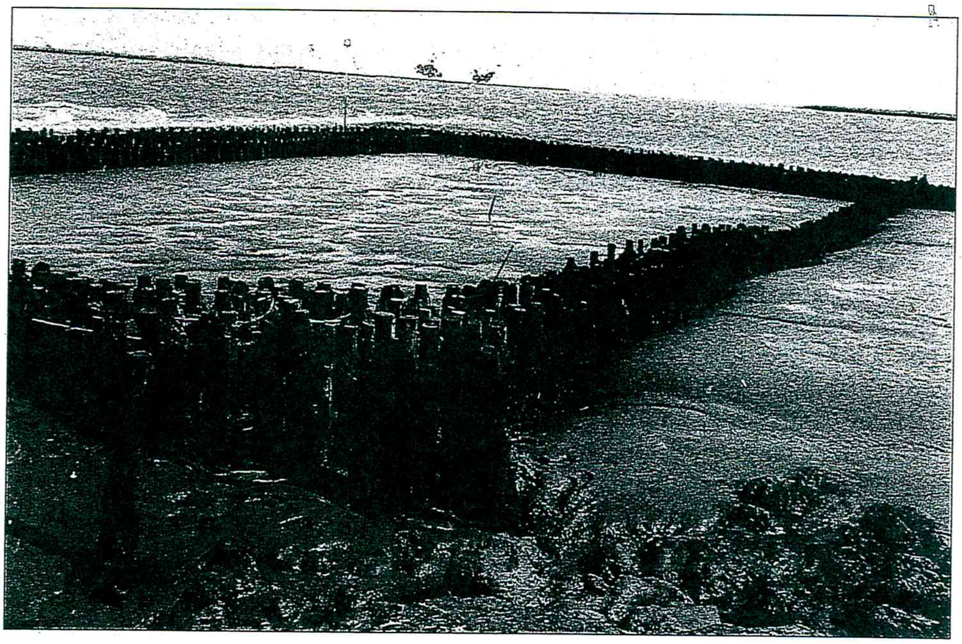

Figure 10 Box-groyne system used to enhance mudflat accretion, Wallasea Island

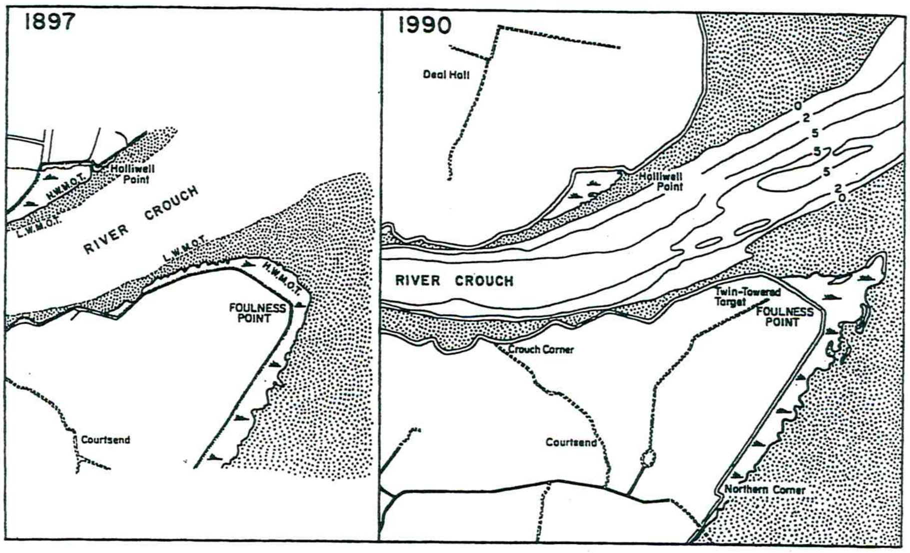

Figure 11 Changes in marsh extent and morphology at Foulness Point, based on Ordnance Survey maps of 1897 and 1990

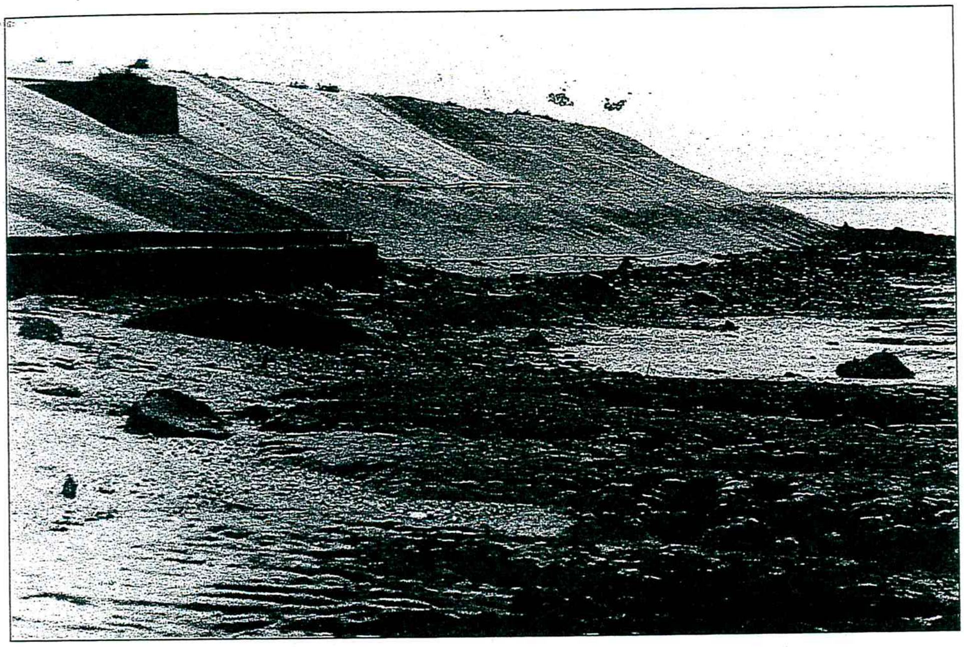

Figure 12 Eroded saltmarsh and concrete sea wall, northern side of Foulness Point

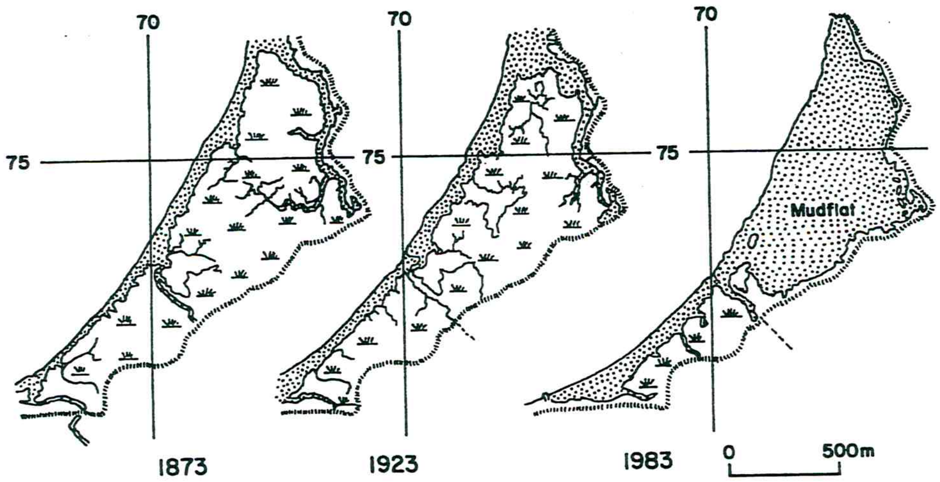

Figure 13 Changes in the extent of saltmarsh at Higham Saltings 1873-1983, based on Ordnance Survey map evidence (after Holt, 1994)

