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Saltmarsh Change in England & Wales:

Its History and Causes

HR Wallingford Ltd

R&D Technical Report W12

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Saltmarsh Change in England and Wales - Its History and Causes

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Technical Report W12

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This document analyzes regional historic changes in saltmarshes and establishes the relative importance of the potential causal factors. Both hydraulic and non-hydraulic causes are investigated. It identifies appropriate management methods to counter-balance the increasing pressures placed on saltmarshes.

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Technical Report W12

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EXECUTIVE SUMMARY

The continued loss and deterioration of saltmarsh in southern England and Wales puts an increasing strain on sea defences. In order to plan future flood protection management strategies, the NRA saw the need to assess historical changes and investigate their probable causes, and from this work determine the likely causes of present erosion and loss in plant vigour.

This study charts regional changes in saltmarsh extent and vigour in England and Wales, and the likely causes of these changes. The relative importance of the various forcing factors (including hydraulic, chemical and anthropogenic) that have the potential for driving the change, was investigated. Natural hydraulic changes, i.e. changes in wave heights, storm frequency, wind direction, relative sea level rise, tidal range, and channel migration, were established using a combination of hindcast modelling, analysis of wind and water level records, and literature review. The variation in these forcing factors were correlated to saltmarsh changes (determined from site visits and literature review) in order to determine the relative importance of each. The significance of non-hydraulic natural factors such as sediment chemistry and sediment supply on saltmarsh change were also considered, as was the impact of human activity. For each potential forcing factors, guidelines were provided on management methods which would counteract or combat saltmarsh loss.

This study concluded that several factors have contributed to saltmarsh change over the last few centuries. Their relative importance varies both spatially and temporally.

General conclusions regarding the causes of saltmarsh change are that even before humans had a noticeable impact, fluctuations in the areal extent of saltmarshes did occur due to variations in climatic factors and shifts in the channel position. In the last few hundred years, human activity has been the greatest cause of change in areal extent of saltmarshes. The most significant activities were reclamation, engineering works, dredging and shipping, and planting *Spartina anglica*, a vigorous cord-grass hybrid. Closer to the present date, the results of this study suggest that the major causes of lateral erosion of saltmarshes in southern England (bar those close to navigation channels) are natural. Coastal squeeze is not a significant problem on the scale of several decades, and the potential transgression if sea walls did not exist is a couple of orders of magnitude lower than erosion of the seaward edge at severely eroding sites. Lateral erosion in Essex seems to be caused by the increasing trend in wave heights and this is exacerbated by the relatively low tensile strength of the sediment (caused by a high water content) and relatively low supplies of offshore sandy sediments which can be transported onshore to buffer the increase in wave energy. Degeneration of *Spartina* saltmarshes on the south coast is also likely to be due to mainly natural rather than anthropogenic causes. Plant damage at the seaward edge is most likely to be due to increases in wave energy. As *Spartina* grows so low in the tidal frame, *Spartina* marshes respond to increases in wave height before marshes dominated by other species. Loss in *Spartina* vigour in the interior of the marsh, particularly in low-lying basins or areas remote from creeks, is probably due to physiological stresses due to a change in sediment chemistry as the sward ages or basins develop due to sediment starvation. Conditions become more anaerobic with associated greater concentrations of plant toxins like hydrogen sulphide, due to a build up of organic matter and reduced flushing and drainage. The weakened plants are rendered susceptible to disease and fungal infections.

The research has established that hydraulic forcing factors such as storminess and wave energy fluctuate significantly, and that these fluctuations cause periods of saltmarsh accretion and erosion. Sedimentological evidence suggests that this has always been the case, but perhaps erosion is more noticeable now as the intertidal area has been narrowed by land reclamation. Thus lateral erosion of 20m on a 40m wide saltmarsh has more impact on flood protection than the same amount of erosion on a 100m wide saltmarsh.

KEY WORDS

Saltmarsh, Historical, Change, Causal Factor, Hydraulics, Waves, Relative Sea Level Rise, Tidal Currents, *Spartina*, Sediment Supply, Human Impact, Enclosure, Shipping, Dredging, Coastal Squeeze, Chemistry, Management.

1 Introduction

1.1 Project objectives

This project forms part of a research programme which is being conducted within the Environment Agency R&D Commission for "Flood Defence - in Coastal and Tidal Defences and Process". It is one of a suite of studies which aim to extend the understanding of saltmarsh processes and their interaction with external influences. The research findings of this study should aid the development of strategic coastal management and planning.

The overall objective for this Research Contract is "to analyse historic changes in saltmarshes, establish the likely reasons for these changes and to identify management methods appropriate to counter-balance the increasing pressures placed on saltmarshes". The perceived need for this information is to provide guidance on (1) how the natural defences provided by saltmarshes can be sustained, (2) whether the factors causing an increase in incident wave energy or greater tidal currents on the saltmarsh can be ameliorated, and (3) if not the need to realign the defence further inland in order to recreate saltmarsh habitat.

In order to achieve these objectives, key goals were established:

(a) Undertake a literature review of information on historical changes in saltmarshes

(b) Undertake a desk top analysis of information gained through (a) above and any further information available to the contractor or the EA

(c) Establish the rates of change and the underlying reasons for such changes

(d) Identify appropriate management methods capable of addressing such changes

(e) Produce an R&D Research note summarizing the above

(f) Produce a draft chapter for the EA's Saltmarsh Management Guide based on the R&D Research note produced in (e) above

It is necessary to determine the cause of saltmarsh change in order to manage the coastline most effectively in the next century and beyond (see section 1.3). In this research report we attempt to identify the causes of change by adopting the following approaches:

- Collect and collate data on changes in physical forcing factors and saltmarshes to investigate whether changes in hydraulic conditions are responsible for saltmarsh change (this will be attempted through correlation analysis and case studies).

- Assess the effect of human activity on saltmarsh change (this work will be achieved through appraisal of the literature, consultations and site visits).

- Investigate the role of sediment chemistry on the health of saltmarsh plants and the erodibility of the sediment.

For each causal factor of saltmarsh loss, advice is given on management schemes which would alleviate the influence of the factor. The causal factors for which it is not possible to retain the saltmarsh in its current position by management intervention are identified. For these cases the only option to maintain the current saltmarsh area is managed realignment.

We also assess the link between saltmarsh erosion and past seawall breaches by determining what factors controlled the position of past breaches (e.g. seawall condition, wave height, saltmarsh width etc). This analysis was used to produce a list of criteria to assess the risk of a seawall breach, which could then be used to identify areas vulnerable to breaching. Where seawalls have breached and saltmarshes have developed landwards of the breach, their development was assessed. Particular attention was given to creek and floral establishment. This information will be useful for advising methodology for the creation of saltmarshes through *coastal realignment.*

This report is made up of eight sections. The remainder of section 1 discusses the causes of saltmarsh change and explains why this information is necessary for strategic coastal planning. Section 1.3 also points out why it is so difficult to decipher what factor, or combination of factors, is causing saltmarsh erosion. Section 2 outlines the method of data collection and interpretation. The changes in saltmarshes of England and Wales are summarised in section 3. The forcing factors that may theoretically cause saltmarsh change are described in sections 4 and 5. The former is confined to hydraulic conditions and the latter to non-hydraulic forcing factors such as human activity and natural chemical and biological cycles. For each of the forcing factors, collected data are analysed to determine whether there is evidence that the factor causes change. Section 6 gives guidance to coastal managers on how to identify what factor(s) are causing erosion on a given saltmarsh/mudflat system. Possible management methods to combat saltmarsh loss are also given. The relationship between saltmarsh loss and breaches in seawalls is examined in section 7, and the necessary criteria to predict the likelihood of breaching are defined. Advances in information regarding the cause of saltmarsh change and the further work needed to improve understanding of this subject are summarised in the concluding section. This section also contains recommendations for future coastal management to maintain the area of saltmarsh habitat. Section 8 presents a summary of the main conclusions and recommendations.

This work was undertaken by HR Wallingford, with support from Reading University.

1.2 Introduction to the processes that cause saltmarsh change

1.2.1 Definitions of saltmarsh change

There are five major categories of saltmarsh change:

- Lateral extent (width and length)
- Elevation (due to accretion or erosion)
- Creek density (caused by creek lengthening, new developments, infilling or truncation)
- Floristic composition (plant species change due to succession, grazing, and change in tidal level relative to vertical sedimentation rate)
- Vegetation vigour

Changes in any of the above can affect the sea defence value of a saltmarsh. The best standard of defence would be provided by a wide, high saltmarsh, with low creek density so that the saltmarsh acts as a solid berm (current and wave dissipation would be less effective with a high creek density as frictional drag is lower in the creek than on the vegetated saltmarsh surface), colonised by tall and dense vegetation which is efficient in dissipating wave energy and tidal currents. A reduction in width, due to erosion or reclamation would reduce its sea defence capacity. Likewise, so would vertical erosion, internal dissection, and probably heavy grazing which greatly reduces vegetation height. A reduction in plant vigour, such as the dieback of *Spartina* in southern England, would also have a deleterious impact on the efficiency of wave and current dissipation across the saltmarsh.

1.2.2 The natural processes that may cause saltmarsh change

Salt marshes occupy the upper part of the inter-tidal zone and should be viewed as a part of a continuum with the adjoining intertidal mudflats or sandflats. The intertidal profile as a whole strives to maintain a form which is in dynamic equilibrium with the hydraulic forces acting on it and with the available sediment supply. The magnitude of these hydraulic forces varies temporally, on timescales varying from a few hours to centuries of even longer. On the open coast, temporal variations in inshore wave conditions are of over-riding importance in the short to medium term, although sea level rise and changes in tidal range are also of great importance in the longer term. Within estuaries, variations in tidal currents are of greater shorter term importance, although wave processes are not insignificant, particularly within larger estuaries. In the longer term, sea level rise, changes in tidal regime and variations in sediment supply exert critical influences on estuarine morphodynamic behaviour.

It is important to remember that saltmarshes are dynamic habitats. They are ephemeral features at a particular location on a geological time-scale. As they are inter-tidal features, their position changes according to sea level fluctuations and the topography of the land. Hence, in periods of sea level fall, the saltmarsh zone would migrate seawards, and under the opposite scenario of rising sea levels (such as we are currently experiencing) the saltmarsh zone will shift landwards, if the topography of the land allows.

The width of a saltmarsh between land and sea is strongly influenced by tidal range, so those in the Mediterranean are generally much narrower than in Britain. Moreover, changes in the shape of the tidal curve could also affect saltmarsh morphology. For instance, a steepening in the ebb limb of the tidal curve means that the ebb velocity must increase and hence there is an increased risk of erosion.

New saltmarshes develop in areas where the hydraulic conditions are calm enough to allow the accumulation of silt particles. The requirement that saltmarshes have for quiet hydraulic conditions explains why they deteriorate and erode when there is an increase in incident mean wave height and/or storm frequency. Like beaches, the saltmarsh/mudflat system responds to changes in wave energy, both short term oscillations and long term secular trends (IECS 1993). Changes in sediment supply may also alter the position or character of saltmarshes. Where sediment supply is adequate, the vertical accretion of a saltmarsh can keep pace with sea level rise as the increased frequency of inundation allows more opportunity for sedimentation.

Spatial distribution and vigour of plant species depend on elevation of the saltmarsh surface, sediments and soil chemistry. For example, upper saltmarsh species such as *Halimione atriplex* can grow on a creek bank at lower levels than it is usually found as the increased rate of flushing and drainage of the pore waters does not allow the build up of toxins (see sections 4.2.3 and 4.3.4). In general, conditions become more difficult for plant growth towards the sea. This is because of the increase in inundation frequency which:

- intensifies hydraulic stress on the plants and
- raises the water table closer to the marsh surface (due to the greater opportunity for water to infiltrate and the reduced drainage period).
- reduces time for photosynthesis

The diffusion of oxygen through saturated sediments is about 1000 times slower than through air. Aerobic bacteria in the surface sediments quickly consume the penetrating oxygen so that the deeper sediments are anoxic. In the absence of oxygen, bacteria use alternative oxidising agents to gain energy from their food, such as ferric ions ($Fe^{3+)}$ and sulphate ($SO_4^{2-)}$. This is called anaerobic respiration and the end products, e.g. ferrous ions ($Fe^{2+)}$ and hydrogen sulphide (H_2S), are deleterious to plant health. The zonation of saltmarsh plant species is greatly determined by tolerance to the photo-toxins produced by anaerobic respiration.

Change in relative sea level can lead to change in species distribution. If the rate of vertical accretion falls below the rate of relative sea level rise there will be a change in the plant community to one which is characteristic of a lower elevation, i.e. an increase in the extent of the pioneer and low marsh species. Conversely, a fall in relative sea level, such as that experienced in parts of Scotland, will encourage competitive displacement of lower saltmarsh plants by upper saltmarsh species.

Vegetation vigour may also be controlled by natural cyclicity of growth and decay. Their is some evidence that the elevation of the marsh surface marsh surface is an important control on the size and sexual reproduction of *Spartina* in the Solent (HR, 1996). To summarise, the only healthy stands of *Spartina* in the Solent are found around the ESSO oil refinery at Fawley. The elevation is lower than elsewhere in the Solent because of the history of oil pollution from 1950-1970 which killed off most of the vegetation and lead to erosion. Since the 1970's a restoration programme has been instigated and the saltmarsh is now revegetated and vertically accreting. By contrast the vertical growth of the *Spartina* dominated saltmarshes in areas like Lymington Harbour continued unimpeded. As the elevation of the saltmarsh surface grows closer to the elevation of mean high water, the rate of sedimentation decreases (French 1993). It may be that *Spartina* and other species needs a supply of sediment with its associated nutients and minerals to maintain healthy growth.

1.2.3 Saltmarsh accretion/erosion

Saltmarsh loss occurs when erosion outweighs accretion, hence loss can either be due to an increase in erosional forces or a decrease in ability of the mudflat/saltmarsh to obtain and hold onto sediment. The principal hydrodynamic and sediment processes that affect accretion and erosion are illustrated in Figure 1.1.

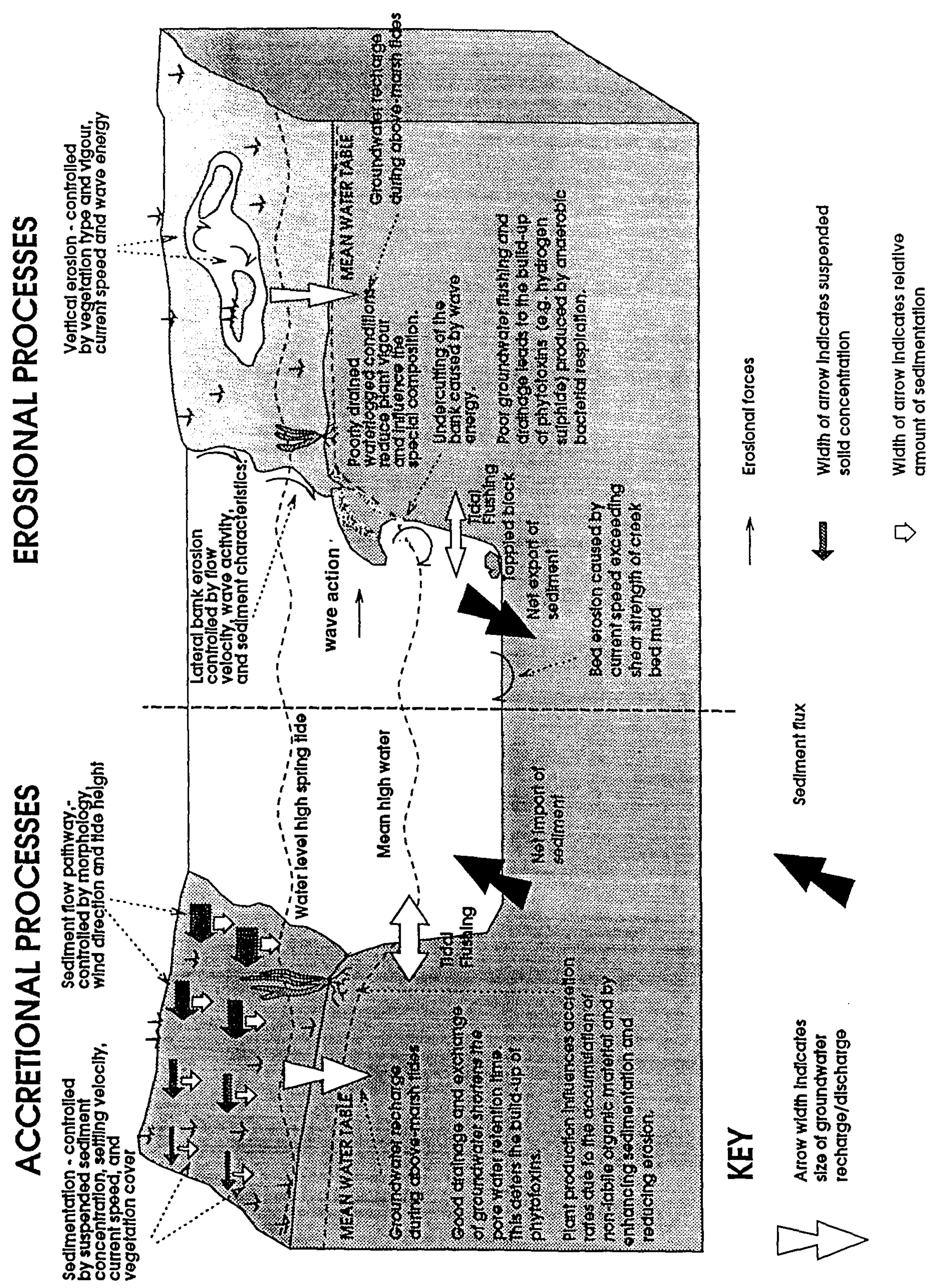


Figure 1.1 **Diagrammatic representation of principal hydrodynamic and sedimentary processes affecting accretion and erosion in saltmarshes**

Saltmarshes can only erode when the shear stress exceeds the shear strength of the sediment. Shear stress may be in the form of waves or tidal currents. Tidal currents are only important in causing erosion of the front edge of saltmarshes when estuarine or offshore channels are migrating. Currents due to water flow from the marsh surface into the creek after large tides that inundate the marsh surface are also an important cause of creek lengthening which causes a loss in the vegetated area of the marsh by internal dissection. Change in wave energy is often a significant factor causing erosion of the seaward edge, hence narrowing of the saltmarsh strip may indicate that incident wave energy is increasing.

1.3 The role of establishing the cause of saltmarsh change in strategic coastal management planning and the difficulties involved

Present saltmarsh change in the British Isles comprises erosion, accretion, decline in plant vigour, and a change in the composition of plant communities (HR, 1996). One of the EA's interest in saltmarshes is from the viewpoint of their sea defence value. Thus they are mainly concerned with saltmarsh changes that affect the sea defence capability of the saltmarsh. These adverse changes include:

- vertical and lateral erosion
- reduction in shoot length or density which reduces the capacity for wave and tidal current dissipation.

Changes in the opposite direction to the ones listed above would enhance coastal protection provided by a saltmarsh. Changes of this sort would still be of interest to the EA as this extra protection should lengthen the active life of existing sea defences and should therefore be considered when forecasting long term expenditure.

To maximise the cost-effectiveness of strategic coastal management planning it is necessary to determine the factors causing erosion and whether the trend is likely to continue in the future. These factors are discussed in the rest of this section and the difficulties in determining the cause of saltmarsh change are outlined.

1.3.1 Determining the factors causing change

Increase in the wave energy incident on the saltmarsh is the main cause of erosion for open coastal marshes, but what is often not clear is the **cause** of the increase in wave energy. What we have to ascertain is why the incident wave energy at the marsh site is increasing. Is it due to climatic changes over which we have no control or could it be caused by human alteration of the coast (e.g. lowering of the foreshore due to dredging, causing deeper water and hence larger potential waves, or waves produced by ship movements)? The following changes in forcing factors could all cause an increase in wave height and hence the potential for erosion.

- Increase in wind speeds
  (increase in mean wind speed causes a linear increase in wave height)

- Increase in mean fetch
  (a change in wind direction may cause wave height increase even if the mean wind speed remains constant, if the mean distance that the wind blows across the water increases. This is particularly important for estuarine saltmarshes where the waves are mainly

internally generated and wave heights are fetch limited)

- Relative sea level rise
  (the increase in water depth increases the potential wave height)
- Lowering of the inter-tidal zone due to slumping after dredging
  (the increase in water depth increases the potential wave height)
- Alteration of the shape of the tidal curve due to dredging
  (steepening of the ebb limb of the tidal curve increases tidal currents and enhances the removal of sediment from an estuary)
- Coastal structures which interrupt longshore drift and starve the downdrift side
  (the increase in water depth increases the potential wave height)
- Failure of sedimentation rate to keep pace with relative sea level rise
- Increase in tidal range
  (the increase in MHW leads to a significant increase in the water depth above the marsh surface and hence increases the potential wave height)
- Increase in storm frequency
  (leads to saltmarsh loss if accretion between storm events does not replace the eroded material)

To rationalise strategic coastal management planning, the relative importance of each of the above factors on saltmarsh erosion needs to be established. For example, if the most significant factor was relative sea level rise, the cause cannot be ameliorated and hence efforts to maintain the saltmarsh in its current position would be futile. In such circumstances the only long term option is to allow retreat. However, if the wave increases are due to dredging, this can be tackled by legislation, changes in dredging practice, or alternative defence measures. Unfortunately, it is often very difficult to differentiate the impact of the different possible causes of an increase in wave height as it is probable that several of the forcing factors may be changing simultaneously. It is only possible to determine the alteration in wave height caused by a particular forcing factor in a controlled environment where only one variable is altered at a time. This could be achieved by physical or numerical modelling (see section 8.4.3). At present, little such research has been conducted and therefore we have great difficulty in determining which hydrodynamic changes are intensifying erosion and suppressing accretion.

As long term temporal data relating to changes in forcing factors and associated morphological changes do not exist (the closest is a two year programme of monitoring wave heights and vertical and lateral change on an Essex saltmarsh (IECS 1988-1991), spatial data have to be substituted for temporal data. Due to the variability in the relative importance of the processes affecting accretion and erosion at the different sites, correlations between the forcing factors and saltmarsh response will be low. For example, an increase in fetch caused by a change in the wind directional variability may be an important contributory factor to saltmarsh erosion at one locationand accretion at another within estuaries but as this factor is much less important at open coastal sites, correlation analysis which includes a wide range of saltmarsh locations might indicate that no significant relationship exists.

1.3.2 Determining whether the observed saltmarsh change is a fluctuation or a secular trend

The previous section points out that saltmarsh change can be induced by variations in many different factors. Before reclamation reduced the inter-tidal zone and seawalls limited the landward extent of saltmarshes, oscillations in these factors, which caused changes in the position of the seaward edge, went greatly unnoticed. But today, fluctuations in saltmarsh width are apparent as the change is a sizeable proportion of the remaining saltmarsh. To rationalise coastal management operations, it is necessary to determine whether saltmarsh erosion is likely to be a short term fluctuation or a secular trend. For example, major works to combat saltmarsh erosion would be a wasted investment if the cause of erosion was just a fluctuation and if left alone, the saltmarsh would have started to accrete before the seawall was in danger. Similarly, it would not be economically justifiable in the long term, to sanction a maintenance scheme that attempted to retain saltmarshes in their current position if the cause of the change was a strong secular trend in a forcing factor. Another management option such as coastal realignment should be considered.

One aim of this research is to investigate the influence that cyclic changes such as the 18.6 lunar nodal cycle has on saltmarshes (see section 4.2.4 and 4.3.5). If this is found to be important, then fluctuations in seaward extent would be predictable. Ideally, if erosion commenced during the rising limb of tidal range coastal managers should wait to see if the situation would reverse on the falling limb before taking interventative action. However, in practice decision makers rarely have the luxury of being able to wait 10 years, since in situations where the saltmarsh is very narrow even a fluctuation in the forcing factor could threaten the integrity of the seawall.

2 METHODS OF DATA COLLECTION AND INTERPRETATION

2.1 Literature review

A search for published literature on saltmarsh change and changes in the forcing factors affecting saltmarshes was undertaken by the following methods:

(a) 114 abstracts of papers relating to changes in British saltmarshes were identified from the Science Citation Index and printed. Copies of the full tect of most promising papers were obtained.

(b) The library database at HR Wallingford was interrogated and data of changes in hydraulic conditions around the UK coastline and measurements to study the cause of saltmarsh loss were abstracted.

2.2 Saltmarsh information form

The published literature on the subject of saltmarsh change is almost entirely written by academics. Site coverage is limited as research tends to concentrate on areas for which background information already exists (such as the Severn Estuary and Scolt Head Island). Therefore, the geographical coverage of knowledge of saltmarsh change is restricted. Moreover, the period of data collection for academic studies tends to cover only a few years, generally the duration of a Ph.D The literature search did not unearth a single study which regularly (i.e. at least once a year) recorded the changes in saltmarsh width and elevation over a medium term time scale (around 20 years). To establish the cause of saltmarsh change, it is necessary to correlate changes in forcing factors with saltmarsh response (see section 1.3). This is only possible if saltmarshes have been systematically monitored to provide a data base of saltmarsh change which can be compared to changes in wind, storm frequency, anthropogenic activity etc.

This research attempted to obtain information on the current accretion/erosion status of UK saltmarshes, and to identify saltmarshes for which systematic monitoring has been conducted, by sending a questionnaire to the many bodies responsible for saltmarshes in England and Wales. These included County Councils, District Councils, EA regional offices, English Nature regional offices, MAFF, Ports and Harbours Authorities, Wildlife Trusts and private owners. In total, 156 report forms were sent. The questionnaire requested:

- Saltmarsh name and location
- Types of saltmarsh change noted
- Whether these changes have been systematically monitored
- If so, how were the changes monitored
- Whether the monitoring results are available in a report

Fifty completed questionnaires were returned, can be found in Appendix B of the project record from the NRA R&D research project 567. Respondents who specified that monitoring had been conducted, and that results were available, were contacted.

2.3 Numerical modelling and analysis of changing hydraulic inputs

2.3.1 Introduction

Many aspects of the natural environment are subject to cyclic or secular changes, which may have an effect on saltmarshes. Parameters such as wave height, wave direction, wind speed, storm frequency, tidal levels and tidal currents may thus be thought of as *forcing factors*. Parameters such as saltmarsh elevation and extent, and health of vegetation, may be thought of as *responses*.

There is a great deal of high quality information on wind speed and tidal levels: data for a small number of stations goes back over one hundred years. Unfortunately there is very little instrumentally measured data on the more important wave height, wave direction, storm frequency and tidal current parameters, not to mention the uncertainty in the records (if any) of the *responses*.

All of this, coupled with the weak dependence expected between some of the forcing factors and some of the responses, makes numerical analysis of correlation between changes a very uncertain procedure. Nonetheless, it seemed worthwhile to draw the best inferences available about the less well-recorded forcing factors from whatever data were readily available.

Tidal current speed is roughly proportional to the tidal range, and in particular, the maximum current is roughly proportional to the maximum rate of change of tidal elevation during the tidal cycle. Thus changes in tidal currents, at least in the vicinity of tide gauges, could be tentatively inferred from long term tidal elevation records.

Long term measurements of waves are scarce, and those that do exist tend to be for deep water locations, well away from saltmarshes. However, long term measurements of winds (which generate the waves) are available for many locations around the UK, with hourly digital data often going back to 1970. Wave hindcasting models were run with several long term wind data sets already held at HR Wallingford, to convert the hourly wind data into equivalent hourly wave data, covering periods of 10-30 years. The key parameters of wave height, wave direction and storm frequency could be extracted from the hourly data.

For any parameter for which long time series data are available, the year-by-year variability and trends can be determined. This can be done, for example, for mean values, and for values exceeded certain percentages of the time, say 10% and 1%. If appropriate, the analysis can be restricted to periods of interest, for example the top one third of the tidal cycle, when saltmarsh surfaces may be under water.

2.3.2 Tidal current modelling

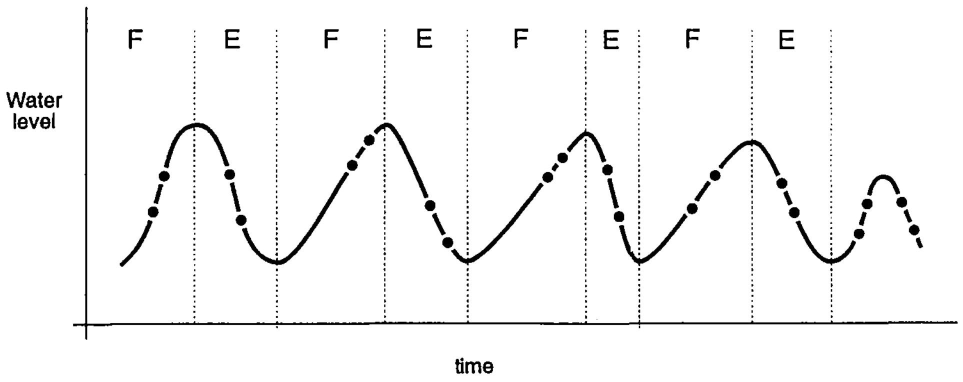
Information on changing mean sea level and tidal range is available in the existing literature. However, the effect of changes in the tidal curve on tidal currents has not been explored. If the ebb part of the tidal curve (i.e. when the water level is falling) steepens over time, the associated increase in ebb currents may remove intertidal sediments. Likewise, an estuary which becomes flood dominant (i.e. maximum current velocities occur during the period of rising water levels) is more likely to be a sediment sink as sediment is swept into it.

A method to identify small changes in the gradient of the tidal curve (and hence peak tidal currents), from water level records, was developed during this research project. The results can be used to ascertain the following at a particular site:

- whether there have been changes in the maximum gradient of the tidal curve which could lead to significant changes in tidal currents
- the impact of dredging operations on the slope of the tidal curve
- the sensitivity of the tidal curve gradient to changes in water level. Changes in water level during 18.6 year lunar nodal cycle are greater or comparable to sea level rise, thus the likely impact of secular sea level rise on tidal currents can be estimated by seeing if the gradient of the tidal curve changes during an 18.6 year cycle.

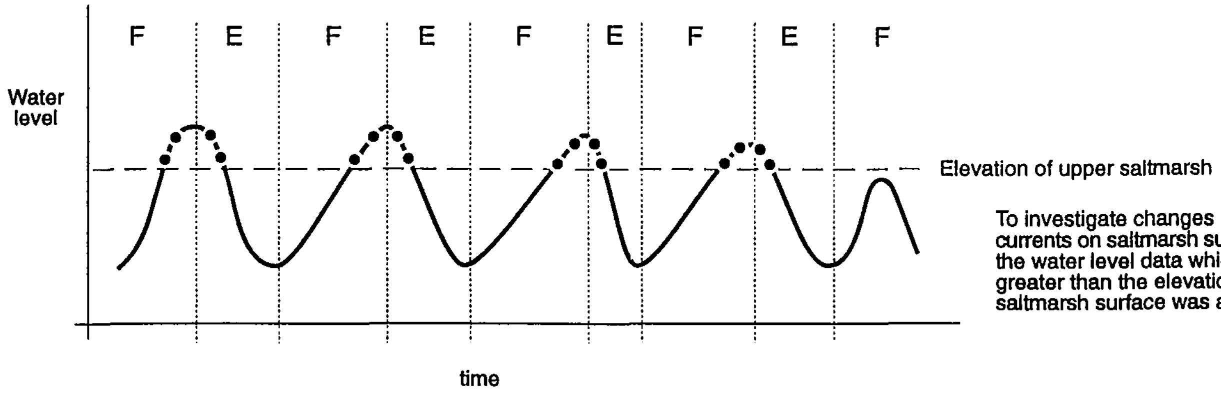
A simple computer program was written to determine the maximum hourly *increase* in water level on each successive flood tide and the corresponding maximum hourly *decrease* in water level on the ebb tide, from measured tidal elevation records. The program was run twice; on the example data set of Immingham water level records, the difference between the runs was the water level range in which the maximum current speeds were predicted. Figure 2.1 illustrates the information extracted by the computer model from the data set. The first run looks for the change in water level for the greatest hourly change in water level anywhere in the flood and ebb portions of the tide. This analysis will give an indication of a change in currents which affect the inter-tidal zone, but not necessarily the surface of the saltmarsh as the increase in tidal current may be associated with an elevation below the saltmarsh. However, increases in erosive forces affecting mudflats can lead to lateral erosion of saltmarshes as the increase in water depth fronting the saltmarshes increases the potential wave height incident on their seaward edge. For the second computer run, only data above a certain threshold corresponding to the saltmarsh elevation were used to analyse changes in the currents which would affect the vertical accretion/erosion of saltmarshes.

For both analysis (a) and (b) illustrated in Figure 2.1, the maximum flood and ebb rates of change of elevation were averaged over successive periods of one year, in order to look for cyclic and longer term trends. Any such change would strongly suggest a corresponding change



The hour experiencing the greatest rate of change in water level in each flood and ebb tide was identified, and the change recorded. The mean maximum water level change was calculated for each year

(a) analysis of change in maximum tidal currents affecting the inter-tidal zone



To investigate changes in tidal currents on saltmarsh surface, only the water level data which was greater than the elevation of the saltmarsh surface was analysed

(b) analysis of change in maximum tidal currents affecting the saltmarsh surface

Figure 2.1 **Illustration of the information extracted by the computer program from water level records. Annual means of the greatest hourly change in water level were analysed to search for cyclic and secular trends in maximum tidal currents**

2.3.3 Wave modelling

Deep water storm wave conditions are primarily dependent upon wind conditions (speed, direction and duration) over the preceding half day a day or so, and the shape and size of the area in which the waves are generated. Waves may be modified nearer to the coast by any local physical features, and by wave transformations in the nearshore zone.

HR Wallingford's well established HINDWAVE and OUTRAY wave models were used to hindcast (i.e. retrospectively forecast) hourly wave conditions at eight locations around the coastline of England and Wales for which corresponding local hourly wind conditions were already held at Wallingford. These sites are shown on the map in Figure 4.9. Each hindcasted record included information on wave height, wave period, and wave direction.

Wave heights were summarised in terms of the significant wave height (H_s) exceeded 50%, 10% and 1% of the time in each successive year. Figure 4.9 shows the calculated annual mean wave heights for the above categories over the modelled period for each location.

Waves in Essex estuaries are mainly internally generated. Therefore the change in wave heights measured or hindcasted for offshore sites like Kentish Knock may be less important than changes in wind direction that increase internal fetches. To investigate whether Essex saltmarsh erosion may be exacerbated by an increase in internally generated waves, wind analysis was conducted that calculated the % time that different velocity winds were blowing from different direction ranges.

To investigate whether fluctuations in storminess (i.e. change in frequency of extreme wave events as opposed to changes in mean wave heights) affected saltmarsh extent, changes in storm frequency were analysed for two sites. These were Clacton (which was chosen to represent Essex sites exposed to the open sea facing roughly south-east) and mid-channel in the Severn estuary, South of Barry (chosen to represent exposed sites in the outer Severn estuary). The hindcasted wave record was analysed to determine the number of storms occurring in each year, the duration and wave heights. These records were then compared to changes in saltmarshes to see whether there was a correlation between storminess and saltmarsh change. Storms were defined as beginning when a certain threshold H_s was crossed by *increasing* wave heights, and ending when the same threshold was again crossed by *decreasing* wave heights. Cyclic and longer term trends were analysed with reference to the number of storms for each successive year.

The modelled changes in offshore wave conditions probably do not reflect the actual change in the wave climate on mudflats and saltmarshes (due to wave dissipation over inshore sand banks and inter-tidal flats). However, the methods were applied consistently at each location, using a consistent source of input wind data. Therefore it seems reasonable to suppose that any trend indicated by the analysis is indicative of a genuine trend, even if there is a high uncertainty about the *rate* of change predicted. However, without any understanding of the underlying causes of change, this type of analysis gives no indication of whether any predicted changes are permanent, or whether changes will continue at the same rate in the future.

2.3.4 Analysis of changes

Information on winds, waves and tidal range, whether measured or synthetic, was grouped into one year blocks, for use in trend analysis. The blocks were not necessarily based on calendar years, but sometimes on other periods, e.g. July to June, in order to maximise the number of blocks, taking account of the start and finish dates and periods of missing data.

The trend analysis involved least squares straight line fitting to graphs of *Year* against *parameter value*. In most cases, the result extracted for use in later correlation analysis was the best fitted rate of change of the parameter per year, without explicit account for the degree of uncertainty in the predictions.

Example end products of this type of analysis were of the following form. At and around Location X, the 10% wave height increased by 0.2cm/year and the storm frequency by 0.1 storms/year over the period 1970 to 1990, whilst the peak tidal currents reduced by 0.1%/year over the period 1960 to 1988. These values would then be correlated with field data on saltmarsh changes in the general area for which results for Location X were considered to be representative.

As there is a concentration of saltmarshes in the areas around the Thames Estuary and Portsmouth, wave models were run to look at wave climate change in these two areas. Wave predictions for Clacton were for a shallow water location about one kilometre from the coast. Wave statistics were analysed in 2-year blocks from 1973 to 1990 to determine the trends both in representative (ie 1%, 10% and 50%) wave heights and in storm frequency. Wave predictions for the Portsmouth area were conducted for eleven shallow water locations spread around Portsmouth, Chichester, Langstone and Pagham Harbours, and in the surrounding coastal area. Wave statistics were analysed in 1-year blocks from 1971 to 1991 to determine the trends in representative (ie 1%, 10% and 50%) wave heights. At each location, a walk-over survey of the inter-tidal zone was conducted to see whether there was a correlation between the modelled rate of change in wave height and the degree of saltmarsh accretion or erosion (see section 2.6 and 4.3.1.1).

2.4 Correlation table

Correlation analysis between data relating to changes in hydraulic conditions and those of saltmarsh change for 50 saltmarsh locations, was one of the approaches adopted in this study to investigate the relationship between hydraulics and saltmarsh change (see section 4.3).

Correlation analysis was achieved by compiling a table. The table was in two parts, with the parameters that could potentially cause change on the left, and types of saltmarsh change and saltmarsh characteristics on the right. The saltmarsh locations selected were within the areas for which HR Wallingford had wind, wave and water level information. These regions of coastline are given below:

(a) SE Irish Sea: Conway to Fleetwood
(b) Bristol Channel: Gower/Ilfracombe to Bristol
(c) Dorset: Lyme Regis to Christchurch Bay
(d) South-East: Portsmouth to Southwold
(e) Lincolnshire: Sheringham to Cleethorpes

The table was completed as fully as possible using data derived from field measurements (i.e. change in wind speed, wave height and sea level rise, tidal range, MHWS), field observation (i.e. changes in saltmarsh as reported in the questionnaire responses) numerical modelling conducted by HR Wallingford (e.g. the majority of the changes in wave height were derived by hindcasting) and deduction by experts (change in sediment supply, change in fetch). For some of these categories, data were not available to quantify these changes, instead a number -1, 0, or 1 was assigned to represent the relative magnitude of the change. 0 represented stable conditions, -1 a decrease and 1 an increase. The categories for which this notation was adopted included: change in fetch and sediment supply, change in vertical elevation and lateral extent of the saltmarsh, and change in creek length.

For each combination of "input parameter" and "saltmarsh response", a least squares linear regression correlation was undertaken. The results of this analysis are given in Appendix A.

2.5 Site visits

Correlation analysis between changes in wave height predicted by hindcast modelling and saltmarsh change indicated that there was no relationship between change in wave climate and saltmarsh erosion. However, this apparent lack of a relationship is possibly misleading because the predicted wave heights do not necessarily reflect the wave heights incident on mudflats and saltmarshes. This is because the model assumes a 10m water depth and hence the reduction in wave height due to dissipation on the foreshore is not incorporated. For example, it appears that wave heights off the North Norfolk coast are greater than those off the Essex coast. However, the saltmarshes of North Norfolk are fronted by extensive sandflats but those of Essex are not; the effect of the sandflats on the wave height actually reaching the saltmarsh is not accounted for. Therefore the investigation into whether change in wave heights is an important factor forcing saltmarsh change had to take a new direction.

HR Wallingford predicted wave heights for the last 20 years at eight sites in Langstone, Pagham and Chichester Harbours using measured wind data. The wave height predictions indicated that there was a substantial variation in the trend of wave height change at the various inshore sites (from 0 to 0.8 cm a year). Although it is unlikely that the wave heights, accurately portray those incident on the saltmarsh, the variation in the trend in wave height between sites indicates the relative change in wave climate at each of the sites. Six of these sites were visited. The aim was to investigate the strength of relationship between change in wave height and saltmarsh response from a walk-over survey at each of the sites. The sites were visually assessed to estimate the degree of erosion/accretion to see whether there is a relationship between change in wave height and saltmarsh response. Much more information can be gleaned from a walk-over survey of a saltmarsh than of a beach. It is possible to infer whether it is recovering from an episodic erosion event (if new saltmarsh is growing in front of a cliffed edge), or steadily progressing seawards (absence of cliffed edge, pioneer vegetation in patches in front of main body of the saltmarsh). In addition, if there are no signs of damage to vegetation due to wave action, but there are signs that the cliff edge of the saltmarsh is actively eroding, it indicates that tidal currents are the major erosive force.

Further site visits were made to assess the saltmarsh development after unmanaged breaching of a seawall. Sowley, on the Solent and Northey Island in the Blackwater estuary were examined by a walk-over survey. Site visits were also made to assess locations vulnerable to breaching.

Extensive saltmarshes fringe the western side of the Duddon estuary north of Millom and the eastern side of the estuary north of Askham in Furness. The Duddon has no protective barrier spit complex at its mouth, and consequently active marshes are poorly developed in the outer estuary. Marshes cover only about 9% of the intertidal area. Four marsh terraces, separated by clifflets or steep ramps, were recognized by Yasin (1991). The oldest unit (the Angerton Formation) may have formed in the mid Flandrian period; it was partly reclaimed during the mediaeval period and used for ridge and furrow cultivation. The second oldest terrace, the Green Road Formation, may have formed in the later Middle Ages. The third terrace, the Millom Formation, which represents the most extensive area of active saltmarsh, post-dates construction of the railway embankment in the 1840's. North of Askham Pier this marsh developed following construction of the pier in the late 19th century. The youngest terrace, the Greety Gate Formation, appears to date from the first half of this century. In places a new marsh is developing in front of the Greety Gate Formation). In many places marsh clifflets front the intertidal flats, particularly where tidal channels lie relatively close to the shore. *Spartina* appeared in the estuary in 1947 but its coverage remains limited, possibly due to the relatively exposed and mainly sandy nature of the estuary.

3 Morecambe Bay

In Morecambe Bay, saltmarshes occur in sheltered back-barrier settings (e.g. behind Walney Island), in the inner parts of estuaries adjoining the bay (e.g. the Leven, Kent, Lune and Wyre), and on more open shores which are fronted by wide intertidal flats (e.g. on the south side of the Cartmel Peninsula, at Silverdale, and between Blackstone Point and Hest Bank (Gray & Scott, 1987). Significant areas of reclaimed marsh occur around the Leven estuary, the Cartmel Peninsula, the Kent estuary, and in southeastern Morecambe Bay (Gray & Adam, 1973). Between 1845 and 1967 the extent of active marsh in different parts of the bay showed considerable fluctuation (Gray & Scott, 1987), due mainly to cycles of lateral erosion and accretion. Silverdale Marsh, located in the northeast corner of the bay, prograded rapidly between 1845 and 1888, but suffered rapid erosion between 1888 and 1915. A second phase of rapid lateral accretion occurred between 1915 and 1975, after which date erosion began again (Pringle, 1995). Since 1975 >800m of marsh has been eroded at an average rate of more than 40 m/yr (Pringle, 1995; Figure 3.3). By contrast, intertidal accretion and saltmarsh development has occurred almost without interruption along the shoreline of the Cartmel Peninsula during the past century.

In the last 30 years, lateral growth saltmarshes has occurred in the more sheltered parts of Morecambe Bay, including South Walney and Rampside in the northern part of the bay, between Pilling and Cockersands Abbey in the southeast, and around Hest Bank to the northeast of Morecambe. Many of the new marshes were initiated by *Spartina anglica* invasion (Whiteside, 1987). *Spartina anglica* was first recorded at Rampside in 1949, but it only spread widely during the mid 1960's. Following rapid accretion in the late 1960's and 1970's, a large area of marsh was reclaimed at Pilling and Cockerham in the early 1980's. In more exposed localities, spread of *Spartina anglica* has been limited, and its overall effect has been smaller than in other west coast estuaries such as the Dee and Ribble (Comber & Hansom, 1994). In more exposed parts of Morecambe Bay, for example between Heysham and Sunderland Point, the saltmarsh edge has been generally stable or has eroded slowly in the past 30 years.

Marsh. There was a significant increase in the total marsh area during the 1960's due to *Spartina anglica* colonization, but by the mid 1980's the area covered by *Spartina* had declined 75% (Burd, 1989), partly due to succession and partly to erosion. The present total marsh area is approximately 848 ha, or 9.5% of the intertidal area (Comber et al., 1993).

6 Dee estuary

The Dee estuary has a long history of net intertidal accretion and progressive down-estuary development of saltmarsh. In the past 250 years the accreting marsh front has advanced some 8 km along the Cheshire shore (Marker, 1967; Pye, 1996a). The northern limit of active marsh now lies between Heswall and Caldy. Salt marshes on the west side of the estuary are presently eroding along their seaward edge except where they are protected artificially.

Spartina anglica was first introduced to the estuary in 1928/29, but it did not become well-established until the 1960's (Taylor & Burrows, 1975), a time which coincided with a period of lower than average wave activity. Expansion was rapid in the late 1960's and 1970's, when invasion of the recreational beaches at Hoylake and West Kirby had to be controlled by spraying. The marshes continued to grow northwards and westwards until the mid 1980's, but in the past few years movement of its northwestern margin has slowed considerably (Pye, 1996a).

7 North Wales coast

Excluding the Dee estuary, areas of active saltmarsh larger than 15 ha occur at nine main localities on the coast of North Wales and Anglesey. Fringing marshes occur in the Conway and Clwyd estuaries, and in the restricted entrance embayment at Malltraeth Sands (Cefni estuary) on Anglesey. Significant back-barrier marsh systems are located at Traeth Melynog and Foryd Bay at the western end of the Menai Straits. Many of these areas experienced rapid spread of *Spartina anglica* in the 1960's and 1970's (Deadman, 1984). In the last decade, marsh growth has stabilized in many areas, with recent erosion along exposed margins.

8 Cardigan Bay

In Cardigan Bay saltmarshes are restricted to sheltered estuaries and small embayments. The most extensive marshes occur in the Dovey and Mawddach estuaries, and at Traeth Bach between Harlech and Porthmadog. Some of these marshes are of considerable age, and significant areas have been reclaimed around Traeth Bach and Broadwater. Periodic progradation of the marsh edge, with intervals of erosion and cliffing, is reflected by the existence of marsh terraces and clifflets (Yapp et al., 1917, Richards, 1934).

Spartina anglica was introduced to the south side of the Dovey estuary in 1920, and a major expansion occurred between 1940 and 1975 (Chater & Jones, 1956). The coverage was reported to be 400 - 600 ha in 1966 (Hubbard & Stebbings, 1967) and 1050 ha in 1978, with further increases in the early 1980's (Deadman, 1984; Davis & Moss, 1984; Burd, 1989). Growth of Spartina also significantly increased the marsh area in the Mawddach estuary after its introduction in 1929, and substantial colonies have been established in the Teifi estuary, at Broadwater, Morfa Dyfryn, and at Traeth Bach. In recent years, areas originally colonized by *Spartina* have been partially invaded by other species, while seaward extension of the margin in most areas appears to have slowed or ceased.

