Important note:

This technical report has been split into two sections to reduce file size for download. This document, part one, represents the main text of *Sand dune processes and management for flood and coastal defence Part 5: Dune management practices and options at selected dune systems in England and Wales.*

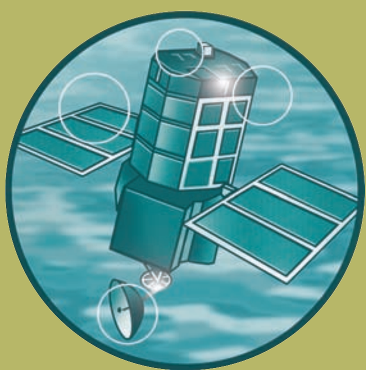
Accompanying figures can be found in part two.

Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

Sand dune processes and management for flood and coastal defence

Part 5: Dune management practices and options at selected dune systems in England and Wales

R&D Technical Report FD1302/TR



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Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Sand dune processes and management for flood and coastal defence

Part 5: Dune management practices and options at selected dune systems in England and Wales

R&D Technical Report FD1392/TR

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Statement of use

This report provides a summary of research carried out to assess the significance of coastal dune systems for flood risk management in England and Wales, to document the nature of the underlying geomorphological processes involved, and to identify alternative strategies and techniques which can be used to manage coastal dunes primarily for the purposes of coastal flood defence, taking into account nature conservation interests and other uses of coastal dunes. The report considers the general effects of changes in climate and sea level on coastal dune systems, and examines the current problems and options for future management at five example sites. The report is intended to inform local engineers and other coastal managers concerned with practical dune management, and to act as stimulus for further research in this area.

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Executive summary

Background
Sand dune systems can provide an important natural coastal flood defence and are also of great importance from nature conservation, recreation and tourism perspectives. This project was based on a recognition that (a) considerable information exists about the ecology of coastal dune systems in England and Wales but geomorphological, sedimentological and engineering management aspects have been relatively neglected, and (b) recent changes in coastal management philosophy towards adaptation and risk management mean that there is increasing interest in developing new methods of managing coastal dunes as dynamic natural defences. To this end a better understanding of the physical nature of sand dune systems, and of sand dune processes, is required.

Project objectives
The main objectives were: (1) to compile information about the geomorphological and sedimentological character, flood defence significance and management status of coastal dune systems in England and Wales; (2) to review available methods for the management of coastal dunes; (3) to evaluate the effects of predicted climate and sea level change on dune systems, and to consider the implications of removing hard defences to recreate more dynamic dune systems; (4) to examine the issues and options for future management in relation to five case study areas; and (5) to identify aspects of best practice and requirements for further work.

Results
The results are summarised in this report which consists of five parts. Part 1 provides an overview of the project, the main issues addressed, the approaches used and the main conclusions. Part 2 presents a review of sand dune processes and the significance of coastal dunes for coastal flood risk management. Part 3 describes the methods used to obtain data and presents brief descriptions, location maps and database summaries for each dune site. Part 4 reviews available methods to manage and modify coastal dunes, and Part 5 discusses the problems and management options at the five example sites (Sefton Coast, Spurn Peninsula, Brancaster Bay, Studland, and Kenfig Burrows). Additional information is provided in publications and a PhD thesis which arise from the work (details given in Part 1).

Coastal dunes in England and Wales presently occupy an area of approximately 200 km^2. A total of 158 individual dune localities, grouped into 112 dune 'sites', were identified. Coastal Cell 9 has the largest total area of dunes (*c*. 48 km^2) followed by Cell 11, Cell 8 and Cell 1. The largest single system is located on the Sefton Coast (*c*. 20 km^2), but there are few systems larger than 5 km^2 and more than 50% of the sites are <1 km^2 in size. The largest systems occur on the west coasts of England and Wales but smaller systems in eastern and southern England are also locally of considerable flood risk management significance. Their importance in this regard lies primarily in their function as barriers to coastal flooding, and is dependent on the asset value of the land behind and the existence or otherwise of other flood defences. Dune systems are especially important where they protect high density

residential or industrial developments, high-grade agricultural land or habitats of international conservation importance. Compared with many other forms of defence, dunes are less visually intrusive, have greater value for wildlife and recreation, and are able to respond more readily to changes in environmental forcing factors (e.g. climate and sea level change, sediment supply conditions).