Figure 14 Air photograph of the Canvey Point area taken in 1988, showing remains of the old sea wall which was breached in 1881 (W), the eroded remains of the reactivated marsh (M), and transgressive shell ridges (S). Scale 1:10,000. Crown Copyright reserved

An example is provided by Canvey Point (Figure 14), where the sea walls fronting the Thames were breached during a storm in 1881, and a significant area reverted to saltmarsh (Cracknell, 1959; IECS, 1993). A further storm in November 1897 breached the walls on the Benfleet Creek side of the Point. Since reactivation of the saltmarsh, approximately 1 m of sediment has accumulated but the seaward margins have continued to erode and parts of the marsh have undergone internal disintegration. Landward reworking of shells from Chapman's Sands has resulted in the formation of shell ridges which are now transgressing across the marsh from the east. Similar sea wall breaches and marsh reactivation, followed by internal disintegration, has occurred on the north side of Benfleet Creek at Leigh Marsh (Two Tree Island) and many other sites in Essex and Kent.

FACTORS CONTRIBUTING TO SALTMARSH EROSION

Sea level rise

Numerous studies have suggested relative sea level rise as a major cause of saltmarsh erosion (Dijkema *et al.*, 1990; Reed, 1990; Kearney & Stevenson, 1991; Kraft, Yi & Khalequzzaman, 1992; Fletcher, 1992). Geological evidence from the Holocene suggests that periods of relative sea level fall are associated with widespread marsh progradation while periods of sea level rise are associated with lateral erosion (e.g. Rampino & Sanders, 1981). However, marshes may continue to accrete both vertically and laterally, despite sea level rise, if sufficient minerogenic or organogenic sediment is available (Stevenson, Ward & Kearney, 1986; Patrick & Delaune, 1990; Delaune *et al.*, 1992). Where there is a sediment shortage, saltmarshes will be eroded or will be buried by the landward migration of tidal flat and subtidal facies (Orson, Panageotou & Leatherman, 1985; DeLaune, Patrick & van Breemen, 1990; van der Spek & Beets, 1992).

Prior to this stage, however, sea level rise can have several related effects on marsh systems:

- reversed vegetational succession, whereby high- and mid-marsh communities revert to low marsh communities, with eventual 'drowning' of the vegetation and reversion to mudflat or pools of standing water (Boorman, Goss-Custard & McGrorty, 1989; Huiskes, 1990; Vanderzee, 1990; Lefeuvre, 1990);
- accelerated erosion of the marsh edge, associated with falling mudflat levels and increased wave damage to the marsh surface vegetation, since larger waves are able to move further inshore in a greater average depth of water (Pethick, 1991);
- increased frequency and severity of marsh loss due to barrier breaching and washover, which may form extensive spreads of sand and shingle which smother the marsh vegetation;
- associated with an increase in mean sea level there may also be changes in tidal range, tidal asymmetry and tidal current velocities which cause hydraulic readjustments in estuarine channels and marsh drainage systems, leading to marsh loss by bank recession and internal dissection;
- where landward movement of marsh habitats is prevented by natural high ground or coastal defences, the marshes will become 'squeezed' and will eventually disappear (English Nature, 1992).

Tide gauge records suggest that global mean sea level has risen by 1-2 mm/yr during the last century (Emery & Aubrey, 1985, 1991; Aubrey & Emery, 1993; Warrick & Oerlemans, 1990; Gornitz, 1993; Woodworth, 1993). The records for United Kingdom tide gauge stations with at least 20 years of continuous data show considerable variation. The most recent analysis undertaken (Woodworth, Tsimplis & Flather, in press) indicates a secular trend of 1.81 ± 0.48 mm/yr at Lowestoft for the period 1960-95, 1.22 ± 0.24 mm/yr at Southend 1933-83, 2.14 ± 0.15 mm/yr at Sheerness 1901-1996, and 1.58 ± 0.91 mm/yr at Tilbury 1961-83.

Comparison and interpretation of these changes is complicated by the fact that the instrumental records are incomplete and not fully coincident. Differences between nearby stations in the same estuary may be due to varying effects of river flows and localised subsidence/compaction, or to variations in recording methods. Significant interdecadal variability is evident in the longer term UK records, reflecting variations in tidal and meteorological factors (Woodworth, 1987; Woodworth et al., in press). However, there is no clear evidence of a recent acceleration caused by global warming.

Shennan (1989) suggested that southeast England has experienced average subsidence of 1.9 mm/yr during the Holocene. However, there is evidence for structurally controlled within-regional variation in subsidence rates in south Essex (Greensmith & Tucker, 1980). In the Lower Thames estuary, Devoy (1977, 1979) recognised five periods of Holocene marine transgression, separated by periods of relative stability or sea level fall. The most recent transgression (Thames V) was apparently initiated around 1750 yr B.P. A broadly similar pattern was inferred in the Essex coastal plain by Greensmith & Tucker (1976). Sea level fluctuations in the last 2,000 years are not well constrained, but the geological evidence suggests that they have not been major. In the central and inner parts of the Crouch estuary, an extensive freshwater peat (the Upper Peat), present at a depth of 0.8 m below the active saltmarshes, has yielded radiocarbon ages of ca. 1,380 ± 80 B.P. (Wilkinson & Murphy, 1995; Figure 15), suggesting only limited sea level rise since that time. An older peat (Lower Peat), which has been dated at ca. 3,760 ± 70 to 4,100 ± 70 B.P., outcrops in the lower intertidal zone, approximately 4 m below the level of the modern marsh surface. A similar peat of the same age occurs extensively in the Blackwater estuary at approximately the same level (Figure 14). Taken together, the stratigraphic and radiocarbon evidence from Essex and north Kent suggests a long-term average rate of relative sea level rise of ca. 1.2 mm/yr over the past four millennia, though shorter term rates may have been higher (up to 2.5 mm/yr).