9 South Wales coast

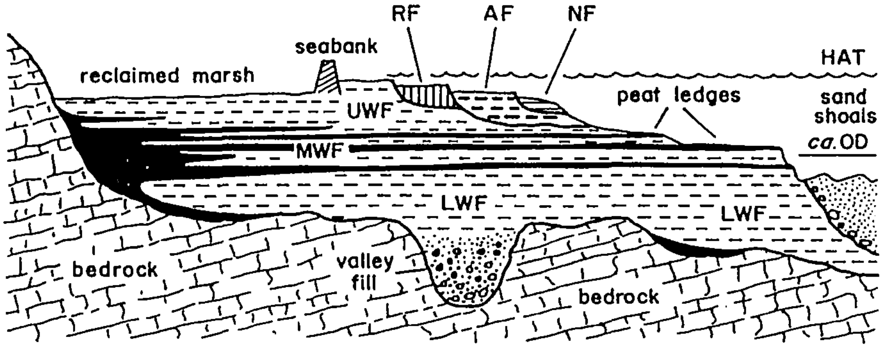
Relatively small areas of fringing and ria-head saltmarsh occur in Milford Haven and its tributaries. The majority of marsh edges are mostly stable or very slowly eroding. Marsh terraces occur in some areas, with up to four surfaces separated by cliffiets (Dalby, 1970). *Spartina anglica* was introduced during the 1940's, and its coverage increased rapidly until the early 1980's (Deadman, 1984), since when its expansion has slowed or ceased. Small areas of formerly reclaimed grazing marsh have reverted to active saltings following breaching of the enclosing sea banks, (e.g. at Gann Saltings and Crabhall Saltings; Dalby, 1970).

Saltmarshes occur in two main areas of Camarthen Bay, in the estuaries of the Rivers Taf, Towy and Gwendraeth, near Carmarthen, and in the Loughor estuary on the north side of the Gower Peninsula. In the former area, marshes fringe the main channels and occur as back-barrier marshes at Ginst Point and Pembrey Burrows. In the Loughor estuary, fringing marshes have developed along much of the north coast of the Gower, and are partly protected at the western end by a dune-capped spit (Whiteford Burrows). On the more exposed northern shore marshes are restricted to the inner part of the estuary between Llanelli and Llangennech. *Spartina anglica* was introduced to the Loughor in 1931 and to the Taf estuary in 1932. Its coverage in the Taf increased dramatically between 1966 and 1982 (Deadman, 1984). Similar expansion occurred in the Loughor in the late 1950's and 1960's. At present the marsh edges are mainly stable or slowly eroding, with evidence of cliffing and wave damage to the vegetation in more exposed areas. However, an apparent decline in the area covered by *Spartina* in the past 20 years is due mainly to successional changes.

The coast of the Bristol Channel includes small saltmarsh areas in Oxwich Bay, the Neath estuary and the Ogmore estuary. At Oxwich, marshes mainly occur in a back-barrier setting and are largely protected from erosion. Marshes in the Neath estuary are also partly protected by barrier spits at the estuary mouth. At Ogmore, fringing marshes up to 200 wide wide are mainly stable, although recently there has been some recent turf stripping, cliff erosion and burial by wave-driven sand sheets near the estuary entrance.

10 Severn estuary

The Severn estuary is flanked by extensive areas of estuarine alluvium, including saltmarsh deposits and brackish or freshwater peats. These deposits are largely of Flandrian age, having accumulated under conditions of generally rising sea level during the last 8,000 years (Heyworth & Kidson, 1982; Allen, 1990). The younger estuarine deposits form a series of off-lapping morphostratigraphic units which reflect episodes of sediment accumulation followed by phases of shoreline recession. The number of morphostratigraphic units present varies from area to area. Allen (1990) recognized five units in the Arlingham area, but elsewhere there is evidence for only three or four. Allen (1987) and Allen & Rae (1987) named four main units which, in order of decreasing age, are the Wentlooge Formation, the Rumney Formation, the Awre Formation, and the Northwick Formation (Figure 3.5). The Wentlooge Formation, which is the most extensive, is divisible into lower, middle and upper sub-units. In most areas vertical accretion of the Wentlooge Formation was halted by extensive embanking and reclamation in Romano-British times. Further embanking and reclamation was also undertaken in mediaeval and later times (Allen & Fulford, 1986, 1990; Allen, 1992). Until recently, retreating cliffs along the seaward margin of the Wentlooge Formation were widely exposed in the outer estuary, notably in the Gwent Levels. At Rumney Great Wharf, cliffs up to 5 m high retreated at a rate of approximately 1 m / yr between the 1840's and 1980's (Allen, 1987), and are still presently retreating. Near Caldicot, marsh cliff retreat averaged 0.2 - 0.4 m /yr in the 1970's and early 1980's. However, in the past decade these cliffs have been largely stabilized by protection works.



RF – Rumney Formation AF–Awre Formation NF– Northwick Formation
WF – Wentlooge Formation (L–lower, M–middle, U–upper)
HAT–highest astronomical tide

Figure 3.5 **Standard postglacial estuarine alluvial sequence in the inner Bristol Channel and Severn Estuary (after Allen, 1992)**

Active saltmarsh occupies only 5.2% of the total intertidal area of the Severn estuary (Davidson et al., 1991), forming a relatively narrow estuarine fringe. The marshes are widest within slight embayments, for example at Woodspring Bay, Portishead, and Slimbridge. Large sections of the marsh edge show evidence of cliffing, although some localities are stable or accreting. Rapid lateral erosion has recently affected the saltmarsh frontage south of Lydney, requiring realignment of the sea banks at Aylburton Warth. Similar set back has been undertaken in the estuary at least since mediaeval times (Allen, 1990,1993).

11 Bristol Channel

Ordnance Survey maps show that no salt marsh was present at Sand Bay, north of Weston-Super-Mare, before about 1930. *Spartina anglica* arrived shortly after 1932 and spread rapidly between the 1950's and mid 1970's, when erosion of the marsh edge began (Carter, 1973). Since then the marsh area has been reduced by almost 50%, creating a series of erosional mudmounds along the seaward margin.

At Berrow Flats, in eastern Bridgwater Bay, Ordnance Survey maps show no marsh present in 1904, but by 1962 a belt of saltings several hundred metres wide had developed. Pioneer Salicornia-Puccinellia marsh vegetation first became established around 1910 (Thompson, 1923, Boley, 1943; Willis 1990). The marsh prograded seaward and progressed to a community dominated by Spartina and Scirpus during the 1930's and 1940's, evolving into a mixed marsh community of considerable diversity by the mid 1960's. In the 1970's the more landward marsh became dominated by Phragmites australis, while the seaward edge began to erode (Willis, 1990). Since 1963 the maximum marsh width has decreased by approximately 90 m at an average rate of 3 m / yr.

At Steart Flats, to the west of the River Parrett mouth in eastern Bridgwater Bay, marshes form a fringe on the seaward side of a relict shingle barrier. *Spartina* was first observed here in 1918 (Davidson et al. 1991), and it spread rapidly after planting in 1928 and 1929. The marsh experienced invasion by mixed marsh species and *Phragmites* in the 1950's and 1960's (Ranwell, 1964a,b; Morley, 1973). Erosion of the marsh edge began in the early 1960's, leading to the development of mudmound topography, and has since accelerated and spread to affect most of the frontage. Lateral erosion has exceeded 60 m in the last 30 years.

12 Devon and Cornwall

In north Devon, formerly extensive marshes behind the Braunton Burrows barrier spit have been reclaimed, and active marshes now occur principally as a narrow fringe, including the south bank of the Taw estuary at Lower Yelland and Bickington. A small area of estuarine back-barrier marsh also occurs behind the shingle ridge at Northam Burrows. *Spartina anglica* was first recorded in the Taw / Torridge estuary in 1934, and its coverage increased from 12 ha to 48 ha between the mid-1960's and mid-1980's (Hubbard & Stebbings, 1967; Burd, 1989). The marsh edges mostly appear stable but are locally cliffed.

On the North Cornwall coast saltmarshes are restricted to sheltered locations in the Camel estuary (Padstow), The Gannel (Newquay), and the Hayle estuary (St. Ives). There is apparent overall stability in the Camel and Hayle estuaries but erosional features are more prevalent in The Gannel. Spartina is present only in the Hayle, where it arrived naturally in 1958 (Murphy, 1974). In south Cornwall, fringing marshes occur in the upper estuaries of the Helford, Fal, Fowey, East Looe and West Looe rivers. In all cases, saltmarsh covers only a relatively small proportion of the intertidal zone (Davidson et al., 1991). The largest expanse of active marsh occurs in the Fal estuary (93 ha; Burd, 1989). Marshes in the Helford River appear to be stable or slowly accreting. Elsewhere, cliffed margins are more common.

Saltmarsh habitat occurs in the upper reaches of the Tamar, Tavy, Yealm, Avon, Kingsbridge, Dart, Teign, Otter and Axe estuaries in south Devon. Marsh area is minor in relation to the total intertidal area, only the Tamar and Exe estuaries having more than 50 ha (Davidson et al., 1991). Areas of net erosion and net accretion occur in approximately equal proportion. All marsh areas in Plymouth Sound except the River Tavy exhibit predominantly cliffed edges and appear to be either stable or experiencing slow lateral retreat. Pioneer marsh communities are poorly developed, although localised pockets of *Spartina anglica* occur. In the Tavy, much of the seaward marsh edge is ramped, with evidence of *Spartina anglica* progradation, although there are also areas of marsh cliff erosion. In the Yealm, Erme, Avon and Kingsbridge estuaries the relatively small marsh areas display stable ramped margins and erosion is localised (Fahy et al., 1993). In the Exe estuary, marshes range from mature high marsh with a diverse flora to young *Spartina* marshes (Parkinson, 1980). *Spartina anglica* was introduced to the Exe in 1935 and its coverage increased significantly between 1967 and 1988. The saltmarsh edge appears to be mostly stable or slowly accreting, although some die-back has been observed near Dawlish Warren. The marshes in the Dart, Teign and Otter estuaries also include areas which are stable, slowly accreting, and eroding, while marshes in the Axe estuary show widespread cliff formation.

13 Poole Harbour

Davidson et al. (1991) reported that salt marshes cover approximately 25% of the intertidal area of Poole Harbour . Despite a mean spring tidal range is only 1.7 m, more than 80% of the intertidal area is exposed at low tide (Davidson et al., 1991). Active saltmarsh occurs mainly around the southern and western margins of the harbour, in Holes Bay and Lytchett Bay.

Saltmarsh was of relatively minor extent until the arrival of *Spartina anglica* around 1899. *Spartina* spread rapidly, both naturally and as a result of planting, achieving rates of lateral advance of up to 5 m /yr between 1905 and 1925 (Hubbard, 1965; Hubbard & Stebbings, 1968). It attained maximum coverage of approximately 844 ha in the mid-1920's, after which it began to decline. There was a net loss of approximately 170 ha between 1924 and 1952, chiefly due to die-back and erosion around Brownsea Island, Parkstone Bay, Brands Bay and in Holes Bay, which more than offset local gains elsewhere (Hubbard, 1965). Further reductions in *Spartina* coverage have occurred since 1952, due to a combination of land reclamation, vegetational succession and die-back.

The *Spartina*-covered area in 1980 was approximately 400 ha (Gray & Pearson, 1984; Gray, 1985), and the total area of active marsh approximately 697 ha (Burd, 1989). Significant erosion took place in several areas between 1974 and 1980, notably in Brands Bay, around Furzey Island and in Holes Bay. Less dramatic change was apparent between 1982 and 1991, although some areas have experienced further erosion (e.g. Brands Bay, Brownsea Island, the southern side of Furzey Island (Gray, 1992), Parkestone Bay and the north of the Sandbanks Peninsula.

14 Christchurch Harbour

Christchurch Harbour is a microtidal embayment which is separated from the sea by a narrow neck of land connecting Hengistbury Head with the mainland. The embayment entrance is restricted by Medford Spit. Saltmarshes occur on both sides of the mid- and inner bay, covering approximately 50 ha or 29% of the total intertidal area (Burd, 1989; Davidson et al., 1991). The marshes are composd mostly of mixed communities, with Scirpus or Phragmites beds in higher and more brackish areas. Pioneer communities, including Spartina, are poorly represented, and much of the marsh edge is cliffed. Documentary evidence indicates that saltmarsh was very restricted before 1903, and that rapid expansion occurred between 1903 and 1968, with localised erosion between 1924 and 1938. Spartina reached the harbour naturally by 1913, and covered 15 ha in the mid-1960's (Hubbard & Stebbings, 1967). This was reduced to 1 ha by the mid/1980's due to the combined effects of succession and erosion (Burd, 1989). Admiralty charts suggests significant lateral retreat of the marshes along the southern side of the bay between 1968 and 1975. At the present time much of the marsh edge is cliffed or steeply ramped but appears to be eroding only slowly.

15 The Solent

Saltmarshes fringe much of the western Solent between Keyhaven and Lepe. The marshes are partly protected from southwesterly waves by Hurst Castle Spit, which partially obstructs the western entrance to the Solent. The existence of the spit explains the presence of the saltmarsh There are significant areas of reclaimed marsh at Keyhaven and Pennington, and in the lower Beaulieu estuary. On the north coast of the Isle of Wight marshes occur in the estuary of the River Yar, while both fringing and back-barrier marshes occur in the Newtown estuary.

Smaller areas of active fringing marsh occur in the River Medina estuary and at King's Quay (Johnston, 1989).

Ordnance Survey maps show there was very little active marsh between Keyhaven and Pylewell Point, east of Lymington, in the early years of this century. *Spartina anglica* arrived naturally at Lymington by 1892 (Hubbard & Stebbings, 1967), and by 1931 it had colonized most of the intertidal area down to mean low water mark. Further expansion occurred around Pylewell Point area between 1931 and 1958. Signs of *Spartina* die-back first appeared in the backmarsh areas at Lymington as early as 1924, and there was extensive channel edge erosion between 1935 and 1946 (Goodman et al., 1959; Ke & Collins, 1993). Since 1924 the seaward edge of the marsh at the entrance to Lymington harbour has retreated by up to 300 m, at an average rate of 5 - 6 m/yr (LRDC International, 1993).

East of the harbour entrance the rate of marsh edge recession accelerated dramatically after 1958. Beyond Pylewell Point the marsh surface is largely de-vegetated and partially buried by shingle and shelly sand (these changes are indicative of increases in wave energy). Serious erosion in the last 30 years has also virtually removed the marshes between Pennington and Lymington. Loss of saltmarsh at Keyhaven has been more limited, although serious storm damage occurred during the 1980's. Prior to 1898 the lower Beaulieu River estuary consisted of bare mudflats, but by 1909 much of the area had been colonized by Spartina, planting of which began in 1898. Saltmarsh along the mainland shore between Inchmery and Lepe experienced major growth between 1920 and 1970. However, by the mid 1970's the saltmarsh towards the eastern end of Needs Ore Point showed signs of erosion, and shortly afterwards marshes on the mainland near Inchmerry House also began to erode. At present these marshes in a considerably degraded condition, having experienced a combination of surface devegetation, marsh cliff recession and internal dissection.

Marshes in parts of the mid Beaulieu estuary suffered some erosion during the 1940's but now appear to be relatively stable. Reactivated marshes occur in a number of formerly reclaimed areas where breaching of the sea walls has occurred (e.g. at Gilbury Hard and Lower Exbury).

The area of saltmarsh in the Yar and Newtown estuaries also increased dramatically following the establishment of *Spartina anglica* in the 1890's, and particularly after planting at Newtown in the 1930's. Since 1967 the *Spartina* coverage has declined from 56 ha to <5 ha in the Yar and from 63 ha to <24 ha at Newtown (Hubbard & Stebbings, 1967; Burd, 1989), in part due to vegetation succession but also to marsh cliffing and localised internal dissection. Some new marsh has formed at Newtown following storm breaching of the sea walls around an area of reclaimed marsh in 1954.

16 Southampton Water

Saltmarshes once formed a semi-continuous fringe around Southampton Water, extending into the lower reaches of the Rivers Test, Itchin and Hamble. Today, however, as a result of reclamation and localised erosion, active marshes are restricted to three areas, around Eling and Bury at the head of the estuary, the River Hamble, and between Hythe and Calshot. Accumulation of fine-grained sediment continues in some higher intertidal areas, but many of the marsh edges show evidence of slow erosion. It is not known whether reclamation has exacerbated erosion of the remaining saltmarsh. On the eastern side of the Hamble, near

Warsash, marsh reactivation has taken place following sea wall breaching, and near Eling and at Fawley there are areas of recent *Spartina* colonization.

Spartina anglica was first recorded near Hythe in 1870, and it spread rapidly to cover c. 477 ha by 1966 (Hubbard & Stebbings, 1967). Dieback was observed in the mid 1950's, partly due to pollution from the Fawley oil refinery (Baker, 1971; Dicks 1976; Dicks & Iball 1981; Shears 1988). In 1971 Esso began a long-term programme of marsh restoration involving improvements to the quality of refinery effluent and transplantation of healthy *Spartina* to areas of damaged marsh. There has been considerable success, although (Dicks & Levell, 1989) concluded that complete recovery of Fawley marsh has not been achieved. Burd (1989) reported the total area of active *Spartina* marsh in Southampton Water to be 103 ha. Recent marsh edge erosion has been associated with a steepening of the intertidal profile (Hooke & Riley, 1987).

17 Portsmouth Harbour

Active marshes were reported by Burd (1989) to cover 181 ha (approximately 15.8 % of the intertidal area), occurring mainly in the northern and western parts of the harbour. Saltmarsh was formerly more extensive but, owing to the long-standing naval importance of the harbour, large areas have been reclaimed for port and urban development.

Following the arrival of *Spartina* around 1900, the marsh area increased significantly, particularly between 1910 and 1930. Growth continued around Horsea Island in the 1950's and 1960's, and in 1966 the coverage of *Spartina* was estimated to be c. 263 ha (Hubbard & Stebbings, 1967). By the mid 1980's this had been reduced to approximately 172 ha (Burd, 1989), partly due to reclamation at Horsea Island and partly due to erosion. In the last ten years there has been further marsh loss, particularly on the banks in the northern part of the harbour, but some new marsh has developed along the shore between Gosport and Fareham.

18 Langstone Harbour

The area of active saltmarsh is now relatively small, but has undergone substantial variations during the past century. Prior to 1900, when *Spartina anglica* arrived naturally, active marsh was limited, occurring mainly in a few pockets around the reclaimed Farlington Marshes in the north. Between 1900 and 1930 Spartina spread rapidly in the northern and eastern parts of the harbour, and in the mid-1960's covered approximately 193 ha (Hubbard & Stebbings, 1967). Die-back was first recorded in the mid-1950's (Tubbs, 1984), and became increasingly widespread in the 1960's and 1970's (Haynes & Coulson, 1982; Haynes, 1984; Budd, 1985). Burd (1989) reported 100 ha of remaining marsh, of which *Spartina* comprised 65 ha. There have been further losses in the past decade, and active marsh has now been widely replaced by mudflats colonised by *Zostera*, *Enteromorpha* and *Ulva.*

19 Chichester Harbour

Chichester Harbour is a rather complex restricted entrance embayment, with four subsidiary arms (the Emsworth, Thorney, Bosham and Chichester Channels). The harbour entrance is restricted by shingle spits which extend eastwards from Hayling Island and westwards from West Wittering. Burd (1989) reported that active saltmarshes cover 1077 ha, representing 31.5% of the intertidal area (Davidson et al., 1991). Discontinuous fringing marshes occur all around the harbour, while significant back-barrier marshes occur behind West Wittering spit. Extensive reclaimed marsh areas are found at Thorney Island and south of Chidham. The active marshes vary from pioneer *Spartina* and *Salicornia* communities to more mature mixed marsh communities.

Areas of active saltmarsh existed in Chichester Harbour when *Spartina anglica* arrived naturally around 1896. However, *Spartina anglica* colonization was rapid between 1910 and 1930, and particularly so between 1932 and 1962, reaching 715 ha by the mid-1960's. (Hubbard & Stebbings, 1967). Die-back began in the late 1960's, and subsequent marsh loss has been most severe along the eastern shore, for example between Itchenor and Rockwood (Tubbs, 1980; Hydraulics Research, 1987a), and on the offshore marsh islands. The area of remaining Spartina marsh was estimated by Thomas (1987) to be 611 ha, although Burd (1989) reported a figure of 815 ha.

20 Pagham Harbour

Pagham Harbour is a small tidal embayment located on the east side of Selsey Bill. The area was once reclaimed and reverted to a tidal embayment after the protecting shingle ridge was breached in 1910. Today the harbour entrance is restricted by two shingle spits. Burd (1989) reported that active saltmarshes cover 33 ha, representing almost 12% of the intertidal area. Pioneer and low-marsh communities, dominated by Spartina, are well-represented. *Spartina anglica* arrived naturally around 1919 and by the mid-1960's covered c.100 ha (Hubbard & Stebbings, 1967). According to Burd (1989), by the late 1980's the area of Spartina had been reduced to only 14 ha, but this figure probably underestimates the present coverage. Parts of the higher marshes (e.g. around Sidlesham) are highly dissected, but there are also large areas where *Spartina* marsh is either stable or actively prograding.

21 East Sussex and south Kent coast

Small areas of active fringing saltmarsh are found in the lower reaches of the River Adur, the River Cuckmere and the River Rother. Growth of the marshes in each case has been facilitated by the eastward growth of protective shingle ridges. The marsh edges are either ramped, in areas of recent accretion, or cliffed due to localised erosion. *Spartina* is not extensive in any of these areas at present.

Large areas of saltmarsh formerly existed at Walland Marsh and Romney Marsh, which form part of Dungeness foreland on the Sussex - Kent border. Extensive salt marsh development, followed by expansion of brackish and freshwater wetlands, occurred on Walland Marsh during the later part of the mid Flandrian, probably in response to the progressive easterly development of a shingle barrier spit complex (Long & Innes, 1995). At Romney Marsh the main phase of saltmarsh growth occurred after about 2000 yrs B.P., following the development of a large shingle ness at Dungeness and the beginning of sand and shingle barrier development between New Romney and Hythe. The marshes were embanked and reclaimed in stages from the pre-Roman period onwards. No active saltmarsh now remains.

Sandwich Bay in northeast Kent includes areas of active saltmarsh in the lower reaches of the River Stour, which is partly sheltered by a spit on its eastern margin, and western Pegwell Bay. The area forms the eastern end of a former channel which, in Romano-British times, was >3km wide and separated the Isle of Thanet from the mainland. Reclamation and land drainage began during the Romano-British period and was essentially complete by the mediaeval period. Most of the more recent marsh development has occurred in southern Pegwell Bay (Robinson & Cloet, 1953). *Spartina anglica* arrived naturally in about 1934, and by the mid-1960's covered approximately 40 ha (Hubbard & Stebbings, 1967). Marsh erosion occurred during the later 1960's and 1970's, and Burd (1989) reported only 8ha of active *Spartina* marsh, mainly along the western side of Pegwell Bay.

Significant areas of reclaimed former marsh also occur at the northern end of the former channel between Reculver and Birchington on the north Kent coast, but no active marshes now survive.

22 The Swale

The Swale is a broad tidal channel which joins the Medway estuary at its western end and opens into Whitstable Bay at its eastern end. It occupies a linear depression between higher ground formed by London Clay outcrops on the Isle of Sheppey and the Chalk ridge of the North Downs to the south. It receives only a small amount of freshwater discharge, principally from Faversham Creek. The banks of the Swale are mostly fringed by sea walls which enclose extensive areas of reclaimed marsh. The area of active marsh was reported by Burd (1989) to be approximately 414 ha, representing 15.4% of the intertidal area. Active marshes form a discontinuous and often narrow fringe in front of the seabanks. The seaward edge is widely marked by a cliff up to 2 m high, seaward of which is an erosional mudflat. The active marshes are best developed on the northern side of the Swale, those on the southern bank having being almost completely removed by erosion. Admiralty charts and O.S. maps show that rapid lateral erosion at Elmley began in the early 1950's. At this time the marsh was more than 600 m wide, but by the early 1970's it had been reduced to less than 50 m. Further east, near the Ferry Inn, a period of rapid lateral retreat occurred in the early 1970's, reducing the marsh width from 237 m to 150 m. Over more or less the same time period, rapid lateral growth of Spartina marsh occurred at Shell Ness, near the eastern end of the Swale. Burd (1992) reported 58.2 ha of marsh loss in the Swale between 1973 and 1988, with low to mid-marsh communities being particularly affected.

23 The Medway estuary

The Medway estuary now takes the form of a broad embayment whose entrance is restricted by outcrops of London Clay on the Isle of Grain and Isle of Sheppey. Burd (1989) reported the active marsh area to be 754 ha, which represents c. 18.8% of the intertidal area. The largest active marshes are found in the southeastern part of the estuary, between Burntwick Island and Lower Halstow. Large areas of reclaimed marsh exist, notably on the Isle of Grain, at Chetney Marshes and at Upchurch.

Archaeological and palaeoecological evidence (Evans, 1953; Kirby, 1990) suggests that marshes first began to form following the onset of marine transgression in the lower Medway valley around 1000 A.D., leading to the burial of an extensive Romano-British to Saxon-age surface which now lies more than 2m below mean sea level. The first embankments were probably constructed before the end of the 12th century, and there was extensive enclosure between 1250 and 1450 (Kirby, 1990). In the 17th century the Medway occupied its present channel position and saltmarshes extended almost to the present low water mark on either side, being separated from a narrow, high level intertidal flat by a low cliff (Kirby, 1969). By 1800 the marsh cliffs had begun to retreat, forming a low-level tidal flat. This process continued during the 19th and

20th centuries and led to progressive dissection of the marshes as lowering of the tidal flats caused downcutting and widening of the marsh creeks. Further loss resulted from extensive mud digging for the brick and cement industries between the mid-19th century and mid-1960's (Medway Ports Authority, 1911; Kirby 1990, IECS, 1993a).

Admiralty charts indicate that the area of Stoke Saltings declined from 1041 ha in 1840 to 435 ha in 1910-13, while that at Burntwick Island declined from 461 ha to 290 ha over the same period (Kirby, 1990). Deterioration of Stoke Saltings apparently began in the late 19th century and progressed rapidly between 1900 and 1920, in part due to mud digging. Today, the area of Stoke Saltings consists largely of an erosional tidal flat with scattered residual marsh hummocks. Similar dissection and area loss has affected the other marshes to varying degrees. In several places erosion of the fringing marshes has led to breaching of the sea embankments and subsequent abandonment of formerly reclaimed land (e.g. at Burntwick Island). Several of these abandoned areas have subsequently experienced serious erosion. Admiralty charts show that formerly enclosed marshes on the south side of the estuary, at Ham Green, Milfordhope, Lower Halstow, Rainham and Copperhouse Marshes, and on the northern side at Hoo Flats, had started to deteriorate by 1889, possibly triggered by breaching of the seabanks during the storm tide of 1874. Stoke Saltings and Bishop's Marsh deteriorated rapidly between 1889 and 1912/13. Deterioration at Nor Marsh, Darnett Fort, Burtwick Island and Greenborough Marshes appears to have occurred mainly after 1912/13 (Pye & French, 1993).

Kirby (1990) reported rates of lateral marsh cliff recession of 10.5 - 320 cm/yr at Stoke Marshes and 0 - 31 cm/yr at Millfordhope Marshes during the mid-1960's. However, the marshes at these localities continued to accrete vertically. Development of new Spartina marshes has occurred in the last 20-30 years in a number of places including Horrid Hill and Eastcourt Meadows near Gillingham. Overall, Burd (1992) reported a net loss of 180 ha of saltmarsh in the Medway between 1973 and 1988, with all vegetation communities being severely affected.

24 Thames estuary

The Thames estuary was formerly flanked by extensive saltmarshes which have been progressively embanked and reclaimed since mediaeval times (Spurrell, 1885, 1889). The embankments were originally constructed close to the marsh edge and subsequent erosion has removed much of what active marsh remained. On the Kent shore active fringing marshes are now restricted to a few shallow embayments in the sea defences, including Higham, east of Gravesend, where the marsh is up to 150 m wide but eroding laterally at 0.5 - 1.0 m/yr. Other active marsh areas occur west of Allhallows-on-Sea, and at Yantlet Creek on the Isle of Grain. Along the Essex shore active fringing marshes occur between Coalhouse Point and Mucking Marshes, at Canvey Point and Two-Tree Island. Extensive but partially degraded marshes are also found along Benfleet Creek and Holehaven Creek.

Many of the Thames marshes are of considerable age. Roman remains, buried by later estuarine deposits, have been discovered at several sites including Canvey Island and Higham. Some of the marsh areas now being eroded were extensively settled during the 1st to 4th centuries A.D., and were abandoned as sea level rose. A period of embanking and resettlement took place during the mediaeval period (Rodwell, 1966; Horner, 1984), since when there has been a complex sequence of abandonment and further reclamation.

According to Burd (1992), 14 ha of net marsh erosion occurred on the Kent side of the Thames between 1973 and 1988, the remaining area in 1988 being 62 ha. Net erosion of 83 ha occurred on the Essex side of the Thames during the same period, reducing the remaining area to 260 ha. An example of the rapid erosion this century is provided by Higham saltings, just east of Gravesend (Pye, 1996b). In 1873, the embayment in the seawall at Higham was almost entirely filled by saltmarsh (Figure 3.6). Between 1873 and 1923 the marsh edge at the western end of the embayment retreated by 35 - 65 m, while between 1923 and 1983 it retreated by a further 50-85 m. The marsh in the northeastern part of the embayment was almost totally destroyed between 1923 and 1983, partly due to natural erosion and partly due to direct removal. Since 1983 the marsh edge as continued to retreat at 1-2 m/yr (Figure 3.7).

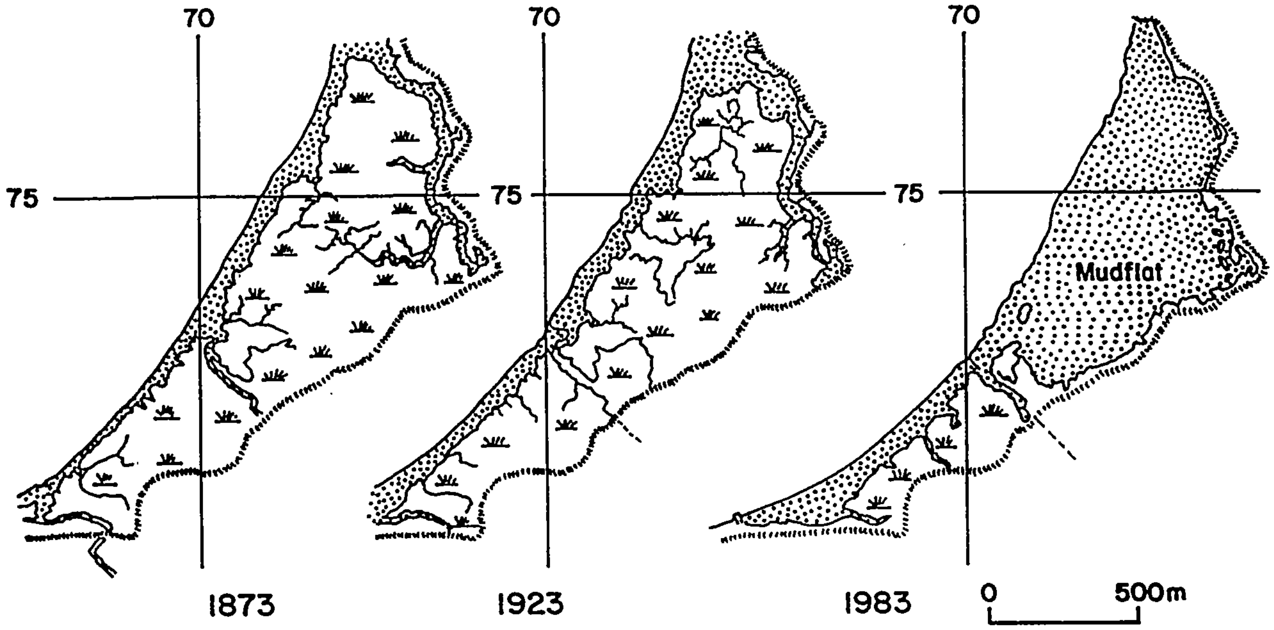


Figure 3.6 **Historic changes in morphology of Higham saltings, Thames estuary, since 1873 (after Pye, 1996b)**

Large stretches of the Thames marshes are cliffed. Where the intertidal flats are higher the marsh edge is sometimes ramped with mudmound topography. Many of the marshes are heavily dissected, being characterised by a high density of highly connected, sinuous drainage channels and bare mud basins. Extensive mudflats with residual marsh hummocks and transgressive shell ridges occur where seabanks have been breached and the former reclaimed land abandoned to erosion (e.g. at the eastern end of Canvey Island). Pioneer communities, including Spartina, are locally present (e.g. on the southern side of Benfleet Creek), but areas of new marsh growth are offset by erosional losses.

fringing marsh was present on both sides of the Island in 1897, but by 1938 the marsh on the Crouch side had been entirely eroded (Pye, 1996b). Erosion spread to affect the marsh around the northeast corner of the island in the 1980's, presenting a threat to the stability of the concrete seawall between Foulness Point and Northern Corner (Hydraulics Research 1987b; Figure 3.8).

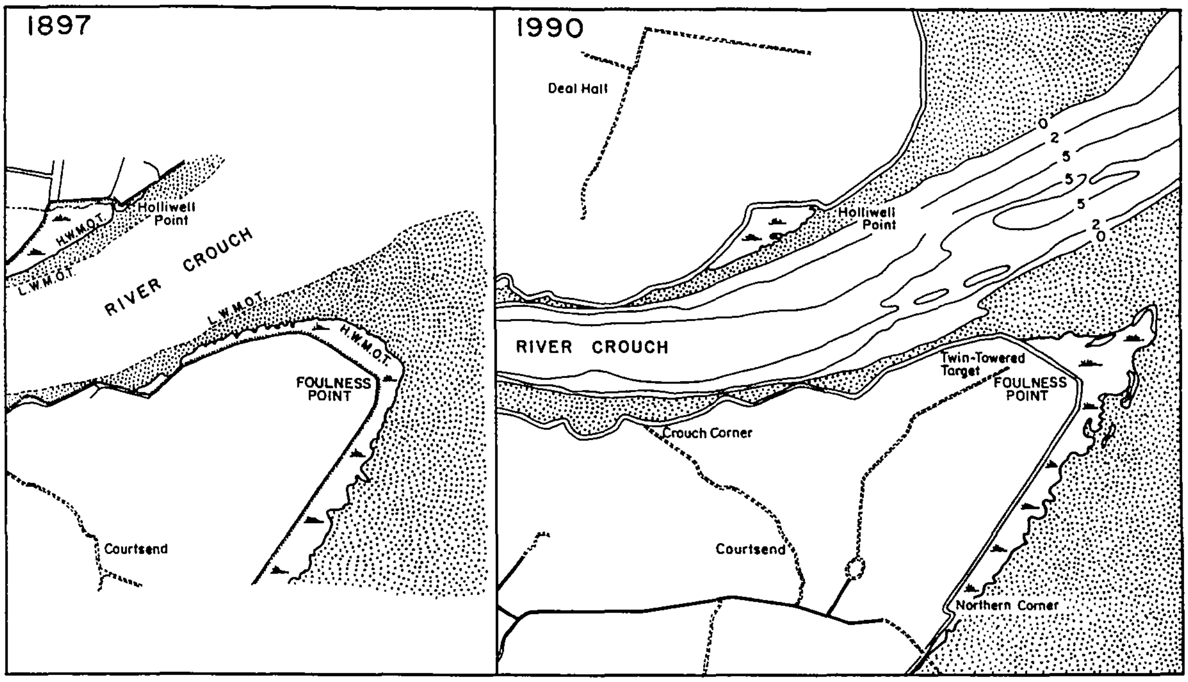
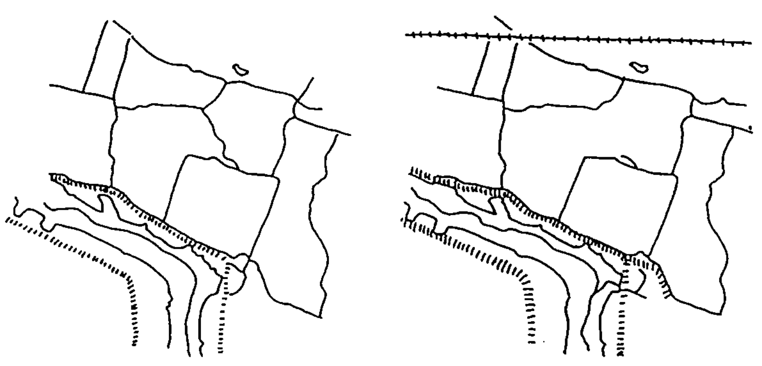


Figure 3.8 **Changes in saltmarsh morphology at Foulness Point, Thames estuary, between 1897 and 1990, based on Admiralty charts (after Pye, 1996b)**

Since 1988 much of the marsh at the northeast corner of the island has been severely eroded, exposing the wall to direct wave attack (Figure 3.9). Growth of new marsh is presently taking place along the central and southern shores of Foulness, superimposed on older eroded topography. Net loss of marsh area between 1973 and 1988 was not quantified by Burd (1992) due to data acquisition problems, but Pye & French (1993) estimated it to be 50 - 100 ha.

breach close to the site now occupied by Fambridge marina (Figure 3.10). By 1988 several other breaches were in existence, and a new marsh with a reactivated tidal drainage system had become established (Figure 3.11). A thickness of 60 - 70 cm of new mud has since accreted on top of the pre 1897 surface (Pye, 1996b). The reactivated marsh here, and at other reactivated sites in Essex, has experienced a reduction in the vegetated area due to creek widening and internal dissection in recent decades, while marsh cliff recession has continued to reduce the width of the fringing marshes along the estuary. According to Burd (1992), marsh erosion in the Crouch estuary totalled 124 ha between 1973 and 1988, representing 26.5% of the 1973 area.

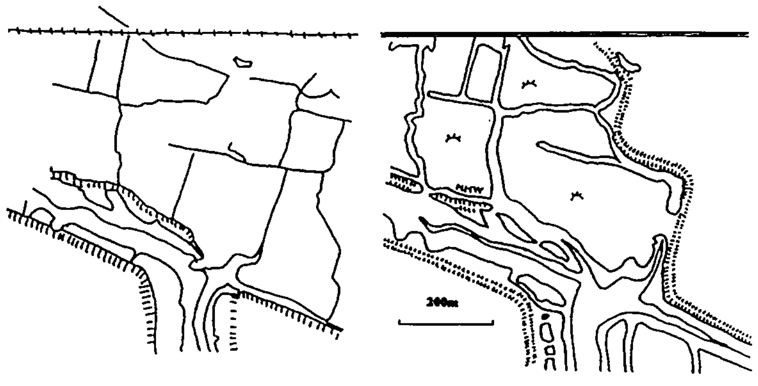
before inundation



Redrawn from 1873 Six inch OS map

Redrawn from 1895 Six inch OS map

after inundation



Redrawn from 1924 Six inch OS map

Redrawn from 1988 1:10000 OS map

Figure 3.10 Breach and subsequent saltmarsh regeneration, North Fambridge, Crouch Estuary (after Pye, 1996b)

O.S. maps and Admiralty charts suggest that the active marshes prograded rapidly between 1870 and 1955, and particularly after 1891-5 (Figure 3.12). The rate of progradation was highest near Howe Outfall where it averaged 9.7m/yr between 1873 and 1955 (Pye & French, 1993; Pye, 1996b). No lateral accretion occurred during this period near St. Peter's Chapel, or south of Watch House. Coincidentally with marsh progradation, mean low water mark moved landwards at an average rate of 28.4m/yr at Sales Point, 8.7 m/yr at St. Peter's Channel and 13.3m/yr at Watch House, leading to a steepening of the foreshore. North of Sandbeach Outfall marsh progradation occurred mainly after 1940.

Greensmith and Tucker (1965) reported that the marsh edge along the northern half of the Dengie Peninsula retreated by up to 270 m between 1953 and 1960. Virtually the entire marsh frontage receded between 1960 and 1981, although there were significant temporal variations within this period (Harmsworth & Long, 1986). Much of the marsh edge accreted between 1960 and 1970, followed by rapid erosion in 1970-73, a period of stability 1973-78, and further rapid erosion between 1978 and 1981. Burd (1992) estimated that net erosion amounted to 46.7 ha between 1973 and 1988. Maximum lateral retreat since 1955, of almost 1000 m, has occurred near Howe Outfall (Pye & French, 1993). Lateral erosion has been accompanied by continued vertical accretion. Monitoring near Bridgewick Outfall between July 1981 and August 1983 indicated a mean annual rate of vertical accretion of 7.5 mm/yr (Reed, 1988). The long term trend, however, is still one of net lateral erosion, despite marsh restoration works, including groynes, sedimentation fields and wavebreaks undertaken since 1980 (Pethick & Reed, 1987; Holder & Burd, 1990). During the past decade lateral erosion has continued along much of the marsh frontage, although the Sales Point spit and backbarrier marsh has stabilized since 1990.

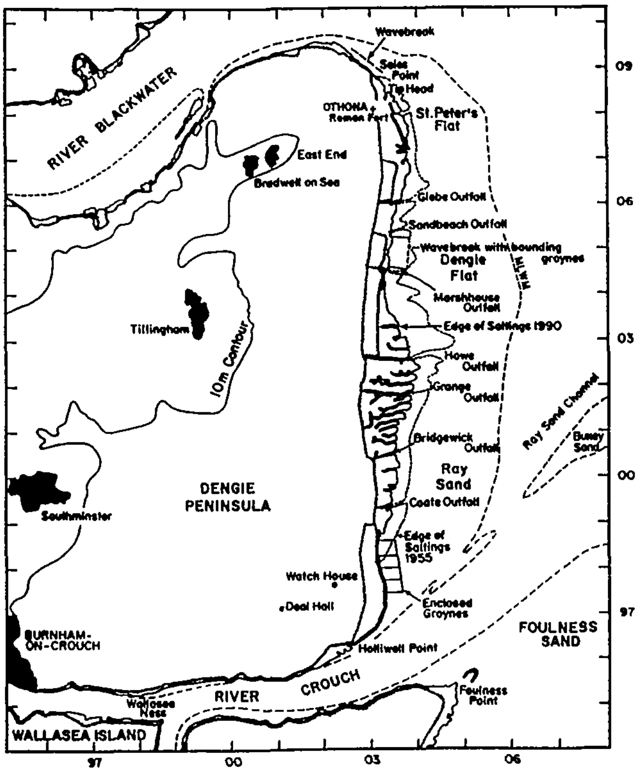


Figure 3.12 **Historical changes on the shoreline of the Dengie Peninsula (after Pye, 1996b)**

28 Blackwater estuary

Reclaimed saltmarsh, up to 1.5 km wide, fringes the mid and inner parts of the Blackwater estuary. The Flandrian alluvial sequence in the estuary consists of: (a) a basal organic rich mud which forms an erosion-resistant bench on the lower foreshore and in places, contains *in situ* oak stumps which have yielded radiocarbon ages of 4190- +/- 80 to 4,030 +/-80 14C yr B.P. (Wilkinson & Murphy, 1995), and (b) an overlying composite transgressive estuarine clay unit, up to 3.5m thick, which contain mudflat and saltmarsh taxa and a number of buried soils.

Active saltmarsh now occurs as a relatively narrow, discontinuous fringe which widens where there are small embayments in the sea defences, and where marsh reactivation has occurred on formerly reclaimed land (e.g. at Northey Island). The total area of active marsh was estimated by IECS (1993b) to be approximately 680 ha.

Most of the reclaimed marsh was embanked before 1774, with the exception of areas around Ramsay Island and Newland St. Lawrence which were enclosed between 1800 and 1840 (Gramolt, 1960). The extent of active saltmarsh in 1838 was much larger than today, suggesting rapid erosion between 1870 and 1935 followed by a period of relative stability which lasted until the 1970's (IECS, 1993b). Since 1978 there has been accelerated erosion which is continuing. The marsh edge is widely cliffed and the marshes are being internally dissected due to deepening, widening and headward extension of the creeks.

Areas of reactivated marsh and mudflat have formed in several areas, including Northey Island, following breaching of the seawalls during major storm surges. The newly accreted marsh muds are extremely soft and are being eroded due to widening of the creeks (Pye,1996b).

Spartina anglica was first planted in the Blackwater in 1924 and was estimated to cover 469 ha in 1966 (Hubbard & Stebbings, 1967). By 1988, its coverage had apparently decreased to 35 ha (Burd, 1989). The total net loss of saltmarsh in the Blackwater, Tollesbury Fleet, Salcott Channel and Strood Channel between 1973 and 1988 was estimated by Burd (1992) to be 200 ha. Groynes and sedimentation fields have been built in several parts of the estuary since 1983 in an attempt to raise foreshore levels and protect the marsh edge from further erosion (Holder & Burd, 1990), but with limited success.

29 Tollesbury Fleet, Salcott Channel and Strood Channel

Tollesbury Fleet, Salcott Channel and the Strood Channel are three residual tidal channels which occupy the western part of a formerly continuous belt of marshes which extended from the northern side of the Blackwater estuary to Fingringhoe in the Colne estuary. Reclamation of much of this area was undertaken before the late 18th century and was completed by 1840 (Gramolt, 1960). The largest remaining active marshes are found around Woodroffe Creek and Old Hall Creek in Tollesbury Fleet, at Abbot's Hall and Copthall Saltings along the inner Salcott Channel, and around Ray Island in the upper Strood Channel.

The active marshes have highly sinuous, high density creek systems with creek-head mud basins. In several places they have been reduced to isolated hummocks separated by bare mud flats, or

The majority of the Colne estuary marshes appear to be slowly eroding. At Colne Point and Cudmore Grove, shell and shingle spits are moving landwards, exposing degraded marsh deposits on the upper foreshore. At the entrance to the Colne Point marsh, the marsh edge is degraded with mud-mound formation. Several marshes show internal dissection and the development of circular creek-head mud basins (Butler et al., 1978). However, these features are not as pronounced as in the Tollesbury and West Mersea marshes. A net total of 92.5 ha of marsh was lost to erosion between 1973 and 1988 (Burd, 1992).

Spartina anglica was first planted in the Colne estuary in 1924 and its coverage in 1966 was reported to be 437 ha (Hubbard & Stebbings, 1967). However, Burd (1989) recorded only 6 ha in the late 1980's due to the combined effects of erosion and vegetation succession.

31 Hamford Water

Hamford Water occupies a broad embayment between Walton-on-the Naze and Harwich. Active saltmarsh fringes much of the embayment and a number of low bedrock islands (Horsey Island and Skipper's Island). The embayment has experienced a complex history of reclamation and abandonment in recent centuries (Gramolt, 1960). The last major phase of reclamation occurred between 1800 and 1840, but high tides in March 1874 and November 1897 caused extensive breaching of the seawalls, many of which were not repaired, allowing reversion to active saltings.

Burd (1989) reported the area of active salt marsh to be 827 ha. There was net erosion of c.169ha between 1973 and 1988, representing 19.3% of the 1973 area (Burd, 1992). Extensive loss occurred along the marsh front at Foulton Hall and Pewit Island, and between Stone Point and the Naze. The northeastern corner of Horsey Island also experienced retreat of the marsh edge, and there was extensive loss around Oakley Creek and Old Moze Hall. Sedimentation fields were constructed on the northern side of Horsey Island in 1987 and a wavebreak composed of lighters positioned in 1989. More recently foreshore recharge has been undertaken at Foulton Hall using dredgings from Harwich Harbour.

