processes governing the formation and dynamics of saltmarshes remain poorly understood and require further study.

It was against this background that a one-day workshop on the 'Morphodynamics, Conservation and Engineering Significance of Saltmarshes' was held at the Postgraduate Research Institute for Sedimentology, University of Reading, on 24 April 1991. Seven leading authorities in British coastal saltmarsh research were invited to summarise the current status of knowledge in their specialist subject areas prior to a discussion of outstanding problems and requirements for further work. The meeting was attended by over fifty participants drawn from a wide range of university departments, Government research establishments, the National Rivers Authority, and engineering consultancy companies. This book, which is based on the formal contributions to the workshop, has been produced with the intention of making available the information presented to a wider international audience.

J.R.L. Allen K. Pye Reading May 1991

Coastal saltmarshes: their nature and importance

J.R.L. ALLEN AND K. PYE

Introduction

Coastal saltmarshes are environments high in the intertidal zone where a generally muddy substrate supports varied and normally dense stands of halophytic plants. These environments grade seawards into mudflats or sandflats, to which they are genetically related, and from which they are often separated by either a ramp or cliff, and may grade upwards and landwards into freshwater marshes and coastal woodland communities. Saltmarshes are widely developed on low-energy coasts in temperate and high latitudes, but in the tropics and sub-tropics they are replaced by mangrove communities. The approximate latitudinal limit for the growth of mangrove species is determined by a mean minimum temperature in the coldest month of 10°C (Chapman, 1977).

Saltmarshes have long been viewed by scientists as intrinsically interesting environments on account of their variability and the rapidity with which physical, chemical and biological processes operate. A number of reviews have been published during the course of the past century (Carey and Oliver, 1918; Chapman, 1960; Ranwell, 1972; Beeftink, 1977; Long and Mason, 1983; Frey and Basan, 1985; Adam, 1990). However, much of the published work has been ecological or geochemical in character, and physical processes have been relatively neglected.

The occurrence of saltmarshes is to a large extent controlled by coastal physiography, since under most circumstances mud can accumulate only in relatively low-energy environments where wave action is limited. Consequently mudflats and marshes are usually found in sheltered embayments and estuaries, and in the lee of barrier islands and spits. An exception occurs in areas where very large amounts of fine sediment are supplied to the coastal zone by major rivers, resulting in the formation of a wide and shallow nearshore zone which absorbs much of the incoming wave energy. In such circumstances, such as occur in the Mississippi Delta and northwest

Fig. 1.1. Generalised distribution of active saltmarshes around the British coast (modified after Burd, 1989).

of the mouth of the Amazon, muddy sediments can accumulate on parts of the open coast and may evolve into saltmarshes or mangrove forests.

The total area covered by active saltmarsh in Great Britain amounts to approximately 44,370 ha, being concentrated largely in eastern and southeastern England, northwest England and the area of the Bristol Channel (Burd, 1989; Fig. 1.1). Active saltmarshes are also locally important in Northern Ireland. Major areas of reclaimed marsh are found in East Anglia, Kent, Somerset, and northwest Lancashire (Gray, 1977). The active marshes can be classified into five main types on the basis of their physical setting: (1) open coast marshes, (2) back-barrier marshes, (3) estuarine fringing marshes, (4) embayment marshes, and (5) loch or fjord-head marshes. True open-coast marshes are poorly developed in Britain on account of the relatively high wave energy experienced along most of the coast, examples being found mainly in Essex along the Dengie Peninsula and on Foulness Island. Open-coast back-barrier marshes are well developed on the shores of north Norfolk (Pye, Chapter 8, this volume) and in south Lincolnshire, but are also otherwise poorly developed in the UK. Estuarine fringing marshes occur in virtually every estuary, including the Severn (Allen, Chapter 7, this volume), Dee, Mersey, Ribble and Solway on the west coast, and the Medway, Thames, Crouch, Blackwater, Humber and Tay on the east coast. Embayment marshes are found in relatively large, shallow coastal embayments which often have a restricted entrance and receive a relatively limited freshwater input. In some instances the entrance to the embayment is partly protected by a sand or shingle barrier. Several examples are found on the south coast of England, including Portsmouth Harbour, Langstone Harbour, Chichester Harbour, Pagham Harbour and Poole Harbour. An east-coast example is provided by Hamford Water, while The Wash and Morecambe Bay marshes can also be regarded as variants of embayment-type marshes. Loch- or fjord-head marshes are typically restricted in size and occur mainly on the predominatly rocky coasts found in northwest Scotland.