A considerable body of archaeological evidence indicates that saltmarshes and freshwater lowland environments were extensively developed in the south Essex - north Kent area in pre-Romano-British times. A former land surface, which bears numerous Neolithic to Romano-British sites and artifacts but which now lies a few metres below mean sea level, has been identified throughout the area (Hazzeldine-Warren, 1911; Reader, 1911; Francis, 1932; Hazzeldine-Warren *et al.*, 1936; Evans, 1953; Ackeroyd, 1972; Greensmith & Tucker, 1980; Kirby, 1969, 1990). This surface became submerged and was partially eroded during the (Thames V) transgression which began after about A.D. 200 (Greensmith & Tucker, 1976). Since that time the position of the shoreline has clearly oscillated, although the net trend has been for continued submergence and landward movement. Extensive saltmarshes already existed in Romano-British times, and they appear to have moved landwards over riverine and other low-lying deposits as sea level rose. Parts of the marshes were embanked and reclaimed from the 12th century onwards (Spurrell, 1885, 1889; Grieve, 1959; Gramolt, 1960; Kirby, 1969), but this may have been driven mainly by economic and social factors rather than by sea level rise. Significant seaward growth of new marshes, which were

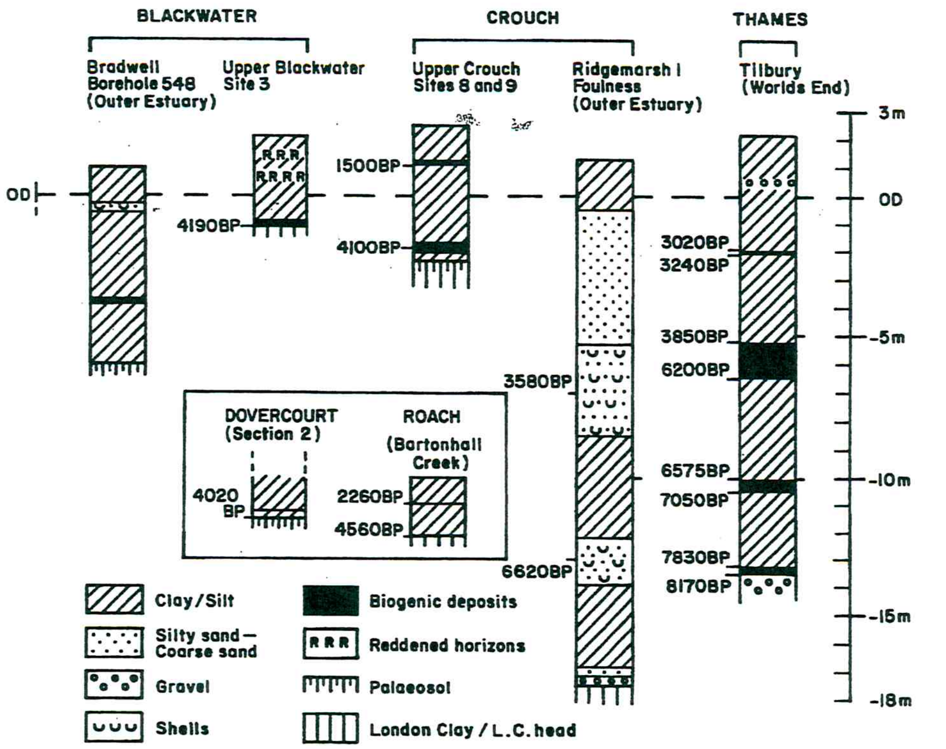

Figure 15 Simplified later Flandrian stratigraphic sequence from the Essex coast, showing radiocarbon-dated peats and associated sediments (after Wilkinson & Murphy, 1995)

subsequently embanked, appears to have occurred between the Middle Ages and the mid-19th century, but it is not certain whether this was induced by a slight sea level fall associated with global cooling during the Little Ice Age, or by other factors.

Map, chart and documentary evidence suggests that the present phase of rapid saltmarsh erosion in the Medway and the Blackwater estuaries had begun by 1870 (Hull University, 1993a,b; Kirby, 1990), but there is no evidence that this was triggered by an acceleration in the rate of mean sea level rise.

Dating of sediment cores from marshes in several parts of southeast England using ^{137}Cs and pollutant metal profiles has indicated that mature marshes (i.e. those which have achieved a surface elevation which is in equilibrium with the moving tidal frame) have accreted at an average rate of ca. 1 to 1.5 mm/yr over the past 35 years, while immature marshes have accreted at typical rates of 3-5 mm/yr (Figure 16). The accretion rates on mature marshes are consistent with the rates of recent sea level rise indicated by tide gauge data.

Numerous studies have shown that vertical accretion of saltmarshes can keep pace with rates of sea level rise in excess of 10 mm/yr, provided that an adequate sediment supply is maintained. Recent vertical accretion rates in coastal marshes of the eastern United States have exceeded 5.5 mm/yr (Armentano & Woodwell,

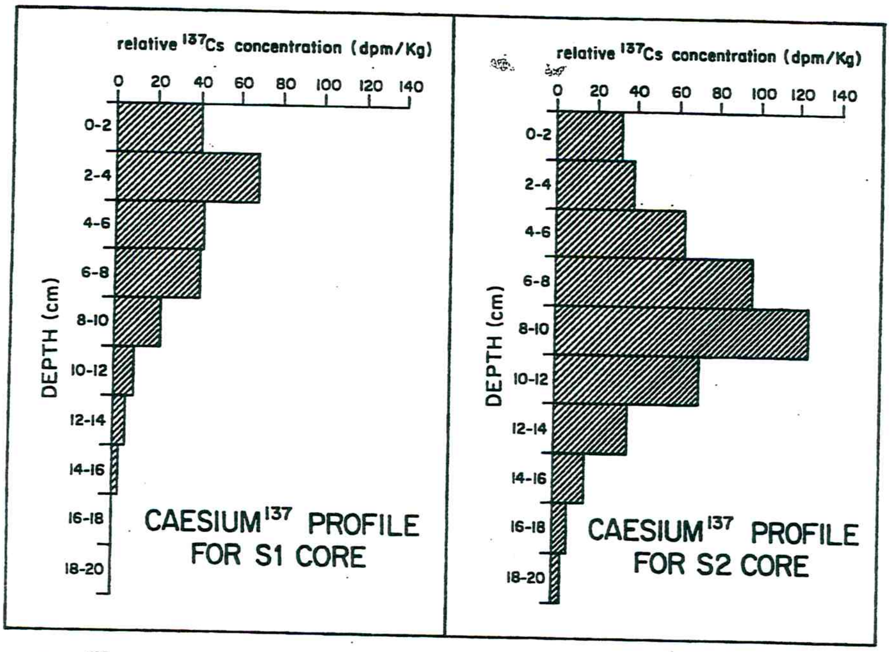

Figure 16 ^{137}Cs profiles from two cores at Old Hall Marsh, Tollesbury. Core S1 was taken from a higher area of a mature marsh; Core S2 was collected from a slight depression midway between two major creeks. The differing depth of the caesium peak indicates varying sedimentation rates related to marsh elevation (the peak ^{137}Cs concentration is related to the maximum deposition from atmospheric bomb testing ca. 1963). (After Saye, 1996)

1975; Delaune, Buresh & Patrick, 1978; Kearney & Stevenson, 1991; Kraft *et al.*, 1992). In the UK, Reed (1988) reported short term vertical accretion rates of 5-14 mm/yr on a Dengie Peninsula marsh, and French & Spencer (1993) reported short term accretion rates of up to 7 mm/yr on a young saltmarsh at Scolt Head Island, Norfolk. The evidence from Holocene sediment sequences in Great Britain suggests that marshes were unable to maintain stability only when sea level rise exceeded about 8 mm/yr (Tooley, 1992). On this basis, it seems unlikely that the rates of mean sea level rise experienced in southeast England during the past two millennia, and more specifically during this century, have been a major cause of saltmarsh erosion.

Increase in tidal range

Several tide gauge stations in northwest Europe show a significant increase in tidal range during the past 120 years, and in a few instances the trend can be traced back to the 16th century (Fuhrboter & Jensen, 1985). Analysis of selected UK tide gauge records by Woodworth, Shaw & Blackman (1991) revealed that mean tidal range has increased by 0.10 to 1.86 mm/yr over variable periods of record, at Southend, Blyth, Immingham, Dover, Newlyn, Avonmouth, Liverpool and Belfast, but decreased by 0.16 to 1.80 mm/yr at Lerwick, Aberdeen, Douglas and Holyhead. Although the effects of embanking, reclamation and dredging, particularly within estuaries, cannot be ignored (Bowen, 1972; Amin, 1983; van Malde, 1992), the observed changes appear to be attributable primarily to variations in the dominant M_2 tidal constituent (Woodworth *et al.*, 1991).