Spartina anglica was planted in Hamford Water in 1927 and by 1966 it covered c.1129 ha (Hubbard & Stebbings, 1967). Young stands of *Spartina* remain in some areas, including east of the Horsey Island causeway, but Burd (1989) reported the total *Spartina* coverage to be only 33 ha. A phase of accelerated erosion began in the mid 1970's (Leeks, 1979) and has continued to the present day. Many of the older marshes show evidence of internal dissection through creek deepening, widening and headward extension.

32 Suffolk estuaries

The Stour estuary is fringed by narrow active marshes which locally attain a greater width in Erwarton Bay, Holbrook Bay and Copperas Bay. Burd (1989) reported 296 ha of active marsh. Reclamation occurred at Harwich and Parkeston after 1800, and has continued during this century (Gramolt, 1960; Beardall et al., 1991; Davison et al., 1991). Burd (1992) reported an erosion loss of 116 ha of marsh between 1973 and 1985, chiefly involving marsh edge recession along both banks of the estuary. Marshes in the outer estuary were particularly badly affected. In Copperas Bay the marsh edge retreated by 3 m in two and a half years in the late 1970's, and the surface level fell by 2 cm in 17 months (Beardall et al., 1991). The remaining marsh edge throughout the estuary is widely cliffed and there is wave damage to the marsh edge vegetation. New *Spartina* colonies occur in only a few localities.

Narrow fringing marshes also occur along both banks of the Orwell estuary between Shotley Point and Ipswich. Saltings were more extensive along the western shore in the early 19th century, but their width was reduced by reclamation between 1800 and 1840 and by later erosion. Active marshes are best developed at Trimley, Chelmondiston and Levington. Recession of the marsh edge occurred throughout the 1980's at Trimley, Shotley Gate, Chelmondiston and Woolverstone Park. Internal dissection was important at Levington and Church End. Net erosion loss between 1973 and 1985 amounted to 32.4 ha (32.6% of the 1973 area; Burd 1992). Since 1988 there has been some marsh expansion at Chelmondiston, on the River Orwell and the beginnings of saltmarsh reactivation (unmanaged retreat after seawall failure) at Trimley.

The banks of the lower Deben estuary are fronted by earth embankments which enclose large areas of reclaimed back-barrier estuarine marsh. Active marshes occur as a discontinuous fringe which attains greatest width north of Felixstowe Ferry, near Hemley, and near Waldringfield. The total area of active marsh was reported by Burd (1989) to be 461 ha, although Beardall et al. (1991) reported only 251 ha. This compares with 182 ha shown on maps from the 1840's. The increase since the late 19th century can be partly attributed to reactivation of saltings following sea wall breaching at Hemley, Martlesham, Sutton and Bromeswell. However, in the last 30 years there has also been significant new *Spartina* marsh development north of Waldringfield and near Stonner Point. *Spartina anglica* was first planted in the Deben in 1929 (Beardall et al., 1991), but the coverage was reported to be only 2 ha in the mid 1960's (Hubbard & Stebbings, 1967). This had increased to 62 ha by the late 1980's (Burd 1989).

Although the marsh edge in the lower estuary is mostly cliffed, it appears to be stable or eroding only slowly. Outside the areas of rejuvenated marsh, there is only limited evidence of creek enlargement and internal dissection.

The estuary of the River Ore and its tributaries, the River Alde and Butley River, contains extensive reclaimed marsh (approximately 5000 ha), including Sudbourne Marshes, Gedgrave Marshes, Boyton Marshes, Stonebridge Marshes, Aldburgh Marshes and Oxley Marshes. The present areas of active marshes form a fringe, being best developed on the western shore of the lower Butley River, on the southern half of Havergate Island, and in the upper Alde estuary. The combined total area of active marsh was reported by Burd (1989) to be 562 ha.

Spartina anglica was planted in the Alde in 1934 and spread to cover 49 ha by 1966 (Hubbard & Stebbings, 1967). The coverage was reduced to 18 ha by the late 1980's (Burd, 1989), in part due to erosion but largely due to vegetation succession. Marsh reactivation, including *Spartina* colonization, has occurred after storm breaching of the seawalls between Snape Maltings and Iken on the upper Alde. Although cliffing of the marsh edge is widespread, particularly on the outside bends of meanders, there is little evidence of extensive internal dissection.

The Blythe estuary contains some 1278 ha of reclaimed marsh (Beardall et al., 1991) and extensive mudflats with localised active saltmarsh formed since it became inundated by the sea during the 1938 storm surge. The present tidal basin is connected to the sea by a narrow artificial channel. The area of active marsh is small (<5 ha).

Active saltmarsh, grading into freshwater marsh, also occurs behind the Walberswick shingle barrier, north of Dunwich. The barrier has retreated landwards in recent decades due to foreshore erosion, burying the marsh behind.

33 North Norfolk coast

Back-barrier and open-coast saltmarshes extend almost continuously for approximately 35 km between Holme-next-the-Sea and Cley-next-the Sea. In places the active marshes are more than 1.5 km wide, and the total area of active saltmarsh exceeds 2100 ha (Burd, 1989). Significant areas of reclaimed marsh occur at Thornham, between Burnham Deepdale and Wells-next-the-Sea and between Blakeney and Cley. Open coast marshes have formed to landward of a wide zone of intertidal sand flats at Thornham and Warham. Elsewhere, the marshes lie in the lee of sand and shingle barriers.

The most inland marshes began to form at least 6600 years ago when sea level lay below its present level (Funnell & Pearson, 1989). The major barrier features of Scolt Head Island and Blakeney Spit were probably in existence by about 4000 years ago (Allison, 1989). During the later Flandrian the marshes have grown vertically at a rate comparable with that of sea level rise. Roman remains at Brancaster and Holkam indicate that the inner marshes are at least 2000 years old. However, the outer marshes on Scolt Head Island, Blakeney and at Warham have developed only within the last few hundred years (Pethick, 1980, 1981). In the past 50 years new marshes have become established at the western end of Scolt Head Island, at Warham and near the western end of Blakeney Spit. Incipient marshes have also formed behind a newly constructed sand barrier between Wells-next-the-Sea and Holkham Gap, at Thornham, and near Gore Point. In the west of the area *Salicornia* and *Puccinellia* are the principal marsh pioneer species, with *Spartina* also important in the east, notably at Morston, Stiffkey and Warham. *Spartina anglica* was first planted in the area in 1907, and its coverage increased to 81 ha by the mid-1960's (Hubbard & Stebbings, 1967) and to 149 ha by the late-1980's (Burd, 1989).

In the last 15-20 years the outer marsh edges have been subjected to erosion in several places, including Stiffkey and Morston, opposite the entrance to Blakeney Harbour, at Warham, between Titchwell and Brancaster, and at Thornham. Overall, however, the marshes are in a condition of dynamic equilibrium and continue to accrete vertically with no evidence of internal dissection.

34 The Wash

The Wash forms part of the once much larger Fenland embayment which is now largely infilled by Flandrian-age sands, silts and peats. Much of the coastline has experienced accretion since Saxon times, a trend which has continued this century (Doody, 1987; Robinson, 1989; Pye, 1995; Figure 3.14). Owing to extensive reclamation since mediaeval times, active saltmarshes now form a fringe up to 1.5 km wide around the western, southern and southeastern shores. Burd (1989) reported the total area of active marsh in the Wash to be 4133 ha, with a further 67 ha at Gibraltar Point.

Spartina anglica was first planted in the Wash in 1910, and by the mid 1960's its coverage had increased to 1914 ha (Hubbard &Stebbings, 1967). However, Burd (1989) recorded *Spartina* coverage of only 138 ha, probably due mainly to vegetation succession. However, since 1973 some of the lower marshes have also experienced marginal erosion (Hill, 1988; Pye, 1995). There has also been some erosion of more landward marshes adjacent to embankments which were constructed during the 1970's at Freiston and Butterwick. Localised creek widening has also occurred in some areas, including Holbeach and Gedney, where there has been incision of creeks which are connected to former borrow pits. At the southern end of Gibraltar Point, located at the northwest corner of the Wash the New Marsh developed mainly between 1946 and 1955, with further growth, particularly of *Spartina*, between 1955 and 1970 (Harper, 1978; Hartnall, 1984). Since 1970 a number of smaller marshes have been created by the development of new sand and shingle ridges at the southeastern corner of the spit complex, but some older areas have been buried by aeolian sand and overwash deposits.

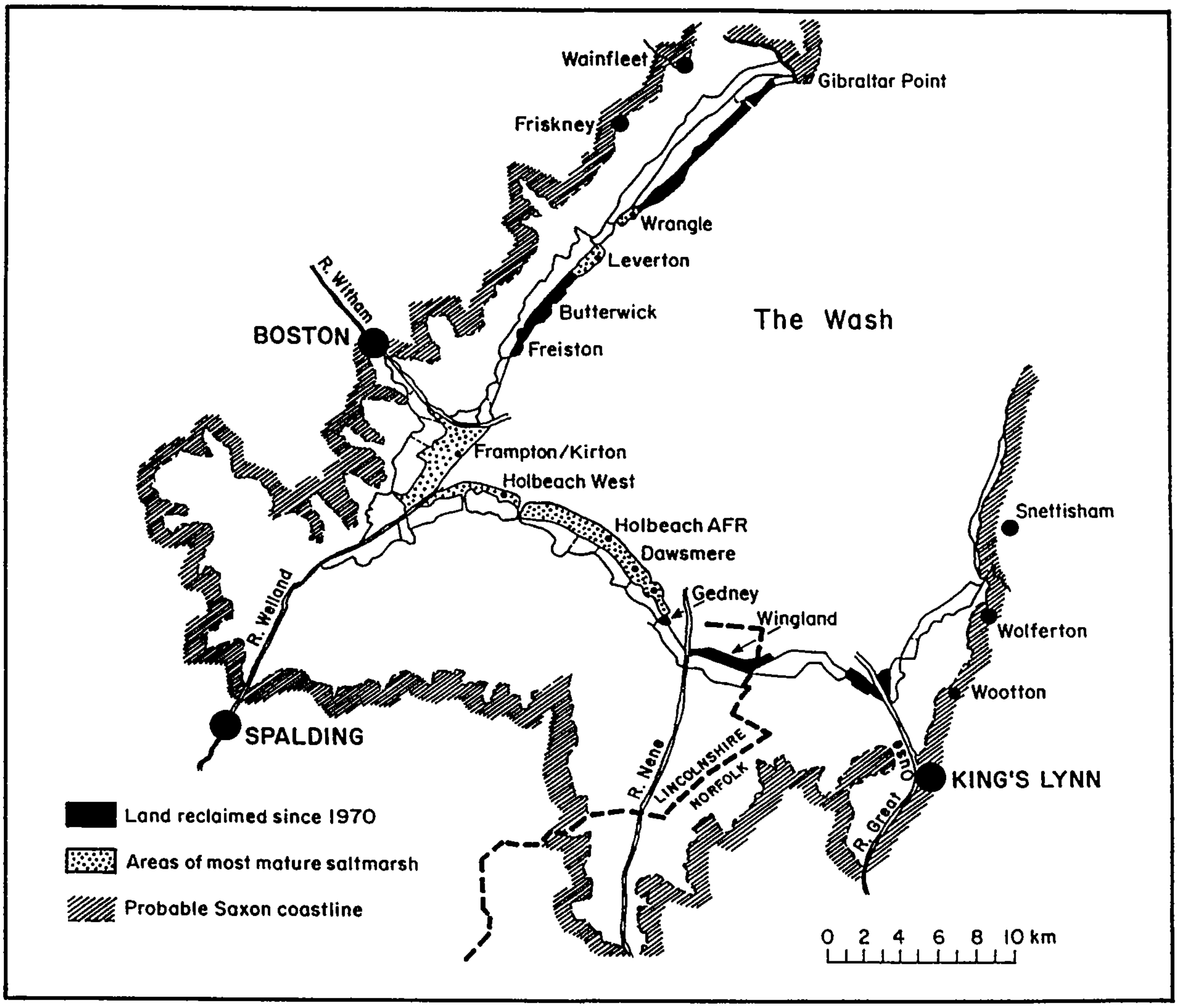


Figure 3.14 Historic changes on the shoreline of the Wash since Saxon times (after Pye, 1995)

35 Lincolnshire coast

The Lincolnshire coastal plain between Gibraltar Point and the Humber estuary formerly consisted largely of tidal marshland which has been reclaimed since Saxon times (Robinson, 1981). These marshes probably formed on a relatively open coast after about 4,000 yr B.P., although partial protection may have been provided by offshore banks and low dune-capped barriers. The shoreline appears to have moved rapidly landwards during the 17th and 18th centuries, when there was a change to a higher energy shoreline regime, exposing the Holocene marsh deposits on the foreshore. A sand dune barrier is present south of Skegness and north of Mablethorpe, but in between there has been almost total erosion of the dunes and the inland area is now protected by hard defences. North of Theddlethorpe St Helen the coastline is prograding by the development of wide sandy intertidal flats, sand bars, low dune ridges and intervening salt marshes. Relatively young salt marsh exceeds 1 km in width near Saltfleet and Donna Nook. Somewhat older, more mature marshes infill embayments in the sea defences at Grainthorpe Haven and Tetney Haven. In recent years marsh vegetation has also started to invade the beaches as far north as Cleethorpes. Burd (1989) reported the existence of 771 ha of active saltmarsh in North Lincolnshire, but this figure has since increased. *Puccinellia, Salicornia* and mixed *Halimione-Aster-Armeria* communities are well represented in the marshes. Pockets of *Spartina* also occur, but extensive mono-specific swards are rare.

36 The Humber estuary

The Humber is bordered by extensive deposits of estuarine alluvium which accumulated during the Flandrian marine transgression (Gaunt & Tooley, 1974). Extensive areas of reclaimed saltmarsh occur on the north bank between Easington and Kingston-upon-Hull, notably around Sunk Island, and between Broomfleet and Goole. On the south bank there are extensive areas of reclaimed marsh between Grimsby and Barton-on-Humber, and between South Ferriby and Goole. Active marshes form a narrow, discontinuous fringe, being well developed on the north shore at Patrington and Welwick, Hawkins Point, Cherry Cobb Sands and Broomfleet, and on the south shore at Read's Island and Blacktoft Sand (IECS, 1994). The total area of active marsh was reported by Burd (1989) to be 648 ha, representing c. 10.5% of the intertidal area, but the saltmarsh area shown on the 1977 O.S. maps is 1148 ha (IECS, 1994). This compares with an area of 1826 ha shown on maps dating from 1824. Despite the relatively small net change in total area, there have been important changes in saltmarsh distribution during the past 150 years. In the inner estuary, many areas have experienced alternating phases of accretion and erosion, e.g. between Hessle and Brough, between Brough and Crableigh Creek, and at Whitton Sands (IECS, 1994). In the outer estuary, a new marsh more than 1 km wide has developed at Welwick, extending east towards the Spurn Peninsula. However, the marsh edge is somewhat degraded with localised development of mudmound topography.

Spartina anglica was first planted in the estuary in 1936, and its coverage increased to 162 ha by the mid-1960's (Hubbard & Stebbings, 1967). This declined to 120 ha by the late 1980's (Burd, 1989), probably due mainly to vegetation succession. In some places two or more marsh terraces are evident, separated by low clifflets. At Killingholme and Barton, for example, two marsh levels post-date the 19th century flood embankments. A clifflet separating the two levels may have formed during an erosional interval between 1910 an 1920, while the lower marsh level probably represents an accretionary episode between 1920 and 1956 (IECS, 1994). The present marsh edge is cliffed and slowly eroding.

36 Northeast coast

Prior to reclamation, salt marshes formed a fringe round the Tees estuary but most of the intertidal area comprised mud and sand flats. The remaining active marsh, Cowpen Marsh, has an area of 34 ha (Burd, 1989), representing 6.7% of the intertidal zone (Davidson et al., 1991). The active marsh at this locality overlies a thick-sequence of early to mid-Flandrian age freshwater peats and estuarine silts (Plater & Poolton, 1992). The marsh is apparently stable.

Small areas of active fringing marsh occur at Castletown Marshes on the River Wear , at Willington Gut on the River Tyne, and at Seaton Sluice. In all cases they predominantly display ramped or cliffed edges which are stable or experiencing slow retreat. Further north, saltmarshes occur within a number of sheltered embayments, harbours and river mouths, notably at Warkworth (15 ha), Alnmouth (24 ha), Long Nanny (9 ha), Budle Bay (9 ha) and at Lindisfarne-Holy Island (209 ha). These marshes are a combination of fringing and back-barrier types.

Spartina anglica was first planted at Lindisfarne in 1929. However, it was not until the 1960's and early 1970's that it began to spread rapidly and required control measures (Corkhill, 1984). *Spartina* coverage at Lindisfarne was approximately 36 ha in 1963 (Hubbard & Stebbings, 1967), 40 ha in 196, and 127 ha in the late 1980's (Burd, 1989). In general the marshes have ramped margins or grade into high level sand flats. Most appear to be stable or are still slowly spreading.

Overview

Since Roman times the area of active salt marshes in many British estuaries and open coastal areas has been reduced significantly by reclamation (areas of reclaimed saltmarsh for the regions where information exists are shown in Table 5.1). The Solway Firth, Morecambe Bay, Ribble, Dee, Severn, Wantlet Channel, Medway-Swale, Thames, Fenland, and Humber all had large areas of estuarine saltmarsh and brackish marsh, that have now largely been reclaimed. Extensive open coast marshes and intertidal flat complexes also existed in West Lancashire, in North Norfolk and on the Lincolnshire coast. However, in some estuaries and embayments, extensive saltmarsh development appears never to have occurred, or occurred only relatively recently. Examples include many of the sandy embayments and estuaries in west Wales, southern Scotland, the rias of the southwest Peninsula, the South Coast harbours, and the sandy embayments of northeast England. A rapid expansion of active marsh was observed in many of these areas following the arrival and spread of *Spartina anglica* during this century (although such an association is not evident everywhere). Saltmarsh expansion after the introduction of *Spartina anglica,* can be explained by the fact that *Spartina* is able to occupy a niche and thrive lower in the intertidal zone where other marsh pioneer species, such as *Puccinellia* and *Salicornia*, find it more difficult to survive (see 5.1.2.3).

The timing of introduction and rapid growth of new *Spartina* marshes varied from area to area. In many locations on the south coast rapid expansion took place between 1900 and 1930, and was followed by a more variable pattern of localized die-back and recolonization. In southwest England and South Wales, *Spartina* and other marshes experienced a marked phase of expansion between about 1920 and 1940, continuing until the 1960's, while in west Wales and northwest England the major phase of expansion did not take place in most areas until the 1960's and 1970's, even though the vigorous *Spartina* hybrid was introduced to these areas in the 1930's and 1940's. During the 1980's and 1990's, further spread of *Spartina* marshes has been very localised. The older *Spartina* marshes have stabilized, been invaded by higher marsh communities, or have experienced erosion, particularly in more exposed locations.

In southeast England, extensive colonization by *Spartina*, and to a lesser extent other pioneer species, has occurred only in a relatively few areas, for example Shellness at the eastern end of the Swale, and scattered localities in the Medway, the Thames, Essex and Suffolk estuaries. Growth of these new marshes has not been sufficient to offset erosional losses of the older marshes elsewhere in the south east. The period 1900-1960 was essentially one of relative marsh stability and low erosion rates in southeast England. Indeed, there was marked progradation in some areas during this period (e.g. on the Dengie Peninsula). The rate of erosion accelerated in some areas during the 1960's, but more widely during the 1970's (Pye, 1996b). This erosional trend is continuing, although at a spatially variable rate and with accretion in some areas. A similar increase in saltmarsh erosion since the 1970's is evident at several places on the south coast, notably in the Solent and a number of the south coast harbours.

On the east coast between North Norfolk and Northumberland, the 1950's and 1960's were also predominantly a period of salt marsh accretion. Since the late1970's, however, marsh edges in many areas have suffered net erosion, and lateral accretion has become more localised. The current pattern is quite complex, related to wider coastal geomorphological changes, but in general, saltmarsh erosion is less serious than in southeast England.

4 HYDRAULIC CONDITIONS AND SALTMARSH CHANGE

The paucity of annual data on saltmarsh change made correlating hydraulic changes (such as an increase in storm frequency in a particular year) to saltmarsh changes difficult. Even though it was not always possible to relate the collected hydraulic data to saltmarsh response, it was still worthwhile analysing these data to determine whether changes in hydraulic conditions had occurred, and whether these changes were following a trend or random fluctuation. If there is no significant change, then it can be concluded that that particular parameter was not a causal factor promoting saltmarsh change. However, if data indicates a change in hydraulic conditions, and our knowledge of coastal processes indicated that this change would be deleterious/advantageous to saltmarshes, it would be possible to predict whether the change in this parameter is likely to cause saltmarshes to accrete or erode.

This chapter forms the main part of the report. Section 1.2.3 explains that shear stress on saltmarshes is exerted by waves and tidal currents. The changes in hydraulic conditions that can cause saltmarsh change, along with the impact of rising mean and extreme water levels, are described more fully in section 4.1. Section 4.2 describes the forcing factors affecting waves, currents and water levels. The last section in this chapter presents the evidence that various potential forcing factors have caused saltmarsh change, and the relative importance of the various forcing factors is considered.

4.1 How changes in waves, currents and water level cause saltmarsh change

- **Waves**

Changes in incident wave energy lead to saltmarsh change. Significant increase in wave energy cause:

(a) increased erosion and reduced sedimentation on the mudflat fronting the saltmarsh. This increases water depth and the potential wave height, and hence the erosive forces attacking the saltmarsh edge.

(b) narrowing of the saltmarsh strip through erosion of the seaward edge. This can take the form of surface erosion (see Figure 4.1, note the plume of muddy water adjacent to the saltmarsh edge caused by resuspension of saltmarsh sediments) or mass collapse due to wave undercutting leading to slumping, rotational fractures and the toppling of mud blocks (see Figure 4.2).

(c) vegetation stress and removal, leaving bare patches on the strip of saltmarsh close to the seaward edge (see Figure 4.3)

(d) if wave energy is high enough and sediment available, natural barriers may be formed, behind which the inner parts of the marsh are protected whilst the outer part erodes.

Figure 4.5 illustrates the process by which the flow of water as it pours from the marsh surface after large tides causes surface erosion. In the foreground, the process of creek formation is evident. The force of ebbing surface water is causing erosion which is cutting back the sediment and initiating a new creek. The direction in which the new creek lengthens will depend on micro-topography which governs the channelling of flow.

- **Water level**

Change in low or high water level may occur due to sea level rise, tectonic movements, or changes in tidal ranges (see 4.2.4). A relative increase in high water levels would increase the frequency and magnitude of flooding. This could have the following effects:

(a) A substantial proportion of groundwater recharge on upper saltmarshes occurs by infiltration through the vegetated surface during 'above-marsh' tides (Carpenter, 1994). Rising high water levels would bring the water table closer to the surface, thus reducing the depth of the unsaturated zone. The associated change in chemistry would cause a change in species composition, favouring invasion of pioneer species into upper saltmarsh communities. Moreover, the rise in water table increases the moisture content of the surface layers, making them more vulnerable to erosion (see section 5.2.2)

(b) Creek lengthening due to enhanced water volumes draining into the creek on the ebb and increased energy impacting the top end of the creek on the flood.

(c) Landward extension of the saltmarsh.

An increase in the low water level would limit the seaward extension of the saltmarsh.

4.2 Description of forcing factors affecting waves, currents and water levels

4.2.1 Wind Speed

- **Affects** - wave height

The main influence of any change in wind speed, in the context of the present study, is in producing a consequent change in wave height. For small changes in wind speed, deep water wave height increases roughly in proportion to wind speed. There are other less significant changes. Wave period would increase roughly in proportion to the square root of wave height. Wave length, wave celerity (speed) and wind-driven currents might also increase marginally.

Perhaps the most relevant parameters from which to infer any consequent effect on saltmarshes are the rate of transmission of wave energy and the wave-induced bottom orbital velocity (the shear stress exerted on the bed). The former is proportional to the square of the wave height times the wave speed, and therefore increases by approximately the square of the increase in wind speed. The latter increases slightly more than in proportion to wave height (and therefore wind speed). The potential changes in the *absolute* values of wave power and bed orbital velocity are not great; even though the water movement at the surface is roughly proportional to wave height, the movement decreases rapidly with increasing depth. For example, an increase in water depth from 4 to 5 m would roughly halve the bed orbital velocity. However, in practice a relatively small increase in the forcing parameter may significantly increase the proportion of time for which the shear strength of the sediment is exceeded, and therefore the time during which erosion will occur.

A change in wind *direction*, towards the longer fetch directions could also marginally increase wave heights. Wind *duration* is also important for open coast locations where the wind must blow for several hours before wave heights reach their maximum levels.

4.2.2 Wind direction

- **Affects** - wave height in fetch-limited areas, and wave direction

The frequency of erosion episodes affecting a saltmarsh can increase even if there is no significant change in wind speed. This is because most saltmarshes are within estuaries, where waves are generally internally generated. Externally generated waves are generally not important due to energy dissipation during propagation up the estuary. Therefore, a change in the proportion of time that winds blow from a certain direction could alter lateral erosion/accretion rates. For example, in the case of south-east facing estuaries (such as the majority of those in Essex, Suffolk and Southampton Water), an increase in the proportion of south-easterly winds, even if the mean wind speed remains constant, could increase wave heights hitting the marshes. This change would alter the beach profile.

In most situations (particularly on sandy foreshores), the movement of sediment perpendicular to the beach contours is a rather minor factor in the long-term evolution of a coastline. The major cause of change is normally the change in longshore transport of beach material from point to point along the coast. Changes in wave height can only affect the rate of transport, whereas changes in the average wave direction will often cause a change in the present pattern as well as the rate of erosion and accretion. In some recent case studies it has been found that erosion problems have recently occurred on stretches of coastline which have been stable or accreting for many years. The onset of erosion fits very well with the modelled changes in drift direction (HR, 1993).

4.2.3 Relative sea level change

- **Affects** - wave height, tidal currents, position of water table, position of high water

Fluctuations in the global climate alter the volume of water in the oceans by controlling the amount locked up in the ice caps and thermal expansion of the oceans, thus the U.K. coastline during periods of glaciation was much further to seaward then it is to day. During the interglaciations sea levels rose and the position of high water migrated inland, flooding the river valleys and pushing the coastline of low-lying areas significantly landward. Obviously as the coastline shifted, so did the distribution of the saltmarshes. Furthermore, the estuaries formed in the flooded river valleys created sheltered sites suitable for saltmarsh development.

On a shorter timescale, in the order of several decades, change in sea level can affect both saltmarsh morphology and community type. If the rate of sedimentation is less than relative sea level rise, the frequency and depth of inundation increases. This may cause the following changes: creek lengthening, change in floral community, landward movement of saltmarsh extent and increase in potential wave height (which may or may not lead to an increase in tensile stress, as although the increase in wave height increases water turbulence, this is counteracted by the increase in depth). Wave-induced bed orbital velocities (i.e. turbulence) rapidly reduce downwards through the water column).

Sea levels aaround Britain have been increasing (but with some minor fluctuations) since the end of the last Ice Age. Generally, rates of sea level rise during this period have been substantially higher than they are today. It is believed that the rate of rise will increase over the next century (Ince, 1990). This may be natural but it is likely that the increase is at least partly due to emissions of "green house" gases through various human activities. The impact of rising eustatic sea levels depends on local tectonic movements. For example the south-east of England is sinking whereas Northern Ireland and northwest Scotland are rising. Thus in south east England, the relative sea level rise is greater than the eustatic rise, but in Scotland, tectonic uplift cancels out eustatic sea level rise in most regions, so that the actual effect is a decrease in mean water level of between 0.5-1mm per year. From this, it can be inferred that the importance of sea level rise, as a factor causing saltmarsh change, differs between regions. It is insignificant in north west England, but potentially more important in the south east. Regional trends in relative mean sea level rise are presented in Table 4.1.

4.2.4 Changes in tidal range

- **Affects** - wave height on saltmarsh surface, tidal currents, position of high water

Cyclic fluctuations in tidal range

Change in tidal range affects saltmarshes by altering the depth of water (and hence the potential wave height) above the marsh surface during inundating tides. Moreover, the increase in tidal volume associated with variation in tidal range, may increase tidal currents which could exacerbate saltmarsh erosion. An increase in tidal range in some estuaries may give rise to stronger flood tidal currents, resulting in increased landward transfer of sediments and enhanced inter-tidal accretion. On the negative side, a reduction in tidal range can lead to longer tidal immersion times and death of plants near the seaward edge of a low marsh (Gray et al., 1989).

Tidal range fluctuates in a 18.61 year lunar nodal cycle (maximum to maximum takes 18.61 years). The fluctuations are due to the cyclical change in the orbit of the moon around the earth. Although the timing of the mean tidal range (MTR) maxima and minima is the same at all points worldwide, the size of difference between maxima and minima varies. For example, in the Severn Estuary MTR varies by about 50cm during the 18.6 year cycle, but the change in Christchurch Harbour is only a few centimetres. Thus the magnitude of influence that the 18.6 year cycle has on saltmarsh accretion/erosion is likely to vary strongly between sites. It will be an insignificant factor in some regions, like Christchurch Harbour, but is likely to have an effect in areas experiencing larger changes, such as the Severn Estuary. In the Severn, the annual change in high water level due to the 18.6 year cycle is almost 30mm per year. This dwarfs relative sea level rise which is thought to be approximately 1-2mm per year.

It may appear that at the maximum in the tidal range cycle (and hence maximum water depth at high tide) the increase in tidal currents and wave heights will automatically cause more erosion than at the minimum of the cycle. However, these effects could tend to be offset by a reduction in wave-induced bed orbital velocities at the highest water levels or by enhanced sedimentation from a larger water volume overlying the marsh. The pattern of increasing or decreasing erosion as a result of increasing high tidal levels would be different at different sites, at different states of the tide, and at different levels on the marsh. The net effect could be predicted by modelling, but each site would have to be considered separately.

It may seem that the increase in high water level, due to the 18.61 year cycle, seems small in comparison to the tidal range, and hence the impact of the cycle will be insignificant. However, proportional difference in water depth on the upper inter-tidal zone will be much greater than for sub-tidal regions. For example, the upper levels of saltmarshes are typically at about the level of MHWS (mean high water springs) and therefore their surface floods only during the portions of large tides that exceed this level. Upper saltmarsh surfaces are rarely covered to a depth of more than several 10's of cm and the difference that the 18.6 year cycle can make to the level of high water is of a similar magnitude. Hence at the maximum of the cycle, the depth of water on top of the marsh surface could be at least twice as much as expected at the minimum of the cycle. This would at least double the potential wave height but also double the reservoir of suspended sediment available for deposition on the marsh surface. Conversely, at the minimum of the cycle, the frequency and magnitude of flooding will be less than average. The net impact of the mean water depth difference would depend largely on the wind climate. If wind speeds are low, the difference in depth will not significantly erosivity.

At the maxima of the cycle, the frequency of inundation as well as water depth will increase relative to the minima of the cycle. The possible impacts of these differences are listed below:

- lengthening of creeks (internal dissection) caused by increase in the volume of surface water draining into creek fingertips due to the increase in frequency and magnitude of surface flooding
- water table may be closer to the surface, which may reduce primary productivity of upper saltmarsh plant species
- lowering of mudflats due to increase in wave heights, potential knock-on effect of causing lateral erosion of saltmarsh edge
- vertical erosion of the saltmarsh surface due to the combination of increased tidal currents and wave heights; or enhanced deposition on account of the increased water depth reducing the bottom orbital velocity induced by the waves
- increased vertical accretion on saltmarsh surface due to increased flooding frequency increasing the opportunity to receive sediment

Note that the net effect of the cycle on saltmarsh accretion/erosion status is similar to the effect of relative sea level rise (see 4.2.3). Therefore, in the years around the maxima of the 18.61 year cycle the impact of sea level rise is exacerbated, but conversely, the effect is combated during the minimum of the cycle.

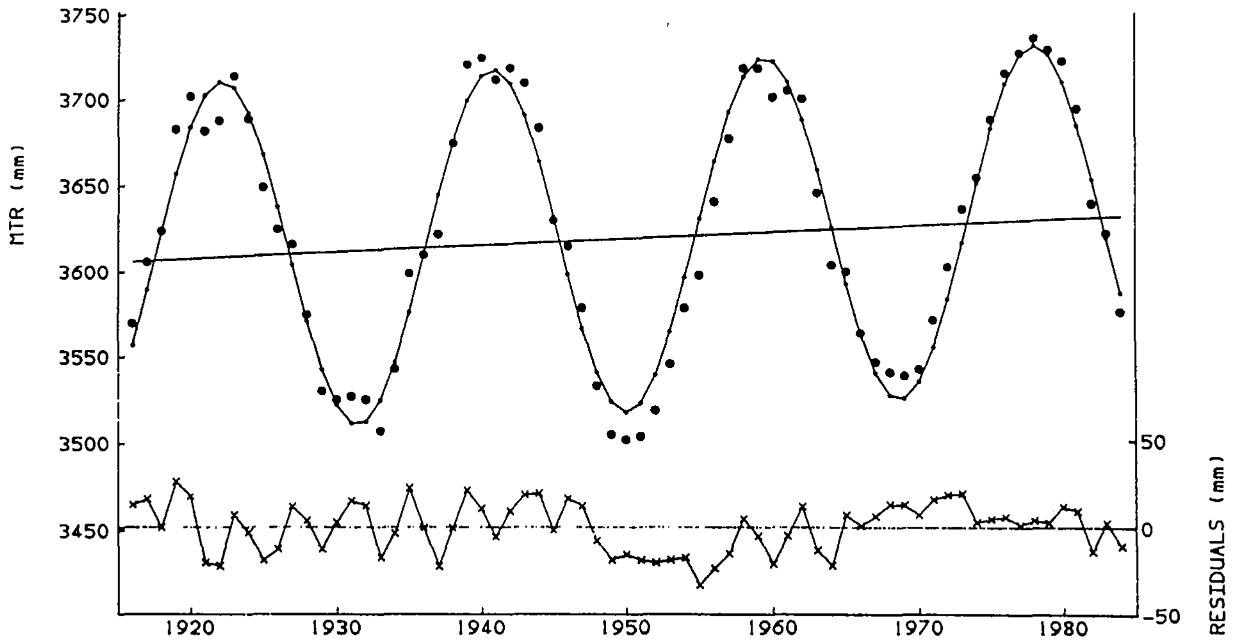


Figure 4.6 **Graph illustrating the 18.6yr lunar modulations and the secular trend in MTR at Newlyn (after Woodworth et al., 1991)**

It is difficult to predict the net effect of the tidal range cycle on vertical accretion/erosion of the saltmarsh as the balance between increased opportunities for sediment deposition and possible resuspension due to increased drainage currents and wave heights is not known.

The most recent past maxima occurred in 1959, 1978, and the minima in 1969 and 1987. If tidal range does have a significant effect on saltmarsh accretion/erosion it would be expected to that internal dissection and lateral erosion would be most severe in 1959, 1978 and 1997 but the rate slowed or reversed around 1969, 1987.

Secular trends in tidal range

Analysis of historic tidal records to identify secular change in tidal range was conducted by Woodworth, Shaw and Blackman (1991). Their research is still the most recent and no-one else has investigated secular changes in tidal range in Britain (Woodworth, 1995; personal communication). Trends in mean tidal range for 13 ports around the British Isles were derived from analysis of at least 15 years of data spanning at least 28 years, i.e. approximately one and a half lunar cycles. The geographical distribution in the results is shown in Figure 4.7. The measured trends in mean tidal range ranged from -1.8 to 1.3mm per annum (see Table 4.1). A positive secular change increases high water level, whilst a negative change decreases it.

The secular change in tidal range equates to a change in high water level of between approximately -1.0 and 0.6mm a year (assuming that an increase in tidal range would be equally spilt between enhancing high water level and lowering low water level). This is the same order of magnitude but normally less than the yearly change in mean high water due to relative sea level changes. Depending on location, the secular change in tidal range would either off set or compound relative sea level rise.

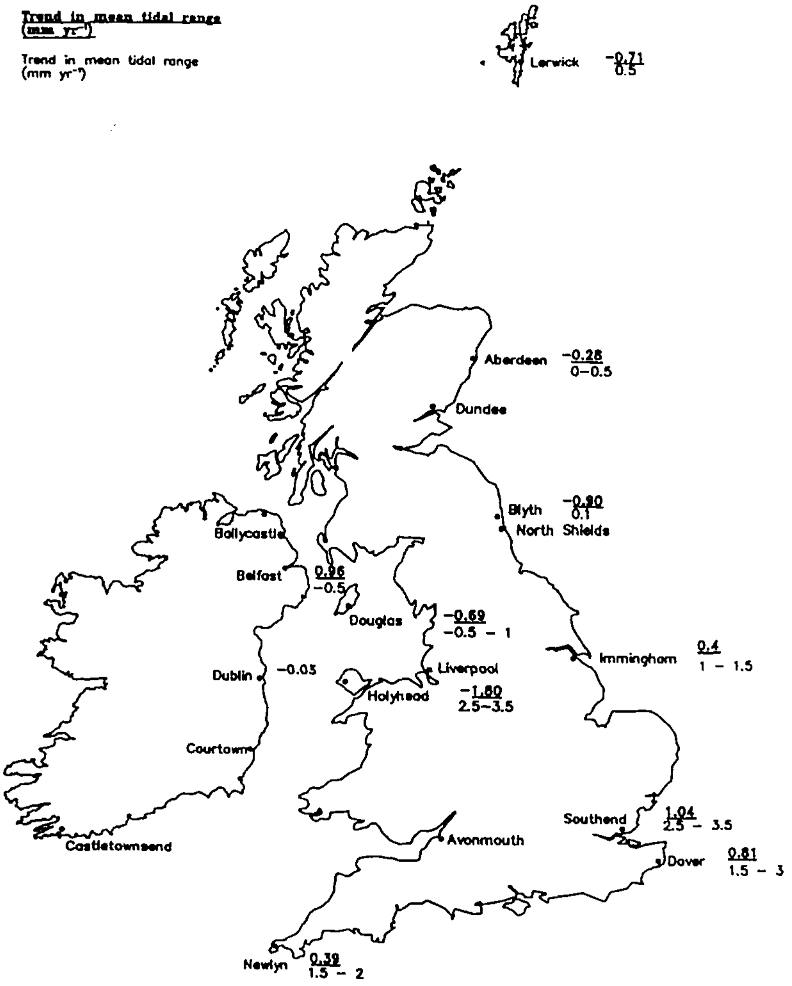


Figure 4.7 **Regional secular trends in mean tidal range and sea level (from data in Woodworth et al., 1991)**

In order to predict how the trend will change in the future it necessary to identify the cause of the change. Due to insufficient research it is not yet possible to do this, however, the following ideas have been put forward:

(1) Sea level change

There appears to be a relationship between the trend in MTR and the trend in mean sea level change. This relationship may be accidental (tidal models predict that tidal range is insensitive to sea level rise). Apart from the outlying points of Holyhead and Belfast there is a strong correlation between these two. These are both ports and so anthropogenic alterations may have caused the deviation.

(2) Changes in estuary bathymetry

These could be caused by natural or man-induced changes in the sedimentation pattern, or modifications to the bathymetry of coastline by dredging or 'reclamation' of the inter-tidal flats. It has been established that dredging has increased the tidal range in Hamburg (Fuhrboter and Jensen, 1985) and the Hooke of Holland (de Ronde, 1983). The deepened channels mean that the water level at low water is lower and hence the tidal range increases. Moreover, there is a lesser effect in that deepening causes a reduction in tidal friction which in turn increases MTR.

Table 4.1 **Secular trends in mean tidal range and mean sea level** (data from Woodworth et al., 1991)

Port	Period	Trend in MTR (mm per annum)	Trend in MSL (mm per annum)
Lerwick	1959-1987	-0.71 +/- -0.14	-1.61 +/- 0.61
Aberdeen	1862-1988	-0.28 +/- -0.07	0.54 +/- 0.08
Blyth	1862-1988	0.90 +/- 0.39	5.59 +/- 1.01
Immingham	1956-1988	0.10 +/- 0.54	1.47 +/- 0.76
Southend	1934-1966	1.04 +/- 1.22	3.11 +/- 0.46
Dover	1926 - 1987	0.81 +/- 0.5	2.30 +/- 0.66
Newlyn	1916 - 1984	0.39 +/- 0.09	1.76 +/- 0.16
Avonmouth	1925 - 1980	1.12 +/- 0.62	0.66 +/- 0.41
Holyhead	1938-1988	-1.80 +/- 0.80	3.10 +/- 0.56
Liverpool	1958 - 1983	1.30 +/- 0.18	2.11 +/- 0.58
Douglas	1938 - 1977	-0.69 +/- 0.47	0.26 +/- 0.67
Belfast	1918 - 1963	0.96 +/- 0.30	-0.25 +/- 0.34
Dublin	1938 - 1988	0.03 +/- 0.27	0.17 +/- 0.35

4.2.5 Shape (gradient) of tidal curve

- **Affects** - tidal currents

Change in shape of the tidal curve would affect saltmarsh morphology. Steepening of the tidal curve would increase current speeds and hence reduce deposition and possibly cause erosion. The shape of the tidal curve depends on estuary/coastline morphology and tidal range. Peak current speeds could therefore alter, if for example, an estuary was extensively dredged, or as a result of the 18.6 year cycle in tidal range.

4.2.6 Storm frequency

- **Affects** - incident wave energy, tidal currents, position of high water

In exposed locations, generation of the largest waves may require the wind to blow for several hours. A change in the sequencing and duration of spells of high winds, without necessarily a change in the overall mean wind speed, may significantly affect the number and sequencing of spells of high wave activity.

Lateral erosion of saltmarshes in exposed locations tends to be episodic. Evidence suggests that in open coast areas, such as Morecambe Bay and outer estuary locations such as those fringing Foulness, episodes of large waves that correspond to high water levels are the most important factor that accounts for saltmarsh recession. In more sheltered estuarine locations, stormy periods have a lesser effect, and hence it is likely that other factors are responsible for the recession.

4.2.7 Migration of channel position

- **Affects** - tidal currents, wave energy

The cross-section of flooded valley estuaries or embayments is not uniform. Tidal flow is concentrated in channels. Estuarine channels naturally change their position and, in estuaries which have not been modified to a major degree by engineering works, this is the most common factor leading to alternating episodes of saltmarsh erosion and accretion. Change may occur gradually, due to meander migration, or more dramatically during periods of high flow, extreme tides and strong winds. The effect of a lateral shift in the position of a deep water channel may be twofold:

(a) a change in the slope of the intertidal profile and hence wave energy at the marsh edge
(b) possible undercutting and destabilization of the marsh cliff, leading to rotational slides or toppling failures.

As the channel migrates, the distribution of current speeds changes. If the channel directly cuts into the edge of the saltmarsh (which is currently occurring at Ince Banks in the Mersey Estuary), the current speed will be sufficient to cause recession of that edge. The opposite side of the channel will often show signs of accretion and saltmarsh advance due to reduction in current speed.

4.3 Evidence that indicates the importance of the various potential forcing factors on saltmarsh change

This section presents the analysis conducted during this study to relate changes in hydraulic conditions to saltmarsh changes. There have been three approaches to this problem.

(1) use of a correlation analysis table containing forcing factors and categories of saltmarsh response for 50 saltmarsh sites around England and Wales

(2) search for secular changes and cycles in the forcing factors (i.e. wave height, tidal range, wind speed and wind direction) and from knowledge of how an increase or decrease in these factors is likely to affect tidal flats and saltmarsh, predicting whether the changes observed would potentially benefit or stress saltmarshes

(3) in cases where adequate records of saltmarsh change exist, relating change in a forcing factor at that site with saltmarsh response, i.e. the case study approach.

Considerable effort was put into collecting the data to enter into the correlation table. The collected or modelled data on climatic changes and changes in saltmarsh characteristics are presented in Appendix A. The results from the correlation analysis are also tabulated and discussed in this Appendix. Correlation coefficients were calculated for each combination of forcing factor (e.g. change in wave height, sea level and fetch) and saltmarsh response (such as vertical and lateral erosion, internal dissection, and *Spartina* expansion). The derived correlation coefficients between changes in forcing factors and saltmarsh change were very low, indicating that there was no statistically significant relationship between climatic changes and saltmarsh response.

There are three possible explanations for the apparent poor relationships. Firstly, there is no relationship between the tested forcing factors and saltmarsh response. Secondly, the value of the correlation analysis depends on the quality of the data. Unfortunately there are few long-term records of measured wave heights, tidal curves or suspended sediment concentrations at saltmarsh sites. Likewise, there has been little systematic monitoring of saltmarsh change on a yearly basis with which to correlate changes in hydraulic conditions (from the questionnaire returns, there was only one instance where change in the lateral extent of the saltmarsh has been monitored for more than 10 years). Due to the scarcity of quantitative data, we were forced to represent saltmarsh change with the values -1, 0 or 1, which represent decreasing, stable and increasing respectively. Thirdly, there are many factors that lead to saltmarsh changes, several of which may be changing at the same time at a particular site, and the direction of change in one factor may compensate for another. This means that when a single factor is correlated against saltmarsh response the correlation is poor even though changes in that particular factor could affect saltmarsh change. Because of the failure of the correlation analysis approach to identify any clear links between forcing factors and responses, approaches (2) and (3) were adopted.

Sections 4.3.1 to 4.3.7 present the evidence for causes of saltmarsh change derived from the latter two approaches.

4.3.1 Wave height

Correlation analysis

The results from the linear correlation analysis, presented in Appendix A, indicate that there is no statistically significant relationship between changes in wave heights and lateral and vertical erosion of saltmarshes. However, the low correlation may not reflect the true relationship between wave energy and saltmarsh loss, as the wave data come from models which are probably poor at indicating inshore wave conditions, particularly in estuaries where the waves are mainly internally generated. There did seem to be a relationship between *Spartina* expansion and a reduction in the *mean* wave height. The only instances of *Spartina* expansion occurred in locations where there was a negative trend in mean wave height. The only way of confirming the relationship between change in wave energy and saltmarsh change, would be to install wave stations at the marsh edge and monitor saltmarsh response.

Data relating to short term changes in wave height

The effect of increased wave height, sustained over a period of a few days or weeks, is to cause landward recession of the saltmarsh edge and to lengthen the intertidal flat (Pethick, 1992). If waves break over the marsh surface, the marsh surface may be lowered by erosion.

Some of the sediment eroded from the marsh edge and/or surface may be redeposited on the mudflat in front of the marsh, thereby raising its level. In other circumstances, however, the effect of breaking waves is to deposit sediment just inland of the retreating marsh edge, causing accelerated vertical accretion in that area. If a large number of shells or pebbles are available, a chenier (pebble/shell ridge) may form just landward of the eroding marsh edge (Greensmith &.Tucker, 1967). Pethick (1992) documented an example of the first type of response at Marsh House on the Dengie Peninsula, Essex. Here, a number of storms between late 1988 and early 1989 caused a slight lowering (c. 0.5 cm) of the marsh surface as well as recession of the marsh edge, while the mudflat fronting the marsh showed contemporaneous vertical accretion of the same magnitude (Figure 4.8). Recovery of the marsh surface to its pre-storm level look approximately 14 months; an observed fall in the level of the mudflat following the storms suggested that this was the main source of mud for marsh recovery.