The location, character and dynamic behaviour of saltmarshes is governed essentially by four physical factors: sediment supply, tidal regime, wind-wave climate, and the movement of relative sea level. To these may be added the variable but secondary role played by marsh vegetation in acting both as a source and as a trapper and binder of sediment. Colonisation of sand or mudflats by vegetation can only begin once the level of the surface has been raised to a

sufficiently high level in the tidal frame by physical sedimentation processes. Once vegetation is established, the rate of sedimentation frequently increases as more of the incoming sediment is intercepted and trapped by the greater surface roughness (Stumpf, 1983; Stevenson *et al.*, 1988), resuspension of deposited material is reduced for the same reason, and organic matter is added to the marsh surface.

Sediment supply

The immediate sources of the sediment found beneath saltmarshes are the tidal waters (which provide mainly mineral matter) and the marsh plants themselves (which supply organic matter). The composition and grain size of the mineral matter varies from sandy silt to clayey silt according to marsh location and marsh height, but is normally referred to as 'mud'. A predominance of mud in the supply leads to the formation of a *minerogenic* marsh, whereas a predominance of organic matter supply (litter, root biomass) leads to the formation of an *organogenic* marsh. The saltmarshes actively forming in Great Britain today are mostly of the minerogenic type.

Relatively little is known about the sources and budgets of fine sediment in British saltmarshes, or about the manner in which these have varied over time during the Quaternary. Potential sources of minerogenic sediment include river catchments, estuarine and coastal cliffs, and offshore mud deposits. Since mud is easily transported in suspension in tidal waters, it may travel considerable distances from its source, and be mixed with material derived from other sources, before arriving at its ultimate site of deposition. The major rivers which drain into the North Sea and Irish Sea at the present day supply relatively small amounts of sediment (McCave, 1987; Eisma and Kalf, 1987; Kirby, 1987), and much of the mud suspended in tidal waters appears to be derived from erosion of unconsolidated Pleistocene glacial sediments exposed in coastal cliff exposures. During the early Flandrian period, when sea level rose rapidly, wave and tidal current reworking of Pleistocene sediments on the floor of the North Sea and Irish Sea probably provided a major source of sediment which was reworked landwards and deposited in protected estuaries and embayments. Most British estuaries have acted as long-term sediment sinks throughout the Flandrian period and many have experienced a marked reduction in estuarine capacity, due in part to natural sedimentation processes but enhanced by human activities

which have included reclamation and dredging (Kestner, 1979; O'Connor, 1987).

The margins of certain estuaries, for example, the Severn, expose substantial thicknesses of postglacial silts which, representing earlier marshes and mudflats, are now undergoing vigorous erosion. Part of the sediment derived from these sources finds its way onto younger marshes further up the estuary (e.g. Allen, 1990).

The availability of suspended fine sediment, and the maximum productivity of marsh plants, together strongly affect the character of saltmarshes and their ability to respond to changing environmental conditions.

Tidal regime

Mud accumulates high in the intertidal zone of tide-dominated coasts because it is only at stages close to high water level that tidal current velocities are sufficiently low to allow fine suspended particles to settle out and remain undisturbed. Since much of the coastline of Britain is either mesotidal or macrotidal, the vertical range of saltmarshes within the high intertidal zone is typically 1–4 m. In most areas, marsh vegetation is limited to the zone between mid neap tide level and high water spring tide level. Most of the British coast experiences a simple semi-diurnal tidal regime, although on parts of the south coast the tidal regime is more complex.