Dieckmann, Osterthun & Partensky (1987) suggested from work on the north German coast that there is a relationship between tidal range, sedimentation rates, and intertidal flat morphology. These authors suggest that the area of mudflat above Mean Tide Level (MTL) increases with increasing tidal range, owing to the fact that tidal flat sedimentation rates are highest above mid-tide level. Consequently they suggested that the observed increase in mean tidal range in the last century has been accompanied by a steepening, and possibly narrowing, of intertidal flats. However, Siefert (1990) found no evidence of a significant secular increase in the level of higher intertidal flats on the same coast. An examination of intertidal flat profiles in four areas in the UK (Humber, Wash, Medway and Severn) demonstrated that there is a relationship between tidal range and intertidal flat morphology, but the relationship is complex, depending on whether a tidal flat is predominantly accretional or erosional (Kirby, 1993). Whereas the hypsometric (area/height) curves for accretional sites are predominantly convex, those for erosional sites are predominantly concave, with a high proportion of the intertidal flat area at relatively low levels. Many of the intertidal profiles in Essex and north Kent, which have experienced some of the largest increases in tidal range in recent decades, are of the latter type (Kirby, 1990; Hull University, 1993a,b), suggesting that Dieckmann *et al.*'s (1987) hypothesis has little relavance in the UK context. There are in fact two reasons why increasing high water levels might be expected to lead to a reduction, rather than an increase, in inner tidal flat levels; firstly, an increased tidal prism at high water should increase the average tidal current velocities on both the flood and ebb tides; second, the greater water depth over the tidal flats should produce an increase in average inshore wave stresses, although the pattern will be spatially variable, and a reduction in the return interval for waves of a given magnitude (Townend, 1990; Mansard, 1990; Pethick, 1991). Both factors are likely to reduce the likelihood of mud accretion on the higher intertidal flats and may increase the likelihood of marsh edge cliffing.

Pethick (1992) argued that the morphology and dimensions of a marsh creek system are dependent on the tidal prism which enters the marsh during the flood phase, and the development of the marsh creeks may therefore be considered as a device whose function is to dissipate tidal wave energy. It follows from this argument that an increase in mean sea level, or in mean high water level, should result in some hydraulic adjustment of the tidal creek network. There are several ways in which the channel system could adjust in order to dissipate additional tidal energy, including widening and shallowing of the main channels, by increasing the total length of channel by headward erosion of the first order creeks, and by increasing the degree of creek sinuosity or bifurcation. All of these adjustments would increase the wetted perimeter and therefore the frictional resistance of the channel system. Conversely, a fall in sea level might be expected to result in a narrowing and deepening of the main channel, and infilling of some of the tributary channels. There is some evidence that such adjustments are taking place in the Essex and north Kent marshes, many of which are characterised by highly sinuous, high density drainage systems in which many of the first order channels end in elliptical mud basins. Comparison of Admiralty charts of different dates has suggested that the Blackwater and the Medway estuaries have shown a net tendency for channel widening and shallowing during the last century (Hull University, 1993a,b; Pethick, 1993). Much of the sediment eroded from the marsh edge and from the upper tidal flats has been deposited below mean low water mark in the outer estuary, although the area occupied by the low water channels has increased slightly, particularly in the inner estuary. However, it is not yet certain that these changes are primarily a response to sea level rise; recent increases in storminess and wave activity may also be important.

Tidal asymmetry

Net bedload and suspended load sediment transport in shallow coastal and estuarine environments is influenced to a significant extent by the nature of tidal asymmetry. The deep water tidal wave becomes distorted as it enters shallow coastal waters and estuaries, the nature of the distortion being dependent on non-linear interaction between the offshore tide and nearshore shelf and estuarine morphology. Distortion is reflected both in the duration of the flood and ebb limbs of the tidal hydrograph, and in the magnitude of the peak (or average) flood and ebb tidal current velocities. The nature and causes of tidal asymmetry in estuaries has recently received much attention (Boon & Byrne, 1981; Uncles, 1981, 1991; Speer & Aubrey, 1985; Aubrey & Speer, 1985; Dronkers, 1986; Friedrichs & Aubrey, 1988; Fry & Aubrey, 1990; Speer, Aubrey & Friedrichs, 1991; Shetye & Gouveia, 1992), but its significance in terms of saltmarsh accretion and erosion has so far received only limited consideration.

In some estuaries the duration of the flood tide is shorter than that of the ebb, and the peak velocities and tidal discharge during the flood are highest on the flood. In others, the ebb is shorter and has higher peak velocities than the flood. Estuaries of the former type are referred to as 'flood-dominant' while those of the latter type are described as 'ebb-dominant'. In practice the situation is more complex, since in many estuaries the nature and magnitude of tidal asymmetry varies spatially and may also vary over time with tidal height.

An asymmetric pattern of tidal current velocities may have important implications for the net direction and magnitude of sediment transport, with net landward movement of sediment being likely in cases of flood-dominance and net seaward movement likely in cases of ebb-dominance (Groen, 1967). Whether net import or export of sediment actually takes place will depend on the magnitude of residual currents (Cheng, 1990), on the calibre and relative amounts of sediment transported as bedload and in suspension, the importance of processes other than tidal currents in entraining and transporting sediment, including the significance of storm events in adding or removing sediment from the system, and on the effectiveness of sediment trapping mechanisms within the estuary, embayment or tidal basin.

At a global scale, numerous examples of both flood-dominant and ebb-dominant estuaries and tidal inlets have been reported. Both types of system occur in quite close proximity on the east coast of the United States (Boon & Byrne, 1981; Boon, 1975; Ward, 1981; Speer & Aubrey, 1985; Stevenson, Kearney & Pendelton, 1985), suggesting that the size and morphology of the inlet and basin systems exerts an important influence on the nature of the distortion. However, it is also evident that open coastal areas may also display a tendency for either flood- or ebb-dominance, although most are flood-dominated, encouraging the shoreward transfer of sediment (e.g. the coast of the Netherlands; Postma, 1967; Groen, 1967; Dronkers, 1986). Areas of ebb-dominance include parts of the English coast between Suffolk and north Kent, parts of the English Channel coast, and the Bristol Channel.

Dronkers (1986) suggested that estuaries are of two basic types in terms of their modifying influence on the tidal regime. Type 1 estuaries were defined as having relatively deep narrow channels with high, extensive tidal flats, whereas Type 2 estuaries have wide, shallow channels and low intertidal flats. In Type 1 estuaries there is a rapid increase in the ratio between the water surface area (A) and cross-sectional area of the entrance channel (a) as the tide rises. The frictional drag exerted by the high intertidal flats increases dramatically for each increment in height on the flood tide, retarding the progression of the flood tidal wave. Conversely, the frictional drag on the flow is exponentially reduced with falling height on the ebb, producing acceleration of the ebb flow as it becomes confined within the main channel. In Type 2 estuaries, there is only a slow increase in the ratio A/a as the flood tide rises. Consequently the flood tide wave crest progresses faster than the ebb tide wave trough, giving rise to higher peak current velocities on the flood than on the ebb.