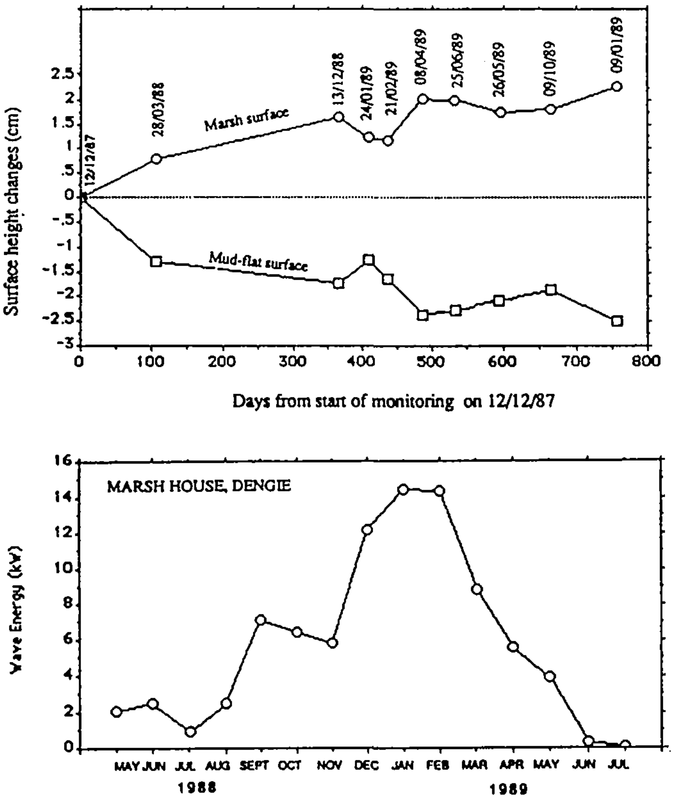


Figure 4.8 **(a) Vertical changes in surface height of an open coast marsh and fronting mudflat at Marsh House, Dengie Peninsula, during 1988-1989. (b) Measured inshore wave energy at Marsh House over part of the same period, showing the effect of storms in early 1989 (after Pethick, 1992)**

Monitoring results from Silverdale marsh in Morecambe Bay illustrate the second type of response; here, recession of the marsh edge during storms is often accompanied by accretion of up to several centimetres of sediment near the seaward margin of the marsh, although turf stripping occasionally occurs (Pringle, 1995). Collapse of root-bound blocks during retreat of the marsh edge raises the level of the fronting intertidal flat, forming a turf-block pavement, although during very severe storms the sediments beneath the turf blocks are scoured and the level of the intertidal flat may fall.

Monitoring of the surface levels on an enclosed tidal mudflat and adjoining marsh in Strangford Lough, Northern Ireland, between December 1988 and October 1990, demonstrated that short term tidal flat elevations are strongly dependent on wind speed and direction, and consequently on locally generated waves (Kirby et al., 1993). A broad seasonal cyclicity was observed, with accretion in the summer months and lowering during the more stormy winter months, especially during gales. Vertical variations of up to 60 cm were recorded. Individual gales on April 1st/2nd and August 4th 1989 redistributed about 50,000 and 27,000 m^3 of sediment respectively. Other work has shown that even small amplitude waves (<7cm) are important in introducing suspended sediment into the estuarine water column and making it available for tidal current transport (Anderson, 1971). However, wave stirring over tidal flats can have a positive effect on the vertical accretion rate of marshes in neighbouring sheltered settings, since accretion rates are positively related to turbidity of the water column overlying a marsh (French & Spencer, 1993).

Further evidence that an increase in wave energy is responsible for saltmarsh erosion is provided by the results of simultaneous measurements of nearshore waves and saltmarsh height at Marsh House on the open coast of the Dengie Peninsula, and Mill Point, in the more sheltered Blackwater estuary (IECS, 1993). Wave recorders were positioned close to the saltmarsh edge and hence these data are more reliable indicators of wave conditions at the saltmarsh edges than offshore measurements or modelled data. The results show a significant difference in the wave heights at the two sites, the open coast site experiencing 6 times the wave energy at the Mill Point station (IECS, 1993). As the rate of lateral erosion was calculated to be about 6 times greater at Marsh House than Mill Point the evidence suggests that waves were the main cause of erosion.

To summarise, from the limited data available, it seems that a relative increase in wave height in an estuary may simultaneously result in mudflat lowering, accelerated recession of the seaward edge of the saltmarsh and accelerated vertical accretion of the backmarsh area.

Regional trends in wave height and their relation to trends in saltmarsh accretion/erosion

HR Wallingford conducted a study of wave climate change for MAFF (HR, 1991). Section 2.4.3 explains that the waves were hindcast from wind records and represent deep water offshore conditions. It should be remembered that these predicted wave heights may not represent the wave climate incident on the foreshore, but as long term records of measured wave heights adjacent to saltmarshes do not exist the data used in this report are the best available. It is hoped that the offshore results will at least indicate the direction of change in wave height even if the magnitude of the change cannot be considered reliable. The graphs of the change in wave height over the study period were redrawn for this research report and are displayed close to the geographic location they represent in Figure 4.9. This figure also indicates the areas of eroding and accreting saltmarshes within the regions which would have a similar wave record to the point for which waves are modelled or recorded. The graphs on the figure show the mean wave height for three wave categories for each year for which data were obtained. These are significant wave heights 1%, 10% and 50% H_s. The trend in these categories is also shown, determined from linear regression analysis.

Apparent trends in the modelled wave heights

Table 4.2 summarises the trends in wave height for the nine wave modelling sites

Table 4.2 Geographical trends in wave height

Annual H_s	**No change in wave height**	**Increasing trend**	**Decreasing trend**
1%	0	8	1
10%	1	5	3
50%	0	4	5

The table above indicates that the annually averaged wave heights associated with extreme conditions (i.e. the wave heights exceeded only 1% of the time) seem to be increasing. Only one site, Sunderland, indicated a slight decrease. However, it is interesting to note that the more normal wave heights did not increase with such a geographical solidarity. In fact, there were more sites which exhibited a decreasing trend in mean wave height than an increase. *Hence it seems that storm intensity has increased throughout England and Wales in the last 25 years but that average wave heights have not shown this widescale increase, the rates of change being generally smaller and the sites are split pretty equally between increasing and decreasing trends.*

When assessing the geographical variation in wave height shown in Figure 4.9, it should be remembered that the data sets refer to different time periods and that the apparent strong trends of the short data sets should be treated with caution. The longest wave record, at Barry, South Wales, has the lowest rate of secular trend in wave height, but within this period there are large, apparently cyclical fluctuations (e.g. annual 1% H_s varies by about a third). This illustrates why it is not possible to conclude that the apparent trends in the shorter data sets will continue. To illustrate this, compare the wave height trend at Barry for the period 1978-1986, covered by the hindcasted wave record at Dowsing (graph H) which indicates a strong increase in wave height. During the same time period there appears to be an increase in wave height at Barry which is of the same magnitude as that at Dowsing.

Relationship between changes in wave height and saltmarsh accretion/erosion

If change in wave climate is an important factor determining the seaward position of the saltmarsh, and it can be assumed that changes in the hindcasted offshore wave records reflect wave climate changes in the intertidal zone containing saltmarshes, it should be expected that recession of the saltmarsh edge should be related to increase in wave height, and progradation, to a decrease in wave height. The absence of change in wave height should be related to a stable saltmarsh edge. Table 4.3 compares the direction of trend in the three wave height categories with the type of saltmarsh change in its area of influence.

Table 4.3 Analysis of change in wave height and saltmarsh response

Annual H_s	Direction of change in wave height agrees with direction of saltmarsh change	Direction of change in wave height does not agree with direction of saltmarsh change
1%	2	5
10%	3	4
50%	5	2

The correlation between trend in wave height and saltmarsh response for the seven wave modelled sites which had saltmarsh in the vicinity of influence, suggests that *the trend in mean wave climate is more important in influencing the longer-trend in the change in seaward extent of the saltmarsh than the less frequent, higher intensity events.* The less frequent high energy events are, however, responsible for the maximum rates of recession. Research monitoring the vertical response of two saltmarshes and their fronting mudflats, at an open coast and estuarine site in Essex, proved that saltmarsh erosion was associated with storm events (Pethick, 1992) but that recovery was relatively rapid. It therefore seems that gradual, persistent erosion is more damaging to saltmarshes than periodic events (as long as the return period is greater than the recovery period).

Limitation of the modelled historic wave height data sets

(1) Both the modelled and measured wave records presented in Figure 4.9 do not take into account the effect that the 18.6 year lunar nodal tidal range cycle has on wave height at the saltmarsh. How this cycle affects the potential wave height is explained in section 4.2.4. In brief, the tidal range cycle affects the elevation of high water and the duration of standing water over the saltmarsh. The change in water depth offshore is insignificant, but the proportional depth change on the saltmarsh surface would significantly affect the potential wave height. Hence there may be fluctuations in wave heights incident on saltmarshes which do not appear in the wave height data sets in Figure 4.9. This is because the majority of the wave records are derived from hindcasting from wind records, and the two measured sites, Perranporth and Seven Stones (graphs C and D), were offshore in deep water, where the effects would be negligible.

(2) The given trends in wave heights calculated from the deep water sites do not necessarily mean that there has been a change in the wave heights incident on mudflats/saltmarshes due to varying frictional drag in the shallow coastal waters and foreshore regions. For example, there appears to be a significant, and comparable increase in wave energy off the Essex and N. Norfolk coasts. However, the saltmarshes in these areas are not affected in the same way. Those in Essex are suffering from severe erosion whilst the pattern of change in North Norfolk is spatially variable (accretion/erosion or stable). If we just correlated saltmarsh change with offshore wave changes, this might falsely indicate that there was no relationship between wave energy and saltmarsh response. However, personal observations at the seaward edge of the saltmarshes at both of these

sites indicate that the incident wave energy is *much* higher on the Essex coast than it is in North Norfolk. The energy hitting the North Norfolk marshes is dissipated by the extensive sandflats fronting the marsh. Furthermore, most of the marshes are behind shingle spits whereas those on the Essex coasts are not so well protected. Hence the offshore conditions in North Norfolk are very different from the intertidal conditions whereas in Essex they may be more similar.

In addition, the sandy Norfolk foreshore may respond to an increase in wave energy in a different way to the more muddy Essex foreshores. Wave energy on the latter can throw up intertidal sandbanks which would act as natural wave breaks and reduce the wave height affecting the saltmarsh. In contrast, when mud particles are resuspended by wave action they can be carried for many miles and therefore removed not just from the inter-tidal zone but from the subtidal area. This in turn leads to an increase in water depth and fetch which has the effect of increasing wave heights and hence erosion of the mudflats and saltmarshes. Hence there is positive feedback.

Numerical modelling of changes in nearshore wave heights

Due to the limitations of the offshore wave heights in reflecting wave height trends incident on saltmarshes, HR conducted extra modelling to generate trends in the *nearshore* wave conditions at various points in the harbours between Portsmouth to Pagham (see Figure 4.10) during the last 20 years (for further explanation see chapter 2.4.4). The results for each harbour site are presented graphically in Appendix B; the trend in wave height was calculated by linear regression analysis and is represented as a dotted line on the graphs. Table 4.4 summarises the rate of change in the three categories of wave height.

Table 4.4 and the graphs in Appendix B show that over the period 1971 to 1991, there is a general increasing trend in wave height in all three harbours. These marshes have eroded over this period, indicating a link with the increase in wave height. To see if the increase in wave height correlated with saltmarsh loss, a search for monitored data was conducted. Fred Haynes, a retired lecturer from Portsmouth Polytechnic, who had studied the demise of saltmarsh in Langstone Harbour, was approached for saltmarsh monitoring data that could be used to tie-in with the wave record. Unfortunately, he has disposed of the records, and so this correlation could not be done.

None of the sites experienced a decrease in wave height over this period. However, there is a marked variation in the size of the increase. To see whether there was a relationship between the magnitude of the increase in wave height and saltmarsh response, sites I, H, G and F (in Langstone Harbour) and E and B in Chichester Harbour were visited in August 1995. Table 4.5 summarises the observations.

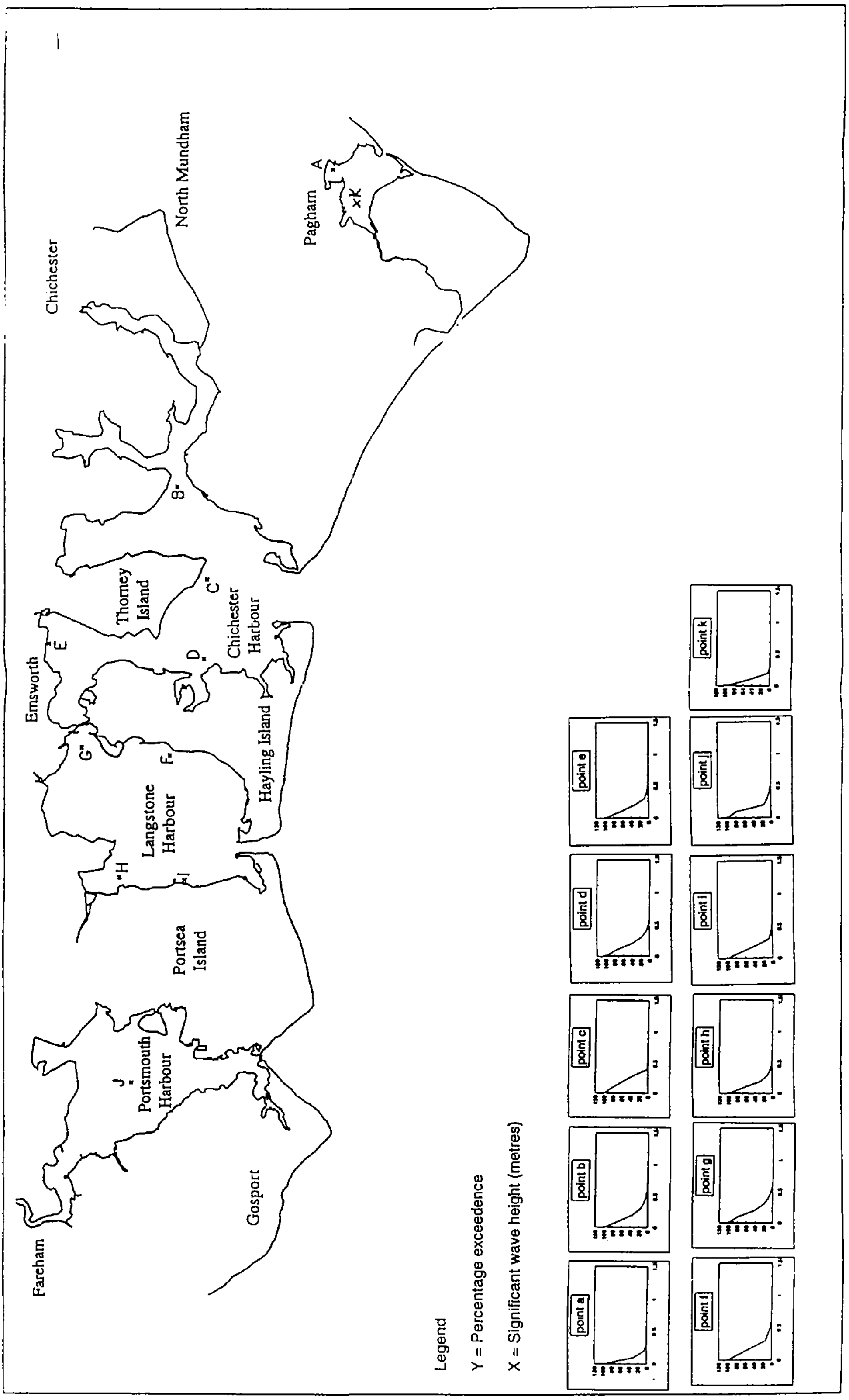


Figure 4.10 Map showing the location of the points for which wave height trends over a 20 year period were determined by HR Wallingford

Table 4.4 Trends in wave height for points in Portsmouth, Langstone, Chichester and Pagham Harbours, from hindcasted wave records generated by HR Wallingford (The value in brackets is the correlation coefficient for the linear regression, the closer to 1, the greater the chance that the trend is genuine)

Point letter	Rate of change in significant wave height (H_s) (cm/year)		
	Average H_s	H_s exceeded 10% of the time	H_s exceeded 1% of the time
A	NS	NS	0.1 (0.59)
B	0.3 (0.70)	0.8 (0.80)	1.0 (0.84)
C	NS	NS	NS
D	NS	0.3 (0.77)	0.5 (0.58)
E	NS	0.1 (0.41)	0.6 (0.75)
F	0.1 (0.74)	0.3 (0.74)	1.1 (0.83)
G	0.2 (0.69)	0.7 (0.78)	0.8 (0.72)
H	0.2 (0.69)	0.3 (0.67)	0.4 (0.41)
I	NS	0.2 (0.54)	0.1 (0.27)
J	NS	0.4 (0.77)	1.0 (0.80)
K	NS	NS	0.1 (0.73)

Positive rates of change of H_s indicate that H_s is increasing with time and negative rates indicate it is decreasing.

NS - No significant trend (less than 0.05cm/year)

Table 4.5 Field observations and their relationship to change in wave climate

Site Location	Field observations	Relationship with modelled change in wave climate
I	No saltmarsh, just mud shingle and *Fucus* seaweed. No evidence that saltmarsh had ever been present	Lowest increase in wave height. Cannot tell if it is eroding from walkover survey, due to nature of substrate.
H	*Spartina* patches extending in some places and stable in others. Evidence of past erosion (see Figures 4.11 and 4.12). Surface sediment (fine sand) is different to sediment of residual saltmarsh mounds (silt)	Moderate increase in wave height fits quite well with observations, as erosion was not as severe as site F, for example. Renewed *Spartina* colonisation suggests wave energy has decreased in the last few years.
E	Soft anoxic mud (suggesting deposition) overlain by green algae. No sign of residual roots in mud , i.e. no evidence that it was once a saltmarsh that has been eroded. Patches of colonising *Spartina* on sea side of channel. Some small clumps of upper saltmarsh by the seawall, plants look stressed	Modelled wave record indicates no change in mean and 10% exceedance wave heights. Only the top 1% showed an increasing trend. Observations therefore fit the wave data.
G	No saltmarsh, stones and algae	Significant increase in all three categories of wave height. Observations do not contradict this.
F	Only two 5x5m patches of severely stressed *Spartina* remain. Evidence that past extent of saltmarsh was much greater. Changes in sediment particle size with increasing depth reflects increasing wave energy, i.e. pebbles to sand to sandy clay	Strong increase in 1% wave height (about 20cm in 20 years). Observations fit well with the changing wave climate
B	Severe erosion of mature saltmarsh, bare mud mounds. Remaining vegetation very stressed	Strong increase in wave height corresponds well with observations.

The observations from the walkover survey summarised in Table 4.5 seem to fit the differences in the modelled trend in wave height, thus supplying more weight to the argument that increasing wave energy is the major cause of saltmarsh edge loss in open coastal areas and embayments (where channel migration is not a significant problem).

4.3.2 Storm frequency

An important question concerns the magnitude and frequency of events which control the erosion / accretion behaviour of saltmarshes and intertidal flats. An individual severe storm, particularly one which significantly raises tidal levels by a positive surge component, can cause catastrophic changes to coastal landforms and sea defences. In some circumstances major breaches are created, tidal inlets diverted, sand banks and ridges thrown up or destroyed. These changes can have a major influence on the pattern of saltmarsh accretion and erosion in the medium to longer term (i.e. 10 - 100 years). An example is provided by the development of the New Marsh at Gibraltar Point, Lincolnshire, after a storm surge in 1922 (Figure 4.13). This storm destroyed the southern end of the existing spit at Gibraltar Point and created a new ENE-WSW orientated sand and shell ridge. The enhanced shelter provided by the new ridge led to more rapid vertical accretion on the Old Marsh, whereas the more exposed New Marsh remained largely as unvegetated mudflats until the development of new sand and shingle ridges to the east allowed accretion to occur to the point where saltmarsh vegetation could become established between 1940 and 1980 (Harper, 1978; Hartnall, 1984). Since the 1970's the sand ridges to the east have been breached and the New Marsh partially buried by overwash deposits and windblown sand (Pye, 1995). Several new N-S oriented sand and shingle ridges have been created, with incipient marshes in between.

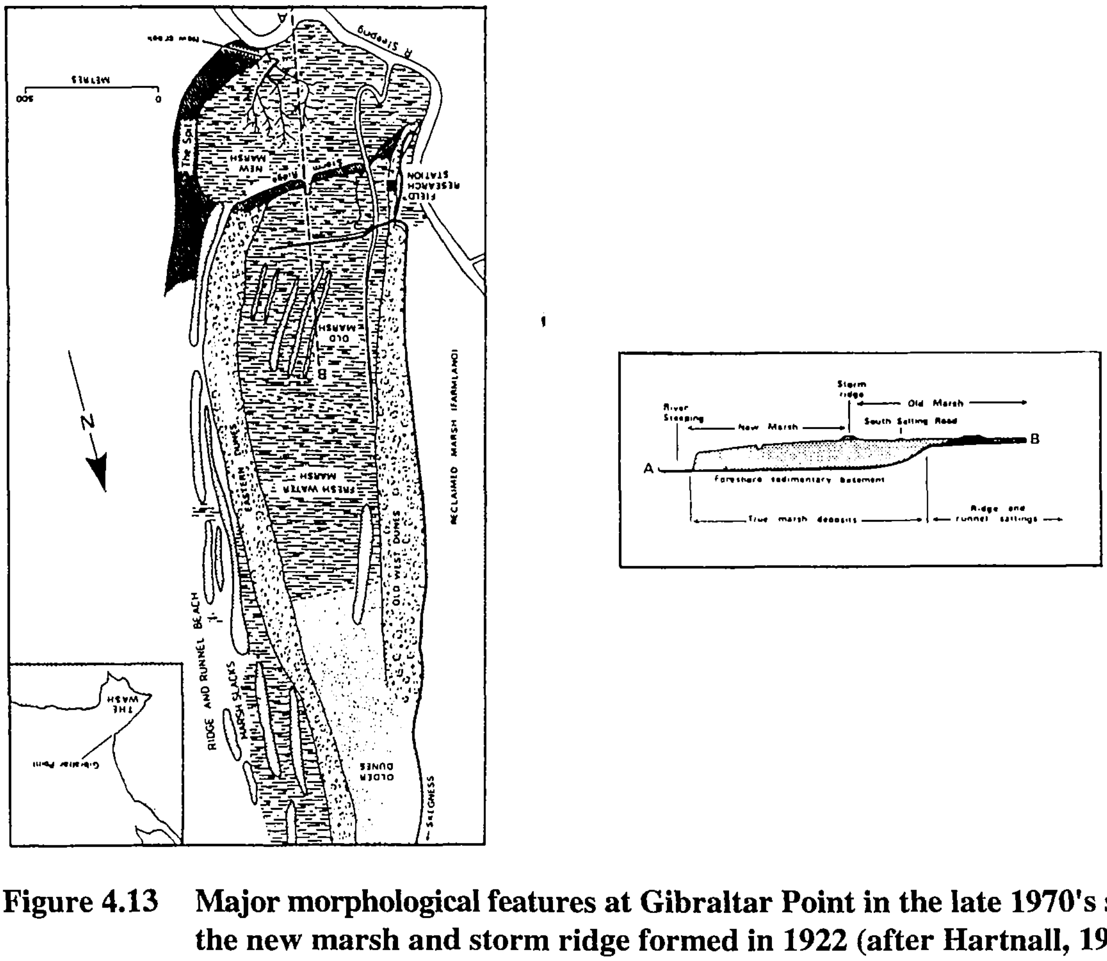


Figure 4.13 **Major morphological features at Gibraltar Point in the late 1970's showing the new marsh and storm ridge formed in 1922 (after Hartnall, 1984)**

There are three main ways in which a storm surge might be expected to enhance saltmarsh erosion:

(1) increased water depth due to the surge will increase wave height
(2) high water levels will be maintained for longer than under non-surge conditions, thereby prolonging the period of wave activity
(3) tidal current velocities and bed shear stresses are enhanced, particularly within the creeks, leading to bed erosion and bank instability.

Although few measurements of marsh edge recession or surface lowering during individual storms have been made, the available evidence indicates that such individual events usually have only a limited impact on longer term marsh development. This is because extreme wave activity is concentrated on the marsh edge and marsh surface for only a few hours, and because most saltmarsh sediments have greater erosion resistance than sand beaches and sand dunes. This conclusion supports the analysis of HR's hindcasted wave record, section 4.2.1, which states that the *trend* in mean wave height is more important than the trend in the extreme wave heights in controlling longer term saltmarsh response. Shell and sand layers may be deposited on the marsh surface following breaching of a protected dune barrier or chenier ridge, as occurred on Scolt Head Island, North Norfolk, during the 1953 and 1978 storm surges (Steers, 1953; Steers et al., 1979), but major scouring of the marsh surface during surges is rare.

The 1953 storm surge did not inhibit the development of a new open coast marsh at Warham and Stiffkey in North Norfolk (Pye et al., 1990). Vegetation cover became well established on this marsh in the 1950's and early 1960's, when the marsh was accreting vertically at up to 2 cm/yr (Pye, 1992). This marsh also suffered relatively little lasting damage during the 1978 storm surge, but since the mid 1980's the seaward edge has experienced degradation and lateral erosion of approximately 100m. Although there have been a number of moderate surges in recent years, none has approached the levels attained in 1978 and 1953, suggesting that frequency and duration of moderate storms, rather than rare extreme events, are of most importance as controls on saltmarsh accretion and erosion. Of particular importance are periods in which storms occur at closely spaced intervals, thereby preventing full post-storm recovery.

Further evidence to support this conclusion is provided by the results of monthly monitoring at Silverdale marsh in northeastern Morecambe Bay (Pringle, 1995) during the period 1984-92. Episodes of rapid marsh edge retreat were observed to occur only when high spring tides coincided with strong winds from a westerly direction (Figure 4.14). Pulses of erosion occurred during most winters but were particularly marked between 1985 and 1988, when several months experienced lateral erosion of >6m. Between the beginning of 1989 and late 1992, only two months (February and March 1990), experienced mean marsh edge erosion of significantly more than 2 m. During the period December 1988 - March 1989 rapid erosion was sustained for four consecutive months, resulting in total average retreat of approximately 18m. This was a period of relatively warm, stormy weather across most of Britain associated with the passage of a number of depressions and frontal systems across the country. It corresponds with the significant erosion even on the Dengie Peninsula documented by Pethick (1992). However, wind records for stations in all parts of the country (see section 4.3.3) show that, overall, 1988 and 1989 were not especially windy years, particularly when compared with 1986 and 1990 which both had higher mean wind speeds and a greater duration of winds >22 knots than 1988 and 1989. Although average rates of marsh edge erosion at Silverdale did not exceed 2m/month between April 1990 and August 1992, mean wind speed and duration of winds >22knots during this period at Squires Gate Airport and Sellafield were approximately the same as in 1988 and 1989. This relatively weak association between measured rates of marsh edge erosion and broad scale wind parameters probably reflects the fact that the former are heavily dependent on the wind speed/wave height/ direction at the time of high water springs, and on the weather history and pattern of foreshore accretion / erosion immediately preceeding a storm.

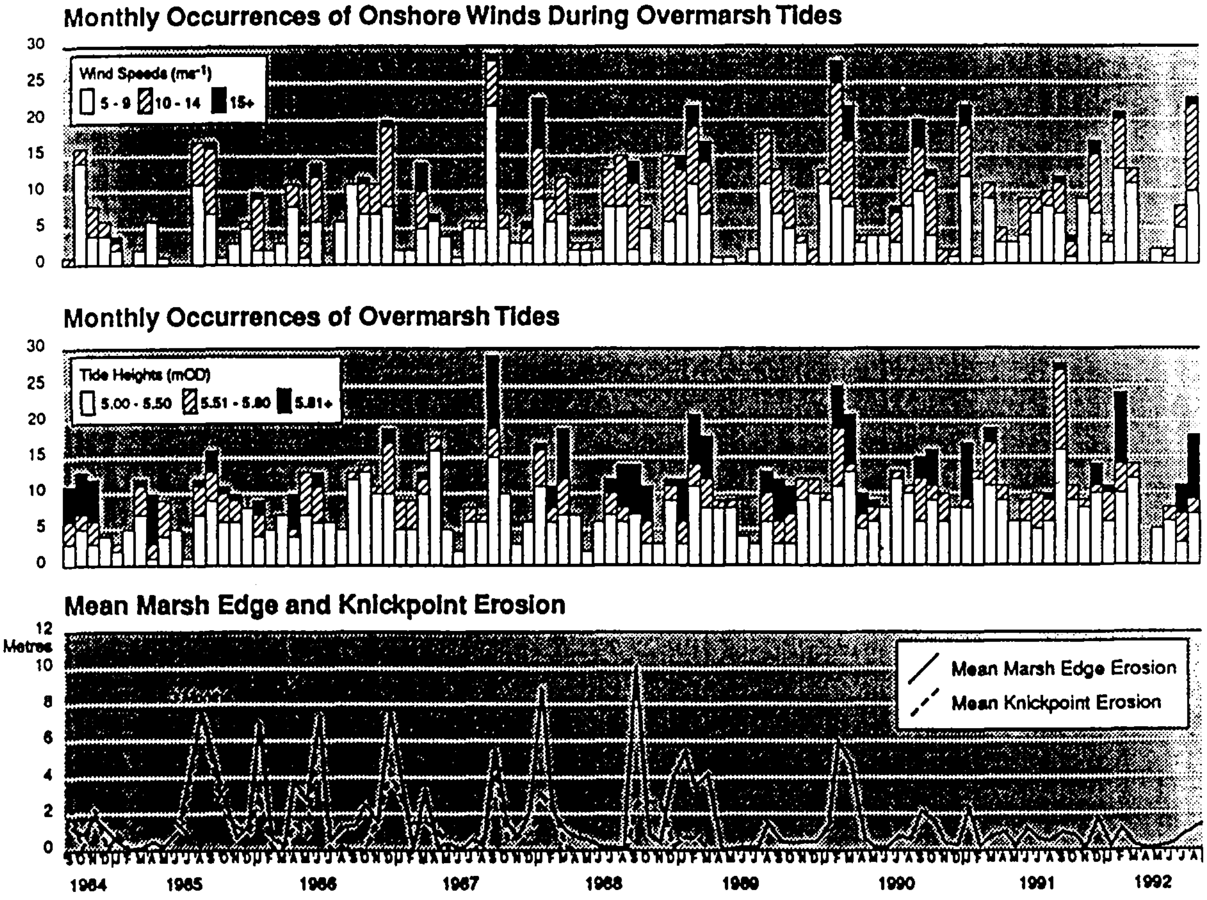


Figure 4.14 **Composite diagram showing mean marsh edge and creek knickpoint erosion, monthly occurrences of overmarsh tides and onshore winds, during overmarsh tides at Silverdale marsh, Morecambe Bay, between 1984 and 1992 (after Pringle, 1995)**

When favourable circumstances combine, for example when storm force winds and waves approach a marsh edge from the direction of maximum fetch over a prolonged period or at frequent intervals, saltmarsh erosion can take place extremely quickly. This is illustrated, for example, by the rapid erosion of the saltmarshes at the northern end of Foulness between 1989 and 1992. Air photographs taken in October 1988 show a large area of healthy marsh, partially protected by chenier ridges, near Northern Corner on Foulness. By July 1992, the marsh and chenier complex had been severely eroded, allowing waves to break directly against the concrete seawall (Figure 3.9).

Numerical modelling of change in storminess in Essex

An investigation was conducted to determine whether an increase in storm frequency could be responsible for saltmarsh erosion. It was decided to analyse the change in storm frequency for a location in Essex (a county suffering from severe erosion problems) to see whether continued saltmarsh loss could be due to an increasing incidence of storm events.

Nearshore waves at Clacton at MHWS were modelled (see section 2.4.3) for the period 1974 - 1989. Three graphs were produced:

(1) Number of storms (for Hs = 1.5m, 2.0m, 3.0m; Figure 4.15)
(2) Wave height (1% and 10% exceedance; Figure 4.16)
(3) Storm duration (for Hs = 1.5m, 2.0m, 3.0m; Figure 4.17)

Figures 4.15 and 4.16 indicate that over the modelled period storminess does fluctuate, but there is no evidence of a trend. The period 1976-1980 was relatively stormy. The calmest conditions occurred in 1982. Figure 4.17, illustrates that storm duration also fluctuates significantly.

4.3.3 Wind speed and wave direction

Figure 4.18 summaries the changes in three categories of wind speed at locations in England and Wales over various time periods. The line passing through the points was determined by linear regression, and the percentage in brackets indicates the significance of the trend. Only three stations experienced a significant change in wind speed. The extreme winds, exceeded 1% of the time, increased at Spurn Point, Shoeburyness and Squires Gate.

Variations in wind-wave conditions around the U.K. coast are heavily dependent on the intensity, frequency and tracks of mid-latitude westerly depressions, all of which show variability on a number of different time-scales (Lamb, 1982). In general terms, periods in which there is a high frequency of westerly (i.e. cyclonic) weather type over the British Isles tend to be relatively stormy, with a high incidence of gales and storm surges. During periods when many of the storm tracks are diverted either to the north or the south of the British Isles (i.e. when anticyclonic blocking conditions become established for long periods over the eastern Atlantic), southwesterly and westerly gales are less frequent and there is a higher incidence of winds from the east and southeast. Analysis of instrumental records and various lines of documentary evidence by Lamb (1982) suggested that there is a rough cyclicity in the frequency of westerly weather type which is superimposed on longer-term climatic variations. During the last four decades of the 19th century the incidence of westerly weather type across the British Isles was relatively low compared with the period 1900 - 1950 (Figure 4.19). Within the period 1880-1950 there were peaks in westerly weather type frequency around 1910, 1925 and 1950. After c.1950 there was a marked decline in the incidence of westerly weather type until the mid 1970's, when it began to increase again.

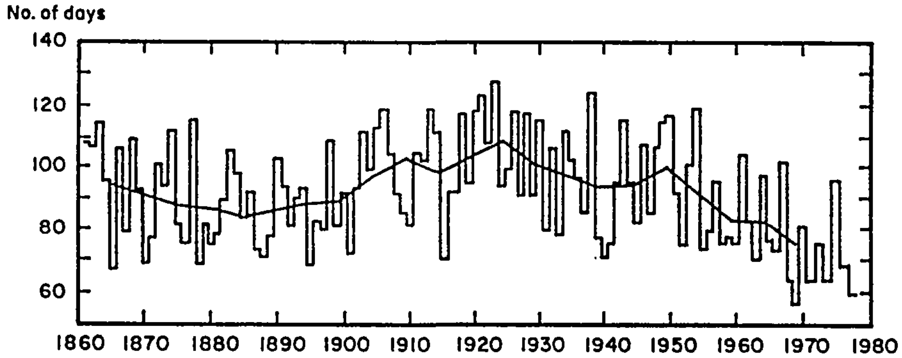


Figure 4.19 **Variations in the incidence of westerly weather type across the British Isles since 1860 (after Lamb, 1982)**

However, Meteorological Office wind records show a spatially as well as a temporally variable pattern of change during this century (Pye, 1996b). The annual duration of winds >22 knots shows a marked decline at several stations on the west coast of England and Wales between about 1915 and 1955, but there was no obvious trend at east coast sites during this period (Figure 4.20). Both west and east coast stations in central and southern England showed a steep increase in the frequency of strong winds between about 1955 about 1965, after which time there was relative stability or a gradual decline, with the magnitude and timing of the changes varying from station to station. Between 1965 and 1992, (after which wind data ceased to be published in Meteorological Office Monthly Weather Reports), there was little net change in either mean annual wind speed or the duration of winds >22 knots at most sites in northwest changes varying from station to station. Between 1965 and 1992, (after which wind data ceased to be published in Meteorological Office Monthly Weather Reports), there was little net change in either mean annual wind speed or the duration of winds >22 knots at most sites in northwest England, and a slight decrease in both parameters was recorded at Valley in Anglesey. However, stations further south on the west coast, and in southern Cornwall, showed an increase in mean wind speed and duration of winds >22 knots during this period (Figure 4. 21). With the exception of South Shields, records from east coast and south coast stations are less complete and reliable. At South Shields there is evidence of an increase in windiness between c.1975 and c.1985, with a subsequent decline. The Shoeburyness record is not continuous owing to changes in recording conditions after 1975, but the available data for this station suggest that a trend towards a higher incidence of strong winds after 1955 was sustained at least until 1986.

Unfortunately, detailed information about changes in wind direction over the same period are not available. However, an analysis of individual storms (Pye, 1996b) has shown that the great majority of strong winds blow from the southwest or west, although in southern and eastern England strong winds from the south or southeast are also significant.

Storms which generate waves in the direction of maximum fetch have the maximum impact on saltmarshes. For the Colne, Mersea Island, Dengie, and the north side of the Thames to Foulness, storms from the south east would cause most damage. In order to determine whether there had been an increase in storms from this direction, hindcasted wave records, held by HR Wallingford, were reanalysed to determine the % time at which wave heights were above 2m, from the direction 100 - 160 degrees east from north.

Table 4.6 Duration that waves over 2m were travelling from the south east, in the nearshore water at Clacton, Essex - from hindcasted wave data (HR Wallingford, 1989)

Year	**% time**
Jan 1974-Dec 1975	0.92
Jan 1976-Dec 1977	2.43
Jan 1978-Dec 1979	2.65
Jan 1980-Dec 1981	1.74
Jan 1982-Dec 1983	0.94
Jan 1984-Dec 1985	1.25
Jan 1986-Dec 1987	1.75
Jan 1988-Dec 1989	1.19

The results show that there was no trend between the years 1974-1989, but the incidence of southeasterly storms did fluctuate. 1976-1979 had twice the duration of south-easterly storms which may have caused an increase in erosion rate. Records of annual changes in Essex saltmarshes over this time period do not exist. Hence, it was not possible to correlation between storminess and saltmarsh erosion. However, an acceleration in erosion during the late 1970's is evident (see section 3).

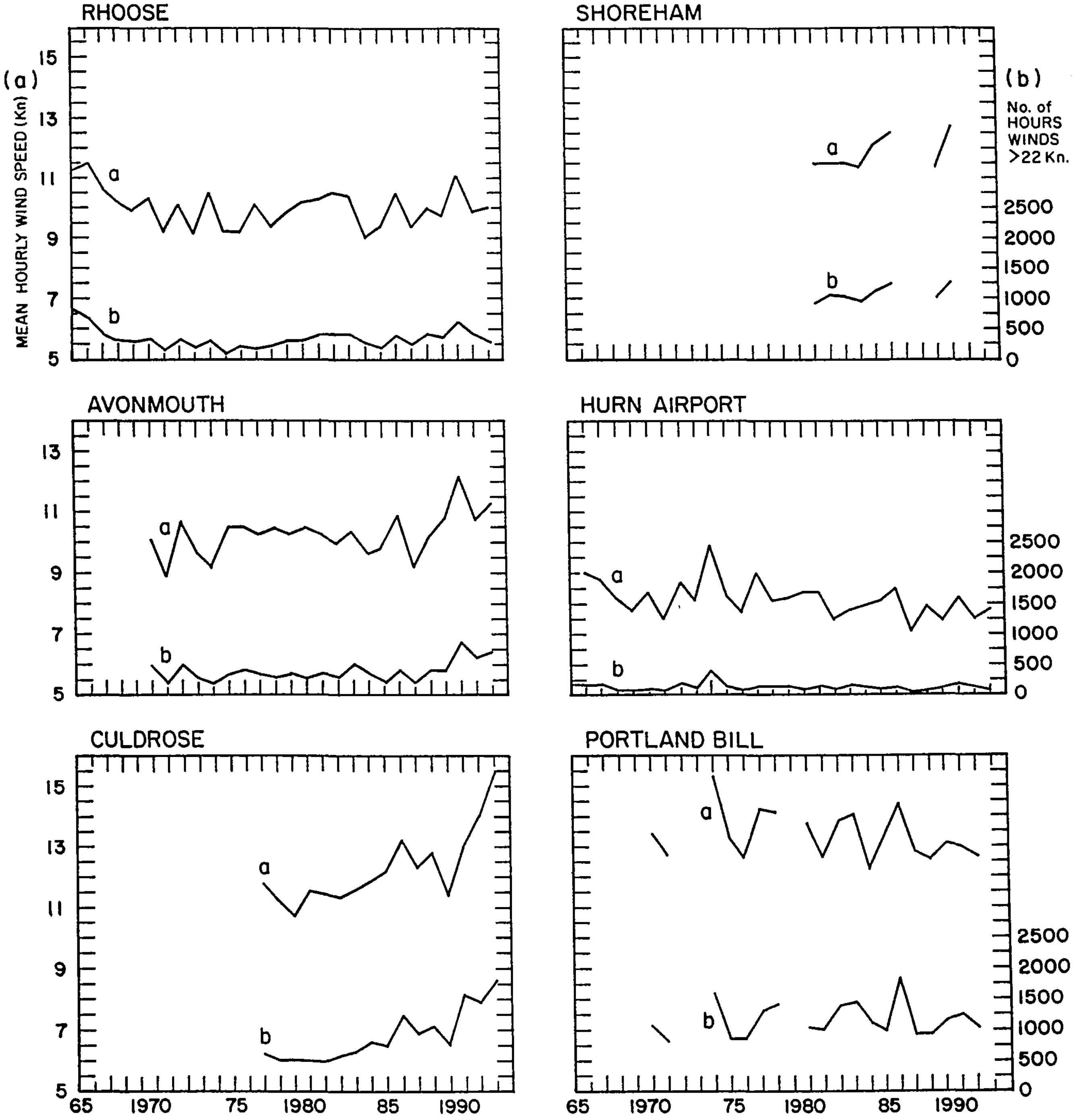


Figure 4.20 Variations in the duration of winds > 22 knots during this century. Compiled from data in the annual summaries of the monthly weather report.

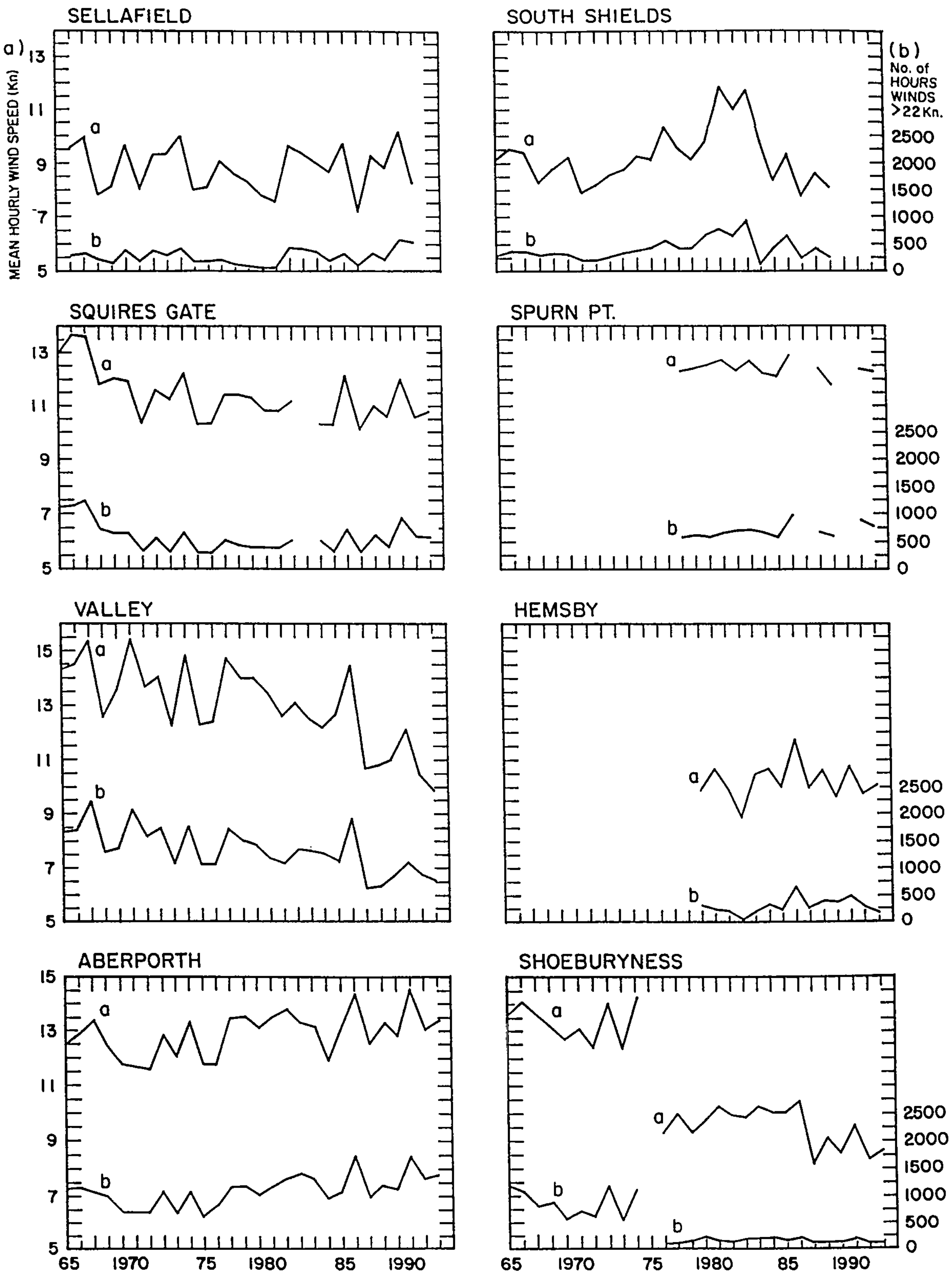


Figure 4.21 Variations in mean hourly wind speed and duration of winds >22 knots during the period 1965-92 (data from annual summaries of the Monthly Weather Report)

How change in wave direction affects longshore movement of sediment

During previous research on climate change (Jelliman, Hawkes and Brampton, 1991) some tests on the sensitivity of beach drift rate to past variations in wave climate were underteaken. During those tests, drift was calculated both left-to-right and right-to-left along the beach, depending on the direction of the waves at any particular time. These two components, the difference of which determines the *net* drift, might be likened to erosion and accretion on a saltmarsh, the net effect of which would show itself as a change in the position of the seaward edge (or the elevation) of a saltmarsh. The tests showed that seemingly small natural year-by-year variations in wave conditions could produce dramatic changes in year-by-year drift rates. Variations of 10% in mean wave height or 10° changes in mean wave direction could cause orders of magnitude difference in drift rate or even reversals of direction between individual years. Admittedly, those tests were for non-cohesive sediments, and the situation for saltmarshes is rather different. However, they do demonstrate that small changes in wave climate can have a very much greater impact on drift rate and erosion.

4.3.4 Relative sea level change

Longer term historical changes

Several studies have shown that relative sea level rise has an important influence on the stability of saltmarshes over medium to longer timescales. The precise effect depends largely on the relative balance between the rate of sea level rise, sediment supply, and the nature of the physiography surrounding the marsh. Geological evidence indicates that, in general, periods of relative sea level fall favour the seaward movement of saltmarshes while their higher parts undergo a transition to brackish marsh, freshwater marsh and then woodland. On the other hand, rising sea level favours a landward movement of salt marshes unless this is prevented by steeply rising land or sea defences, resulting in 'coastal squeeze'. Section 5.1.1.2 contains a calculation which estimates the rate of landward movement due to a given rise in relative sea level (assuming no vertical accretion).

Marshes may continue to accrete both vertically and laterally, despite sea level rise, if sufficient sediment is available (French, 1991, 1992). Where there is a sediment shortage, saltmarshes will experience a transition from high marsh to low marsh or mudflat habitat, may be partly or wholly eroded, and become buried by the landward migration of subtidal and intertidal sedimentary facies.