The combination of a macro- or mesotidal regime and comparative shallowness means that most British barrier coasts, embayments and estuaries are dominated by a flood-tide regime which favours the landward movement of sediment from the offshore zone and which encourages the retention of river-borne sediment close inshore.

Due to the fact that saltmarsh and mudflat sediments are exposed to the atmosphere at low tide, their geotechnical characteristics differ from those of fine sediments which accumulate wholly subaqueously. Drying between tides and during the summer season of comparatively low tides gives intertidal muddy sediments a head start on the path to consolidation before any significant load has been experienced. Additionally, drying creates fractures which frequently influence the pattern of erosion during subsequent high tides. Such fractures can play a major role in determining the nature and rate of marsh cliff retreat (Allen, 1989).

Wind and wave climate

Although tide-dominated, the barrier coasts, embayments and estuaries of Great Britain and Northern Ireland are not devoid of wave influences. The effectiveness of waves in these environments depends on wind strength and directional variability, fetch (distance of open water over which waves can be generated), and on the frequency distribution of water stages. Powerful waves can quarry large blocks of sediment and cause undercutting and collapse of saltmarsh cliffs. They may also destroy the integrity of the surface vegetation, particularly near the seaward marsh edge, leading to widespread scouring of the underlying mud surface and promoting a generally unstable local environment. Waves and wave-induced bottom currents may prevent the settlement of mud at high tide, and may resuspend material deposited by earlier tides. Storm waves may also influence saltmarshes through the construction or destruction of shingle barriers (Fig. 1.2).

Although wave height tends to increase linearly with wind speed, wave energy varies as the square of wave height; consequently relatively modest fluctuations in local wind-wave climate may bring about substantial changes in the high intertidal zone.

Instrumental and proxy records demonstrate that climate in the British Isles has experienced considerable temporal variability on a variety of timescales during the last few thousand years (Lamb, 1982). Saltmarshes and the mudflats from which they evolve may well prove to afford a sensitive historical record of the local effects of these fluctuations (Allen, Chapter 7, this volume).

Movements of relative sea level

The behaviour of relative sea level can have a major influence on the medium and long-term evolution of saltmarshes (Reed, 1990). The causes of relative sea-level movements can be divided into three main groups: (1) eustatic factors, which are essentially global in extent, including changes in ice volume, thermal expansion/contraction of the oceans, and changes in ocean volume due to sea floor spreading and hydrostatic loading (Warrick and Oerlemans, 1990; Wigley and Raper, 1991); (2) regional factors, including subsidence/uplift due to crustal movements and sediment compaction/dewatering, geoid changes and tidal variations; and (3) local factors, including changes

Fig. 1.2. Storm-generated shingle washover fan, composed largely of shell debris, transgressing over marsh vegetation, north side of the Blackwater Estuary, Essex.

in coastal, estuarine and shelf morphology, which may affect tidal regime (Woodworth *et al.*, 1991), and changes in barometric pressure and wind field, which in turn have an influence on mean water levels (Woodworth, 1987, 1990; Pugh, 1990).

Relative sea-level movements in the British Isles over at least the past few centuries appear to have been dominated by regional neotectonic factors, but the eustatic contribution due to thermal expansion of the oceans and decreasing ice volume may become more significant in the next century (Warrick and Oerlemans, 1990; Warrick and Wigley, 1991) The present net sea-level trend remains downward in northwest Britain, where the land is still rising isostatically following removal of the former ice load approximately 10,000 years ago, but in the southern part of the country the trend is upward, albeit apparently locally variable (Fig. 1.3; Woodworth, 1987, 1990; Tooley, Chapter 2, this volume). This rise in relative sea level can in part be attributed to long-term subsidence of the southern North Sea Basin, but the relative contribution of other factors remains a matter of controversy. A zone of neutral crustal movement (and, effectively, sea-level movement) has been identified running across the country