Several previous studies have suggested that the development of tidal asymmetry within estuaries is also related to the development of 'over-tides', notably involving interaction between the dominant semi-diurnal (M_2) tidal component and its first harmonic, the M_4 tidal component (Aubrey & Speer, 1985; Speer & Aubrey, 1985; Uncles, 1981, 1991). When the M_2 and M_4 constituents are in phase, the flood tide is strengthened and the ebb tide is weakened; the reverse occurs when the M_2 and M_4 tides are out of phase. The M_4 tide has no astronomical source and may be generated as a non-linear, first-order interaction of the M_2 component.

In the Blackwater estuary, for example, there is a tendency for ebb-dominance in the outer estuary where relatively deep low water channels exist between the estuary mouth and Osea and Northey Islands, but in the inner estuary, which is relatively shallow and broad, there is a tendency for flood-dominance (Hull University, 1993b). The ebb-dominance in the outer estuary is mainly governed by the shape of the tidal curve in the adjacent open sea and is reinforced by the shape of the estuary. The Medway estuary is in many respects similar, have a narrow entrance at Sheerness, a large tidal basin in the mid-section, and an inner narrow section upstream from Chatham. The tidal regime between the entrance to the Medway and Bee Ness is ebb-dominated, but in the central tidal basin between Bee Ness and Chatham, where there are a series of relatively deep channels and low-level intertidal flats, there is a tendency for flood-dominance (Hull University, 1993a).

Upstream from Chatham the estuary narrows and the regime once again becomes ebb-dominated, possibly being reinforced by fluvial discharge. In the outer estuary peak ebb velocities reach 0.9 m/s, while peak flood velocities only reach 0.4 m/s. In the central section maximum flood velocities exceed 0.95 m/s and maximum ebb velocities are 0.55 m/s, while in the inner estuary maximum ebb velocities are 0.6 m/s and the maximum flood velocities 0.4 m/s.

Many of the estuaries in southeast and southern England show a tendency for ebb-dominance. By contrast, most of the estuaries and open-coast areas in northwest and eastern England, including the Dee, the Ribble, north Norfolk and the Wash, show a tendency for flood-dominance. However, there is presently great uncertainty concerning the significance of these trends in explaining the observed regional differences in saltmarsh accretion/erosion trends. Other things being equal, flood-dominance will tend to favour net movement of sediment into an estuary, whereas ebb-dominance will favour net export of sediment (Dronkers, 1986; Ward, 1981; Stevenson *et al.*, 1985). Under some circumstances, however, net landward transport of suspended sediment may occur despite ebb-dominance, for example where estuarine mixing processes produce landward residual currents (e.g. Gao, Xie & Feng, 1990), or where periodic storm events introduce large amounts of sediment to parts of an estuary from which it cannot subsequently be removed by normal tidal processes. Fine sediment is readily transported in suspension even by relatively low velocity flood tidal currents, and it may be deposited on higher intertidal flats and saltmarshes where ebb velocities are too weak to resuspend it. In this context wave processes clearly play a crucial role in determining whether sedimentation can take place; if material is retained in suspension it will be carried out again by the ebb tide. A further area of uncertainty concerns the fact that saltmarsh creek systems are to some extent capable of producing their own modified tidal regimes (Bayliss-Smith *et al.*, 1979). Much of the sediment deposition on the surface of a saltmarsh is induced by short term velocity pulses which are generated within the marsh creek system itself. It may therefore be possible for a marsh to accrete even though the sediment transport regime of the adjacent estuary is ebb-dominated.

Increases in mean sea level and tidal range may be expected to bring about significant changes in the way in which tidal waves propagate within estuaries. Preliminary work suggests that the nature of the response will vary significantly between estuaries of differing length, depth and plan morphology (Prandle, 1989), and further work is required to model individual cases. Modelling of palaeotidal changes during periods of sea level change has been initiated but is still in its development stage (e.g. Hinton, 1991, 1993).

Increase in storminess

Three main types of changes in wind/wave climate are of possible significance for the stability of saltmarshes:

- change in mean (or significant) wave height (and correspondingly in the return interval for a wave of a given height);
- change in wave direction;
- change in storm surge frequency.

Changes in wave height and crossing period are important determinants of the erosional power of the waves at the mudflat/saltmarsh interface. If there is an increase in significant wave height, or a reduction in the recurrence interval for waves of a given height, more erosion is likely to be accomplished in unit time, and the period available for recovery of the marsh between erosive events will be reduced. Changes in the directional variability of waves are equally important, because quite small changes in direction can significantly alter wave fetch and can have a major effect on longshore sediment transport rates. Since inshore wave height is strongly dependent on water depth, and wave energy is a power function of wave height, changes in the frequency of storm surges may be of particular importance. Storm surges also exert an important control on the occurrence of extreme tidal current velocities.

Visual observations and wave recorder data suggest that mean wave height in the northeast Atlantic and North Sea has increased in the past three decades, but the significance of these changes for coastal processes in the UK is not clear. At the Severn Stones Light Vessel, located in the Southwest Approaches, average wave height increased at about 1% (2 cm) per year between 1962 and 1986, although increases in predicted 'extreme' waves were much smaller (Bacon & Carter, 1989; Carter & Draper, 1988). Hoozemans (1991) and Hoozemans & Wiersma (1992) also reported that mean wave height increased in the southern North Sea during the period 1960-85. However, according to these authors, the increases in mean wave height are due mainly to an increase in the background 'swell-wave' component, there being no observed increase in local wind speeds over the period.

A more comprehensive survey of wave data from several stations around the UK over the period 1962-85 confirmed that there has been a significant increase in mean wave height since about 1965, increasing at about 2% per year (Bacon & Carter, 1991). Insufficient data are available to determine with certainty whether extreme wave heights also increased, although it is likely that they did increase at a slower rate than mean wave height. Since 1985, the UK has experienced a number of recent stormy winters, notably 1987-88, 1988-89 and 1989-90, which would reinforce the increase in extreme wave heights.

HR Wallingford examined variations in wind conditions and predicted changes in locally-generated wave conditions at several locations around the UK coast using their HINDWAVE model (Jelliman, Hawkes & Brampton, 1991). The results indicated considerable regional variation. Simulated 10% exceedance significant wave heights at Sunderland were found to decrease by 1-1.5% per year during the period 1976-88, whereas those at Dowsing and Kentish Knock increased by 1.5% per year over a similar period. There was very little change in significant wave height at Great Yarmouth, Littlehampton, St. Helier, Barry and in North Wales, although all areas except Barry showed a slight upward trend (approximately 0.3% per year) at the 1% exceedance level.