Different parts of the UK have experienced contrasting sea level histories during the Holocene, and even during the past few hundred years (Devoy, 1977, 1979; Greensmith & Tucker, 1971, 1976, 1980; Shennan, 1986a,b, 1987a,b; Funnell & Pearson, 1989). In the Lower Thames estuary, for example, Devoy (1977, 1979) recognized five periods of marine transgression, the most recent (Thames V) being initiated at approximately 1750 yr B.P., separated by periods of relative stability or sea level fall. A broadly similar pattern was identified in the Essex coastal plain by Greensmith and Tucker (1976). Geological, palaeoecological and archaeological evidence clearly point to an overall relative rise of 2 m or more in southeast England in the last 1-2000 years (Evans, 1953; Ackeroyd 1972; Devoy, 1979; Greensmith & Tucker, 1980; Kirby, 1990; Wilkinson & Murphy, 1995). In the Thames estuary there is evidence of a slight fall in relative sea level between 1,750 and 1,000 years ago, followed by renewed transgression. During the relative low stand, brackish and freshwater communities spread along the margins and inner regions of the Thames and adjoining estuaries such as the Crouch and Blackwater (Devoy, 1979;

Wilkinson & Murphy, 1995). During the subsequent transgression these were buried by estuarine tidal flat and saltmarsh sediments. Since saltmarshes grow in the upper part of the tidal frame, there is often an abrupt stratigraphic change in estuarine alluvial sequences from woodland or reed marshes to saltmarsh. If the rate of sea level rise is rapid (>5-10 mm/yr, depending on sediment availability, saltmarsh at a particular point is likely to be 'drowned' and buried by intertidal flat or subtidal deposits. However, if the rate of sea level rise is slow, or large amounts of sediment are available for deposition in a relatively low energy environment, the saltmarsh may grow vertically at a rate more or less equivalent to the rate of sea level rise. In the inner Crouch estuary, for example, estuarine marsh and mudflat clays overlie a freshwater peat deposit which has been dated at 1500 yr B.P. (Wilkinson & Murphy, 1995; Figure 4.22). Other peat deposits within the saltmarsh sediments of the Blackwater have been dated to be around 3500 yr B.P. (HR, 1996b). This peat, which may be equivalent in age to reddened soil horizons in the Blackwater estuary alluvial sequence, probably represents a minor sea level fall. On the basis of the lithostratigraphic evidence it can be inferred that relative sea level has risen in the inner Crouch estuary by approximately 1.2 m in the last 1500 years (at an average rate of 0.8mm/yr).

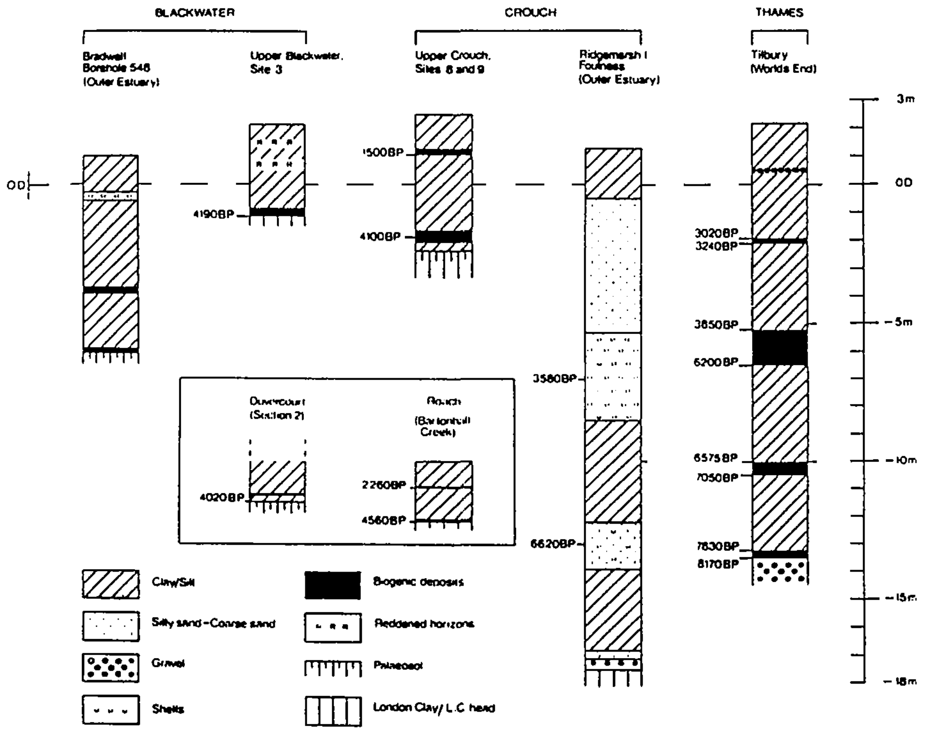


Figure 4.22 **Simplified stratigraphic sequences from the Essex Coast, reflecting sea level oscillations during the Flandrian Period (after Wilkinson and Murphy, 1995)**

In the Severn estuary, accumulation of estuarine alluvium has taken place against the background of a long term trend of rising sea level upon which a number of still-stands, and possibly minor regressions, have been superimposed (Heyworth & Kidson, 1982; Allen, 1990b; 1991, 1992a). The effect of rising sea level has been to drive the inter-tidal sedimentary environments up the Severn Vale. Erosion of the sequence in the outer estuary has exposed early Flandrian silts and peats on the foreshore and in cliffs along the estuary margin. Much of the eroded sediment has been re-deposited on vertically accreting marsh surfaces further up the estuary. As noted in section 3, a series of off-lapping marsh sedimentary units bears testimony to a number of alternating phases of lateral erosion and accretion during this process. However, there is no evidence that fluctuations in sea-level were responsible for these alternations. The older marshes have been extensively reclaimed since Roman times, with the result that, under conditions of rising sea level, each new marsh developed seaward of an embankment has attained a higher elevation than the reclaimed older marsh landward of the embankments (Figure 4.23).

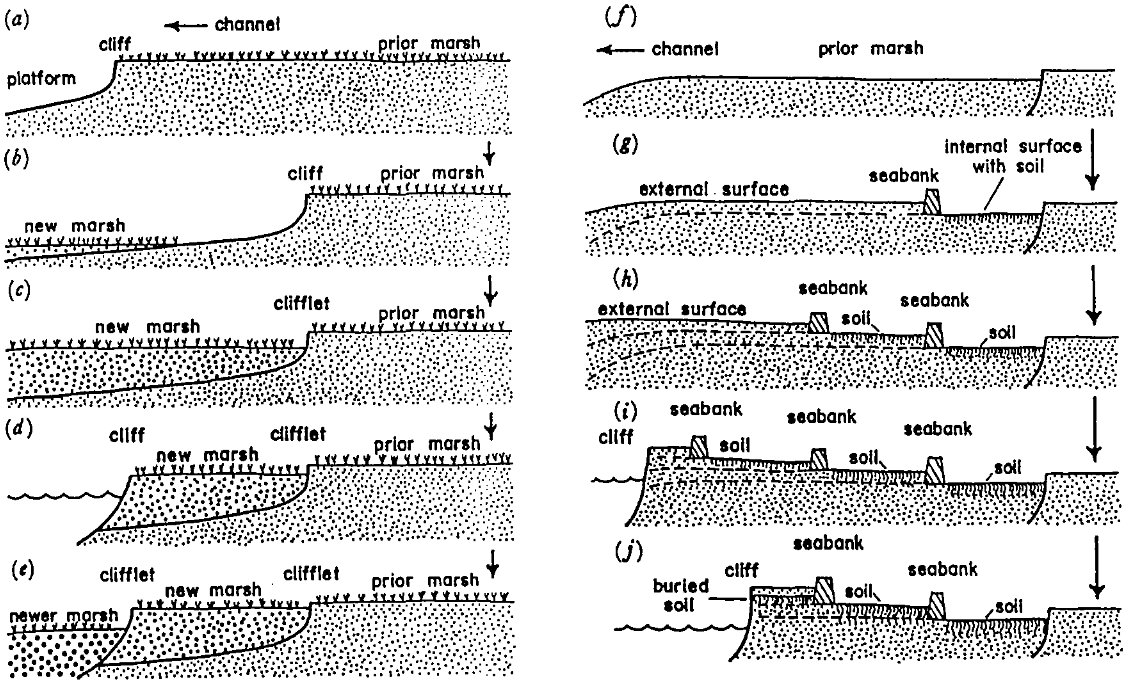


Figure 4.23 **A model for the morphostratigraphic development of postglacial alluvium in the Severn Estuary under the influence of rising sea level (a-e) and progressive reclamation (f-j) (After Allen, 1990a).**

Shorter-term trends in mean sea level

Tide gauge stations with at least 20 years of continuous data show considerable regional differences in recent sea level trends (Woodworth, 1987; Woodworth et al., 1991; see Table 4.1). This is probably partly due to harbour works, embanking and tide gauge modifications, but mainly to natural oceanographic, atmospheric and geological factors.

The observed rates of mean sea level rise are well within the capacity of saltmarshes to grow vertically, provided sufficient sediment is available. Rates of vertical accretion in the range 2 - 7mm/yr have been widely recorded on British marshes, including those on the open coast of Essex (e.g. Reed, 1987; French & Spencer, 1993). However, sediment starvation can affect marsh surface levels if the concentration of suspended material in tidal waters is very low. As pointed out by Pye & French (1993), sediment enters a marsh either by way of the creek system or across the marsh front. In marshes which have a low drainage density and which lie in sheltered, non-turbulent locations, sediment deposition is likely to be non-uniform over the marsh surface. Areas remote from tidal creeks may receive little or no sediment, and over a period of time their elevation will fall below that of creek marginal areas, creating poorly drained basins within which plants find it difficult to grow. Eventually such areas break up *into* a series of mud basins which are surrounded by vegetated levees along the major creeks. Many of the estuarine marshes in Essex currently display this type of morphology (Pye, 1996b). On relatively low energy open coasts, sedimentation near the landward margin may be significantly lower than that on the more seaward marshes, giving a net landward slope (Pye, 1992). Near Lymington, for example, the seaward *Spartina* marshes have a mean elevation 10-20 cm higher than that of the marshes closer to the seawall (Ke & Collins, 1993), where plant growth tends to be inhibited by waterlogging, excessive build up of decaying organic matter and root zone anoxia (Figure 4.24).

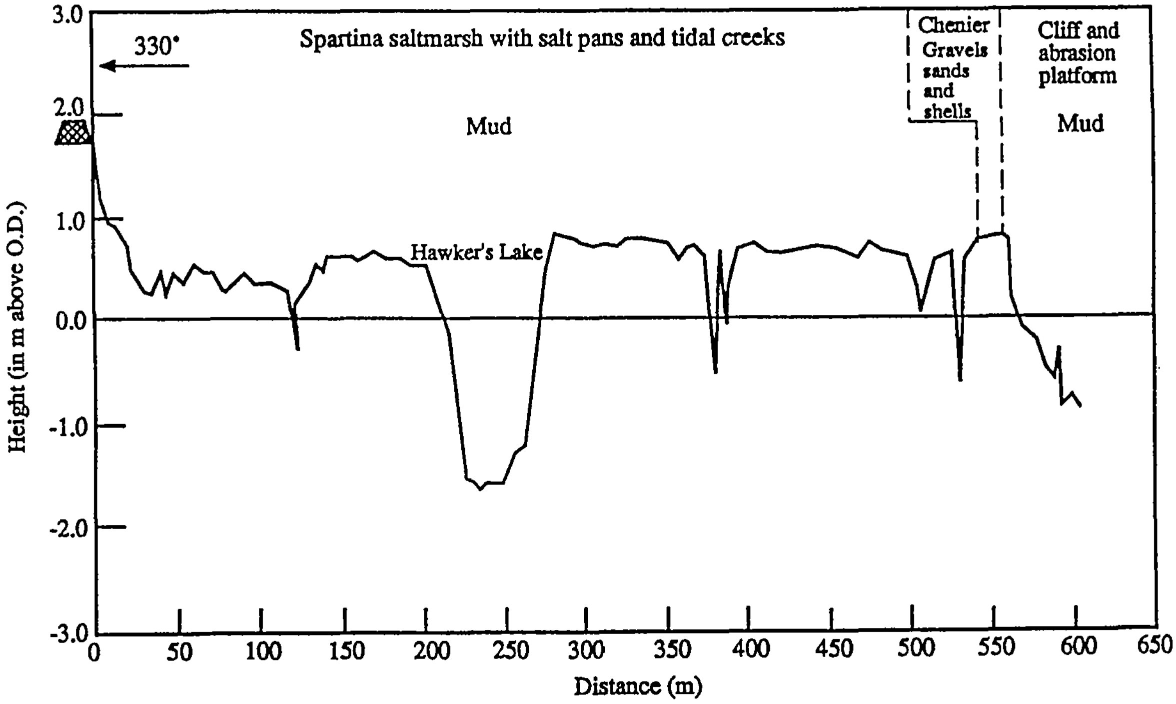


Figure 4.24 Cross-section showing variation in marsh surface elevation with distance from creeks and the seaward edge, near Lymington, Hampshire (after Ke and Collins, 1993)

As discussed in Section 3, the rate and timing of episodes of marsh erosion has varied considerably in different parts of southeast England during the past 150 years, *suggesting that mean sea level change has not been of dominant importance as a forcing factor over that time period.* There was comparatively little erosion in the Blackwater estuary between 1935 and 1978 (IECS, 1993b), and rapid lateral accretion occurred on the Dengie Peninsula in the first half of this century (Pye, 1996b), even though the Southend tide gauge record showed a steep rise in mean sea level between 1930 and 1966. The Southend and Sheerness tide gauges both showed a slight increase in sea level between 1972 and 1982, but this in itself is unlikely to have been sufficient to trigger the observed acceleration in marsh erosion in the mid 1970's.

If vertical saltmarsh accretion, for whatever reason, fails to keep up with relative sea level rise, the plant species composition is likely to change. This has been documented in a saltmarsh in Long Island Sound, U.S. (Warren and Niering, 1993). Brackish water species (e.g. *Juncus*) were replaced by salt saltmarsh species. The paper pointed out that these changes would have knock-on effects on primary productivity and may change the animal community.

4.3.5 Tidal range

Relationship between saltmarsh change and lunar nodal modulations of MTR

- Wave height

The following example illustrates the extent to which the 18.6yr tidal range cycle affects the potential wave height on the saltmarsh surface. Analysis of tide gauge records from Newlyn (Woodworth et al., 1991) shows that during the 18.6yr lunar cycle there is approximately a 20cm change in MTR (see Figure 4.6). This roughly translates to a difference of 10cm between MHW at the maximum and minimum parts of the cycle (i.e. a difference of 10cm in the depth of water above the marsh surface). *As potential wave height is approximately 0.6 of the water depth, at the maximum of the cycle waves on the saltmarsh surface are potentially 7.5cm higher than at the minimum of the cycle.*

- Current speeds

Section 2.4.2, describes the method developed by HR to determine whether the 18.6 year cycle affected the mean annual maximum slope of the ebb and flood tide. This analysis was conducted to assess whether the tensile stress due to currents, fluctuated over the cycle (as current speed is related to rate of change of water level). Appendix C contains the calculated annual means of the maximum hourly change in water level.

The results are presented graphically in Figure 4.25. The curves suggest that the maximum rate of water level change on the flood tide was affected by the 18.6 year tidal cycle. Maximum rates of mean annual water level rise coincided with the timing of maximum tidal range and the minimum with the period of lowest tidal range. *Hence there is evidence that the 18.6 year cycle, can affect tidal currents.* However, there was no sign that the tidal range cycle affected ebb velocities, or those above the vegetated saltmarsh surface (which relates to the data set above 2.7m O.D.

From this study, relating to Immingham, the following conclusions can be drawn:

(1) Flood currents did seem to be influenced by the tidal range cycle, but the variation would be slight. This fluctuation would only be significant if the tidal currents were already close to the erosion threshold of the sediment. If this were the case, lateral erosion could occur.
(2) No evidence that tidal range cycle affected ebb velocities .
(3) No evidence that rate of water flow across the marsh surface was affected by the cycle. Therefore vertical sedimentation/erosion would not be affected.

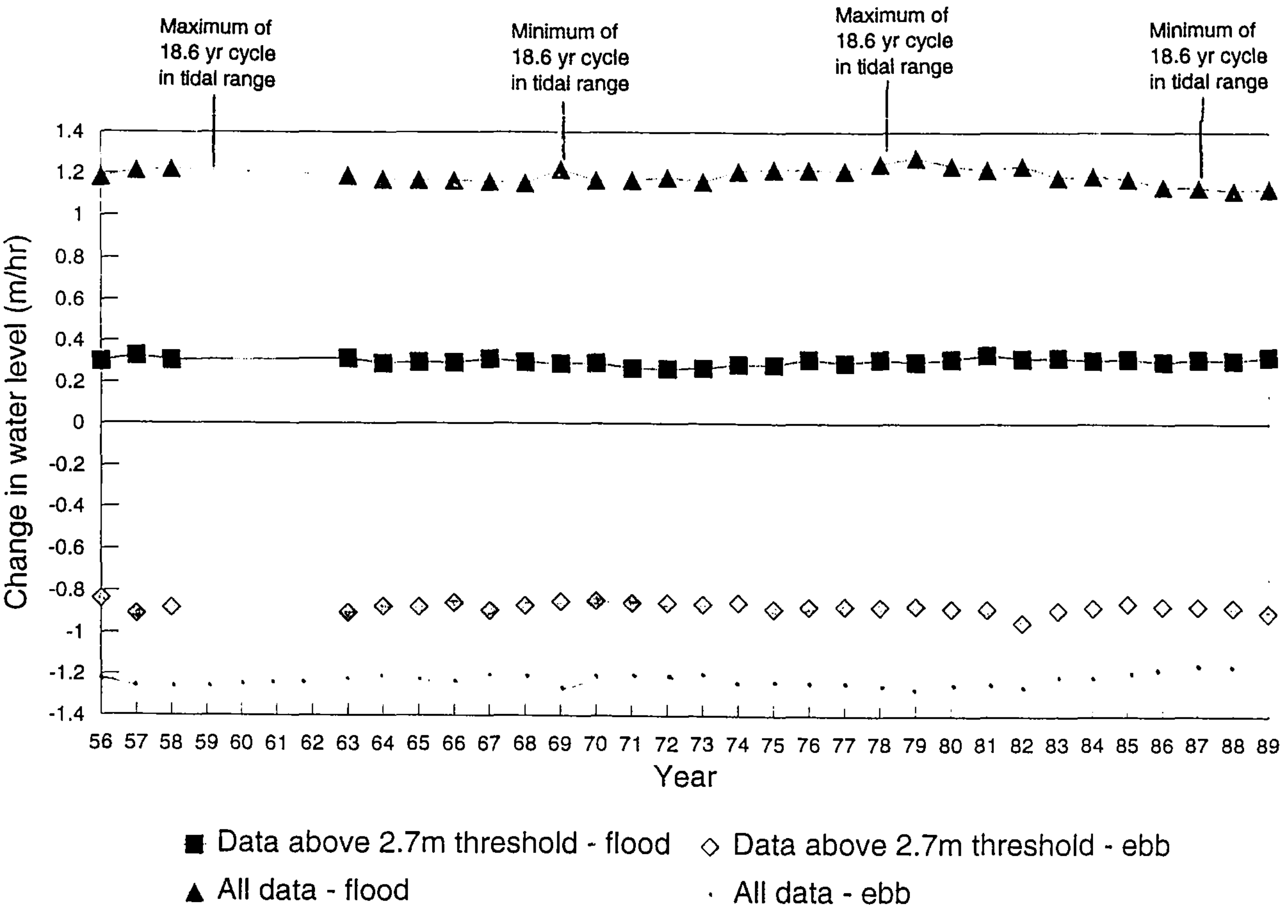


Figure 4.25 **Annual mean of maximum hourly change in water level (m/hr)**

- Evidence of affect on accretion/erosion on saltmarshes

It would be possible to assess whether the lunar 18.6 year cycle influences accretion/erosion of saltmarshes if data relating to the annual rate of saltmarsh change were available over a 19 year period. Unfortunately there is very little systematic monitoring of saltmarshes at present and practically none in the past (HR Wallingford, 1995). Therefore the only way to establish past rates of change is to analyse a time series of aerial photographs. Harmsworth and Long (1986) analysed a time series of aerial photographs of the saltmarsh on the eastern side of Dengie Peninsula, Essex, for the years 1960, 1970, 1973, 1978 and 1981. Between 1960 and 1970 the area of saltmarsh increased, coinciding with the falling limb (1960-1969) of the 18.6 year cycle of MTR. During the next 10 years, when MTR was increasing, the saltmarsh eroded. However, there is evidence that another factor, other than the change in MTR, was also influencing accretion/erosion processes, as the accretion during the falling limb was substantially outweighed by the erosion during the rising limb.

Further evidence that the 18.6 year tidal range cycle's effect on saltmarsh accretion/ erosion is overshadowed by the effects of variations in wind climate and nearshore morphology is provided by Pringle's (1987) data from Silverdale marsh in Morecambe Bay. This shows decreasing rates of erosion of both the marsh edge and creek bed knick points after 1988, despite the fact that the lunar nodal cycle was moving towards a maximum (see Figure 4.14). A similar pattern is evident in The Wash. Tide gauge data for Lawyer's Sluice for the period 1950-90 indicate a variation in recorded MHW of about 12 cm between predicted nodal minima and maxima (Figure 4.26). A survey by Hill (1988) showed that, excluding the effects of saltmarsh loss due to land claim, the area of active marsh in the Wash increased by 781 ha (16%) between 1971-74 and 1982/85, corresponding with the increase towards a nodal maximum, again suggesting this is not a significant factor. Most of the gain occurred on the western shore between Gibraltar Point and Butterwick and on the southern shore between the River Welland and the River Nene. There was, however, some erosion along the southwestern shore between Butterwick and the River Witham, but this can be attributed to the effects of embanking and reclamation in 1979 (Pye, 1995).

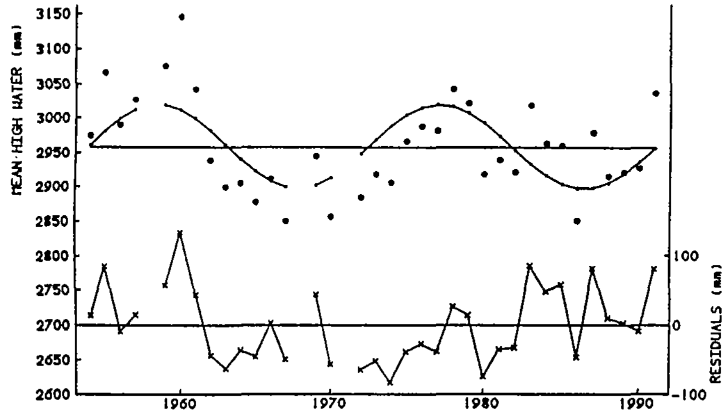


Figure 4.26 Variations in measured (dots) and modelled (solid line) tidal levels at Lawyers Sluice (The Wash) between 1950 and 1992 (data supplied by POL)

Relationship between saltmarsh change and secular trend in tidal range

Figure 4.7, compiled using the secular trends in mean tidal range (from Woodworth, Shaw and Blackman (1991)) and information on the erosion/accretion status of the neighbouring saltmarshes, indicates that there is not a perfect association between change in tidal range and saltmarsh response. Whilst Avonmouth and Southend are experiencing a strong increase in tidal range which corresponds with erosion of the neighbouring saltmarshes, Liverpool is experiencing the greatest increase in tidal range but neighbouring saltmarshes are expanding. However, the hydrodynamics of The Mersea have been greatly altered by anthropogenic activity, which may have counteracted the effect of the increasing tidal range.

4.3.6 Change in channel position

The effects of natural channel migration have been well documented in several estuaries including the Wyre and the Lune (Inglis & Kestner, 1958a). As pointed out by O'Connor (1987), under natural conditions many estuaries maintain a condition of dynamic equilibrium over timescales of 10^3 years, within which channel migration acts as a natural mechanism for periodically flushing excess sediment out of the system. Alternating saltmarsh edge erosion and accretion in response to estuarine channel shifts have been described from the Solway Firth (Marshall, 1962), Morecambe Bay (Gray, 1972; Pringle, 1995) and the Humber (IECS, 1994).

An example of this process is provided by recent bank erosion at Aylburton Warth on the west bank of the Severn estuary (Figure 4.27). Rapid landward movement of a subsidiary low water channel of the River Severn has cut into the estuary margin of the alluvial deposits which extend south from Lydney Harbour to beyond Aylburton. There is evidence of previous shoreline fluctuations in this area, with a period of rapid progradation after 1921 (Allen, 1993). Since 1966 the bank north of Cone Pill has been cut back by almost 1 km and in early December 1995, the eroding marsh edge had reached the toe of the main flood embankment (see Figures 4.28 and 4.29), requiring set back of the line of defence. The main mechanism of slope retreat at this location involves the development of tensile fractures parallel to the cliff edge and subsequent rotational sliding. As the main channel has moved landwards, the gradients of creeks draining into it (such as Cone Pill) have been steepened, resulting in faster ebb flows and bed incision. This has de-stabilized the banks of the Pill, giving rise to slope failures and secondary breaching of the sea banks along its margins (Figure 4.29; Allen and Pye, in press).

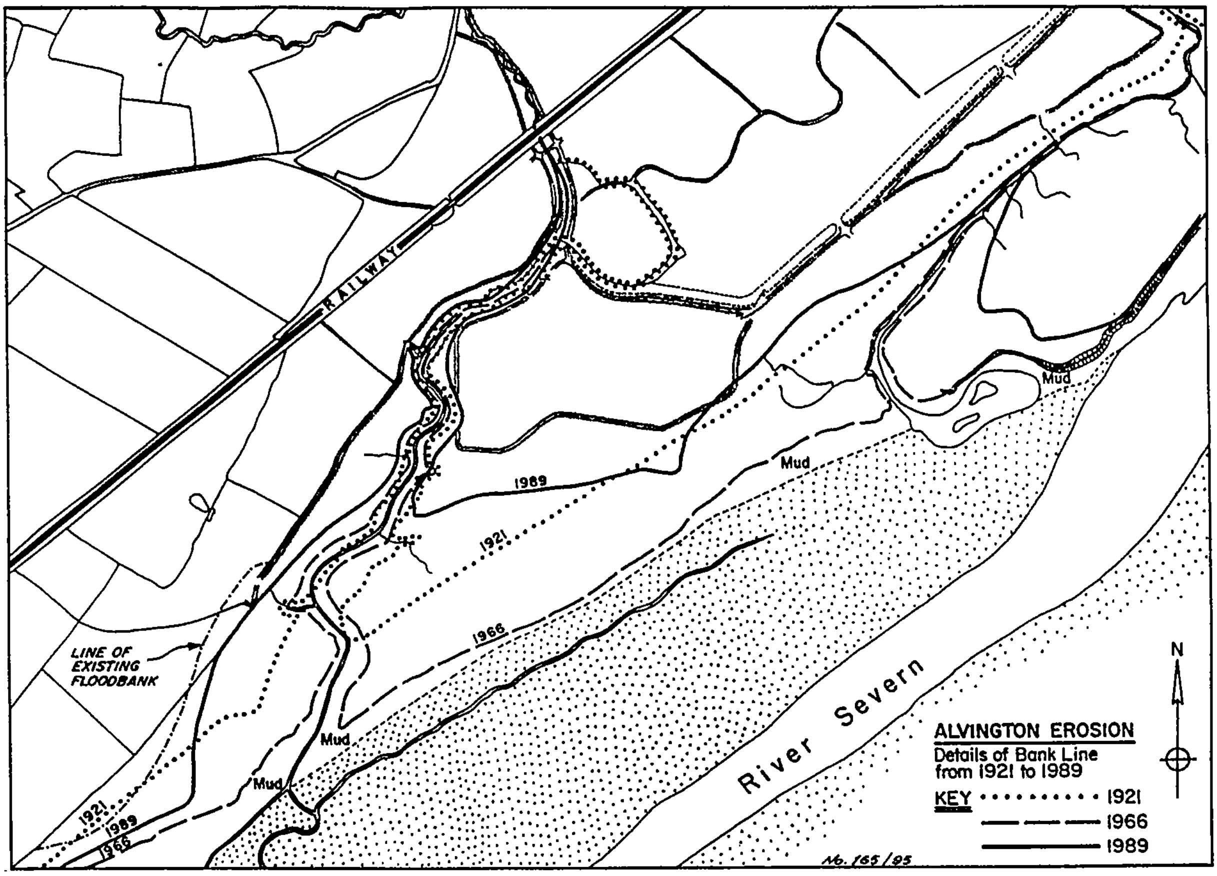


Figure 4.27 **Changes in the western shoreline of the Severn estuary near Aylburton Warth between 1921 and 1989 (based on Ordnance Survey 1:2500 maps; after Allen and Pye, in press)**

5 NON-HYDRAULIC FACTORS AND SALTMARSH CHANGE

Whilst hydraulic factors (i.e. changes in wave and wind climate and sea level) are undoubtably the major cause of saltmarsh erosion or extension, man's actions have greatly affected the areal extent of saltmarshes on a local basis. Activities which reduce saltmarsh area include enclosure for land reclamation (this causes saltmarsh loss both directly and also indirectly by exacerbating loss in saltmarsh area, due to sea level rise, by preventing landward saltmarsh regression through the erection of flood embankments). Other negative activities include navigation, dredging, mud digging, *Spartina* control and possibly grazing and pollution. Positive effects of human activity on saltmarsh area also exist; saltmarsh area has been increased by the planting of *Spartina anglica*, and the construction of coastal structures, such as jetties and training walls, which increase sedimentation rates and initiate saltmarshes. There has also been an increase in saltmarsh area to a much lesser extent through the installation of saltmarsh maintenance and enhancement techniques, and managed retreat schemes. How these activities affect saltmarshes, their relative importance, and examples are discussed in section 5.1.

Section 5.2 considers non-hydraulic factors, other than human activities, which cause saltmarsh change. Sediment supply is an important control on saltmarsh health and extent. There is growing evidence that sediment chemistry affects the erodibility of sediment by controlling the moisture content (see section 5.2.2) and hence its tensile strength. Moreover, sediment chemistry also directly influences plant vigour, which in turn affects accretion and erosion rates.

5.1 Impact of human activity on saltmarsh change

5.1.1 Negative impacts (causes of saltmarsh loss)

5.1.1.1 Enclosure

Upper saltmarsh has been reclaimed for pastoral and agricultural use since the Roman occupation of England. Parts of the upper saltmarsh were enclosed in a piecemeal fashion, when the saltmarsh had accreted sufficiently to be considered 'ripe' for reclamation. The walls were made of material dug from a ditch (borrow dykes) on either the seaward or landward side of the embankment. These embankments formed the landward limit of flooding and hence defined the position of the coastline. Although the approach has been piecemeal, the total area of saltmarshes which has been enwalled is vast. Figure 3.14 charts saltmarsh enclosure of The Wash since 1970. Note how small the current area of saltmarsh is in comparison to the enclosed area which was once saltmarsh. MAFF's Database of British Saltmarshes (Pye and French 1993) collates data on enclosure for each estuary and bay in the British Isles. In the cases where records are inadequate to allow quantification, a qualitative description of the extent of reclamation is given. Where possible, the enclosed area is reported along with the area of active saltmarsh, so that the extent of reclamation can be envisaged. The regions for which quantitative data exist have been summarised in Table 5.1 below.

Table 5.1 Comparison of the extent of enclosed saltmarsh with existing saltmarsh area

Location of Saltmarsh	Reclaimed Area (ha)	Area of existing saltmarsh (ha)
Ribble Estuary	2320	2184
Mersey Estuary	490	848
Dee Estuary	6000	1237
Severn Estuary	84000	349
Taw and Torridge	480	240
Exe Estuary	830	66
Poole Harbour	1052	697
Portsmouth Harbour	1819	181
River Stour	1601	297
River Orwell	983	119
Deben Estuary	2242	461
Alde Estuary	1450	163
Butley River	1004	124
River Ore	2515	275
North Norfolk	1500	2127
The Wash	47000	4133
Humber Estuary	75110	648
River Tees	3300	34
Alnmouth	50	24
Total Areas	**233746**	**14207**

Table 5.1 illustrates that for the saltmarshes where quantitative data exist, the reclaimed area is approximately 16.5 times larger than the area of existing saltmarsh. However, this does not mean that the present area of saltmarsh should be 16.5 times larger than that which currently exists. The area of saltmarsh enclosed does not equate to the area of saltmarsh lost for two reasons: (1) In areas of sedimentation like the Wash, if reclamation had not been conducted, natural succession would have replaced saltmarsh flora with terrestrial flora. (2) There is an argument that enclosure increases the rate of accretion and hence saltmarsh advance by reducing the tidal volume, which in turn reduces tidal currents (Inglis and Kestner, 1958).

Rising sea levels and reduced sedimentation have resulted in stable or retreating low and high water positions in many UK regions (in particular south east England). This prevents the seaward advance of saltmarsh, which means that the area of saltmarsh lost through embankimg is not replaced. This makes further reclamation non-viable as it would:

- increase embankment maintenance costs (due to intensifying wave heights)
- result in a permanent reduction in the area of saltmarsh habitat.

However, enclosure is still occasionally being undertaken in the UK, particularly in Scotland. Reclamation schemes have been proposed or recently conducted which will eliminate the saltmarshes in several areas. The sustainability of these reclamation schemes is highly questionable as the saltmarshes at many of these sites are laterally eroding.

The artificial changes in estuarine morphology, caused by enclosure of saltmarshes, have probably had a significant effect on the progression of the tidal wave, and hence on tidal levels and tidal currents (Bowen, 1975). However, the evidence indicates that estuaries may respond in different ways to such changes. In some cases, reclamation has apparently enhanced intertidal accretion due to its effect in reducing the tidal prism and therefore average current velocities throughout the system, including the main estuarine channels, whose cross-sectional areas have been progressively reduced by sedimentation. Such changes occurred in the Dee, Ribble and the Wash, where considerable amounts of sandy sediment were available for landward transfer into the estuaries from adjacent offshore areas (Kestner & Inglis 1956; Kestner 1962, 1975). In a second type of situation, which applies to estuaries such as the Medway and Blackwater, reclamation caused an immediate reduction of the intertidal area, but the cross-sectional area of the entrance channel remained more or less unchanged because little sediment was available offshore to move into the estuary and reduce its cross-sectional area at the mouth. Consequently, frictional dissipation of tidal energy was reduced, and the flood tidal wave progressed more rapidly up the estuary, leading to an increase in both tidal range and current velocities. The remaining saltmarshes on the outside of the sea embankments have therefore experienced edge erosion due to lowering of the intertidal flats, and subsequent dissection due to deepening, widening and headward extension of the creeks (e.g. Pye, 1996b). Part of the sediment derived from marsh and intertidal flat erosion has been re-deposited subtidally in the main channels as they strive to regain an equilibrium cross-section (cf. Pethick, 1993, 1995), but in areas of ebb dominance a high proportion may be exported to the open sea. 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 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).

5.1.1.2 'Coastal squeeze' due to seawall construction

Past saltmarsh reclamations could now be contributing to saltmarsh loss in areas where the accretion rate of the intertidal zone is falling behind the rate of relative sea level rise. The resulting increase in depth of water over the intertidal area exacerbates shear stress by allowing larger waves (as wave heights are limited by breaking to about 0.6 times water depth). This results in lateral, and more rarely vertical, erosion of the saltmarsh. Without the embankments formed by past reclamations, this loss would have naturally been offset by the re-activation (i.e. terrestrial vegetation reverts to saltmarsh vegetation) of old saltmarsh caused by renewed tidal inundation (due to the rise in relative sea level). However, the embankments and seawalls prevent this from happening, resulting in narrowing of the saltmarsh zone. In addition to coastal squeeze, the presence of seawalls generally cuts out the zone of transitional vegetation, such as shrubby seablite *(Sueda vera)*, rushes *(Juncus* sp.) and reeds *(Phragmitis australis)*. The losses of this rare habitat is regretable.

Analysis of MAFF's Database of British Saltmarshes indicates that out of the *forty-four* saltmarsh sites in England and Wales that are experiencing lateral erosion, *thirty-two* were backed by an earth embankment or armoured seawall. *Three* had some parts protected and other parts natural. A further *three* of the sites that were not backed by wall, were bounded by naturally rising relief which prevented regression of the saltmarsh in the same way as the seawalls. Hence only *six* (approximately *14%*) of the sites graded gradually into terrestrial vegetation and were free to respond to sea level rise by migrating landwards. The situation is probavly worse than these percentages suggest. For example, in Essex only 900m out of 440km (0.2% of the length) of saltmarsh coastline are not backed by embankments.

The following calculation provides an example to illustrate the magnitude of landward movement that could occur. It uses the same method used to predict beach response to rising sea levels. It relies on the concept of the upper part of the beach profile remaining in the same position relative to mean sea level. As a consequence it will tend to retreat as sea level rises by a horizontal distance proportional to the increase in level divided by the "average" intertidal slope.

Assume: Relative annual sea level rise of 4mm, slope of saltmarsh surface 4%
Therefore: recession rate = 4÷0.04 = 100mm per annum, or *1m in 10 years.*

The calculation indicates that the effect of coastal squeeze due to seawall construction is much slower than the current rate of saltmarsh edge erosion in Essex. Hence even if the saltmarsh was unconstrained, landward extension would not compensate for the current rate of erosion. However, in a different situation, where, the land behind the saltmarsh is low-lying and almost flat, lanwards migration may compensate for loss of the seaward edge of the saltmarsh.

The presence of a sea embankment backing a saltmarsh can cause localised saltmarsh erosion by reflecting waves. Example are Freiston and Wrangle in the western Wash, reported in Pye (1995). Saltmarsh in front of an convex corner in the sea wall (where wave action is concentrated) has been eroded and in places reduced to mudflat. However, on a larger scale, embankments do not appear to stop seaward growth of saltmarshes in areas which are naturally accreting. Accreting saltmarshes in England and Wales were identified, again using the MAFF Database of British Saltmarshes. Out of *fifty four* accreting areas of saltmarsh, *thirty nine* were backed, or partially backed, by embankments and seawalls.

5.1.1.3 Construction on saltmarshes

Past perception of saltmarshes by developers and the general public alike was that of waste land. Even in these more enlightened days when the economic, wildlife, scientific and recreational value of saltmarshes is more widely appreciated, this negative attitude still lingers.

This attitude has made saltmarshes easy targets for developers. The land is inexpensive and there is little public opposition. Saltmarshes have been lost due to the construction of industrial buildings (particularly those that need a large water supply such as power stations and chemical works, or need to be close to materials that are transported by sea, such as oil refineries), marinas and ports. Examples of past developments on land claimed from specific saltmarshes are given in Table 5.2 below.

Table 5.2 Examples of construction works on saltmarsh sites

Saltmarsh location	Development
Duddon Estuary	Urban, port and industrial development
Morecambe Bay- South Walney	Docks
Ribble Estuary	Urban and industrial
Dee Estuary	Industrial
Cardigan Bay - Morfa Dyffryn	Airport
Bristol Channel - Sand Bay	Urban development
North Cornwall - Camel Estuary	Urban development
South Devon - Dart Estuary	Railway line
Southampton Water - Fawley	Oil refinery, chemical works, power station
The Solent - Lymington	Marina and berths cut out of the saltmarsh
The Solent - River Hamble	Marinas
Sussex Coast - Rye Harbour	Infrastructure
Medway Estuary - Queensborough	Possible dock development
Thames Estuary	Industrial and residential development
River Stour, Essex	Dock and marina development
River Orwell, Essex	Dock development
Humber Estuary	Industrial development
River Tees	Industrial and dock development

5.1.1.4 Grazing

Sheep, cattle and pony grazing is a common use of saltmarshes. Most saltmarshes in Wales, north west, south west and north east England are grazed. Grazing also occurs to a lesser extent on saltmarshes of the south and south east coasts (from the 1993 MAFF Database of British saltmarshes). Some of these grazed saltmarshes are eroding and hence the pressures on the flood embankments are increasing. It is therefore pertinent to assess how grazing affects saltmarsh accretion and erosion.

Listed below are a number of ways by which grazing may change saltmarsh morphology and physical properties. Some effects are positive and others negative in terms of their effect on altering the erodibility of saltmarshes.

(1) grazing reduces the surface roughness coefficient of the saltmarsh - (*reduces wave and tidal current dissipation, hence increases shear stress on the saltmarsh surface*).

(2) grazing reduces accretion rates and hence maintains saltmarsh at a lower elevation than it would be if ungrazed (Ranwell, 1968) - (*increases the potential wave height and hence risk of vertical erosion of the saltmarsh surface*)

(3) trampling flattens the creek profiles. In marshes with shallow creeks, which animals cross, the creeks banks are degraded - (*changes current profile*)

(4) trampling and grazing favour grass species such as *Puccinellia*. The root structure of grass is dense but shallow; this differs to the root structure of a mixed saltmarsh

community, which has a wider spread of root depth - (*changes the tensile strength profile and thereby the rate and mode of marsh edge erosion*).

(5) summer grazing on relatively firm upper saltmarsh, shortens and makes the sward more uniform and less tussocky (from the results of work ITE conducted for CIRIA investigating how vegetation type on seawalls altered its erodibility), therefore flow is linear and erosion due to channelling of flow is less likely - (*grazed swards which are not churned up by hoof damage may stand higher velocities before erosion* ***commences*** *than ungrazed vegetation*)

(6) trampling on wet saltmarshes churns up the sediment and produces a hummocky surface - (*increases surface roughness but would increase erodibility as the destruction of young plants and disruptions of algal mats would reduce the stability of the mud surface*). Trampling on higher, dryer saltmarshes could increase compaction and hence tensile strength. However, this may retard soil aeration and act to limit growth of plants such as *Halimione* (Jensen, 1985)

(7) the development of sheep tracks across seabanks may lead to the formation of low points which are exploited by high tides, acting as foci for seabank failure (Figure 5.1).

A literature review and consultations with researchers (Drs. Alan Gray and Laurence Boorman) established that research associated with grazing on saltmarshes has largely been confined to its effect on ecology (i.e. species diversity, nutrient cycling and the effect on succession) rather than how it changes hydrodynamics. A little work has been conducted into how grazing affects accretion rate (Ranwell, 1968; Randerson, 1979) and research in the Wadden Sea has been proposed to investigate the effect of grazing on sedimentation and erosion processes (from the 1989 conference, Saltmarsh Management in the Wadden Sea Region). However, there has never been a comprehensive study that assesses the impact of grazing on saltmarsh morphology (i.e. levels, creek cross-section, quantity of debris on the drift line, surface roughness) and how these alterations affect wave and tidal current dissipation.

(3) Ship-induced rapid water level draw-down

Ship movement through a narrow channel causes a rapid rise and fall in water level. Changes in water level due to a passing ferry on the banks of Horn Reach in Lymington Harbour were recorded during field work conducted by HR Wallingford (1991). The water velocities produced by the rise and fall in water level ($0.5ms^{-1}$) to ($1.0ms^{-1}$) are much higher than the tidal velocities, and are capable of eroding the soft deposits at the edge of the channel. The degree of water level draw-down increases with:

- the square of the ship speed
- proximity of ship to channel bank
- blockage ratio
- decrease in keel clearance of the bed
- reduction in vessel length, if all other parameters are the same

A study of the causes of mud erosion in Lymington Harbour, Hampshire was conducted by HR Wallingford (HR, 1991). Table 5.3 summarises the relative magnitudes of the factors contributing to erosion of the saltmarshes along the banks of the channels. From experiments to determine the shear strength of the bed and bank material (shear stresses needed to erode the low shore samples = $0.4 - 0.6Nm^{-2}$ and $1.0 - 2.0Nm^{-2}$ for the high shore samples) it was possible to predict whether each causal factor could produce erosion. The aim of the work was to assess the effect of ferry movements on saltmarsh erosion and predict the effect of introducing new, larger, ferries.

Table 5.3 indicates that shipping activity *does* cause erosion. The dominant factors responsible for erosion, at this site, appear to be ship return currents, ship-induced water level draw-down and wind waves. The shear stress due to wind waves is smaller than the other two effects, but acts for a larger percentage of the time. The calculated depth of channel erosion based on the excess shear stress and the duration of the year over which this acts is around 0.3m over a 10 year period, which corresponds well with the observed depth of erosion during the same period. This increase in channel depth is almost certainly responsible for recession of the banks of the saltmarsh around the main channel. An increase in channel depth of *0.3m* is likely to lead to the banks receding by up to *20m* to retain the same slope on the mudbanks. This is visually much more obvious than the increase in depth.

Table 5.3 Relative magnitude of factors contributing to bank erosion in Lymington Harbour

	Max. velocity m/s)	**Max. wave ht. (m)**	**Bed shear stress (Nm^{-2})**	**% time**	**Erode Bed?**
Tidal velocities	0.3		0.1	1	No
Wind waves		0.28	0.5	1	Yes
Ship waves		0.1	0.2	0-0.5	No
Ship return currents	1.0		1.0	0.3	Yes
Water level draw-down	0.5-1.0		0.5-1.5	0.2	Yes

Ship-induced erosion of the saltmarsh fringing the channels is not necessarily confined to the navigation channels. Shipping activity in Lymington Harbour has resulted in deepening of the main channel through dredging and ship-induced erosion. This in turn increases the tidal volume and hence tidal currents in the channels. Studies of saltmarsh loss in Lymington Harbour (personal communication, Andrew Bradbury, New Forest District Council) show that erosion is also happening along the unnavigated, smaller, secondary and tertiary channels. It is possible that this erosion is at least partly induced by the increase in tidal volume which has resulted from the widening and deepening of the main channels.

5.1.1.6 Dredging

It has been argued that dredging to keep open navigation channels in estuary and coastal waters may be deleterious to saltmarshes by:

- causing foreshore slumping (see Figure 5.2)
- increasing the tidal volume and hence tidal currents (although modelling conducted by HR to predict the impact of various dredging schemes on tidal currents suggests that the increase is minimal)
- changing the pattern of flow through the estuary; the proportion of total tidal discharge which takes place through the main channel may increase, causing a corresponding reduction in the velocities and average shear stresses over the adjoining tidal flats, and hence enhanced accretion in the intertidal zone
- modifying the up-estuary progression of the tidal wave, with implications for tidal current velocities and asymmetry
- through the deepened areas acting as a trap for sediment which would otherwise have been deposited on the mudflats and saltmarsh
- removal of vast quantities of sediment from the estuary sediment budget (if the dredged material is dumped at sea or land) which may cause a sediment deficit and a net sediment loss from the estuary.

Figure 5.2 shows the theoretical slumping after removal of sediment to deepen the channel, create a berth, or extract aggregate. The cut face will be unstable and liable to slump to regain the stable slope, unless supported by sheet piling. The distance affected by slumping depends on the stable slope angle (influenced by sediment character, waves, currents and sediment supply) and the depth of the dredged hole. For example, if the stable slope is 1:50 (a typical figure) and the dredged channel is 10m deep, the region that could potentially slump could be up to 500m from the edge of the dredged channel. The slumping could exacerbate saltmarsh erosion in two ways: firstly by directly lowering the saltmarsh surface (if the area of influence extended to saltmarshes) and hence stressing the vegetation; and secondly by a reduction in the elevation of the fronting mudflats increasing water depth, and leading to larger waves hitting the saltmarsh.

Although dredging has been implicated with saltmarsh loss in a number of places overseas (Hackney and Cleary, 1987), no scientific studies have been undertaken in the U.K. to confirm or refute the allegations that dredging lowers the elevation of the inter-tidal zone or reduces accretion rates by decreasing sediment availability. However, to conduct such investigations would be a straight forward procedure. The impact of dredging activity on the adjacent inter-tidal area could be established if a pre-dredge baseline study was conducted (bathymetry and intertidal survey and sedimentation measurements) and subsequent changes in the sub-tidal and inter-tidal levels and sedimentation rates after dredging. ABP probably already have data which could be used to investigate whether slumping after dredging has occurred. Unfortunately, given the scope of this project, this avenue could not be pursued further.