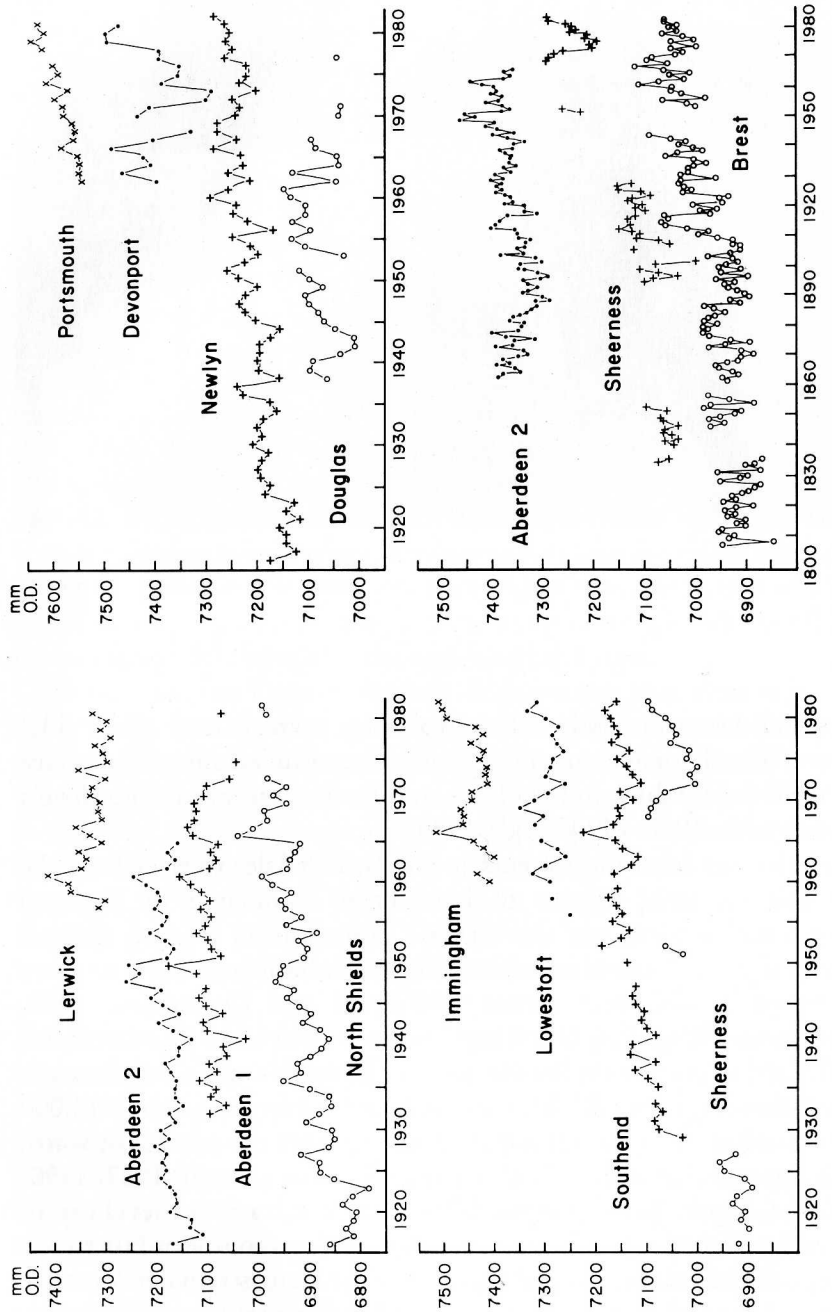

Fig. 1.3. Trends in mean sea level at a number of UK stations (after Woodworth, 1987).