Analysis of changes in long-term wind-strength and directional variability of winds based on meteorological records for UK coastal stations suggests significant but locally variable trends in the past few decades. Local wind and wave conditions around the UK are heavily dependent on the tracks of mid-latitude westerly depressions, which show variability on a number of time-scales. The annual duration of winds >22 knots showed a marked decline at several west coast stations around the coast of England and Wales between 1914 and 1955, but there was no obvious trend at east coast stations during this period (Figure 17). Several west and east coast stations showed a marked increase in the frequency of strong winds between 1955 and 1965, after which time there was relative stability or a gradual decline. Between 1965 and 1992, after which date wind data ceased to be published in the Meteorological Office Monthly Weather Reports, there was a further increase in mean annual wind speed and the duration of winds >22 knots in SW England and West Wales (Figure 18), but little or no trend in NW England. Unfortunately data for east coast stations are less complete and less reliable, and detailed information about changes in wind direction over the same period are not available. However, analysis of individual storms has shown that the great majority of strong winds blow from the southwest or west, although in SE England strong winds from the south and southeast are also significant (cf. Burt & Mansfield, 1988; McCallum & Norris, 1990). Taken overall, the available meteorological data and independent evidence suggests a significant increase in the frequency and intensity of S and SW winds over southern Britain in the past 30 years.

Winds which generate waves from the direction of maximum fetch have greatest impact on saltmarshes. In the case of the Colne, Mersea Island, Dengie Peninsula and the northern side of the outer Thames estuary, storm waves from the southeast are likely to cause most damage, although easterly waves are also important. An analysis of hindcast wave records for the area off Clacton showed clearly that the period 1976-79 had a particularly high incidence of southeasterly waves; many saltmarshes and beaches in the area experienced rapid erosion during this period (Carpenter & Pye, 1996).

Storm surges frequently result in the breaching of sea defences and may trigger a progressive phase of erosion of former reclaimed marshland if the breaches are not repaired. The North Sea coast of eastern and southeast England is particularly prone to storm surges of up to 2 m which can produce extreme high water levels, e.g. Robinson (1953). Notable events which resulted in significant coastal flooding and erosion occurred in 1874, 1897, 1928, 1938, 1949, 1953 and 1978, and statistical analysis suggests that the frequency of extreme high water levels is increasing.

Natural estuarine channel variability

Estuarine channels experience natural periodic shifts in position, due to gradual meander migration, or more sudden changes during periods of high river flow, extreme tides or strong winds. A lateral shift in the position of the deep water channel produces a change in the slope of the intertidal profile and may alter the wave energy at the marsh edge (Carpenter & Pye, 1996). In general, periods of enhanced estuarine channel instability are related to periods of other climatic and tidal extremes; consequently the past 20 years have seen a relatively high degree of change, though perhaps less in SE England than in some other parts of Britain.

Dredging and navigation

Dredging carried out to increase or maintain the depth of water in an estuarine channel can potentially have one of two effects on the adjoining intertidal flats and saltmarshes. First, deepening may increase the flow velocities and the proportion of total tidal discharge which takes place through the main channel, reducing the velocities and average shear stresses over the adjoining tidal flats. Under such circumstances, net stability or accretion may be expected in the intertidal area. The second potential effect of dredging is to cause a progressive net movement of sediment from the intertidal flats into the dredged channel. This may arise through a variety of processes, including large-scale slumping of sediment on the margins of the channel, rill incision or increased wave erosion on the steepened margins of the channel. Channel deepening may also have a similar effect to embanking in modifying the up-estuary progression of the tidal wave. The over-deepened section of a dredged channel may also act as a sediment sink for coarser-grained sediment entering the estuary which would otherwise have been deposited in the intertidal or higher sub-tidal zones. Furthermore, since in many instances dredged material is dumped in the open sea, sediment may be permanently lost from the system.

Dredging has been implicated with saltmarsh loss at a number of overseas locations (e.g. Hackney & Cleary, 1987), but direct evidence of its negative impact on saltmarshes in the UK is limited. Both dredging and navigation have been suggested as factors contributing to saltmarsh erosion in the Suffolk estuaries (e.g. Beardall, Dryden & Holzer, 1991), but the effects have not been accurately quantified. Navigation has the effect of enhancing marsh edge erosion through the effect of boat wash, while settling of mud on the intertidal flats may be impeded by the increased turbulence generated by ship propellers. The problem is most severe in relatively narrow estuaries with a high density of navigation traffic, such as the Orwell estuary. However, speed restrictions are applied in many estuaries to reduce the problem.

Embanking and reclamation

Many British estuaries now have a much smaller intertidal area than formerly due to embanking and reclamation. A change in the estuarine morphology may be expected to significantly affect the progression of the tidal wave up the estuary. However, evidence suggests that estuaries can respond in at least two different ways to such changes. In some cases (e.g. The Wash and Ribble estuary), reclamation has apparently led to enhanced intertidal accretion due to its effect in reducing the tidal prism and therefore reducing average current velocities throughout the system, including the main estuarine channels, whose cross-sectional areas are progressively reduced by sedimentation (Carpenter & Pye, 1996). In the second type of situation, little sediment is available in the offshore areas, and a fully compensating reduction in estuarine channel capacity following reclamation and decrease in tidal prism is not possible. It can be expected that, if the area of intertidal flats and saltmarsh is reduced by embanking and reclamation, but the cross-sectional area of the entrance channel remains more or less unchanged,