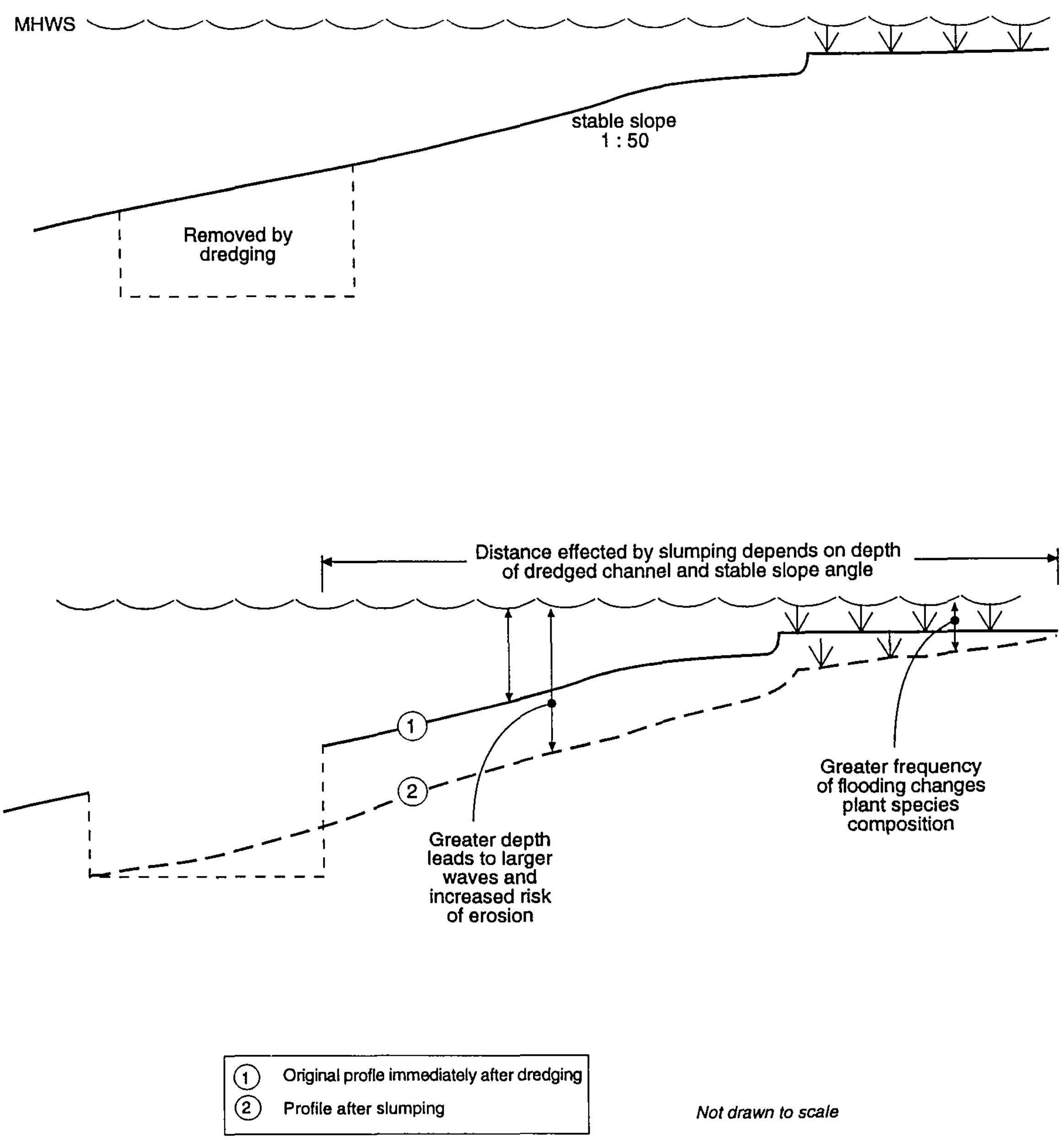


Figure 5.2 **Conceptual diagrams to illustrate slumping after dredging and the possible impact on the saltmarsh**

Direct evidence of dredging adversely affecting saltmarshes in the U.K is limited. Both dredging and navigation have been suggested as possible factors contributing to saltmarsh erosion in the Suffolk estuaries (Beardall *et al.*, 1991) and in the entrance to Lymington Harbour (Goodman *et al* 1959), but the effects have not been quantified. Indirect evidence suggests that it is likely that nearshore dredging does affect the intertidal profile. Cardiff Bay is an example of how maintenance and capital dredging forced the morphology of the Bay to be out of equilibrium with the natural regime. In areas where dredging has ceased, such as the Roath Channel in 1978, siltation has occurred as the system moves towards equilibrium (HR, 1988). Figure 5.3 charts the increase in saltmarsh area associated with ending dredging.

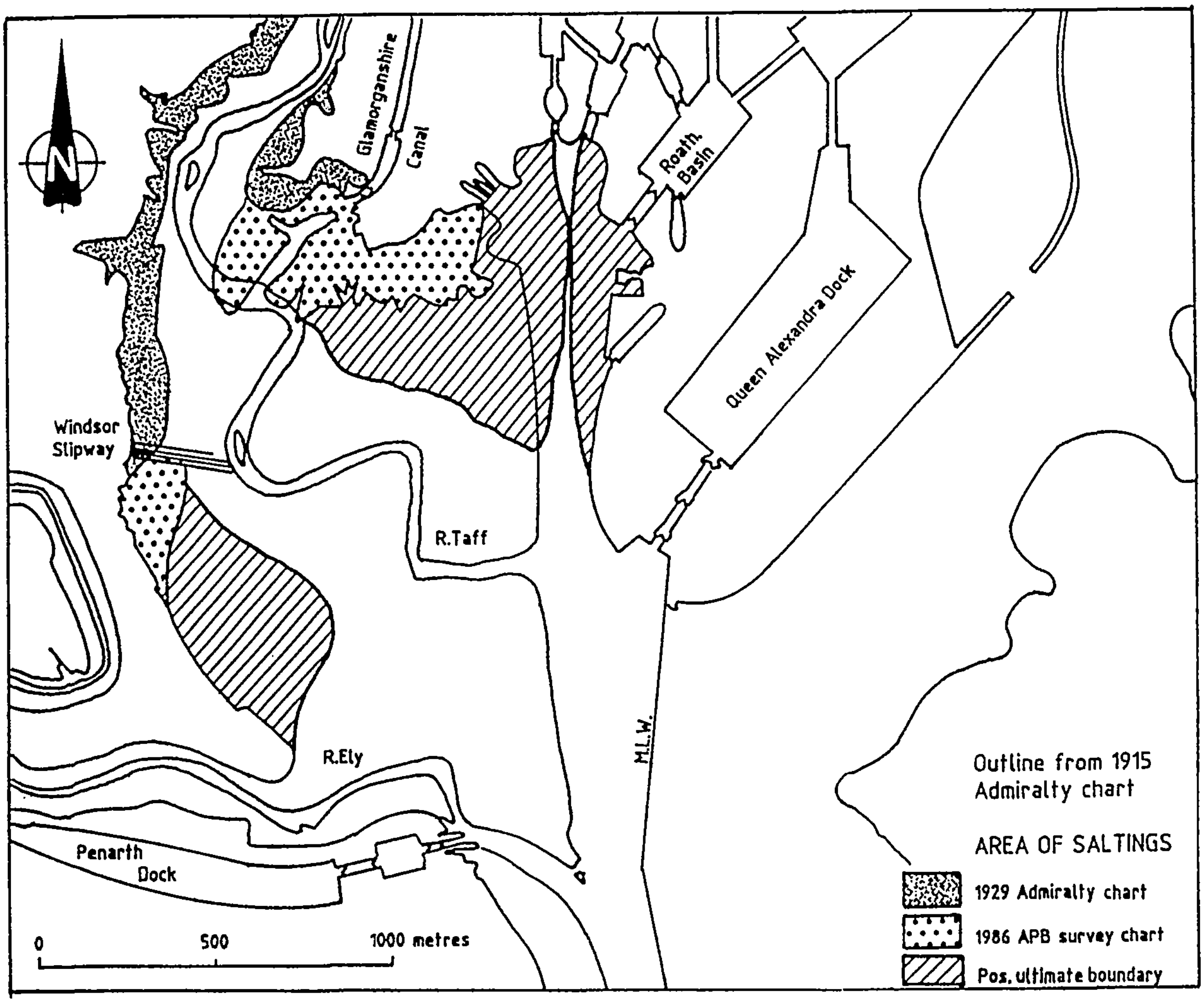


Figure 5.3 Growth of saltmarsh 1915-1986, Roath channel, Cardiff Bay (after HR, 1988)

5.1.1.7 Mud digging

Many British marshes have been affected to a relatively minor degree by direct sediment removal associated with turf cutting, development of oyster pits and boat moorings, and sea bank construction. However, mud digging on a much larger scale for the brick and cement industries was undertaken in the Medway estuary, particularly during the late 19th and early 20th centuries. Extraction was prohibited at the marsh edge, but the central parts of some marshes were dug to a depth of several metres, cuts being made to allow removal of the dug clay by barge. The activity was licensed by the Medway Conservancy, but a considerable amount of unauthorised extraction also appears to have taken place. The last licence was issued in 1931, and the last shipment of clay made in the mid-1960's, but peak extraction occurred around the turn of the century. The total amount of clay removed has not been quantified, but returns for just one company at a single site (West Hoo Creek) suggest at least 1.4 x 10^6 t between 1881 and 1911 (Medway Ports Authority, 1911). Similar clay digging was undertaken on a smaller scale at a number of sites in Essex including Bridgemarsh Island in the Crouch estuary.

5.1.1.8 Pollution

- Synthetic substances

Concern has been expressed over the presence of man-made compounds within saltmarsh systems and their potential impact on saltmarsh stability. However, there is currently, a lack of information regarding the toxicological effects of contaminants to saltmarsh biota at environmental concentrations. To date, there is no conclusive evidence as to whether contaminants are impacting on the vigour of saltmarsh plants or animal community. Although research has been conducted to determine the concentration of contaminants in saltmarsh sediments, the actual toxicological effect on the biota is not known. Therefore, at present, the best we can do to establish whether there is a link between contaminants and vegetation die-back is to compare the timing of die-back episodes with historic changes in the use and occurrence of contaminants over the last century.

Direct contaminant inputs to individual saltmarshes vary spatially and will be site specific. Agricultural, industrial and domestic activities are the principal sources and at each saltmarsh site the amount of input from each of these three sources varies. For example, intensive agricultural practices in East Anglia may lead to agrochemicals reaching its estuarine and coastal salt marshes. While in other areas such as the Humber and Mersey estuaries, industrial activities dominate and metals and organic micro-contaminants from current and historical industrial discharges contaminant saltmarsh sediments. In addition to spatial variability, however, contaminant uses and, therefore, inputs and biota exposure have varied temporally over the last century as indicated in Figure 5.4. Use patterns for the relatively more recently introduced synthetic organic micro-contaminants can be traced. For example, polychlorinated biphenyls (PCBs) have been commercially available since the 1930's, however, in the U.K. they have been manufactured from 1954 to 1976 (Department of Environment, 1995). Tributyltin (TBT) has been used as an antifoulant on hulls of vessels since the late 1960s and on fish-cage netting during the early 1980's. The severe toxic effects of TBT have been recognised (Langston et al., 1987; Bryan et al., 1986). A ban on the use of TBT for boats less than 25m in length was subsequently introduced in 1987. Synthetic organic herbicides, such as the chlorophenoxy acid herbicides, were first introduced in the late 1940s with intensive agriculture over the last few decades subsequently increasing their use.

Changes in plant vigour have been recorded. *Zostera* (eelgrass) meadows were eradicated from large areas of the East Anglian coast in the 1930s with *Spartina* die-back occurring in the 1950's. Changes in benthic (mud dwelling) organisms/ communities are less easily observed and few have thus been recorded. The timing of these episodes of die-back in comparison with the use of contaminants is presented in Figure 5.4. It is evident that the onset of *Spartina* and *Zostera* die-back did not coincide with a new input of contaminants.

On a site by site basis, historic patterns of contaminant occurrence can be ascertained, to some extent, from sediment profiles (Fletcher *et al.*, 1994; Fletcher *et al.*, 1995; Scrimshaw *et al.* 1994). As information is gathered and bioassay methods to establish toxic effects are conducted it may become possible to link more conclusively the role of changing contaminant inputs to historical changes in saltmarshes.

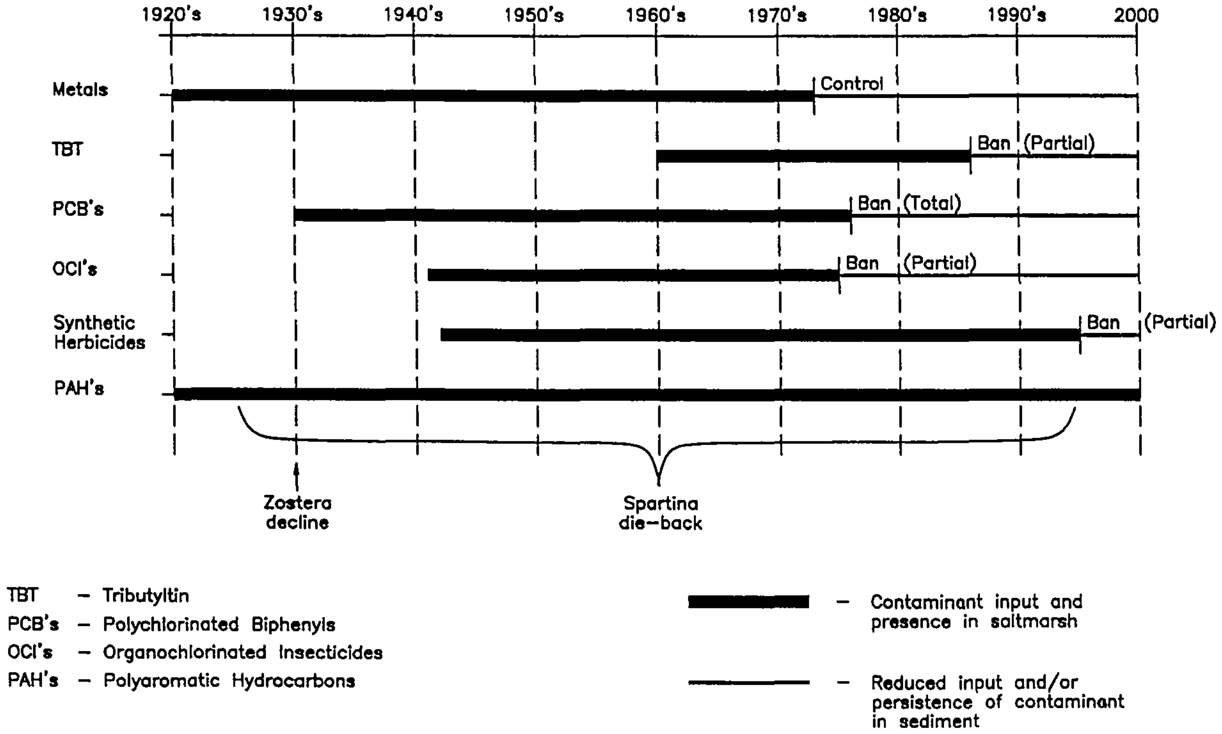


Figure 5.4 **Historical changes in contaminant sources and subsequent occurrence in the environment**

- Oil

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 (Baker, 1970; Dicks, 1976; Dicks & Iball, 1976). The areas most at risk are located near major oil refineries and storage depots, many of which have experienced spillages or more prolonged discharges of refinery effluent (e.g. Milford Haven, Fawley in Southampton Water, the Isle of Grain and Bee Ness in the Medway, Canvey - Holehaven in the Thames, and Stanlow on the Mersey). Saltmarsh was decimated in these areas. However, in the past 20 years there have been big improvements in the quality of refinery discharges, and in many such areas the saltmarsh vegetation appears as healthy, if not healthier (as in the case of

5.1.1.9 Refuse disposal

Saltmarshes have been used as refuse disposal grounds. In some cases dumping is illegal, but in others it is managed and precedes land reclamation (as the refuse is free material to build up the land level). Examples of sites which are currently being used as dumping grounds are given in Table 5.5 below.

Table 5.4 Refuse disposal on saltmarshes

Saltmarsh Location	Nature of disposal material
Pembrokeshire Estuaries - Cosheston Pill	Refuse disposal followed by reclamation
North Wales - River Clwyd	Tipping on part of marsh
Southern England - Langstone Harbour	Refuse disposal
Moray Firth - Conon Islands	Dumping of farm waste
Orkney, Black Rock marsh	Proposed refuse disposal
Longman Tip, Inverness	Refuse disposal
Canvey Island, Essex	Refuse diposal

Tipping refuse would obviously be detrimental to saltmarshes and result in loss of saltmarsh habitat.

5.1.1.10 Trampling

Saltmarsh vegetation (bar certain grasses such as *Puccinellia maritima*, *Festuca rubra*, and *Elymus* sp.) is very sensitive to trampling. Human footpaths, off-road vehicles and car parking, all lead to the damage and disappearance of vegetation. Stiffkey saltmarsh in North Norfolk provides an example of the erosive power of walkers. North Norfolk saltmarshes are particularly attractive to walkers because of the firm substrate and the saltmarshes are not internally dissected so there are not so many creeks to cross.

Trampling is deleterious to vegetation through direct damage to the shoots and also compaction of the sediment which reduces pore spaces and hence gaseous exchange. It is actually used as a method of *Spartina* control in the Camel Estuary at Wadebridge. Figure 5.6 shows the success of 'trampling parties' conducted by the local conservation volunteer group, on reducing the vigour of *Spartina.*

Trampling is insignificant from the point of view of causing widespread saltmarsh damage. However, it can be the cause of localised saltmarsh degradation. To minimise the impact, pedestrians could be managed by constructing and signposting footpaths, and erecting information boards to educate people of the damage trampling causes. Possible options are shingle paths, and raised boardwalks.

in that the cost of instigating managed retreat plus the value of the land which will be flooded, is lower than the cost of maintaining the current degree of flood protection at the present line of defence. Secondly, the main driving force behind the interest of conservation groups such as the National Trust, English Nature and RSPB, is that the recreation of saltmarshes and mudflats partially compensates for the loss of habitat through the process of coastal squeeze (see section 5.1.1.2).

At present, managed retreat in Britain is largely experimental (the first small scheme was conducted four years ago). Several techniques are being tested and monitored (for description of the various techniques see HR (1995). If the pilot schemes are successful the area of saltmarsh recreated by managed retreat in the future could be substantial. Table 5.5 lists the location of the current managed retreat schemes and their size.

Table 5.5 Location and size of managed retreat schemes

Location	**Size (ha)**
Burnham-on-Sea, Parrot Estuary Blaxton Meadow,	6
Plym Estuary, Devon	6
Orplands, Blackwater Estuary, Essex	38
Northey Island, Blackwater Estuary, Essex	0.6
Tollesbury, Blackwater Estuary, Essex	21
Horsey Island, Hamford Water, Essex	<1
Abbott's Hall, Salcott Creek Essex	20

5.1.2.2 Current techniques to encourage seaward advance of saltmarshes

The current management techniques used to encourage the seaward advance of saltmarshes are reviewed in the EA R&D note 567/2/SW 'Maintenance and enhancement of saltmarshes'. prepared by HR Wallingford. The techniques which have been used in an attempt to stop further erosion and to instigate accretion and the seaward growth of saltmarshes are listed below:

- Sedimentation fences and polders
- Beach sills (onshore breakwaters)
- Offshore breakwaters
- Sediment recharge (using cohesive and non-cohesive sediments)

- Repositioning of firm dredged material to restructure saltmarshes
- Replanting

It should be emphasised that with the exception of polders (which were installed at 19 sites in Essex) the other forms of management have only been conducted on a limited scale, and are largely experimental. Therefore, even though some of the assessed schemes were successful in instigating saltmarsh advance, (such as *Spartina* replanting around the effluent outfalls at the ESSO refinery in Southampton Water; construction of an onshore wave break in the form of a ridge of rocks, Humber Estuary; and extension of saltmarsh area using firm dredged material, Blackwater Estuary) the actual area of saltmarsh created is very small. In addition, it is inappropriate to attempt to maintain or extend currently eroding saltmarshes on an estuary wide scale. The majority of erosion in the south and south-east is a natural response to changes in estuary/coastal processes. Preserving or increasing the current extent of saltmarshes, on a major scale, will produce an artificial estuary geomorphology which is out of equilibrium with the hydrodynamic conditions. Therefore, maintenance and enhancement techniques that attempt to advance the saltmarsh seaward, cannot compensate for the loss of saltmarshes through erosion. This type of action is neither economically viable nor sustainable.

5.1.2.3 *Spartina anglica* planting

Spartina anglica is a type of saltmarsh cordgrass which originated in Southampton Water in the last century. It is a fertile hybrid, formed by the hybridisation of *Spartina alterniflora* (an American species, probably introduced to Southampton Water by shipping) and the native species *Spartina maritima*. The hybrid was discovered in 1870 and given the name *Spartina townsendii*. Although vigorous, this species was infertile and could only spread vegetatively. Its rate of natural dispersion was suddenly improved when the plant became fertile due to a gene mutation which doubled the number of chromosomes (Marchant, 1967), allowing each chromosome to be paired so that successful meiosis, and hence sexual reproduction, became possible. The new fertile form was named *Spartina anglica.*

Its rapid spread can be partly attributed to the fact that it was physiologically able to invade and occupy a position low in the intertidal zone (around mean high water neaps) where other pioneer saltmarsh species like *Puccinellia, Armeria* and *Plantago* found it difficult to survive (Gray *et al.*, 1989, 1995; Gray, 1992). The rate of vertical accretion was also extremely rapid. Because of these qualities the value of *Spartina anglica* in land reclamation and coastal protection was recognised. As early as 1923, 40,000 *Spartina anglica* plants that were propagated in a nursery in Poole Harbour, Dorset, were exported to the Netherlands to aid land reclamation (Hubbard, 1965). The success of these trials lead to the introduction of plants, supplied from the same nursery, to 17 sites around Essex and Suffolk in 1925. This was followed by its introduction to many other sites around England and Wales (see Figure 5.7). Its present day distribution reflects this planting pattern.

The initial speed of colonisation may also have been favoured by climatic and hydraulic factors (e.g. a reduction in wind/wave intensity, or slight fall in tidal levels) Its establishment in many west coast estuaries between 1920 and the mid 1960's was probably encouraged by a declining incidence of strong winds (and, by inference, less wave activity and greater substrate stability). Conversely the observed increase in the duration of strong winds from the mid 1970's onwards would have made saltmarsh colonisation more difficult except in sheltered locations. The flowering, seed production and lateral rhizome growth of *Spartina* are known to be strongly influenced by climatic factors (Mullins and Marks, 1987; Marks and Truscott, 1985).

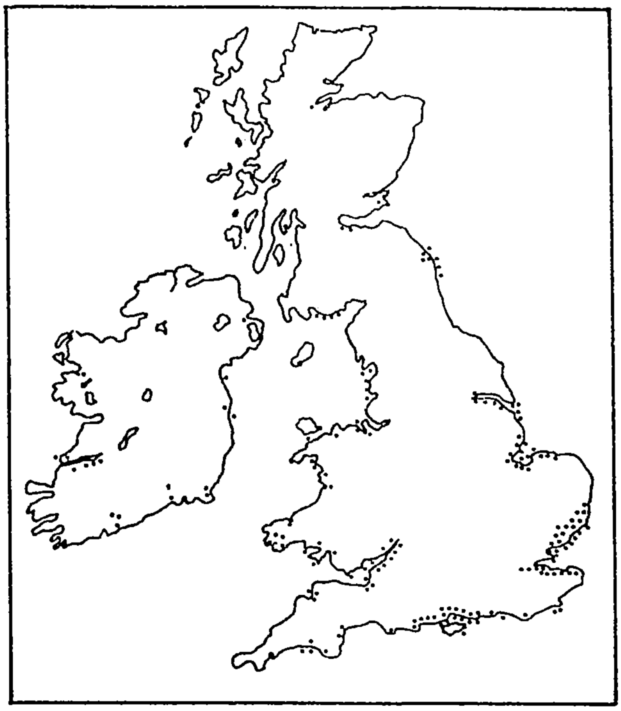


Figure 5.7 Distribution of *Spartina anglica* and *Spartina townsendii*

The spread of the introduced *Spartina anglica* across previously uncolonised mudflats has lead to the creation of a substantial area of saltmarsh. Unfortunately, the actual area of saltmarsh created has not been defined in the literature. Although much of the *Spartina alterniflora* saltmarsh in the south is suffering from die-back (see section 5.2.1), there is continued spread in estuaries of northern England and Wales (from questionnaire responses). At present there are attempts to control this spread by the use of herbicide, digging and removal, cutting and trampling. The work is conducted by District Councils and various conservation groups. The perceived justification for the works are listed below:

- displacement of *Zostera* (sea grass), which is the indigenous coloniser of mudflats
- invasion of mudflat; the reduction in mudflat has been associated with decline in wader population (Goss-Custard and Moser, 1988; Davis and Moss, 1984)
- encroachment on to tourist beaches, reducing their amenity value because the enhancement of deposition of fine sediments turns the sandy beaches muddy.

It is arguable that attempts to destroy *Spartina anglica* by control methods (particularly when it is conducted under the banner of conservation) is not in the interest of management of the saltmarsh resource on a national scale. This point of view is clearly expressed by Thompson (1990):

" ..the evidence for its (*Spartina anglica*) detrimental effect on other *Spartina* species, the succession of natural plant communities, and the abundance of invertebrates and wader birds is all circumstantial. What is more, the catalogue of concern is often balanced by contrary evidence, which introduces a beneficial slant to the colonisation and spread of *S. anglica*. In view of the predicted rises in sea level, the enhanced development of estuarine saltmarsh by vigorous colonies of *S. anglica* may help to offset the expected massive losses of this habitat."

Moreover, the die-back presently evident in the older stands of *Spartina alterniflora* is now being reported in the younger stands of the north, such as the Lytham area of the Ribble Estuary (from a questionnaire return). Therefore, it is better to let nature run its natural course than to use herbicides which have an adverse environmental impact (see EA R&D note 567).

5.1.2.4 Creation of saltmarsh in the lee of coastal structures

Estuarine and coastal structures often affect localised accretion/erosion by altering hydrodynamics. If engineered structures provide shelter from waves or tidal currents for an area in their lee, sedimentation will be enhanced. This is well illustrated by Figure 5.8 which shows the change in bed-form one year after the construction of West Thurrock Jetty, located in the stretch of the Thames known as Long Reach. Erosion occurred outside the jetty, but substantial vertical accretion (1-4m) occurred on the sheltered side, producing an increase in intertidal mudflat area.

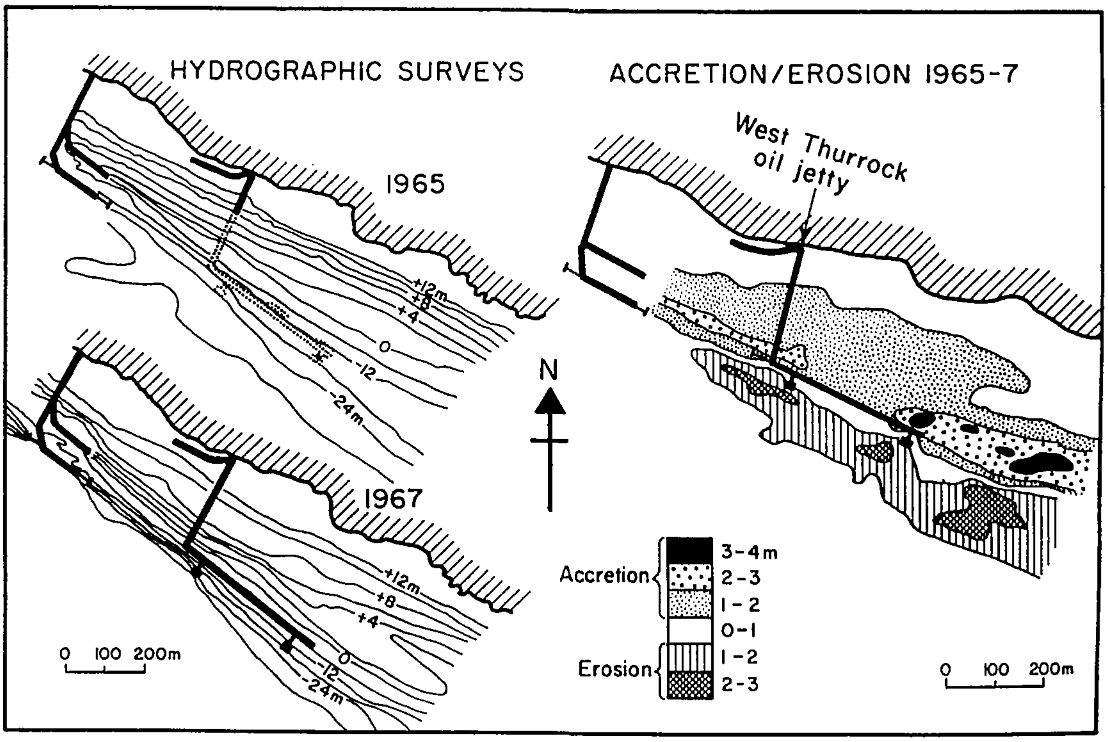


Figure 5.8 Pre- and post-jetty construction bathymetry and an accretion/erosion diagram in the vicinity of West Thurrock oil Jetty (from Kendrick, 1994)

The hydraulic regimes of many British estuaries have been profoundly influenced by training wall construction designed to control the natural instability of their deep water channels for navigation purposes (Inglis & Kestner, 1958 a, b; McDowell & O'Connor, 1977; O'Connor, 1987). In many cases, however, it is difficult to separate the effects of training wall construction from those of other activities such as maintenance dredging, embanking and reclamation. Perhaps one of the clearest examples is provided by changes around the outfall of the River Witham in the Wash (Inglis & Kestner, 1958b). The outfall of the Witham was trained towards Boston Deeps in 1884. Evidence from Admiralty surveys shows that between 1828 and 1871 the saltings along the adjacent shore at Butterwick had been advancing seawards at c. 14m/yr. After completion of the new outfall, the rate of seaward advance leapt enormously, exceeding 100m/yr between 1903 and 1917/18 (Figures 5.9 and 5.10). Rapid accretion continued in this area until the early 1980's allowing a series of reclamations to take place in 1942, 1955, 1965, 1972 and 1979 (Robinson, 1981, 1987).

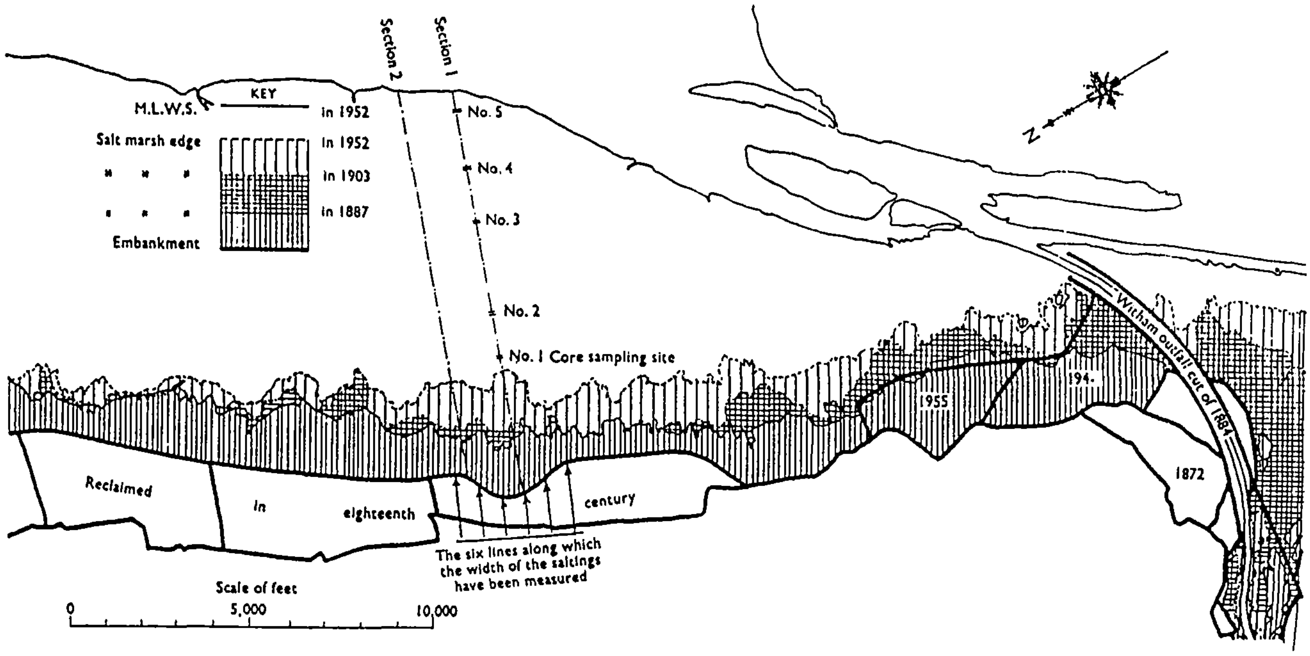


Figure 5.9 **Changes in the saltmarsh edge at Butterwick western side of the Wash, following completion of the training works at the River Witham outfall in 1884 (after Inglis and Kestner, 1958b)**

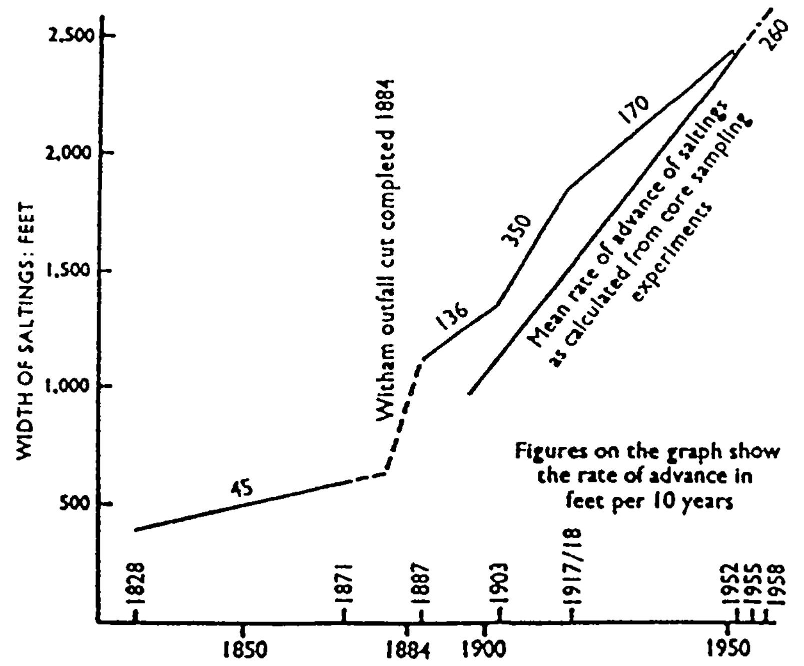


Figure 5.10 Rate of seaward advance of the saltings at Butterwick between 1828 and 1956 (after Inglis and Kestner, 1956b)

In the Ribble estuary, training works were commenced in the inner estuary between 1840 and 1847 and gradually extended some 37 km down the estuary by 1937 (Barron, 1938; O'Connor, 1987). The effect was to confine the main ebb flow within the trained channel and to create areas of flood dominance across the sand banks on either side. In 1850 the outer estuary of the Ribble contained three major channels, the North Channel, the Pinfold Channel and the South Channel (Figure 5.10). The North and South Channels had largely filled up with sediment by 1900, and in 1980 only a vestige of the Pinfold Channel remained. In parallel with this infilling, large scale intertidal accretion and saltmarsh growth occurred along the south shore. This process allowed, and was probably partly encouraged by, embanking and reclamation which reduced the tidal capacity still further. Major reclamations were undertaken in 1860, 1880, 1891, 1895, 1974 and 1980 (see Figure 5.11). At the present time only Longton Marsh and Clifton Marsh in the inner estuary remained unreclaimed. After the cessation of dredging of the trained channel, and closure of the port of Preston in 1979, a large sand bank extended southwards from the Lytham shore and partially blocked the trained channel. Since then there has been some deepening of the former Pinfold and South Channel as the estuary has sought to achieve a new morphodynamic equilibrium. Saltmarsh growth on the south side of the estuary has continued, assisted by the effects of a roadway constructed between the embankment at marshside and a sand winning area on Horse Bank. This feature has acted as a groyne, retarding tidal movements across the upper intertidal zone and enhancing the establishment of *Spartina* and *Puccinellia* marsh (Pye & Neal, 1994).

The total area of saltmarsh created due to enhanced sedimentation from coastal structures has never been determined for British saltmarshes. Therefore it is not known to what extent, this compensates for saltmarsh loss.

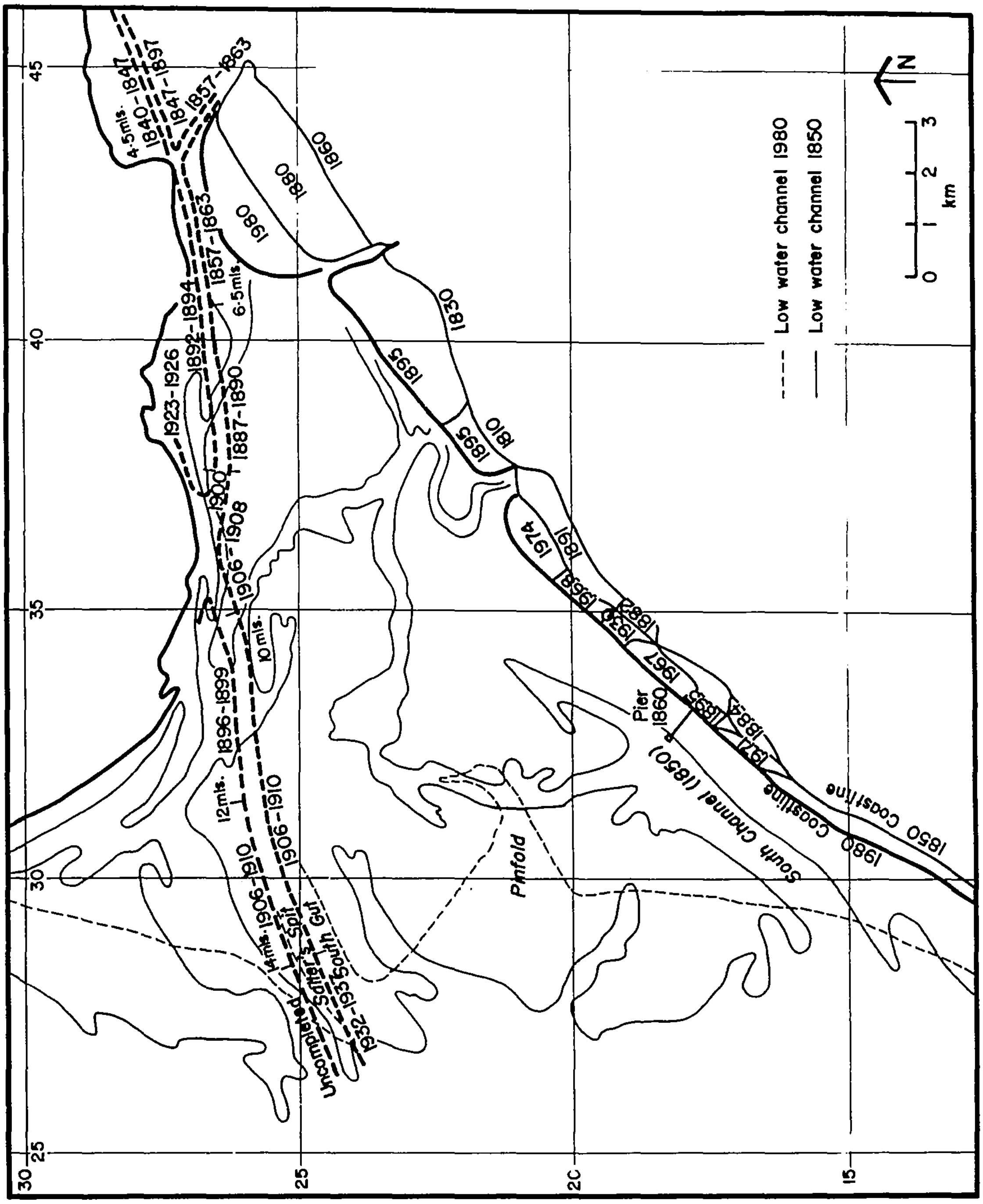


Figure 5.11 Extension of the Ribble training walls between 1840 and 1937. Saltmarsh reclamations between 1830 and 1980 are also shown (after Pye and Neal, 1994)

5.2 Impact of natural biological/chemical factors on saltmarsh change

5.2.1 Soil chemistry and plant vigour/species composition

It is noticeable that in some *Spartina* dominated saltmarshes (such as Lymington Harbour), although the elevation of the marsh surface relative to the tidal regime has accreted sufficiently to be appropriate for species of saltmarsh plants which are characteristic of an 'upper saltmarsh' community, colonisation by these species has been poor. This could be due to the adverse chemistry associated with the intensely reducing conditions of the organic rich, waterlogged sediments. The section above describes how poor conditions reduce the vigour of *Spartina,* but other saltmarsh species would not be able to survive in these conditions at all. 'Upper saltmarsh' species, such as *Halimione atriplex* (sea purslane) are less tolerant to saturated anoxic conditions than *Spartina.* This is partly explained by the varying extent to which different halophyte species have developed mechanisms to oxidise the sediment around their roots. (Howes et al., 1981). The oxidized zone protects the plants by oxidizing the toxins into a harmless form before they come into contact with the plant. For example, hydrogen sulphide is oxidised to harmless sulphate and dissolved Fe^{2+} ions are precipitated as Fe^{3+} minerals. *Spartina* is particularly efficient at oxidizing the sediment around its roots using two strategies:

(1) passive diffusion or advection through the continuous gas spaces, which extend from shoot to root (Teal and Kauwisher, 1966)

2) leaching of oxidising substances through the roots (Bedford et al., 1991; Howes et al., 1981).

5.2.1.1 Soil chemistry and *Spartina* die-back

As early as 1928 the first signs of *Spartina anglica* 'die-back' were reported in the Beaulieu Estuary and later in other parts of Hampshire. 'Die-back' is a term used to describe loss in plant vigour: although the plants do not necessarily die, they are much smaller and set seed less frequently. It is of relevance that die-back first occurred in the vicinity of Southampton Water, the birth place of the hybrid (see 5.1.2.3). This provides circumstantial evidence that the cause in decline is age-related. More recent studies have compared the vigour and survival of *Spartina* populations of different ages. The results add weight to the theory that the sward loses vigour as it matures (Thompson, 1990).

Many theories have been put forward to explain loss in vigour, such as old age of clones, infection by ergot fungus, physical damage due to increase in wave energy, waterlogging and reduction in accretion rate. The first explanation can probably be dismissed. The reasoning behind the theory that loss in health is due to age of the plant is the following. *Spartina* can reproduce sexually or vegetatively (i.e. new plants, clones, and sprouts from the rhizomes). When the clumps of *Spartina* expand to form a continuous sward, it is difficult for seedlings to establish on top of the root mat. Therefore, there are no new plants and all that exists are clones from the original plants and as their collective age increases they lose vigour. If this theory were true, transplants of young plants into areas of die-back should grow well and conversely, plants removed from a degenerating sward and transplanted in a healthy location should not regain vigour. However, this is not the case. Results from transplant studies indicate that the reason for the decline is not the age of the clone. It is also unlikely that the ergot fungus is the primary cause of die-back. More likely it is a contributing factor and a sign that there are other stresses on the plant which make it more susceptible to fungal infection. The argument of increase in wave stress causing decline in vigour can be clearly seen in some areas where the *Spartina* at the seaward edge of the sward shows visible signs of wave damage, i.e. it is shorter and more sparse than the *Spartina* growing inland. However, increase in wave energy cannot explain cases of *Spartina* die-back which affects the whole sward uniformly, regardless of distance from seaward edge.

Work by Mendelssohn in North Carolina, USA has established a definite link between soil drainage and the growth of *Spartina alterniflora* (Mendelssohn, 1980; Mendelssohn and McKee, 1988). Plant stress is due to the build up of phyto-toxins (such as hydrogen sulphide, ethanol, ferrous and manganese ions) which are produced directly and indirectly by anaerobic bacterial respiration. Research in America has shown that there is a direct relationship between the concentration of sulphide and the height of *Spartina alterniflora* shoots. This is because hydrogen sulphide is a respiratory inhibitor and interferes with nutrient uptake in plants (Howes et al., 1981). The chemical conditions in *Spartina anglica* saltmarshes are particularly intense due to the large store of organic matter in the sediment. *Spartina* is highly productive and the biomass of the roots is about 8 times that of the shoots. The dead roots thus provide an abundance of food for bacteria. If the sediments are not flushed with seawater sufficiently, the oxygen is quickly stripped from the sediment and bacteria resort to anaerobic respiration which produces chemicals toxic to plants. Hence an explanation of *Spartina* die-back in areas which are not experiencing an increase in incident wave energy, is that as the sward matures, the chemical conditions in the pore water become less favourable for plant growth.

If die-back is due to deteriorating chemical conditions caused by falling redox potentials as the sward ages and there is a build up of organic matter, it is likely that in time, all the stands of *Spartina anglica* and *Spartina townsendii* in England and Wales will die-back. Hence, the stands in the north of the country that are not yet showing signs of die-back, probably because they were colonised later than those in the south, are likely to lose vigour as they mature. It should be emphasised that as the plants reduce in size, the protection the salting provides to the seawall decreases. We therefore recommend that strategic planning takes account of this likely future decrease in natural sea defence value. We also suggest that EA commission research into determining whether die-back is due to high concentrations of toxins in the porewater, and if so whether this can be ameliorated by improving drainage.

5.2.2 Available calcium concentration and erodibility

There are current lines of research into how the chemical make-up of saltmarsh sediment relates to its erodibility. Whilst this is not a primary factor that explains why some marshes are accreting and others eroding, the chemical make-up of saltmarsh sediments affects its erodibility. Recent research at the University of Reading has shown that variations in the moisture content, shear strength and other bulk geotechnical properties of saltmarsh sediments are strongly dependent on a number of sedimentological factors, including the particle size distribution and the calcium carbonate content (Pye and Crooks, 1996). The calcium carbonate content plays a major role in governing the cation exchange properties of the clays and on the development of a dispersed sediment structure which in turn, is related to low erosion resistance. Many of the saltmarsh sediments in sheltered estuary settings in Essex have very low carbonate contents, high moisture contents and very low shear strengths compared with marsh sediments in other locations such as the Severn estuary (Pye and Crooks, 1996). It has been recognised that the wetter the sediment the lower the current or wave action needed to erode it. Back in 1938, work was conducted to see how moisture content affected the erodibility of Mersey muds. Mud samples were divided into sub-samples and dried to produce a range of moisture contents. These samples were put into an apparatus which could measure the amount of substance eroded at a given water flow. The results showed that resistance to erosion increased as the moisture content decreased. Some of the curves illustrating the relationship between water content and erodibility are given in Figure 5.12 (Department of Scientific and Industrial Research, 1938).