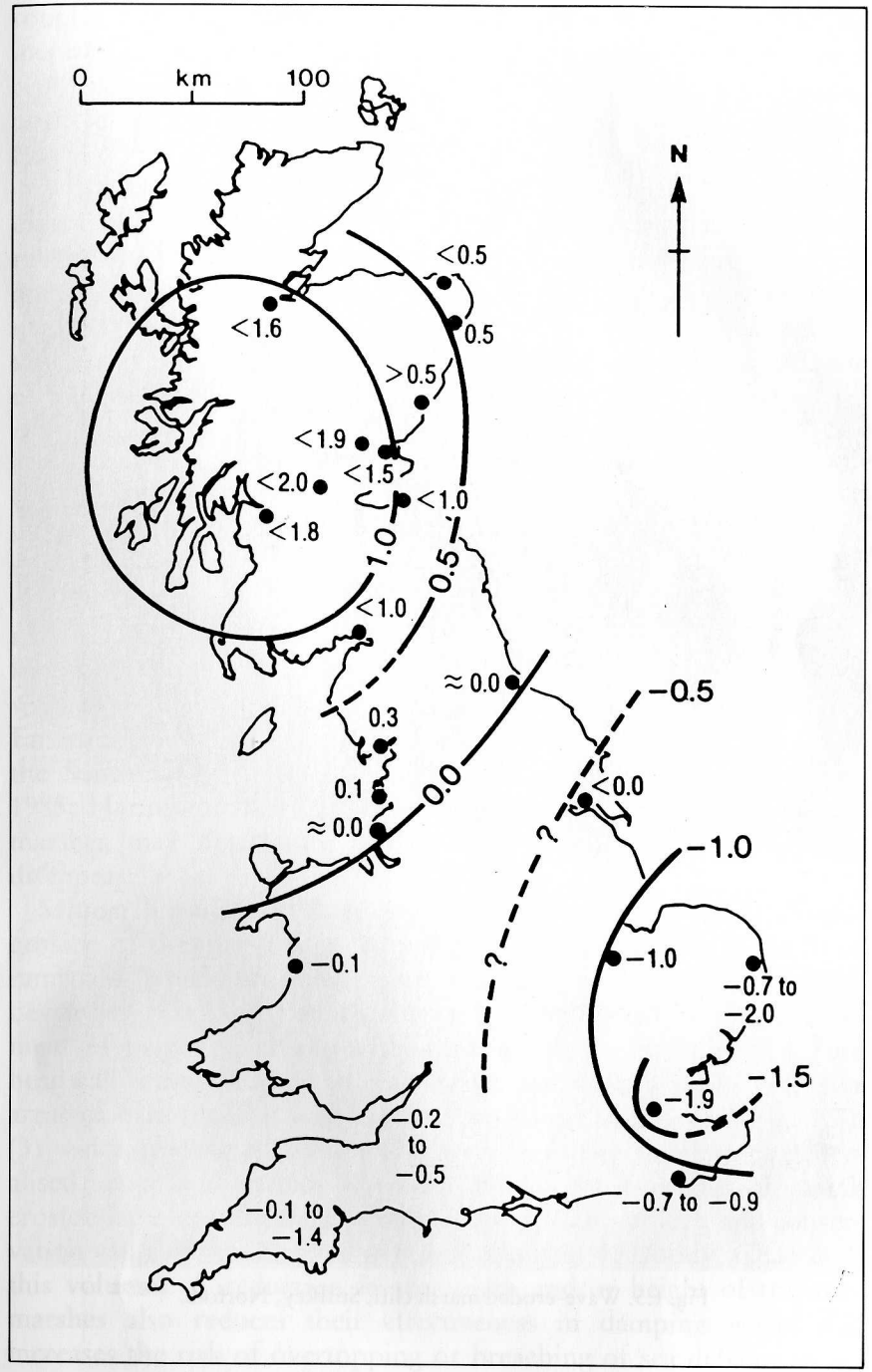

Fig. 1.4. Holocene crustal movements in the UK (after Shennan, 1989).

Fig. 1.5. Wave-eroded marsh cliff, Stiffkey, Norfolk.

roughly from the Mersey to The Tees (Fig. 1.4; Shennan, 1989). The increase in the rate of global sea-level rise forecast during the next century will serve to shift the zone of neutral sea level change northwards and will enhance the upward sea-level trend in southern England, where many major saltmarsh complexes are located.