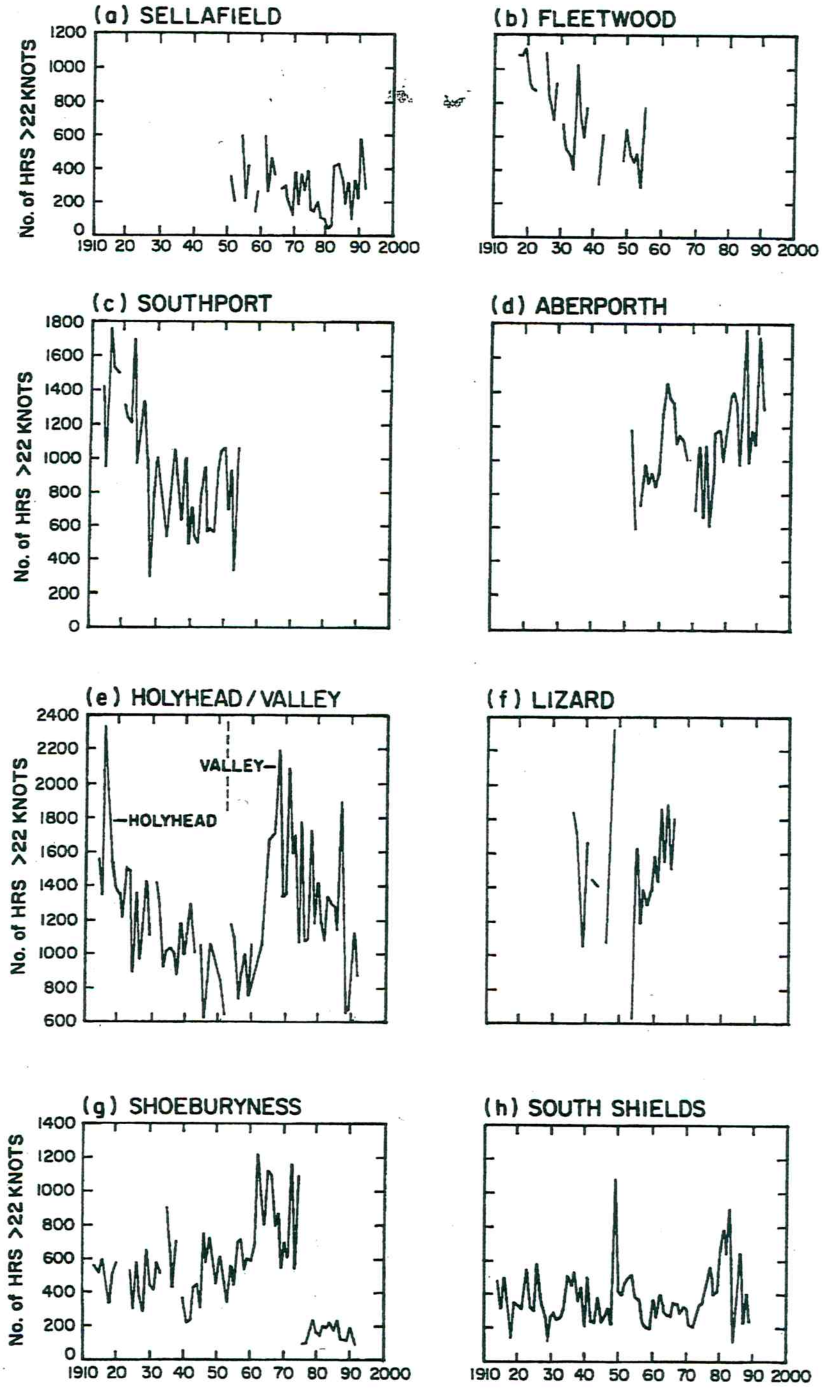

Figure 17 Variation in mean annual wind speed and duration of winds >22 knots at selected UK stations for the period 1914-1992, based on Annual Summaries of the Monthly Weather Report

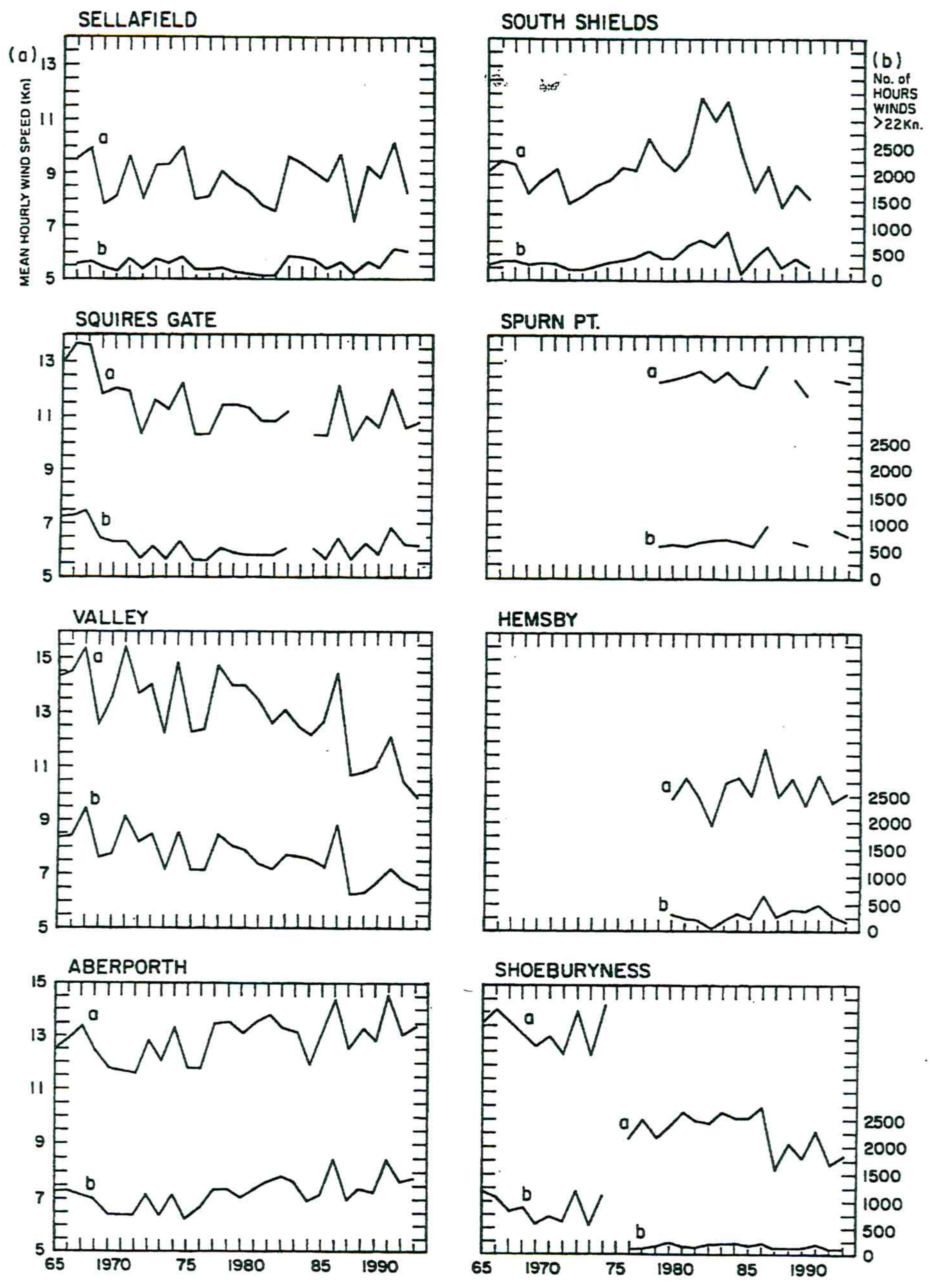

Figure 18 Variations in mean annual wind speed and duration of winds >22 knots at selected stations for the period 1965-1992, based on Annual Summaries of the Monthly Weather Report

frictional dissipation of tidal energy will be reduced, the flood tidal wave will progress more rapidly up the estuary, and both tidal range and current velocities will increase. The remaining saltmarshes on the outside of the sea embankments are therefore likely to experience erosion due to lowering of the intertidal flats, retreat of the marsh edge, and internal dissection as marsh creeks undergo deepening, widening and headward extension. Part of the sediment derived from marsh erosion will be re-deposited in the main channel as it strives to regain an equilibrium cross-section, but in areas of ebb-dominance a high proportion may be exported to the open sea. Such a situation appears to prevail in many of the Essex and north Kent estuaries at the present time. At least part of the increase in tidal range and tidal wave celerity observed in the Thames estuary over the last 200 years can be attributed to the effects of embanking and dredging (Bowen, 1972; Amin, 1983), and these changes have been reflected in the changing pattern of sediment accumulation within the estuary (Kendrick, 1984).

Breaching of sea defences

In many areas of reclaimed marshland the natural creek systems have been infilled or modified, and in some instances reticulate networks of artificial drainage ditches have been created. Furthermore, in the years following embanking there is normally an increasing height difference between the surface of the reclaimed marsh and that of the active marsh on the outside of the sea wall. This change in relative height is brought about by dewatering and compaction of the reclaimed marsh sediments, and by continued sedimentation associated with rising sea level on the surface of the active marsh.

If the sea defences are breached after a period of decades, a considerable depth of tidal water is able to flood the former reclaimed area. If the surface level is too low, pioneer and low saltmarsh communities may be unable to establish themselves, and the area will revert to mudflat or standing water. Even if saltmarsh vegetation does become established, the artificial drainage network will be hydrodynamically unstable and the system will readjust by attempting to recreate a new channel network which is more nearly in equilibrium with the prevailing tidal conditions. This process involves progressive enlargement and coalescence of the drainage ditches, ultimately creating complex channel networks with extensive areas of bare mudflat and residual marsh hummocks. Disintegration of the marsh normally begins close to the breach and progresses inland, but in the later stages, if there is still excess flood tidal energy, formation of mud basins may also occur near the landward limit of the rejuvenated marsh. There are many examples of this process, in varying stages of development, in Suffolk, Essex, and Kent (e.g. North and South Fambridge, Northey Island; Burd, 1994; Crooks & Pye, in press).