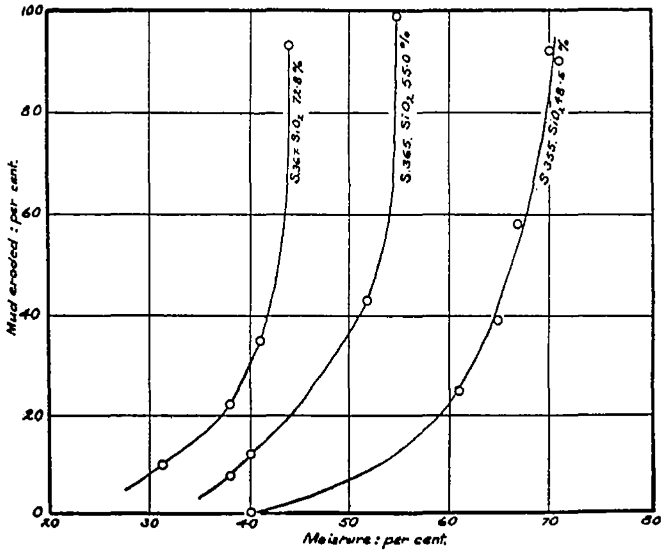


Figure 5.12 **Relationship between erodibility and water content of 3 samples of Mersey Mud (Department of Scientific and Industrial Research, 1938)**

The 1938 study also determined the moisture content and composition of saltmarsh and intertidal sediments from a number of British estuaries (these tables have been reproduced in Appendix D). *It is interesting to note that the Essex saltmarshes, have the highest moisture contents, whilst those in areas in which saltmarshes are stable or currently expanding, generally have a lower moisture content.* Thus there is circumstantial evidence that moisture content does affect the degree of erosion resulting from a given tensile stress.

The ratio of calcium to sodium ions in the sediment affects erodibility by controlling the thickness of the water layer that surrounds the silt/clay particles. This in turn changes the strength of the force that attracts the particles together (the further apart they are forced by the water layer the lower the force of attraction). Around each sediment particle are ion attachment sites, these can be filled with either Ca^{2+} or Na^{+} ions. If Ca^{2+} ions occupy the sites, the thickness of bound water is about 10nm. This compares to 30nm if Na^{+} occupies the sites. Thus, all other things being equal (such as particle size), calcium rich sediments resist erosive forces better than calcium deficient sediments.

Pye and Crooks (1996) compared the chemical composition of sediment samples taken from the Severn Estuary and several sites in Essex. They concluded that the concentration of exchangeable calcium (the concentration of dissolved calcium in the porewater) was much lower in the Essex saltmarshes. Hence it is likely that given the same shear stress, erosion will be more severe on Essex saltmarshes than it would be on those in the Severn Estuary. This work on how sediment chemistry affects erodibility has repercussions on the erodability of reclaimed soils, which are re-opened to tidal inundation through managed retreat schemes. The erodibility of the managed retreat site could differ from adjacent natural saltmarsh if land-use and leaching had altered the calcium concentration. Future work is proposed to test whether low calcium concentration can be ameliorated and if so, to what extent this increases the tensile strength of the sediment.

5.2.3 Sediment supply

Various authors and organisations have speculated that a possible factor in the decline of saltmarshes is a decrease in the amount of sediment available to estuary systems. Wave action on the open coast causes both erosion of cliffs and the nearshore seabed, and the estuaries will hence be supplied with turbid, sediment-laden water during the flood tide. Within the estuary, where wave action is less intense, it could be expected that some of this sediment would settle out of suspension, hence adding to the stock of material within it. English Nature have expressed reservations about the impact of cliff protection schemes, especially in eastern England, which reduce the inputs of fine-grained sediment (for an explicit assessment of the problem see Pye and French (1992). An additional effect is the reduced sediment load from rivers, which over recent decades have been more strictly controlled to prevent flooding. In this context, however, many "estuaries" have only very small river flows (eg the Blackwater & Crouch) and it is difficult to believe that the input of riverine sediment was ever significant.

At a broad scale, there is a clear association between the availability of sediment and the extent of saltmarsh development within an estuary or embayment. For example, the relatively deep, sediment starved rias in southwest England and Wales, and the majority of lochs in Scotland, contain only very limited areas of saltmarsh, mainly near the estuary heads where small rivers and streams provide a source of sediment. At the other extreme, embayments such as the Wash, which has acted as a sink for reworked glacial and fluvio-glacial sediment throughout most of the Flandrian period, are characterized by very extensive saltmarshes.

On a more local level, Ranwell (1974) documented the seaward growth of saltmarsh and tidal *Salix / Alnus* woodland in the upper part of the Fal estuary between 1878 and 1973, caused mainly by enhanced sediment supply from china clay workings (see Figure 5.12). The river Fal drains a long, narrow catchment within which are extensive china clay workings and spoil tips which were responsible for high suspended loads in the river (up. to 31,000 p.p.m.). As a result of heavy sedimentation near the head of the estuary, zones of *Puccinellia / Agrostis* marsh, *Festuca-Scirpus* marsh and *Alnus/Salix* woodland extended progressively down estuary as the scale of china clay working increased in the 19th century. Marsh extended seaward by approximately 800m between 1878 and 1973, while valley woodland invaded the landward limit of the marsh at approximately the same rate.

An attempt was made in this study to determine whether the quantity of suspended sediment had changed in the vicinity of saltmarshes, and whether there were regional differences. Records of suspended sediment concentration were requested from each of the EA water quality departments which have water sampling stations in the vicinity of the tabulated saltmarshes. The names and map reference of each of the saltmarshes in which we were interested were passed onto the relevant personnel. Although the response was good, in that all the EA offices contacted provided us with weights of suspended sediment in collected water samples. We were not able to use these data sets to determine whether there had been changes in suspended sediment, or compare the amount of suspended sediment in different areas. This was because the samples were collected for the measurement of water quality parameters and hence the sampling regime was not designed to provide comparable suspended sediment samples (e.g. same part of the tidal cycle, same position in neap-spring cycle). Due to the manner in which the samples were collected, the suspended solid concentrations are so variable that trends over time, or between areas, are not discernible.

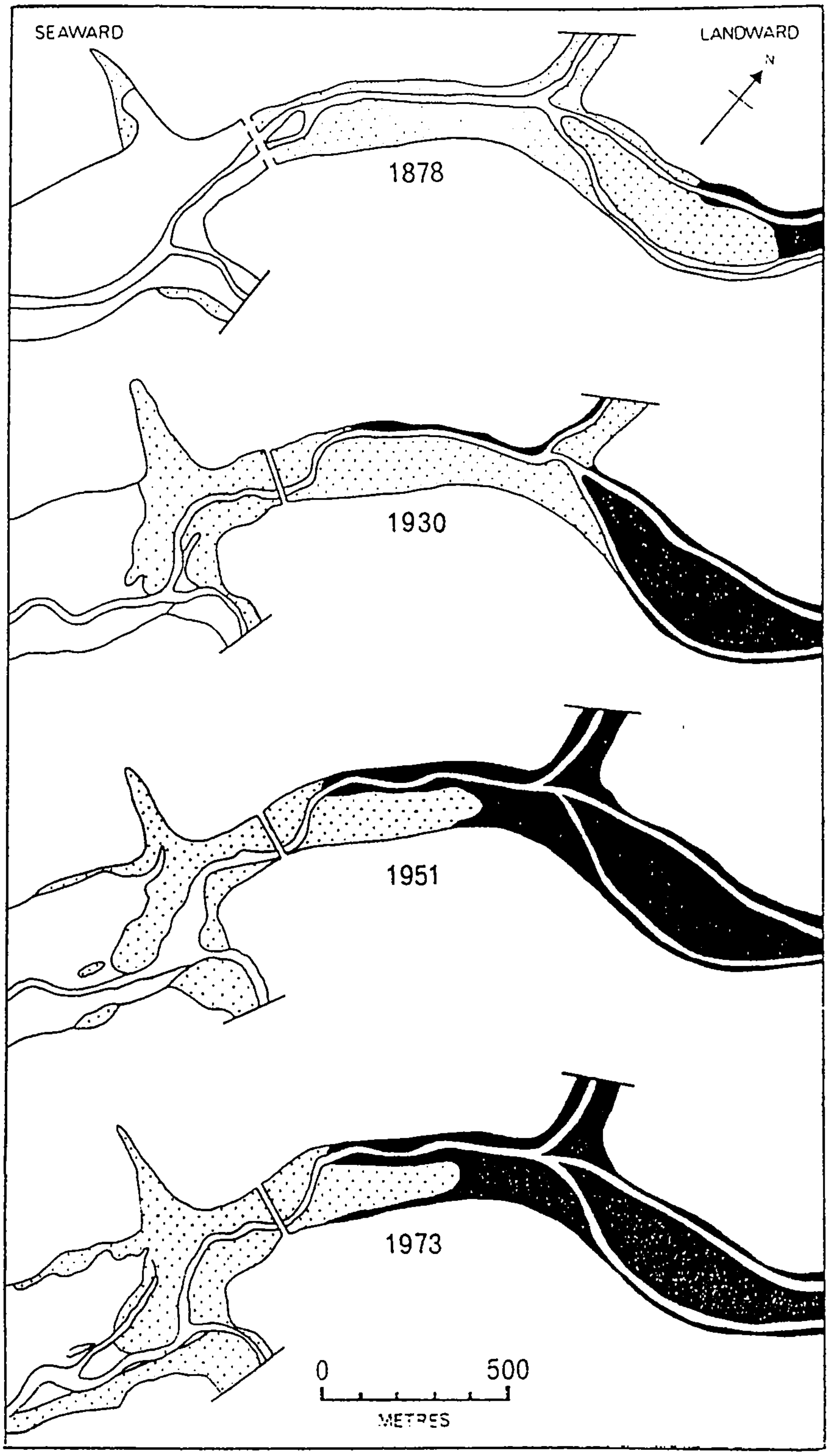


Figure 5.13 **Historical changes in saltmarsh (stippled) and tidal woodland (black) over the period 1878-1973, Fal estuary, Cornwall (after Ranwell, 1974)**

6 MANAGEMENT OF SALTMARSH LOSS

6.1 Identification of the likely forcing factor(s) causing change

Attempts to control saltmarsh deterioration or erosion will only be successful if the cause is established. This section provides a guide to the information required to differentiate between the potential causes of the various types of change.

- Erosion of the seaward edge of the saltmarsh

This may be due to increase in incident wave energy an increase in tidal currents or foreshore lowering due to channel migration. Evidence of wave attack, such as stressed vegetation on the saltmarsh nearest the front edge (see Figure 4.3), or site observations of wave activity, will indicate that the erosion is due to waves rather than an increase in tidal currents. Analysis of changes in estuary bathymetry will indicate if the erosion is due to a shift in channel position or dredging. Analysis of water level records will determine changes in tidal range (this would change the speed of tidal currents). If water level records or not available but records of edge recession are, the rate of loss could be correlated with the position in the 18.6 year tidal cycle (see sections 4.2.4 and 4.3.5).

- Erosion of saltmarsh adjacent to navigation channels

This may be due to ship induced waves and currents, or increase in tidal volume due to dredging. To determine whether ship activity could cause erosion, hydraulic field surveys of waves and currents produced by ship movements could be used to calculate the resulting shear stress. This could be compared to measurements of shear strength of the sediment to deduce whether erosion could occur.

- Change in plant species composition from 'upper' to 'lower' saltmarsh species

Change in species composition, for example if *Halimione atriplex* (sea purslane) or *Sueda vera* (shrubby sea blite) were replaced by *Aster tripolium* (sea aster) or *Limonium vulgare* (sea lavender), indicate that the area has become more poorly drained. The most likely reason is insufficient sediment supply to those areas so that vertical accretion is not keeping pace with sea level rise. This may be compounded by a spatial variation in sedimentation rate so that areas close to the creeks are accreting at a higher rate than areas remote from creeks, leading to poor drainage into the creeks. To determine whether this is the case, the rate of sedimentation could be monitored at points across the saltmarsh and the rates compared to the change in high water level. A topographic survey will reveal the presence or absence of depressions which would cause poor drainage.

- *Spartina* dieback

Loss of vigour in *Spartina* plants may be induced by the natural build up of toxins produced by anaerobic respiration (see 5.2.1.1), oil pollution or wave attack. If the plants in areas remote from the seaward edge have lost vigour, and the plants on the creek banks appear more healthy, the problem is likely to be induced by reducing conditions in the sediment. If loss in vigour is limited to the seaward edge of the saltmarsh, than wave action is the most probable cause. A walkover survey should be sufficient to indicate whether oil pollution is likely to be causing the change.

6.2 Possible management to combat each of the forcing factors

Possible management techniques to combat changes in the various forcing factors that may be responsible for saltmarsh loss are summarised in Tables 6.1 - 6.4 below. Full details, including locations at which the type of scheme has been tested, practical methods, addresses of contractors, monitoring methods and assessment of success of the schemes, are presented in EA Research Note 473. Untested management techniques that should mitigate the adverse factors in theory are also provided.

Table 6.1 Management techniques in current use that would combat hydraulic forcing factors

Hydraulic Factor Causing Saltmarsh Change	Possible Management Techniques
Increase in wave energy	Offshore wave breaks; nearshore wave breaks, rock mounds have been successful but look unnatural, artificially constructed cheniers (see section 8.3)
Change in wave direction (which may affect beach levels by altering long-shore drift)	Groynes
Relative sea level rise	Sediment recharge (on to mudflats and directly onto the saltmarsh surface if vertical accretion is failing to keep pace with SLR); managed retreat
Channel Migration	Training walls (but this is probably prohibitly expensive); dredging; managed retreat

Table 6.2 Management techniques in current use that would combat natural, non-hydraulic causes of saltmarsh loss

Natural Factor Causing Saltmarsh Change	Possible Management Techniques
Insufficient sediment supply	Trickle recharge with silts close to the saltmarsh; introduction of coarser grain sizes to the foreshore.

Table 6.3 Management techniques in current use to combat human-induced forcing factors

Human Activity Causing Saltmarsh Change	Possible Management Techniques
Reclamation and construction	These activities should cease as its important to maximise the size of the buffer zone
Coastal Squeeze	Managed retreat should be considered for strategic coastal management
Grazing	The impact has not been quantified, but ceasing heavy grazing on a narrow strip of saltmarsh will probably increase the degree of coastal protection to the sea wall
Ship and boat movements	Control boat size (blockage ratio), speed, number, hull design, and mooring within saltmarshes
Dredging	Where possible, sediment should not be removed from the system; use to trickle feed eroding mudflats and saltmarshes
Pollution	Reduce nutrient and oil inputs by treating discharges
Trampling	Erect information signs for walkers of the importance of staying on the footpaths
Managed retreat	Results are promising, continue

Table 6.4 Untested management techniques that would combat factors causing saltmarsh deterioration in theory

Factor Causing Saltmarsh Change	Possible Management Technique
18.6 year tidal range cycle	Temporary wave breaks to counteract the increase in wave height around the maxima of the cycle
Undesirable sediment chemistry, leading to plant stress	Increase drainage and flushing by increasing the frequency of the creek network by increasing creek density and/or regrading creek beds
High soil moisture content due to low calcium concentration (which makes the mud relatively more vulnerable to increases in tensile stress)	Possible artificially introduce calcium, either using a saturated calcium solution, or top feeding with calcium carbonate

Note that it is not wise to embark on management to maintain or enhance saltmarshes without first considering the consequences of interference on estuarine processes. An integrated approach to coastal management is required to ensure that the works will not exascerbate erosion elsewhere in the coastal cell.

7 SALTMARSHES AND SEA DEFENCES

7.1 Saltmarsh loss and seawall breaching

Failure of seawalls can occur as a result of an number of mechanisms which may act in combination:

(1) undermining of the toe of the embankment, causing rotational slumping and possible catastrophic failure of the bank (*this mechanism is exacerbated by saltmarsh loss)*

(2) lateral wave erosion of the seaward side of the embankment, usually over more than one tide (*this mechanism is exacerbated by saltmarsh loss*)

(3) erosion of the crest and landward side of the embankment by overtopping discharge, which results in gullying and can cause catastrophic failure under extreme conditions (*this mechanism is exacerbated by saltmarsh loss)*

(4) water flow through the embankment (piping). Preferential flow pathways caused by animal burrows or a sandy layer of greater permeability for example, can lead to seawall failure (*this mechanism may be exacerbated by saltmarsh loss)*

On more exposed sections of shore within an estuary, and particularly on the open coast, which experience higher levels of wave activity, the risks of a sea bank failure increase the narrower and lower are the fronting saltings. A high, wide zone of saltmarsh acts as an effective baffle against both wave and tidal energy. Overtopping discharge is inversely related to saltings width (Brampton, 1992), but the water depth over the saltings (i.e. marsh height) is also important as a control on the height of waves reaching the seabank.

Failure is most likely to occur at a point where the saltmarsh is narrowest or lowest (e.g. where a large creek crosses the marsh, or where there is an embayment in the marsh edge). Direct wave erosion of the seaward side of an embankment may occur if the marsh is eroded altogether and the foreshore level drops below a critical level. An example is provided by Wallasea Ness at the confluence of the Crouch and Roach estuaries. Here, combined tidal current and wave erosion of the fronting saltings ultimately required the line of flood defence to be set back by about 50m.

Where a width of at least 10 m of fronting saltmarsh remains, embankment failure is more likely to be due to scouring of the landward side of the embankment as overtopping discharge runs down the landward slope. The presence of a dense sward of vegetation on the embankment helps to reduce erosion but cannot prevent it under conditions of high overtopping discharge. There were many examples of this problem affecting the embankments along the Dengie Peninsula during the 1953 and 1978 storm surges. The severity of bank damage was greatest in areas where the saltings were narrowest, for example near Deal Hall (Figure 3.12).

Catastrophic failure of seabanks in relatively sheltered locations often takes place following a relatively rapid deepening or migration of an adjacent channel or marsh tidal creeks. This is favoured by net saltmarsh edge erosion which leads to a progressive steepening of drainage channels, in turn causing bank instability. This is a particularly serious problem in macrotidal environments where creeks draining a marsh may be several metres deep. An active example of this process is provided at Aylburton Warth and Cone Pill in the Severn estuary (Figure 5.29). Rotational failures and other mass movements are common along the banks of the pills in the Severn estuary (Allen, 1985), particularly after extreme high tides or sustained periods of high land drainage.

Another common cause of localised seabank failure, although not usually catastrophic, is headward erosion of saltmarsh tidal creeks which run parallel with the sea wall. An example is provided at Mill Point in the Blackwater estuary (Pethick, 1992), where headward creek extension and widening progressively removed the marsh immediately adjacent to an earthbank, requiring it to be protected and raised using sheet steel piling. Creek extension of this type can occur anywhere within an estuarine system but is most likely where the tidal creek system is out of equilibrium with hydraulic conditions, often as a result of embanking and beheading of major tidal creeks.

Extreme high tides, without major wave activity, may overtop embankments. However, the formation of a major breach during a single surge tide is rare. It is most likely to take place where the wall has been weakened, for example by previous wave erosion or by burrowing animals. Slight depressions in the crest level of the wall will favour a concentration of flow on both the flood and ebb tides, leading to localised erosion. Depressions in the crest level of a wall may be caused by subsidence, compaction by vehicles or livestock. The rate of breach widening will depend heavily on the discharge through the incipient breach and the erosion resistance (shear strength) of the embankment material. Numerous small breaches of this type were created in the inner estuaries of Essex and North Kent during the 1897 and 1953 storm surges. Those which were left unrepaired were subsequently further enlarged by later high tides. An example is provided by the breach near the site of the present North Fambridge marina in the Crouch estuary which was initially during the storm surge of November 1897 (Figure 3.10).

The condition of the seabanks is also a critical factor which determines whether an actual breach takes place. Historical studies (e.g. Gramolt, 1960) have clearly shown that embanking, reclamation and maintenance of sea walls has varied cyclically in recent centuries in response to socio-economic factors which have caused large fluctuations in the value of agricultural production from estuarine land. The damaging storm tides of 1897 and 1901 were preceded by a period of several decades in which economic conditions led to widespread neglect of seawall maintenance. By contrast, during the early 19th century economic conditions favoured the undertaking of new reclamation schemes in many parts of southeast England and sea walls were generally well maintained. More recently, following the extreme floods of 1953, extensive improvements were made to sea defences in many parts of eastern and southern England, but in the past decade a further downturn in the value of agricultural land to National economics has led to curtailment of seawall maintenance and improvement in less critical areas.

Historical evidence also points to a long history of cyclic accretion / reclamation and erosion / setback in some areas (e.g. Allen, 1990a), reflecting natural variations in environmental forcing factors, such as channel migration. In places, longer term trends are apparent, reflecting estuarine dynamics on the scale of centuries to millennia. For example, at Arlingham in the

Severn estuary, there has been progressive accretion and reclamation on the head of a large meander loop since medieval times, but predominant erosion since 1725 has affected both sides of the meander neck. Here, and at many other locations in the Severn, there have been periodic requirements to reposition the sea defences. This points to the need to have an understanding of the geomorphological context within which erosion/ accretion changes and sea wall failures are taking place.

7.2 Information required to assess risk of breach

Seawall failure is caused by one, or a combination, of waves, currents and the pressure exerted by high water levels. For each factor, the locations at greatest risk from breaching, differs. Methods to identify the sites of potential breaching are given below:

- Waves

Wave attack can lead to seawall failure through damage to the seaward or landward faces, or by undermining. The wave energy incident on a length of seawall is not uniform. Locations most at risk are those in the most exposed areas. To identify these, the plan shape of the coastline should be studied. Potential breach areas are those in which wave action is concentrated at a particular site, such as a convex corner of a seawall, or where the saltmarsh strip is narrowest, or badly dissected.

- Currents

High water velocities due to tidal currents can cause undermining of the seawall. The most important cause of this is channel migration within estuaries. The change in channel position can be charted from a time series of bathymetry maps or air photographs. This could then be used to predict the areas most at risk from erosion.

- High water levels

High water levels due to surge tides exert pressure on seawalls. Unlike wave attack, saltmarshes provide only limited protection against this cause of breaching. Width of saltmarsh does not necessarily indicate vulnerable areas. What is important is the depth of water (which is dependent on the elevation of the foreshore, saltmarsh and predicted water level) and the strength of the seawall. Locations with geotechnical weaknesses, either within the wall itself, or in its foundations, are most at risk. Walk-over surveys, could identify wall condition, and hence those areas of greatest risk.

There is evidence that a number of past breaches through to land which was reclaimed saltmarsh, coincided with the position of relict creeks. It is thought that the seawall foundations at these positions were relatively weaker and that energy is concentrated as this spot as it propagates up the channel which still exists on the mudflats. To identify these areas aerial photographs could be examined to locate the positions where major relict creeks intersect with the sea embankment.

A list of information required to assess the risk of a future breach in a particular area has been compiled. It takes into account all three forcing factors:

- Short term
  - (a) Predictions of likely water depth at the seawall under surge conditions
  - (b) Likely maximum wave height for various water depths (dependent on fetch and maximum hourly wind speed)
  - (c) Marsh height and width
  - (d) Creek density
  - (e) Characteristics of saltmarsh vegetation (height, shoot density)
  - (f) The condition of the wall (height, width, shear strength, internal integrity, vegetation cover and uniformity)

- Longer term
  - (g) Rate of lateral movement of the marsh edge fronting the wall
  - (h) Rate of vertical marsh accretion compared with rate of sea level rise and rate of increase in extreme high water levels
  - (i) Magnitude and timescale of historical shoreline fluctuations (in particular pattern of channel migration)

7.3 Evaluation of past breaches

The effect of breaching on the hinterland

As noted in section 3, there have been numerous sea wall breaches during storm surge events in the past century which have led to abandonment of former agricultural land and the reactivation of saltmarshes and mudflats. How successfully a new saltmarsh develops is partly a function of the elevation of the re-flooded surface with respect to the tidal frame (IECS, 1994). Following embanking and drainage there is normally a lowering of the height of the reclaimed marsh due to dewatering, chemical changes and consolidation. The height difference between the reclaimed marsh surface and that of the active marsh outside the seawall will be enhanced over time due to sea level rise (Figure 4.23). 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 until a sufficient thickness of mudflat sediment has accumulated. In abandonment situations, the drainage network which initially develops may be hydrodynamically unstable and the system will gradually re-adjust. During this process the marsh surface may experience rapid incision and lateral erosion, in some instances leading to the removal of a high proportion of the newly accreted sediment (Pye, 1996b). There are many examples of this process, in varying degrees of development, in Suffolk, Essex, Kent, Hampshire and the Isle of Wight.

Figures 7.1 and 7.2 show 'unmanaged retreat sites at Northey Island, Essex (breached in 1897); and Sowley, Hampshire (breached in 1972). The original drainage ditches, and the linear depressions caused by plough lines, have become drainage channels. At Sowley the creek to vegetation ratio was 1:1 this is much smaller than on a healthy natural saltmarsh. This emphasises the importance of artificially re-establishing a creek network before allowing seawater inundation in managed retreat schemes, as existing drainage channels are likely to be permanent features of the managed retreat site, and reduce the sea defence value of the saltmarsh which develops.

The effect of breaching on the estuary

If accomplished on a large sale, set-back may significantly influence the tidal regime of an estuary. In an estuary which is already ebb dominated, an increase in the tidally flooded area in the inner estuary is likely to enhance the tendency for ebb dominance, whereas widening of the estuary cross section near its entrance through set back may be expected to have the opposite effect (Pethick, 1993, 1995). An increase in the tidal storage capacity of the inner estuary should, over time, result in an enlargement of the main estuarine feeder channel and may threaten marshes in the outer estuary (Pethick, 1995). However, the scale of historical seawall failures in Essex and Kent has been too small to identify any such a effect with certainty. The Crouch estuary has one of the largest areas of reactivated abandonment marsh, relative to its mouth cross-sectional area, of any British estuary, large reactivated marshes being found at North and South Fambridge and Bridgemarsh Island (Figures 3.10 and 3.11). The fringing marshes fronting the seabanks along the outer estuary have experienced lateral erosion in recent decades, but it is not possible to separate the effects of increased tidal prism in the inner estuary due to abandonment and set back from those due to sea level rise, channel migration and increases in wind/wave activity. The Colne estuary has larger areas of reactivated saltmarsh than the Crouch, but the saltmarsh is stable. Thus for the Colne at least, the increase in tidal volume due to reactivating saltmarsh did not lead to erosion of existing saltmarsh.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Causes of saltmarsh change in England and Wales - past and present

Several factors have contributed to saltmarsh change over the last few centuries. Their relative importance varies both in spatial and temporal terms. In northwest England, many estuaries existed in a state of dynamic equilibrium until the 19th century when engineering works, including training wall construction, dredging, embanking and reclamation, altered their regimes. The general effect was to enhance intertidal accretion and encourage the expansion of saltmarsh. This trend was enhanced from the 1950's onwards by the arrival and artificial planting of *Spartina*. The estuaries responded in this way primarily because a large supply of sediment was available in adjacent offshore areas which could be moved landward into the estuaries, and because rates of relative sea level rise were low. The Welsh estuaries have mostly responded in a similar way, although engineering works and reclamation have been undertaken on less extensive scale. The majority of areas have experienced net accretion or stability in recent decades, although there has been some localised erosion due to channel migration and an increase in the frequency of westerly and southwesterly storm waves in the past 20 years. Sea level rise and changes in tidal regime appear to be of relatively minor importance in this region.

In the Severn estuary, large scale embanking and reclamation in the Roman and Medieval Periods probably contributed to enhanced long-term accretion in the inner estuary, reinforcing the effect of rising sea level which has been to drive alluvial sedimentary environments back up the Severn Vale. Channel migration and fluctuations in wind /wave climate have also had a significant influence on marsh edge morphodynamics, as did the arrival of *Spartina* after 1920.

The harbours of southern England appear to have existed in a state of dynamic equilibrium, with relatively small areas of fringing saltmarsh, until the arrival of *Spartina* at the end of the last century. *Spartina* colonisation led to a rapid increase in saltmarsh area which entrapped large quantities of silt. In the past three to four decades, there has been a reduction in *Spartina* vigour and areal coverage. This is due to a combination of sediment starvation, changes in sediment chemistry and an increase in wave energy. This trend has made the saltmarshes more susceptible to the increase in erosive forces. The recent slight increase in wind/wave activity (see 4.31; Table 4.4) and increased frequency of extreme high water levels have led to localised channel deepening and both vertical and lateral erosion of saltmarshes in Portsmouth, Langstone and Chichester Harbours. Although short term tide gauge records for Portsmouth suggest a recent acceleration in mean sea level rise, there is no substantive evidence that this factor is primarily responsible for the observed saltmarsh erosion trend. Rather, the harbours and estuaries appear to be returning to a condition more in keeping with the regime which existed before the arrival of *Spartina*. However, increases in tidal levels and ebb tidal current velocities will act to enhance this trend as have the anthropogenic impacts such as dredging and ship movements in Lymington harbour (which increases the tidal volume, removes sediment and causes draw-down currents and ship waves, respectively) and oil pollution in Southampton Water in the 1960's.

In southeast England, extensive reclamation from the Medieval Period onwards, together with the effects of dredging in the Thames and Medway, produced major changes in estuarine morphology and hydraulic regime which were fundamentally different to those which followed similar activities in northwest England and the Wash. The main reason appears to be that insufficient sandy sediment was available in the adjacent offshore areas, and the balance of hydraulic forces was not conducive, to move large quantities of sediment into the estuaries in order to achieve a new equilibrium between estuary morphology and hydraulic forcing factors. The problem has probably been exacerbated by a rising sea level trend. On a shorter timescale, an increase in storminess since the 1970's has contributed to an acceleration in rates of marsh edge recession and internal dissection due to steepening of tidal creek gradients. This lowering of the intertidal zone has a positive feedback on near-shore wave heights, as potential wave height increases with water depth. Although attempts have been made to introduce *Spartina* and *Zostera* as an counter-erosion measure in several areas, they have been relatively unsuccessful owing to the unfavourable sediment budget and wave climate.

In North Norfolk, the Wash and north Lincolnshire, intertidal accretion is a natural process which may have been enhanced by human activities such as embanking and reclamation. Most of the marshes are now stable or slowly accreting, although there has been edge erosion in some places due to increased storminess since the mid 1980's. The Humber estuary is probably also continuing to experience net sediment accretion, although episodes of saltmarsh erosion and accretion along its shores continue to reflect patterns of natural channel migration. To date, dredging and other engineering works have had a relatively small effect on this large estuary compared with others.

Sediment type and availability affect the impact that intensifying erosive forces have on saltmarshes. Although the offshore wave heights and the size of the increasing trend in recent years off North Norfolk (see Figure 4.9) are comparable to those off Essex, the wave heights incident on the saltmarshes in these two areas are very different. The extensive gradually sloping sand flats fronting the North Norfolk saltmarshes can buffer the increase to a much greater extent than the steeper more muddy profiles of Essex. Only the most exposed parts of North Norfolk coast such as Stiffkey and Moreston have suffered erosion after the last 15 years. The prime reason for the greater sediment availability in northern and central England compared with southern and southeast England is the widespread occurrence of glacial and fluvio-glacial sediments in the former areas, both in coastal locations and offshore. Extensive coastal protection works in southern and southeast England during the past century have served further to reduce the sediment supply to coastal waters.

8.2 Summary of the review of the relative importance of the potential forcing factors in causing saltmarsh change

Accretion/erosion of saltmarshes is controlled by a number of factors (see section 1.2). This study has highlighted that saltmarsh loss in England and Wales cannot be attributed to a single cause. Many factors have an effect and they are intrinsically linked. For example factors that result in loss in plant vigour, render the saltmarsh more susceptable to increases wave energy and relative sea level rise. The combination of causes varies between sites. For example, the rapid erosion in Essex appears to be due to an increase in wave energy and comparatively low sediment supply (see 8.1). The magnitude of erosion resulting from a given increase in shear stress is likely to be greater than in saltmarshes of the Severn Estuary or North of England, due to the relatively high soil moisture content (see 5.2.2). In contrast, the principlal cause of saltmarsh loss on the southern bank of the Humber, at Aylburton Warth in the Severn Estuary, and at Ince Bank in The Mersey, is migration of the low water channels (see 4.3.6)

Tables 8.1 - 8.3 summarise the factors that cause saltmarsh change in England and Wales. The relative importance of each factor is stated, and conclusions drawn from the study presented.

Table 8.1 Summary of the potential hydraulic causes of saltmarsh change and their relative importance

Factor	See Sections	Relative Importance	Type of Saltmarsh Change	Conclusions
Increase in wave height	4.1, 4.2.1, 4.2.2, 4.3.1	Increasing wave energy is the major cause of saltmarsh edge erosion in open coastal areas and embayments, where channel migration is less of a significant problem.	Increase in wave energy causes: - lowering of mudflat - erosion of seaward edge - stressing of vegetation - may increase vertical accretion rates on saltmarsh due to resuspension of mud on intertidal flats - occasionally may decrease elevation of the seaward edge of the saltmarsh due to scour or turf stripping	- Countrywide increase in the height of the waves exceeded 1% of the time in the last 20 years, whilst trends in mean wave height are variable - Seemingly large and comparable increase in the wave heights off the Essex and N.Norfolk coast (from modelled wave records between 1977 and 1987). Saltmarsh response differs. - Impact of offshore wave heights on change in wave heights incident on the saltmarsh depends on substrate type and sediment abundance. If sand, gravel or shell are available, the impact is lessened as cheniers (which form natural wave breaks) are thrown up. - Trend in mean wave height seems to be more important in influencing the trend in lateral saltmarsh accretion/erosion than the trend in the less frequent higher intensity events (H_s 1%, H_s 10%). - Change in significant wave height can vary markedly at points even in the same harbour. Walkover surveys to assess the state of the saltmarsh indicated that the predicted change in wave height correlated well with the observed degree of erosion. - Seaward expansion of *Spartina* seems to be limited to areas which are experiencing a decreasing trend in wave height.

Table 8.1 (continued)

Factor	See sections	Relative importance	Type of saltmarsh change	Conclusions
Storms and storm frequency	4.2.6, 4.3.2	Infrequent, extreme events on muddy coastlines are a lesser control on longterm horizontal recession than the more frequent moderate events. Increase in the frequency of moderate storms so that recovery between events is not possible can cause rapid erosion	Increase in storminess causes: - lowering of mudflats - erosion of seaward edge of saltmarsh - change in the pattern of accretion and erosion if sand banks, spits or cheniers are created or destroyed.	- There are very few examples of catastrophic change in *existing* saltmarsh from individual storms. - Individual storms usually have only a limited impact on longer term marsh development. This is because extreme wave activity is concentrated on the marsh edge for only a few hours and because most saltmarsh sediments have greater erosion resistance than sand beaches and sand dunes. -However, a single storm may have a major influence on accretion/erosion if the sediment type on the foreshore is non-cohesive, and spits, sand banks etc. are created or destroyed. Likewise if breaches in seawalls occur, old saltmarsh, may be reactivated. - Change in the frequency of moderate storms can have a pronounced effect on saltmarshes - Saltmarsh erosion can take place very quickly if moderate storm events occur at frequent intervals, e.g. rapid erosion of Foulness Point between 1989 and 1992. - Analysis of modelled nearshore wave records from Clacton (a site chosen to represent storm frequency changes in Essex), at MHWS between 1976 and 1989, indicated that: - wave height and storm duration did fluctuate but there was no obvious trend - The period 1976-1980 was relatively stormy

Table 8.1 (continued)

Factor	**See Sections**	**Relative importance**	**Type of saltmarsh changes**	**Conclusions**
Wind speed and direction	4.2.1, 4.2.2, 4.3.3	<u>Increase in wind speed</u> induces the same types of saltmarsh changes as listed for increase in wave height, earlier in the table. <u>Change in wind direction</u> is more important in embayments and estuaries with narrow entrances, where waves are internally generated, than in open coastal sites. In sheltered sites wind direction affects fetch and hence wave heights.	<u>Wind speed</u> see entry under 'wave height and storminess'. <u>Wind direction</u> changes fetch which affects wave height in areas which are fetch limited. Wave height affects the intertidal profile. Change in wind direction also affects the longshore movement of material and hence foreshore levels.	Analysis of Meteorological Office wind records showed a spatial as well as temporal variation in the pattern of change during the last century: <u>1915-1955</u> there was a marked decline in annual duration of winds >22knots on the west coast of England and Wales, but no obvious trend at east coast sites during this period. <u>1955-1965</u> both west and east coast stations in central and southeast England showed a steep increase in the frequency of strong winds. <u>1965-1992</u> at most sites in north west England there was little net change in annual wind speed or duration of winds above 22 knots. - the west coast and southern Cornwall experienced a general increase in mean wind speed and duration of >22 knots - south east England has an incomplete data set, but there was a suggestion of a trend toward higher incidence of strong winds after 1955 to at least 1986. This corresponds well with the acceleration of saltmarsh loss. Analysis of modelled nearshore wave records at Clacton to determine the annual duration of storm waves from the southeast showed no trend over the period 1975-1989 but there was marked variability between years. 1976-1979 had twice the duration of southeasterly storms. This may have increased erosion rates in many Essex saltmarshes.

Table 8.1 (continued)

Factor	See sections	Relative Importance	Type of saltmarsh change	Conclusion
Relative sea level change	1.2.2, 4.2.3, 4.3.4	- Changes will only occur if sediment supply is limited and accretion cannot keep pace with sea level rise. - Not the dominant factor in causing present saltmarsh loss in Essex Important factor in shaping long term changes in saltmarsh position.	Relative increase in sea level rise may induce: - increase in rate of vertical accretion on the saltmarsh -Lateral shift either landward of seaward (but this is small, the example calculation in section 5.1.1.2 estimates a migration rate of 1m per decade as the upper limit) - a change in vegetation community - slight increase in potential wave height	- The precise long term effect of rising sea level depends largely on the relative balance between the rate of sea level rise, sediment supply and coastal topography. Major changes in sea level which change the position of the coastline do have a great effect on the location and extent of saltmarshes -Saltmarsh sediment cores from North Norfolk show a continuous presence of saltmarsh despite rising sea levels over at least the last 6,000 years. Hence saltmarshes can vertically keep pace with sea level rise. However the saltmarsh will still creep landward. - The present rates of mean sea level rise in England and Wales are well within the capacity of saltmarshes to grow vertically. Rates of vertical accretion in the range of 2-7mm/yr have been widely recorded on British marshes, including those on the open coast of Essex. However, the landward end of the saltmarsh (and areas remote from creeks), may suffer more from relative sea level rise, due to sediment starvation in parts of the marsh furthest from sediment entry. This results in poor drainage which may change plant species composition. - If accretion in the lower intertidal zone does not keep pace with sea level rise, edge erosion of the saltmarsh could be exacerbated. - Mean sea level rise appears not to have been the dominant forcing factor over the last 150 years, as the rate and timing of episodes of saltmarsh erosion has varied in different parts of SE England during this period.

Table 8.1 (continued)

Factor	See Sections	Relative Importance	Type of Saltmarsh Change	Conclusions
Tidal range	1.2.2, 2.4.2, 4.3.5, 4.2.4	The 18.6 year tidal range cycle does not appear to be a major control on saltmarsh change. However, it may be a contributing factor if a relatively stormy period coincides with the period of maximum tidal range.	Potential for vertical and lateral erosion is increased at the maximum of the cycle. Rate of internal dissection is likely to be greater at the maximum of the cycle compared to minimum Vertical sedimentation rates may be enhanced during periods of maximum tidal range due to more frequent overmarsh tides, greater overmarsh tidal prism and greater duration of tidal inundation	- Depth of water above the saltmarsh surface are the greatest at the maximum of the cycle. Hence, potential wave height on the saltmarsh surface is significantly greater. - Greater volume of water flooding the saltmarsh surface, at the maximum of the 18.6 year cycle will lead to increased drainage into the creeks, and hence higher velocities which may increase rates of internal dissection. - Numerical modelling conducted during this study, suggests that the velocity of tidal currents *are* affected by the 18.6 year tidal range cycle, but the change is slight. - Based on limited time series monitoring data of saltmarshes, the fluctuation in tidal range does not seem to be a major factor causing change, but it may contribute.
Change in channel position	1.2.3, 4.2.7, 4.3.6	A major cause of change in saltmarsh extent in estuaries	Saltmarsh edge erosion on the side of the estuary the channel is shifting towards, and enhanced accretion and saltmarsh development on the opposite bank.	- Saltmarsh loss and creation due to channel migration is a natural process. - Training walls that have stabilised channels have resulted in artificial saltmarsh extent.

Table 8.2 Summary of the potential anthropogenic causes of saltmarsh change and their relative importance

Factor	See Section	Relative Importance	Type of Saltmarsh Change	Conclusion
Enclosure (land reclamation)	5.1.1.1	- Most important influence on saltmarsh area since Saxon times - Greater impact than climatic induced fluctuations	-Loss of landward end of saltmarsh - May be encouraging saltmarsh advance by enhancing sedimentation	- For the saltmarshes for which quantitative data exist, the reclaimed area is 16.5 times larger than the area of the existing saltmarsh. - Enclosure has reduced the size of the intertidal zone and hence the buffering capacity to respond to climatic fluctuations. - These artificial changes in estuarine morphology have probably had a significant effect on the progression of the tidal wave and hence tidal levels and tidal currents. - Further reclamation is not recommended.
Coastal squeeze due to seawall construction and sea level rise	5.1.1.2	- Not a major control on the lateral extent of saltmarshes in the short term, but is a longer term (several decades) concern. - Cannot explain the current rate of loss in Essex.	- Saltmarsh migration in response to relative sea level rise is prevented, resulting in narrowing of the saltmarsh - Rate of migration depends on the rate of sea level rise and vertical sedimentation rate	- Potentially a large scale problem, out of 44 saltmarsh sites in England and Wales, 36 were backed by sea defences and 3 by natural relief. Only 14% graded gradually into terrestrial vegetation. - Short term effects of coastal squeeze are small. For example, in a worst case situation, a relative sea level rise of 4mm per annum on a saltmarsh of gradient 4% would result in migration of the landward margin of 1m in 10 years. - Even if saltmarshes in Essex were unconstrained with respect to landward movement, transgression would not compensate for the current rate of erosion of the seaward edge, i.e. the current rate of loss from the seaward edge is much greater than 1m in 10 years.

Table 8.2 (continued)

Factor	See Section	Relative Importance	Type of Saltmarsh Change	Conclusions
Construction on saltmarshes	5.1.1.3	Locally important, particularly in estuaries	Loss of habitat	Saltmarshes are still easy targets for developers as the public do not realise the true value of saltmarshes. To achieve this, a detailed economic appraisal of all saltmarsh functions and uses should be conducted.
Grazing	4.2.8, 5.1.1.4	Presently unassessed	Severe grazing may: - change the plant community -reduce vertical accretion rates and wave damping efficiency - trampling may increase the shear strength of the sediment but cause flattening of creek banks	Research into the impact of saltmarsh grazing has been almost entirely confined to its effect on ecology. There has never been a comprehensive study to assess the impact of grazing on saltmarsh morphology and wave and current energies.
Ship movements	5.1.1.5	An important cause of edge erosion at sites where narrow navigation channels are fringed by saltmarshes.	Channel widening and deepening due to erosion caused by increased currents and waves.	Research has proved that shipping is capable of causing saltmarsh loss Increased shear stress is caused by: - return currents - waves - rapid water level draw-down Research at Lymington Harbour predicted that extra shear stress of proposed ferry movements would cause a 0.3m deepening of the channel in 10 years. This could lead to 20m recession of the fringing saltmarsh if the angle of the bank is maintained. Navigation may also induce channel erosion in unnavigated channels by increasing the tidal volume caused by ship-induced erosion and dredging. To reduce impact of shipping, limit: ship size (blockage ratio), speed and optimise hull design.

Table 8.2 (continued)

Factor	See Section	Relative Importance	Type of saltmarsh change	Conclusions
Dredging	5.1.1.6	Unquantified, but the effect is probably significant in estuaries and harbours	May cause foreshore slumping leading to greater water depths therefore greater potential water heights and edge erosion May reduce sediment availability and hence accretion as: - deepened areas act as a sediment sink - dredged material may be dumped out of the system	Direct evidence of dredging adversely affecting U.K saltmarshes and mudflats is limited due to lack of research. However, indirect evidence suggests that nearshore dredging does affect the intertidal profile. For example, when dredging ceased in Cardiff Bay, saltmarsh area increased.
Mud digging	5.1.1.7	Generally minor, but historically significant in the Medway estuary	Direct loss of saltmarsh	Practice has now ceased.

Table 8.2 (continued)

Factor	**See Section**	**Relative Importance**	**Type of saltmarsh change**	**Conclusions**
Pollution	5.1.1.8	Synthetic chemicals: - No evidence that they have caused loss in plant vigour Oil: - Repeated surface oiling can be devastating on a local scale Heavy metals: - No evidence that they have caused loss in plant vigour Nutrients: - Locally important	Synthetic chemicals: - None observed Oil: - Plant death and poor seedling establishment Heavy metals: - None observed Nutrients: - Enhanced growth of algae, which covers mud and hinders seedling establishment	Synthetic chemicals and heavy metals Although research has proved that synthetic chemicals such as TBT exist in saltmarsh sediments, there is no evidence that these concentrations have reduced the vigour of saltmarsh plants. The same conclusion is valid for heavy metal contamination. Oil Repeated episodes of oil pollution do cause vegetation death. These have been observed around the outfalls of oil refineries. Nutrients Enhanced algal growth due to nutrients (e.g. in the vicinity of seawage outfalls) can hinder seedling establishment. The seedlings can not grow through the thick algal mats.
Refuse disposal	5.1.1.9	Locally important	Direct loss of habitats	
Trampling	5.1.1.10	Not significant	Vegetation loss and degradation around paths	
Managed retreat	5.1.2.1	Not significant yet , but importance may grow in the future	Increase in saltmarsh area	To date, 66ha of upper intertidal area have been produced by managed retreat. This is small when compared to the current rate of saltmarsh loss. However, the scheme has potential for future widespread adoption and hence its significance may increase.

Table 8.2 (continued)

Factor	**See Section**	**Relative Importance**	**Type of saltmarsh change**	**Conclusions**
Maintenance and enhancement techniques	5.1.2.2	Not significant	Attempts to halt erosion and extend saltmarsh extent	The various management methods to hold or extend marshes have been largely experimental. Some schemes appear to have slowed or halted lateral erosion, but none have significantly increased seaward growth of saltmarsh in areas which are naturally eroding.
Spartina anglica planting	5.1.2.3	Very significant	Caused major seaward extension of saltmarsh, as the introduced hybrid could grow further down the intertidal profile than any other species (bar *Zostera*)	Introduction of *Spartina anglica* had a major effect on saltmarsh area. Initial colonisation was enhanced by the relatively gentle wave climate of that time (1920's - 1950's). The area of saltmarsh created by *Spartina* colonisation has not been quantified. Only areas presently experiencing *Spartina* expansion are those where wave energy is decreasing.
Creation of saltmarsh in the lee of coastal structures	5.1.2.3	Important on a local scale within estuaries	Increases sedimentation and hence may create saltmarsh	Structures which alter estuary hydrodynamics can lead to rapid saltmarsh growth in their lee.