Whereas wind-wave climate has most influence on the horizontal extent of mudflats and saltmarshes, sea-level, combined with tidal range (which may be expected to vary with relative sea level), mostly affects their vertical growth. Under normal circumstances, saltmarshes do not grow higher than the level of the highest astronomical tide, since the frequency and duration of tidal flooding controls the introduction of minerogenic sediment. In northern Britain, where relative sea level is falling, saltmarshes have the potential, once they have reached a high enough position in the tidal frame, to evolve into brackish or freshwater organogenic marshes. and then into coastal scrub or woodland. By contrast, in southern Britain, saltmarshes have the task of maintaining a combined rate of vertical minerogenic and organogenic accretion which can keep pace with the rate of sea level rise. The physical and ecological response of saltmarshes to the forecast increase in rate of sea-level rise in the next century is of widespread concern (Boorman *et al.*, 1989; Department of the Environment, 1991). Many saltmarshes in Essex, Kent and parts of the South Coast are already experiencing serious erosion (Kirby, 1985; Harmsworth and Long, 1986), and there is concern that the marshes may deteriorate further and, in some areas, eventually disappear.

Saltmarsh erosion in these areas currently takes several forms; (1) erosion of the marsh edge, forming either a steep cliff (Fig. 1.5) or ramp on which erosional spur and groove topography is well developed (Fig. 1.6; Pethick, Chapter 3, this volume); (2) enlargement of pans and creeks within the marsh by bank collapse and headwall retreat, leading to coalescence and appearance of extensive areas of bare mudflat with residual vegetated hummocks (Fig. 1.7); (3) widespread deterioration of marsh vegetation, leading to generalised scour and surface lowering. All of these modes of marsh erosion have a profound effect on the vegetation ecology and conservation value of the saltmarshes (Gray, Chapter 4; Doody, Chapter 5, this volume). A reduction in the width and/or height of the saltmarshes also reduces their effectiveness in damping waves and increases the risk of overtopping or breaching of sea defence structures on their landward side (Brampton, Chapter 6, this volume). As

Fig. 1.6. Erosional spurs and grooves on the seaward margin of the Dengie marshes, Essex.

yet, however, it is by no means established with certainty that increased marsh erosion in southeastern England is associated with changing sea level; the role of changes in inshore wave energy, sediment supply and the effects of human activities including dredging and channel modification have not yet been fully evaluated.

Outstanding questions about saltmarshes and requirements for future research

Although saltmarshes represent an attractively complex and relatively accessible environment, and have consequently been studied from several standpoints over many decades, many of the fundamental questions concerning them (and the intertidal flats from which they develop) remain incompletely answered. In the context of British saltmarshes these questions include:

(1) What are the sources and amounts of fine sediment currently supplied to particular saltmarsh complexes?

(2) Can geochemical, mineralogical and physical characteristics be used to identify sediment transport paths and quantify sediment budgets?

Fig. 1.7. Residual mud mounds formed by internal marsh erosion, Tollesbury marshes, Essex.

(3) What are the basic depositional and erosional mechanisms, as governed by the tide, waves and plants, involved in the formation of saltmarshes and mudflats?

(4) What are the current rates of vertical and lateral accretion/erosion on British saltmarshes?

(5) What is the degree of geomorphological and sedimentological variability of British saltmarshes and mudflats, and what is its explanation?

(6) What is the relative importance of factors which control the vigour of saltmarsh vegetation, and why are certain species prone to periodic die-back? Can this be managed and controlled?

(7) In what ways, and to what degrees, have saltmarshes and mudflats responded to historical changes in such forcing factors as tidal regime, wind-wave climate and sea-level movement, and what has been the importance of essentially local factors, such as shifting channels and shoals?

(8) Can models be developed which will predict the likely response of existing marshes to changes in relative sea level, wind-wave climate, and sediment supply over the next century,

Fig. 1.8. Marsh restoration works, Deal Hall, Dengie Peninsula, Essex.

and can these models be developed sufficiently quickly that they can be incorporated into cost-benefit analyses relating to future coastal management strategies?

(9) Can measured short-term accretion rates on marshes be used as indicators of the rate of sea-level rise? Do we understand enough about post-depositional modification and consolidation of marsh sediments, and about spatial and temporal variations in accretion rates, to identify a meaningful sea-level 'signal' against background 'noise'?