Vegetation dieback

Saltmarsh vegetation can experience periodic dieback due to a range of environmental stresses, either natural or human-induced. Natural stresses may be caused by excessive drought or waterlogging, burial by tidal debris or excessive sediment, sediment starvation, natural build-up of toxic substances in the root zone, biological parasites and diseases, or an increase in wave action. Human activities may influence many of the foregoing 'natural' processes, but the most common human-induced cause of dieback involves pollution by oil, toxic chemicals or farm waste. More rarely, dieback is caused by excessive trampling, over-grazing or other inappropriate land use, and in some instances is brought about by deliberate spraying with herbicide.

Extensive 'dieback' is a phenomenon which has been reported to affect primarily *Spartina* marshes in the UK, particularly on the south coast of England but locally elsewhere. It was apparently first recorded in the Beaulieu estuary in 1928, and became significant elsewhere, including Lymington and Poole Harbour, in the 1940s and 1950s. The nature and possible causes of the phenomenon were investigated by Goodman *et al.* (1959), Goodman (1959, 1960) and Goodman & Williams (1961). Two types of dieback were recognised, 'channel margin' dieback, and 'internal' or 'pan' dieback. The former affects a zone 1-5 m wide along the main estuarine channels and tributary marsh creeks, while the former affects the inter-creek areas. These surveys concluded that the problem is essentially a physiological/ecological one, in which poor-drainage plays an important role. Associations between dieback and areas of fine-grained, poorly aerated sediment, containing high sulphide concentrations, and with areas in which accretion of new sediment had been halted, were noted. The immediate mechanism of dieback was identified as involving the soft-rotting of the rhizome apex, although no unequivocal evidence of primary pathogenic fungal involvement was found (Goodman, 1959).

Experimental work by Havill, Ingold & Pearson (1985) showed that soluble sulphide concentrations significantly retard the growth of many higher marsh plants, although *Salicornia europea* and *Aster tripolium* were found to be relatively unaffected. The apparent toxicity of high sulphide levels may involve one or more suggested mechanisms, including (1) direct toxicity of the sulphide ion or of hydrogen sulphide, (2) the formation of highly insoluble sulphides of Fe, Cu and Zn, making these elements, and possibly sulphur itself, unavailable to plant roots, and (3) sulphide-inhibition of nitrogen uptake by plant roots (King *et al.*, 1982). However, the real importance of these mechanisms has not been determined. Other ionic species in reduced marsh sediments, such as ferrous iron and manganese, are also known to be potentially toxic to some saltmarsh and fen plants, at least in high concentrations (Singer & Havill, 1985; Rozema, Luppes & Brockman, 1985; Snowden & Wheeler, 1993). However, high concentrations of Fe, Cu, Zn and Mn are rarely found in marine and estuarine sediments where abundant sulphate is available for microbial sulphate reduction and sulphide production.

Several studies in the United States have shown that the vigour of *Spartina alterniflora* is closely related to the rate of input of new sediment (Delaune *et al.*, 1978; Nyman, Delaune & Patrick, 1990). Sediment accretion helps to prevent the development of poorly drained, excessively anoxic conditions in the root zone; the higher, better drained areas are subject to more effective tidal flushing, receive more nutrients and are less prone to the build-up of toxic products than low-lying areas. Marsh vigour is rapidly lost in areas where the supply of sediment is cut off, and frequency of tidal flushing reduced, following the diversion of tidal channels or embankment construction.

Pollution can have major effects on saltmarsh vegetation, but the effects are fairly localised and in some instances are short-term. Field studies (e.g. Beeftink *et al.*, 1982; Rozema *et al.*, 1985; Rozema *et al.*, 1990) have shown that marsh plant tissues can contain very high levels of heavy metals with little apparent adverse effects on vigour. Determinations of heavy metal concentrations in marsh and intertidal sediments in Essex and north Kent revealed levels that are unlikely to pose a serious threat to the health of the vegetation (Pye & French, 1993). High metal concentrations were found only in a few localities, such as the Holehaven Creek area, and even here they are of little significance in explaining the pattern of marsh erosion.

Spartina marshes are generally able to recover from a single oil spillage by producing new growth from protected underground buds, but they cannot tolerate chronic pollution of this type (Baker *et al.*, 1990). Heavy oils smother the plants and interfere with the process of oxygen diffusion from the shoots down to the roots. Light oils penetrate the plant tissues and disrupt membrane structures (Dicks, 1976; Dicks & Iball, 1981). The areas most at risk from this type of pollution are located near major oil refineries and storage depots, many of which have experienced spillages or more prolonged discharges of refinery effluent (e.g. the Isle of Grain and Bee Ness in the Medway, Canvey - Holehaven in the Thames). While there have been a number of documented spillages, the effects appear small-scale and short-lived by comparison with those of wave-induced erosion. *Spartina* marshes are not very extensive in SE England but where they occur (e.g. Shellness, Benfleet Creek, Isle of Grain, Stour estuary) they show little evidence of serious dieback.

Locally significant damage to saltmarshes can also occur where farm or sewage effluent is discharged on, or close to, saltmarshes. Eutrophication resulting from high levels of nitrogen and phosphorus can produce algal blooms which smothers the vegetation or produces high levels of toxic sulphide during decomposition. However, at a regional or national scale, such pollution is of minor significance compared with other causes of saltmarsh loss.

Reduction in sediment supply

Local variations in sediment supply result from the shifting behaviour of estuarine channels and coastal barriers, but at a larger scale there is evidence that there has been a general reduction in sediment supply to the coastal zone in the past two centuries as a result of coastal and river engineering works (Clayton, 1989, 1990). This problem is particularly acute on the coasts of southern and southeast England, where a very high proportion of the coastline is now protected, the rivers are highly regulated, and where supplies of sediment from the offshore zone are limited. On the east coast the main sources of sediment input to the coastal zone are provided by soft cliff erosion along Holderness and the north-eastern part of the East Anglian coastline, and by erosion of intertidal and subtidal clay outcrops areas between Suffolk and north Kent (McCave, 1987; Kirby, 1987). Satellite data and the results of water sampling suggest that the waters of the Outer Thames estuary and adjacent southern North Sea are characterised by relatively recreation urgently need to be explored. One possibility for further investigation is the creation of a series of artificial back-barrier marshes and tidal flats on more open sections of the coast and in the larger estuaries, using capital dredgings and selective use of armour stone to provide a semi-rigid framework. A number of 'foreshore recharge' trials have already been carried out, in Hamford Water and elsewhere, using dredged material, and offshore breakwaters are being increasingly used in beach management schemes (e.g. at Sea Palling in east Norfolk). Permeable wave breaks consisting of Thames lighters have been employed on the Dengie Peninsula and in Hamford Water with some promising results, although the negative aesthetic impact of these measures is considerable. For the future, the need is to design flexible but effective 'structures' which simulate the behaviour of natural features and blend in with the environment in which they are placed.

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