Table 8.3 Summary of the potential natural non-hydraulic causes of saltmarsh change and their relative importance

Factor	See Section	Relative importance	Type of saltmarsh change	Conclusions
High phyto-toxin conc., produced by anaerobic bacterial respiration in poorly drained, waterlogged sediments.	1.2.2, 5.2.1	Most probably the major cause of *Spartina* 'die-back' in the interior of saltmarshes	Reduces plant vigour Prevents succession of 'upper saltmarsh' plant species into the *Spartina* sward	The build up of organic matter in the sediment as the sward ages, leads to increased bacterial respiration. Due to the long residence time of pore waters in the sediment, conditions become more reducing. The toxins produced affect plant vigour. Loss in vigour may also be compounded by reduced sedimentation rate as the elevation of the sward increases over time. Even though the surface elevation, with respect to the tidal frame, of some *Spartina* swards is suitable for succession by other saltmarsh species, adverse chemical conditions may be preventing this.
Sediment moisture content	5.2.2	Not a major factor, but differences affect tensile strength and hence the magnitude of erosion resulting from a given increase in wave or current increase.	Affects saltmarsh erodibility	The moisture content of clays; governed largely by the ratio of Ca^{2+} to Na^{+} ions, affects erodibility Many Essex marsh sediments have relatively low Ca^{2+} concentrations Essex, Kent and some South Coast saltmarshes have the highest moisture contents, whilst those in regions in which saltmarshes are expanding, generally have a lower moisture content
Sediment supply	1.2.3, 5.2.3, 8.1	An important control on both estuarine and open coastal saltmarshes.	Rate of vertical accretion controls saltmarsh response to sea level rise	Sediment type and availability affect the impact of intensifying erosive forces on saltmarshes. The greater the sediment supply, the lower the impact. There is greater sediment availability in northern and central England compared with southern and southeast England.

The following generalisations about the cause of lateral saltmarsh erosion can be made:

- Exposed locations - Change in wave climate is the dominant factor; the magnitude of the response depends on sediment supply, shear strength of sediment and plant vigour.
- Sheltered estuarine locations - Channel migration and anthropogenic impacts are the most significant causes of change

The following generalisations regarding the loss in *Spartina* vigour can be made:

- Seaward edge of sward only - Increase in wave energy is responsible
- In the saltmarsh interior particularly away from the drainage channels - Natural 'die-back' due to a change in sediment chemistry as the sward ages (see 5.2.1.1) or the development of poorly drained basins due to non-uniform sedimentation

During the last few hundred years, human activity (including reclamation and the introduction of *Spartina*) has had a greater effect on saltmarsh area than fluctuations in natural forcing factors. However, at present the major cause of saltmarsh change on the more exposed areas in Essex seems to be an increase in wave energy. If reclamation had not been so extensive, the fluctuation in wave energy may not have been noticed, but now, because the saltmarsh strip is so narrow, in many places, a 20m recession is important. In the past, fluctuations in wave heights were much less noticeable because if the edge of a 0.5km saltmarsh receded 20m, it would not make any difference to the wave height at the landward margin.

8.3 Recommendations for future coastal management to maintain saltmarsh habitat

Chapter 6 gives advice on how to identify the possible causes of saltmarsh changes and suggests management techniques that would help to ameliorate the impact. This section provides guidance on how to deal with four types of saltmarsh change. Details of methodology are given in 'Maintenance and Enhancement of Saltmarshes' EA R&D note 567/2/SW, produced by HR Wallingford.

Lateral erosion of the seaward edge (saltmarsh cliff recession)

- Open coastal or exposed estuary/harbour sites

Increase in wave energy seems to be the dominant forcing factor. The relative abundance of sediment reduces the impact of increases in wave energy by dissipating the wave energy (see section 8.1 and Tables 8.1 and 8.3).

Possible management solution (e.g. exposed sites in Essex):

1) Large scale sediment recharge on the foreshore to reduce the gradient of the intertidal zone

2) Construction of artificial cheniers or spits on the intertidal flats seaward of the saltmarsh, parallel to the shore. This would protect the saltmarsh, reduce re-erosion of the sediment added in the recharge scheme and enhance accretion (i.e recreate a back-barrier saltmarsh). Roll-back of the ridges could probably be prevented if they were designed to be sufficiently high and broad to prevent wave overtopping. Care should be taken to design the ridges so that water flow on and off the marsh is not impeded.

- Sheltered estuarine sites

Channel migration and anthropogenic factors such as navigation and dredging are dominant causes. Channel migration is a natural process. It may be possible to control it by the construction of training walls but this is solution may be unacceptable on environmental grounds and is very expensive. Managed retreat should be considered if the channel is cutting towards the see defence (see 4.3.6). The impact of ship and boat movements can be reduced through regulation (e.g. lowering speed limit, size of vessel and hull shape).

Spatial variation in the rate of vertical accretion causing poor surface drainage in the back marsh and areas remote from creeks

Rate of sedimentation on saltmarshes decreases with increasing distance from creeks or the seaward edge. Those areas relatively remote from the sediment source become relatively lower with respect to the creek banks, creating poorly drained areas. Relative sea level rise compounds the problem, and these areas experience change in species composition (from upper saltmarsh species to those that can better withstand water logging), or become mud basins.

Possible management solution (e.g. near Lymington, Hampshire):
Rainbow discharge of silt on to the basins to raise the level so that water drains into the creeks. It is best to do this in summer just over spring tides, so that silt has time to consolidate before next flooding tides. It would be inappropriate to adopt this form of management on a large scale, but it would be an option for a limited area to protect a site of particular value.

Increase in internal dissection (i.e creek lengthening and mud basin formation)

The main cause of creek lengthening is most probably an increase in the frequency and magnitude of surface flooding. This could either be due to relative sea level rise, an inctrease in wave energy or an increasing secular trend in tidal range, because it is close to the maximum tidal range in the 18.6 year cycle.

Possible management solution:
Very difficult, raising the elevation of the saltmarsh surface may help, possibly by rainbow discharge of silt directly on to the marsh surface or trickle feeding. In theory, management that increased the hydraulic roughness of the system so that the tidal velocities were reduced, would reduce internal dissection.

The best long term management solution to natural changes is to realign the coast landward of its current position to provide a larger inter-tidal area which will act as a buffer to:

- fluctuations in wind speed and direction
- channel migrations (within estuaries and offshore)
- cyclic changes in tidal range due to the lunar nodal cycle
- relative sea level rise

Further 'reclamation' projects should not be taken as these restrict the room that is available for natural response to changing forcing factors.

8.4 Recommendations for future work

8.4.1 Data Collection and monitoring

Modelled wave data poorly represent the actual incident wave climate at the saltmarsh edge. Furthermore, the objective of this project in determining saltmarsh response to changes in forcing factors was severely handicapped by the marked scarcity of annual records of saltmarsh/mudflat change.

Future resources should be directed towards the collection of field measurements rather than reviewing past work. At present the data are inadequate to draw firm conclusions. Synchronised, long term measurements of the following parameters at several sites around the British Isles, representing stable, eroding and accreting saltmarshes, would be desirable.

Natural forcing factors

- Wave climate close to the saltmarsh edge and across the saltmarsh
- tidal currents at the saltmarsh edge, in the creeks and across the marsh
- tidal range and shape of the tidal curve
- relative sea level changes
- bathymetry and changes in the intertidal profile (particularly after dredging)
- wind speed and direction
- suspended sediment concentration and grain size

Saltmarsh Response

- lateral accretion/erosion (mudflat and saltmarsh)
- vertical accretion/erosion
- change in creek network
- change in species composition

New Forest District Council are keen to do collaborative research regarding saltmarsh response to individual events. They are well set up for this type of research, as a platform has been erected at the mouth of the Lymington estuary, from which a continuous record of tidal levels, wind and waves is made.

8.4.2 Further research

Academic research

To understand how changes in the magnitude of forcing factors such as tidal range for example, affect saltmarshes it is necessary to have a greater understanding of saltmarsh processes. Integrated research which links a range of research areas including hydrodynamics, plants, sedimentation/erosion, biogeochemistry, and geomorphology, would aid prediction of saltmarsh response to changing variables.

Modelling

(1) Physical or numerical modelling could be used to determine the relative importance of the various factors which increase wave height and cause saltmarsh erosion at a given site. If more than one factor is affecting wave height, it is only possible to determine the sensitivity of a saltmarsh to change in a particular forcing factor in a controlled environment where only one variable is changed at a time. Real archived data could be used e.g. wind records, tide gauge, bathymetry changes. A series of model runs would determine how change in each of the forcing factors would affect incident wave height.

(2) To determine whether estuarine saltmarsh change is due to a change in wave energy or tidal currents, or a combination of both. The computer model developed for this research project and described in section 2.4.2 and 4.3.5, is used to analyse historical records for changes in the rate of flood and ebb water level fluctuations (and hence the maximum flood and ebb currents), could be run for more sites for which adequate data exist. This would identify whether there were significant cyclical changes or a secular trend in tidal currents. These predicted changes in tidal currents could then be compared with changes in saltmarsh accretion/erosion.

Establish the role of creeks in affecting vegetation,sedimentation and erodibility

The density of drainage channels affects plant vigour, sedimentation rates and probably erodability of the sediment because:

- adverse chemical conditions related to anaerobic conditions are the most probable reason for reduced plant vigour in areas remote from creeks. This is due a combination of waterlogging, poor groundwater flushing and drainage rates, and high organic concentrations
- sedimentation rates decrease with increasing distance from the sediment source
- shear strength is related to water content of the sediment, which in turn will alter according to the position of the groundwater table

Research should be conducted to quantify the effect of drainage efficiency and creek proximity to the above characteristics. If the effect is great than trial field experiments to alter the drainage efficiency and creek network could be attempted. Possible schemes are listed below:

(1) Reduce pore water retention time and moisture content of surface sediments by hydraulically improving the creek network. Perhaps cut extra creeks, or deepen existing ones.

(2) Survey surface topography to determine whether poor drainage is due to basin formation due to differential sedimentation rates. If so, could attempt silt application directly to the basins.

Establish the impact of contaminants the vigour of saltmarsh plants

Concern has been expressed over the presence of man-made compounds within saltmarsh systems and their potential impact on saltmarsh stability. However, there is currently, a lack of information regarding the toxicological effects of contaminants to saltmarsh biota at environmental concentrations. To date, there is no conclusive evidence as to whether contaminants are impacting on the vigour of saltmarsh plants or animal community. Although research has been conducted to determine the concentration of contaminants in saltmarsh sediments, the actual toxicological effect on the biota is not known. There is a need to conduct ecotoxicological experiments to determine whether contaminants such as herbicides, TBT, PCB's and metals, at environmental concentrations have acute or chronic effects on saltmarsh vegetation.

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APPENDIX A: CORRELATION ANALYSIS

Description of Collected data

The 50 saltmarsh locations in Table A, which contained the data used in the correlation analysis, were chosen on the grounds that they are situated in areas for which HR had wind and water records. The table is spilt into two by double vertical lines. This separates the forcing factors from the saltmarsh response. The correlation analysis analysed the relationship between each forcing factor with each type of saltmarsh change. As the type face is small, and the column titles have been abbreviated, the full title for each column is given below. The source of the information is also given.

Forcing Factors

1 Change in wave height (cm/yr) for wave heights exceeded 1% of the time
Source: numerical modelling from wind data conducted by HR Wallingford

2 Change in wave height (cm/yr) for wave heights exceeded 10% of the time
Source: numerical modelling from wind data conducted by HR Wallingford

3 Change in wave height (cm/yr) for wave heights exceeded 50% of the time
Source: numerical modelling from wind data conducted by HR Wallingford

4 Relative sea level change (mm/yr)
Source: Database of British Saltmarshes (Pye and French, 1993)

5 Change in average wind speed (cm/s/yr) for winds exceeded 1% of the time
Source: analysis of long term measurements of winds held by HR Wallingford

6 Change in average wind speed (cm/s/yr) for winds exceeded 10% of the time
Source: analysis of long term measurements of winds held by HR Wallingford

7 Change in average wind speed (cm/s/yr) for winds exceeded 50% of the time
Source: analysis of long term measurements of winds held by HR Wallingford

8 Change in fetch
Source: Deduction by HR staff. For each saltmarsh location, the change in mean wind direction has been assessed and the impact on fetch estimated

9 Tidal range for mean spring tides (m)
Source: Database of British Saltmarshes (Pye and French, 1993)

10 Mean high water spring (m O.D.)
Source: Database of British Saltmarshes (Pye and French, 1993)

11 Sediment supply
Source: Qualitative deduction from HR staff. Changes in sediment supply over the last 40 years were estimated from knowledge of coastal defence and river management works within the coastal cell.

12 Change in storm frequency (number of storms with waves above 2m per year)
Source: Analysis of hindcasted wave records produced by HR Wallingford, see 2.4.3.

13 Grazing

Source: Database of British Saltmarshes (Pye and French, 1993)

Saltmarsh response

14 Change in surface elevation
Source: Database of British Saltmarshes (Pye and French, 1993) and questionnaire responses

15 Change in lateral extent
Source: Database of British Saltmarshes (Pye and French, 1993) and questionnaire responses

16 Change in creek length
Source: Database of British Saltmarshes (Pye and French, 1993) and questionnaire responses

17 Vegetation die-back
Source: Questionnaire responses

18 *Spartina* expansion
Source: Questionnaire responses

19 Elevation of upper saltmarsh (mO.D.)
Source: Database of British Saltmarshes (Pye and French, 1993)

20 Elevation of seaward edge of saltmarsh (mO.D.)
Source: Database of British Saltmarshes (Pye and French, 1993)

Further analysis

21 Depth of flooding on upper saltmarsh on mean spring tides (m)
Source: Subtract column 19 from column 10

22 Depth of flooding on lower saltmarsh on mean spring tides (m)
Source: Subtract column 20 from column 10.

Note that for columns, 8, 11, 13, 14, 15, 16, 17 and 18, in Table A, quantitative data on saltmarsh change was not available and the following notation had to be adopted:
-1 = decrease
0 = stable
1 = increase

Correlation analysis

Table B contains the results from the linear correlation analysis. The first column states which pairs of forcing factor and saltmarsh change parameter are being correlated. The calculated correlation coefficients are given in the forth column. The closer the value is to 1 the stronger the relationship between the forcing factor and saltmarsh change.

Examination of the values in column four, indicates that there is no proof that changes in any of the forcing factors, cause change in any of the listed saltmarsh characteristics. The poor correlations suggest that it is not the same factors which cause the change at every location.

Unfortunately, the only strong correlations, greater than 0.8 were associated with characteristics rather than changes (For example, the correlation between spring tidal range and the elevation of the upper saltmarsh was 0.79; and that for mean high water springs and the elevation of the upper saltmarsh was 0.8, see Figure A).

Some of the tentative conclusions from the initial interpretation of the results are listed below.

- The only instances of *Spartina* expansion occur in locations where there is a negative trend in mean wave height (i.e. there is a decrease in average wave height (see Figure B).
- Tendency for *Spartina* expansion when saltmarsh elevation is above MHW.
- No statistically significant relationship between changes in wave heights and lateral and vertical erosion of saltmarshes (however this could well be due to the quality of the data, which does not relate to wave heights actually hitting the saltmarsh.
- No creek dissection in saltmarshes where MHWS is below the elevation of the upper saltmarsh (this is logical as creeks are elongated by the erosive force of water draining back into them after a tide which floods the surface).

	FORCING FACTORS													Saltmarsh Response								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
LOCATION	WAVE HT CHANGE (mm/yr)			SEA LEVEL CHANGE (mm/yr)	WIND SPEED CHANGE			FETCH	RANGE TIDE (m)	MHWS ht (m)	SED SUPPLY	STORM FREQUENCY	GRAZING	VERTICAL	LATERAL	INTERNAL DISS	VEG DIE	SPART EXPAN	ELEVATION		10-18	10-20
	1%	10%	50%		1%	10%	50%												UPPER	SEAWARDS		
Morecambe Bay	1.1	0	-0.2	1.5	7	1	-1	0	8.3	4.5	0		1	1	1	0		1	8.3	4.8	-0.8	-0.1
Rockcliffe				0.8	7	1	-1		8.4	4.3			1	1	-1	0	0	0				
Ribble	1.1	0	-0.2	1.75	7	1	-1	0	7	4.2	-1		1	1	1	0		1	4.2	3.2	0	1
Dee	1.1	0	-0.2	1.75	7	1	-1	0	8	4.5	0		1	1	1	0						
Wye	1.1	0	-0.2	1.5	7	1	-1	0	8	4.2	0		1	1	0.8	0			5.3	4.8	-1	-0.2
Clwyd	1.1	0	-0.2	1.75	7	1	-1	0	3.4	4.7	0		1	1	1	0						
Conwy	1.1	0	-0.2	1.75	7	1	-1	0	8.7	3.5	0		1	1	1	0						
Cefni	1.1	0	-0.2	1.75	7	1	-1	0			0		1	1	1	0	0	1				
Llanrhidian	0.05	0.01	-0.04	1.5	-2	-1	-1	1			0		1	1	1	0	0	1				
Oxwich	0.05	0.01	-0.04	1.5	-2	-1	-1	1	8.4	4.3	0		0	1	0	0						
Crymlyn	0.05	0.01	-0.04	1.5	-2	-1	-1	1	8.4	4.5	0		1	1	0	0	0					
Ogmore	0.05	0.01	-0.04	1.5	-2	-1	-1	1	8.7	4.8	0	-0.13	1	1	1	0	0					
Severn (N)				1.5					12	6.5	0	-0.13	1	1	-1	1	1	0				
Severn (S)				2					11		0	-0.13	1	1	-1							
Bristol Ch (S)	-0.004	-0.008	-0.001	2	-2	-1	-1	1	11.5	8	0	-0.13	1	1	-1	1	1		4.5	3.8	1.5	2.1
Exe	0.05	0.01	-0.04	1.75	-2	-1	-1	1	11.1	5.8	-0.5		0	-1	-1	1	1		8.3	3.3	-0.6	2.5
Taw & Torridge	2.8	-0.5	-0.8	1.75				0	8	4.4	0		1	1	0.5	0						
Camel	2.8	-0.5	-0.9	1.75				0	5	3.5	0		0	1	1	0	1	1				
Hayle	2.8	-0.5	-0.8	1.75				0	5.5	3.2			1	1	1	0	0	1	5.3	5.1	-2.1	-1.9
Axe				1	1	0	-3	1	4.4		-1		1	0	0	0						
Fleet				1	1	0	-3	1	1.9	1.2	0		0	0	0	0			0	0	1.2	1.2
Lodmore					1	0	-3	0	0	0	0		1	0	0	0						
Poole				1.25	1	0	-3	0	1.6	0.7	0		1	1	0	0	1	0	0.8	0.2	-0.1	0.5
Christchurch				1.25	1	0	-3	0	1	0.9	0		1	-0.5	0	0						
Solent				1.25	1	0	-3	1	2.7	3.3	0		0	-0.5	-1	1	1		2.4	2	0.9	1.3
Portsmouth	1	0.4	0	1.25	1	0	-3	0	4.1	2	0		0	0	-0.75	1	1	0				
Langstone	0.8	0.4	0.1	1.5	1	0	-3	0	4.7		0		1	0	0	1	1	0	2	0.9		
Chichester	0.3	0.3	0.1	1.5	1	0	-3	1	1	0.9	0		1	-1	-1	1	1					
Pagham	0.1	0	0	1.5	1	0	-3	0	4.4	2.2	0		0	1	1	0	0	0	2.4	2.05	-0.15	0.15
Rye	1.3	0.5	-0.2	1.5	1	0	-3	0	6.6		0		1	1	0	0						
Pegwell	0.5	0.8	-0.2	2	1	0	-3	0	3.2	2	0		1	1	0	0	0	1				
Stour	1.3	0.8	-0.2	2	1	0	-3	0	3.2	2	0		1	0	-1	0						
Swale	0.5	2.5	1.2	2.25	8	10	4	0	8	2.75	-1		1	1	-1.5	1	0	0	2.8	2.25	0.25	0.5
Medway	0.8	2.5	1.2	2	8	10	4	0	5.2	3.1	-1		1	0	-1	1	0	0	2.8	2.8	0.15	0.5
Thames	0.8	2.8	1.2	2	8	10	4	0	5.8	3.1	0		1	1	-1	0.5			2.8	2.75	0.2	0.35
Crouch	0.5	2.5	1.2	2	8	10	4	0	5	2.85	0		1	1	-1	1			2.8	2.55	0.25	0.3
Roach	0.5	2.8	1.2	2	8	10	4	0	5	2.8	0		0	0	-1	1			2.8	2.6	0.2	0.3
Dengie	-0.8	-0.1		2.5	8	10	4	0	4.8	2.8	0	-0.5	0	0	-1	1	1	0	2.1	1.85	0.5	0.45
Blackwater(N)	-0.9	-0.1		2.5	8	10	4	0	4.75	2.85	0	-0.5	1	0	-1	1	1	0	2.6	2.45	0.05	0
Blackwater(S)	0.5	2.5	1.2	2.5	8	10	4	0	4.75	2.85	0	-0.5	1	0	-1	1	1	0	2.8	2.85	0.05	0
Colne	0.8	2.5	1.2	1.75	8	10	4	0	4.5	2.8	0		1	1	-1	1	1	0	2.5	2	0.15	0.6
Hamford	-0.9	-0.1		1.5	8	10	4	0	3.8	2.4	0	-0.5	0	1	0	0.5			1.8	1.8	0.8	0.8
Stour	0.5	2.5	1.2	1.75	8	10	4	0	3.75	2.1	0		0	0	-1	0.5	1	0	2	2	0.1	0.1
Orwell				1.75	8	10	4	0	3.75	2.1	0		0	1	0	1			2	1.8	0.1	0.3
Deben				1.75	8	10	4	0	3.8	2.1	0		1	0	0	0.5			1.8	1.8	0.2	0.5
Alde				1.75	8	10	4	0	2.4	1.5	0		1	1	-0.5	0			1.2	1	0.15	0.3
Butley				1.75	8	10	4	0	2.8	1.8	0		0	-0.5	-1	0			1.4	1.2	0.15	0.3
Ore				1.75	8	10	4	0	2.4	1.25	0		1	-0.5	-1	0			1.1	0.8	0.2	0.35
N Norfolk	6.4	3.4	1.5	1.75	8	8	4	0	5.4	2.8	0		0	1	0	0	0	0	3	2.2	0.08	1.4
N Lincoln	6.4	3.4	1.5	1.25	8	8	4	0	5.8	3	0		1	1	1	0			2.8	2	0.25	1

Table A Data used in Linear Regression Analysis

Corr. pairs	Constant	standard error (y)	R^2	Obs	deg free	X coef	standard err (coef)
1 ~ 14	0.59880	0.599857	0.0058	36	34	0.01606	0.036061
1 ~ 15	0.20521	0.857290	0.1130	36	34	-0.1072	0.051537
1 ~ 16	0.31927	0.472788	0.0391	36	34	0.03345	0.028422
1 ~ 17	0.59220	0.518246	0.0257	21	19	-0.0272	0.038429
1 ~ 18	0.50304	0.503844	0.0505	18	16	-0.0377	0.040906
1 ~ 19	3.66430	1.293282	0.0994	21	19	-0.1306	0.090250
1 ~ 20	2.93847	1.067069	0.0362	21	19	-0.0629	0.074464
2 ~ 14	0.66367	0.600233	0.0045	36	34	-0.0322	0.081809
2 ~ 15	0.19794	0.804032	0.2197	36	34	-0.3391	0.109586
2 ~ 16	0.29978	0.451836	0.1224	36	34	0.13412	0.061583
2 ~ 17	0.54001	0.524381	0.0025	21	19	-0.0208	0.093753
2 ~ 18	0.59029	0.415106	0.3555	18	16	-0.2264	0.076221
2 ~ 19	3.77327	1.210582	0.2109	21	19	-0.4294	0.190557
2 ~ 20	3.11657	0.990787	0.1691	21	19	-0.3066	0.155959
3 ~ 14	0.68480	0.602224	0.0079	33	31	-0.0601	0.120442
3 ~ 15	0.17558	0.742342	0.3507	33	31	-0.6075	0.148465
3 ~ 16	0.27933	0.408829	0.2739	33	31	0.27963	0.081764
3 ~ 17	0.48799	0.526546	0.0049	19	17	-0.0367	0.126138
3 ~ 18	0.58209	0.383047	0.4783	16	14	-0.3300	0.092113
3 ~ 19	4.06606	1.058345	0.4214	18	16	-0.8924	0.261412
3 ~ 20	3.31530	0.918674	0.3358	18	16	-0.6454	0.226913
4 ~ 14	0.56037	0.637850	0.0000	49	47	-0.0052	0.167053
4 ~ 15	0.73526	0.787672	0.1163	49	47	-0.5132	0.206291
4 ~ 16	-0.23999	0.430062	0.1699	48	46	0.34626	0.112823
4 ~ 17	0.63082	0.517004	0.0019	25	23	-0.0395	0.184703
4 ~ 18	0.29143	0.495392	0.0008	21	19	0.02285	0.183458
4 ~ 19	2.26772	1.488647	0.0081	29	27	0.23142	0.491414
4 ~ 20	1.29126	1.205902	0.0589	29	27	0.51770	0.398078
5 ~ 14	0.41768	0.648180	0.0097	45	43	0.01504	0.023079
5 ~ 15	-0.01673	0.794689	0.0441	45	43	-0.0398	0.028295
5 ~ 16	0.26657	0.461099	0.0454	45	43	0.02349	0.016418
5 ~ 17	0.52579	0.521621	0.0023	22	20	0.00540	0.024950
5 ~ 18	0.44894	0.459040	0.0663	18	16	-0.0308	0.028891
5 ~ 19	3.13421	1.396931	0.0493	28	26	-0.0815	0.070160
5 ~ 20	2.12415	1.134176	0.0008	28	26	0.00827	0.056964
6 ~ 14	0.51565	0.650526	0.0026	45	43	-0.0067	0.020192
6 ~ 15	0.09899	0.719473	0.2165	45	43	-0.0769	0.022332
6 ~ 16	0.22246	0.430722	0.1670	45	43	0.03926	0.013370
6 ~ 17	0.49854	0.517541	0.0178	22	20	0.01376	0.022799
6 ~ 18	0.50584	0.400950	0.2877	18	16	-0.0506	0.019936
6 ~ 19	3.33091	1.323127	0.1471	28	26	-0.1130	0.053392
6 ~ 20	2.44948	1.115100	0.0341	28	26	-0.0431	0.044998
7 ~ 14	0.48405	0.650410	0.0029	45	43	0.01146	0.032083
7 ~ 15	-0.16308	0.750997	0.1463	45	43	-0.1006	0.037045
7 ~ 16	0.35433	0.439620	0.1323	45	43	0.05553	0.021685
7 ~ 17	0.54470	0.522070	0.0006	22	20	0.00414	0.037170
7 ~ 18	0.31830	0.431785	0.1739	18	16	-0.0607	0.033116
7 ~ 19	2.79981	1.400647	0.0442	28	26	-0.0989	0.090144
7 ~ 20	2.20327	1.133804	0.0014	28	26	-0.0142	0.072970
8 ~ 14	0.58108	0.630375	0.0460	47	45	-0.3310	0.224671
8 ~ 15	-0.10135	0.827076	0.0024	47	45	-0.0986	0.294777
8 ~ 16	0.35135	0.467438	0.0018	47	45	0.04864	0.166599
8 ~ 17	0.56250	0.518780	0.0000	23	21	0.00892	0.235092
8 ~ 18	0.33333	0.485071	0.0952	19	17	0.66666	0.498363
8 ~ 19	2.61400	1.474507	0.0268	29	27	0.686	0.794046
8 ~ 20	2.27400	1.243064	0.0000	29	27	0.026	0.669410
9 ~ 14	0.03574	0.588497	0.1605	48	46	0.09188	0.030974
9 ~ 15	-0.27114	0.809269	0.0009	48	46	0.00893	0.042594
9 ~ 16	0.29652	0.471742	0.0091	47	45	0.01676	0.026065
9 ~ 17	0.70805	0.507980	0.0108	23	21	-0.0174	0.036418
9 ~ 18	0.12914	0.461977	0.0152	19	17	0.02478	0.048371
9 ~ 19	-0.07437	0.679284	0.7934	29	27	0.55392	0.054386
9 ~ 20	0.26247	0.784731	0.6014	29	27	0.40108	0.062828
10 ~ 14	-0.00702	0.599185	0.1612	44	42	0.17625	0.062032
10 ~ 15	-0.52378	0.823160	0.0320	44	42	0.10053	0.085220
10 ~ 16	0.31377	0.472516	0.0057	44	42	0.02415	0.048918
10 ~ 17	0.65827	0.514637	0.0039	22	20	-0.0207	0.073372
10 ~ 18	0.04668	0.464636	0.0434	18	16	0.07542	0.088468
10 ~ 19	-0.27820	0.675683	0.8015	28	26	1.05622	0.103080
10 ~ 20	0.14211	0.747849	0.6342	28	26	0.76607	0.114089
11 ~ 14	0.54150	0.639177	0.0097	48	46	0.22040	0.326684
11 ~ 15	-0.15340	0.815661	0.0117	48	46	0.30816	0.416885
11 ~ 16	0.36351	0.470188	0.0156	47	45	-0.2033	0.240596
11 ~ 17	0.66484	0.485531	0.0963	23	21	0.51648	0.345204
11 ~ 18	0.31250	0.491347	0.0002	19	17	-0.0208	0.309132
11 ~ 19	2.46079	1.373237	0.0813	28	26	-1.2422	0.818840
11 ~ 20	2.08429	1.108226	0.0460	28	26	-0.74	0.660818
12 ~ 14	1.26351	0.353553	0.6	8	6	2.02702	0.675676
12 ~ 15	-0.41216	0.790569	0.0322	8	6	0.67567	1.510857
12 ~ 16	0.59347	0.413320	0.0801	7	5	-0.5630	0.853185
12 ~ 17	0.54955	0.408248	0.2	6	4	-0.9009	0.900901
12 ~ 18	not enoug						
12 ~ 19	5.28176	0.394757	0.8944	5	3	6.01351	1.192843
12 ~ 20	4.49291	0.525000	0.7336	5	3	4.56081	1.586400
13 ~ 14	0.28571	0.615134	0.0647	50	48	0.35317	0.193749
13 ~ 15	-0.33929	0.822932	0.0158	50	48	0.22817	0.259199
13 ~ 16	0.50000	0.462253	0.0332	49	47	-0.1857	0.146177
13 ~ 17	0.75000	0.499360	0.0689	25	23	-0.2794	0.214099
13 ~ 18	0.16667	0.483046	0.05	21	19	0.23333	0.233333
13 ~ 19	2.35000	1.466239	0.0377	29	27	0.57777	0.561140
13 ~ 20	1.87273	1.199044	0.0696	29	27	0.65227	0.458882
a ~ 14	0.49948	0.649890	0.0231	28	26	-0.1470	0.187560
a ~ 15	-0.31058	0.739684	0.2013	28	26	-0.5465	0.213474
a ~ 16	0.47399	0.456369	0.0974	28	26	0.22072	0.131709
a ~ 17	0.62088	0.491808	0.0970	14	12	0.19229	0.169366
a ~ 18	0.19251	0.317825	0.5185	13	11	-0.4521	0.131383
a ~ 19	2.87550	1.278239	0.2896	28	26	-1.2012	0.368903
a ~ 20	2.44778	1.020995	0.3182	28	26	-1.0266	0.294661
b ~ 14	0.59286	0.635179	0.0668	28	26	-0.2108	0.154543
b ~ 15	-0.22776	0.796238	0.0745	28	26	-0.2804	0.193730
b ~ 16	0.41997	0.464405	0.0654	28	26	0.15243	0.112993
b ~ 17	0.54525	0.485796	0.1189	14	12	0.16268	0.127819
b ~ 18	0.29510	0.412173	0.1902	13	11	-0.2459	0.153016
b ~ 19	2.72954	1.516627	0.0000	28	26	0.00836	0.369005
b ~ 20	2.53940	1.192715	0.0696	28	26	-0.4049	0.290195

Table B **Results of Correlation Analysis**

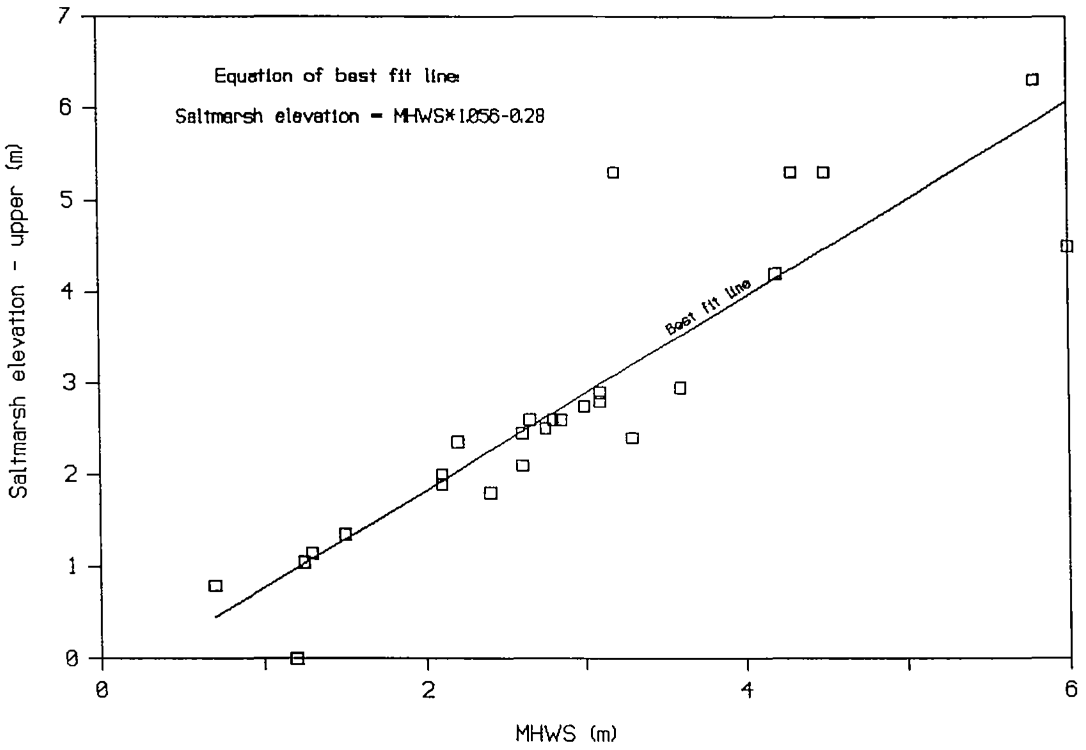

Figure A Graph to illustrate the relationship between the elevation of the upper saltmarsh and MHWS

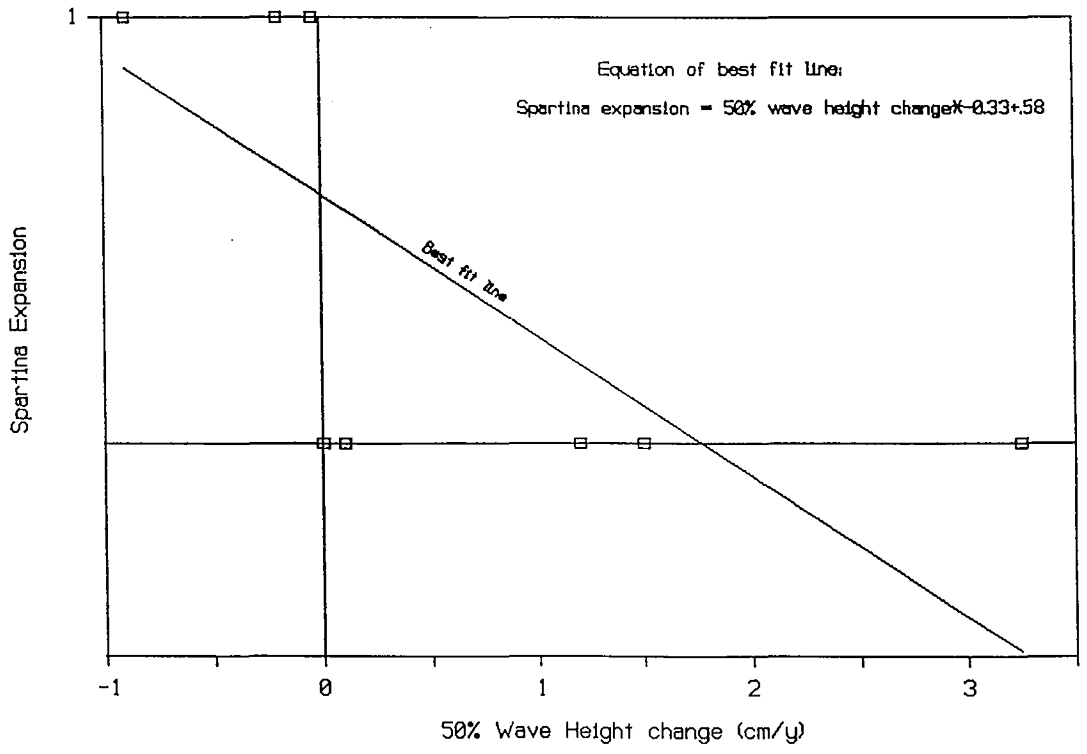

Figure B Graph to illustrate the relationship between *Spartina* expansion and decrease in wave mean wave height

APPENDIX B: CHANGES IN WAVE CLIMATE AT NEARSHORE LOCATIONS IN LANGSTONE, CHICHESTER AND PORTSMOUTH HARBOURS, BETWEEN 1971 AND 1990

APPENDIX C: RESULTS FROM ANALYSIS OF WATER LEVEL RECORDS AT IMMINGHAM TO DETERMINE CHANGES IN THE MAXIMUM RATE OF WATER LEVEL RISE AND FALL

Immingham data - analysis of rate of change of tide level

With 2.7m threshhold			All records	
Year	Flood	Ebb	Flood	Ebb
56	0.2992	-0.838	1.1824	-1.2118
57	0.3286	-0.9094	1.2151	-1.2469
58	0.305	-0.8805	1.2214	-1.2552
63	0.3148	-0.9052	1.189	-1.2269
64	0.2915	-0.8755	1.1731	-1.208
65	0.2963	-0.8777	1.1696	-1.2218
66	0.294	-0.8567	1.1673	-1.2303
67	0.3134	-0.8951	1.1614	-1.2014
68	0.2971	-0.8695	1.1544	-1.2013
69	0.2908	-0.8504	1.2191	-1.2642
70	0.2949	-0.8466	1.1702	-1.2005
71	0.2688	-0.8579	1.1699	-1.2013
72	0.2675	-0.8572	1.1835	-1.2089
73	0.2681	-0.8643	1.1626	-1.1953
74	0.2883	-0.8556	1.2139	-1.2411
75	0.2854	-0.8852	1.2216	-1.2296
76	0.3115	-0.8754	1.22	-1.2389
77	0.2949	-0.8722	1.2161	1.2343
78	0.312	-0.8738	1.2471	-1.247
79	0.2984	-0.8696	1.276	-1.2727
80	0.3146	-0.881	1.2385	-1.2501
81	0.3376	-0.8846	1.2213	-1.2404
82	0.3167	-0.9473	1.2393	-1.2597
83	0.3202	-0.8907	1.1857	-1.2077
84	0.308	-0.8778	1.1926	-1.2105
85	0.3139	-0.8568	1.1783	-1.1901
86	0.3012	-0.8712	1.1408	-1.1683
87	0.3128	-0.8721	1.1344	-1.1498
88	0.3077	-0.8769	1.1225	-1.155
89	0.3265	-0.9025	1.1312	-1.1513

APPENDIX D: PERCENTAGE MOISTURE CONTENTS OF INTER-TIDAL DEPOSITS AND SALTMARSHES IN THE BRITISH ISLES (FROM WATER POLLUTION RESEARCH, TECHNICAL PAPER NO. 7, 1938)

Locality from which the deposit was taken	Sample No.	Moisture (%)
Norfolk salt marshes, between Blakeney and Wells-on-Sea	U 1	53.4
	2	45.8
	3	44.6
	4	36.2
Tamar Estuary, Devonshire	U 8	58.4
	9	53.2
	Tamar 3	55.3
	4	62.8
Beach at Burnham-on-Sea, Somerset	U 14	30.8
Dee Estuary, Cheshire and Flintshire	Dee 1	26.4
	2	28.4
	3	20.8
	4	30.7
	5	28.6
	6	22.8
	7	24.0
	8	25.4
	9	20.8
	10	23.8
	11	23.9
	12	22.5
	17	20.3
	18	20.4
	19	19.2
	20	22.6
	21	23.4
	24	20.3
	25	23.3
	26	23.1
	27	24.8
	28	25.9
Ribble Estuary, Lancashire	R 1	27.3
	2	21.8
	3	23.3
	4	19.9
	5	24.0
	6	18.4
	7	25.5
	8	27.2
	9	22.8
	10	34.7
	11	33.3
	12	31.4
	13	35.6

Morecambe Bay, Lancashire	L 1	20.8
	2	22.0
	3	23.0
	4	21.6
	5	21.9
	6	21.8
	7	23.7
	8	20.9
	9	20.9
	10	20.4
	11	25.3
	12	21.1
	13	17.6
	14	18.7
	15	18.6
	16	17.3
	17	18.9
Tay Estuary, Perthshire, Scotland	Tay 1	69.5
	2	51.9
	3	55.6
	4	56.4
	5	45.7
	6	41.0
	7	34.7
	8	34.8
	9	45.2
	10	41.7
	11	35.3
	12	32.4
	13	33.8
	14	58.0
	15	66.4
	16	57.6
	17	35.7
	18	31.3
	19	46.1

Deben Estuary, Suffolk	Deben 1	70.4
	2	62.8
	3	64.7
	4	60.1
	5	63.4
	6	63.6
	7	58.5
	8	57.5
	9	69.8
	10	72.5
	11	71.4
	12	49.6
	13	40.0
	14	54.3
	15	41.9
	16	50.9
	17	54.9
	18	44.0
	19	47.0
	20	48.0
Orwell Estuary, Suffolk	Orwell 1	23.6
	2	61.4
	3	48.6
Stour Estuary, Essex	Stour 1	73.0
	2	77.3
	3	57.6
	4	75.1
	5	72.5
	6	73.2
	7	62.7
	8	70.0
	9	43.4
	10	40.1
Hamford Water (salt marsh), Essex	Ham- 1	71.6
	ford 2	74.8
	3	68.4
	4	67.2
	5	62.2
	6	65.7
	7	58.0
	8	62.3
	9	60.3
	10	59.6

Colne Estuary, Essex	Colne 1	60.0
	2	59.1
	3	52.7
	4	51.3
	5	48.6
	6	43.1
	7	58.0
	8	55.7
Mersea Island, Blackwater Estuary, Essex	Mersea 1	42.9
	2	49.9
	3	36.9
	4	38.5
	5	41.2
	6	60.8
	7	59.8
	8	64.3
Blackwater Estuary, Essex	Blackwater 1	50.2
	2	50.3
	3	47.9
	4	53.1
	5	53.6
Crouch Estuary, Essex	Crouch 1	47.3
	2	41.7
	3	58.8
	4	60.2
	5	48.4
	6	40.8
	7	47.2
	8	53.8
	9	57.3
	10	59.3
Roach Estuary, Essex	Roach 1	43.0
	2	34.6
Wye Estuary, Monmouthshire	Wye 1	41.5
	2	46.1
	3	50.5
	4	45.7
	5	36.8
	6	40.9
Severn Estuary, Monmouthshire	Severn 1	55.7
	2	49.6
	3	31.3
	4	46.8

Lough Foyle, Northwest Ireland	F 1	39.8
	2	68.8
	3	40.2
	4	36.6
	5	60.0
	6	47.4
	7	43.4
	8	48.9
	9	52.7
	10	53.5
	11	45.2
	12	51.9
	13	39.8
	14	46.6
	15	36.1
	16	43.3
	17	32.2
	18	42.1
	19	58.7
	20	44.4
	21	64.9
	22	54.5
	23	59.1
	24	48.4
	25	54.0
	26	63.0
	27	52.0
	28	43.3
	29	42.3
	30	64.9
	31	44.7
	32	65.6
	33	64.9
Suir Estuary, Co. Waterford, Ireland	Suir 1	45.2
	2	42.8
	3	45.3
	4	51.2
	5	57.5
	6	48.6
Barrow Estuary, Co. Waterford, Ireland	Barrow 1	61.7

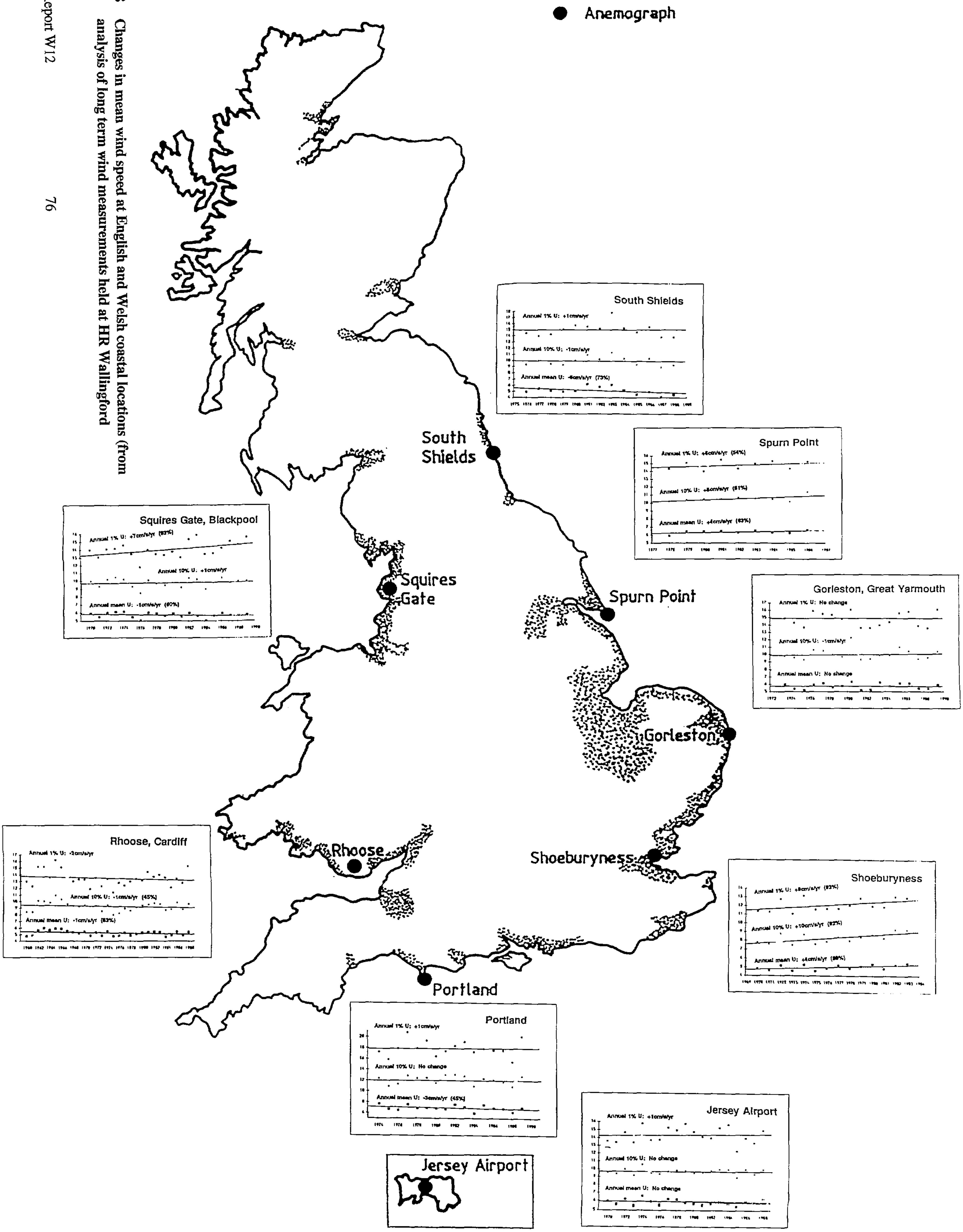

Figure 4.18 Changes in mean wind speed at English and Welsh coastal locations (from analysis of long term wind measurements held at HR Wallingford