(10) Can monitoring of changes in marsh vegetation give an early warning of stress to the system induced by sea-level rise or other environmental changes (Vanderzee, 1988)?

(11) What are the implications of increased marsh erosion in polluted estuarine systems? Will this result in a pulse of contaminants being released into the water column? If so, what are the likely effects?

(12) What effects will accelerated sea-level rise and possible changes in wind/wave climate have on marsh vegetation communities and their associated fauna? Will there be an increase in the area covered by low and mid-marsh communities at the expense of

Fig. 1.9. Experimental planting of *Spartina* on artificial mud mounds, Dengie Peninsula, Essex.

high-marsh communities, or will low-marsh and mudflat environments become less extensive in response to a steepening of the nearshore profile? How will these changes affect migratory birds and other species?

(13) What methods are most appropriate in the British context for the artificial creation and rehabilitation of eroding saltmarshes? Are the 'polder' technologies which have been developed in North Germany, The Netherlands and Denmark likely to prove successful in the UK context (Figs. 1.8, 1.9)? Is 'marsh nourishment', involving pumping of sediment onto marshes from adjacent mudflats or from imported dredge spoil (Delaune *et al.*, 1990), a viable alternative? How successful are artificial roughness elements and wave breaks (Seneca *et al.*, 1975) in accelerating the accretion rate on mudflats and saltmarshes? Is mudflat 'ploughing' a worthwhile and effective way of increasing the suspended sediment concentration and marsh accretion rates? What are the best methods of establishing vegetation on unvegetated mudflats under different conditions? What methods should be used to deal with eroding saltmarsh cliffs? Are the engineering methods devised for

application in fluvial systems (Coppin and Richards, 1990) appropriate for intertidal systems?

(14) What will be the physical and ecological effects of abandoning or repositioning existing sea walls? Is this a cost effective, environmentally acceptable and politically feasible policy?

A number of recent reports have gone some way towards establishing the basis on which these questions can be addressed (Doody, 1985; Hydraulics Research, 1987, 1988; Boorman *et al.*, 1989; Gray and Benham, 1990; Cannell and Hooper, 1991; Department of Environment, 1991), but much fundamental research remains to be carried out before definitive answers can be given.

Acknowledgements

We are grateful to Rosemary Gillespie for assistance in preparing this and the other written contributions arising from the Saltmarsh workshop. University of Reading PRIS Contribution No. 141.

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2

Recent sea-level changes

M.J. TOOLEY

Introduction

The Quaternary period (last 2.47 Ma) has been characterised by climatic changes and sea-level changes which have had a profound effect on coastal environments including saltmarshes. In middle and high latitudes, interglacial and interstadial conditions alternated with glacial conditions with the latter more characteristic than the former. In low latitudes, humid and arid conditions alternated. Associated with the glacial/interglacial conditions of middle and higher latitudes, especially in the Northern Hemisphere, were large amplitude and long period changes in sea level. Elevated beaches in formerly glaciated areas provide evidence of a changing relationship between land levels and sea levels. The massive transfer of load from land areas and some continental shelves to the ocean basins of the world during deglaciation had an impact on sea level through adjustments in geoid relief, and both isostatic adjustments and phase changes in the aesthenosphere have also affected this relief pattern over a longer time scale. Over shorter timescales (10 to 1000 years), there is great regional variability of sea-level behaviour which has an important effect on coastal processes.

Sea level can be recorded directly by satellite altimetry or, where it intersects a landsurface, by tide gauges. It can also be recorded indirectly but less sensitively from the geological record. Employing an objective methodology, a data base of sea-level index points can be built up and used to quantify rates of sea-level change and recent vertical earth movements.

Many sea-level problems, both fundamental and strategic, have been addressed in the last 20 years with foci provided by the INQUA Commission on Quaternary Shorelines, the International Geological Programme and the International Geographical Union (Tooley, 1987b). Conference proceedings and edited volumes bear witness to this fertile area of research (e.g. Kidson and Tooley, 1977; Suguio *et al* 1979; Greensmith and Tooley, 1982; Smith and Dawson, 1983;