Virtually all dunefields in England and Wales have formed entirely in the last 5000 to 6000 years, and in most places the present dune topography is less than a few hundred years old. Dune migration occurred on a large scale during the Little Ice Age, but many sites still had extensive areas of bare sand as recently as the 1970's, largely as a result of human activities. Dune stabilisation measures since the 1950's, and particularly in the 1980's and 90's, have stabilised most dunefields to a high degree. Areas of aeolian activity are now restricted mainly to sections of eroding coast and a few inland blowouts which have remained active due to local wind acceleration and increased turbulence.

Approximately 35% of the total dune frontage in England and Wales has experienced net erosion or is protected by hard defences, 35% has experienced net stability and 30% net seawards accretion. The extent of frontal dune erosion may increase in the next century as a result of increased storminess and sea level rise, and this may have negative impacts on the extent of some dune habitats and the effectiveness of dune systems as flood defences. However, the consequences of such changes will vary from location to location, reflecting differences in natural processes and beach-dune sediment budgets.

Most dune systems in England and Wales are composed of quartz sands, and marine carbonate is important only in some systems in Devon and Cornwall and southwest Wales. The main sources of sand in the past were marine reworking of glacial sediments on the sea bed and in coastal cliffs. These sources are much less significant at the present time. Increased storminess and rising sea level are likely to cause more widespread erosion, leading to re-distribution of existing coastal sediments. Accretion can be expected at the down-drift ends of sediment transport cells, but dunes at the up-drift ends will experience accelerated erosion and greater risk of breaching/overtopping.

Conclusions and Recommendations

Wherever possible, coastal dune and beach systems should be allowed to respond naturally to changes in forcing factors and sediment supply conditions. Where accommodation space exists and conditions are favourable, frontal dunes should be allowed to roll back to establish a new equilibrium. However, in areas of low wind energy or strongly negative beach sediment budget, dune dissipation is likely to occur unless nourishment with fine-grained sand and artificial dune profiling are undertaken. It is recommended that a detailed Geomorphological Evaluation Study should be undertaken at each dune site, or group of sites, to assess the requirements and to identify the most appropriate management strategy. This will require nature conservation and other interests to be taken into account. Where not in existence, systematic monitoring programmes should be set up to provide early warning of dune change. Data should be obtained in a standardised format which can be exported for centralised analysis.

Contents

5.1 Introduction

This part of the report discusses the morphology, process regime, development and management issues relevant to flood defence at five example dune sites. High resolution lidar (laser altimetry) data, complemented by data obtained from conventional topographic and bathymetric surveys, has been used to examine relationships between frontal dune morphology and dynamics and beach morphology at each site. This information is used to provide a framework for an evaluation of key strategic management issues at each site.

The five sites considered are: (1) Sefton Coast (Merseyside), (2) Spurn Peninsula (Humberside), (3) Brancaster Bay (Norfolk), (4) Studland (Dorset) and (5) Kenfig Burrows (South Wales) (Figure 5.1). These sites were chosen to provide wide geographical coverage and contrasting examples of system attributes, process regime, and management issues. Spurn Peninsula and Studland are both barrier spit systems, although they occur in different process regimes and have significantly different morphology, whilst Kenfig Burrows and the Sefton coast are open coast inland transgressive systems. The Brancaster Bay dune system forms part of a barrier island dune system which is now attached to the mainland by sea embankments and partly reclaimed salt-marshes. All five sites are of major nature conservation importance but vary in their flood defence significance.

The major controlling environmental variables for the five sites are compared in Table 5.1. All of the sites except Studland have a mean spring tidal range >4 m and can be classified as macrotidal according to the scheme proposed by Davies (1964). Studland is classed as micro-tidal (mean spring tidal range <2 m; Table 5.2). The highest energy wave conditions are experienced at Kenfig, followed by Spurn and Sefton, although at all three sites the wave energy regime can be described as moderate. The beaches at Sefton, Studland and Brancaster are predominantly sandy, while those at Kenfig and Spurn frequently contain a higher proportion of shingle. However, in all areas except Sefton the beach sediments show significant spatial and temporal variation in response to fluctuations in wave and tide conditions. Sediment supply to the beaches at the present day is low to moderate at Sefton and Spurn, and low at Kenfig, Studland and Brancaster.

5.2 Sefton Coast

5.2.1 Location and physical environment

The Sefton coastal dune system is the largest in England and Wales and has been the subject of the greatest amount of scientific research. The dune system is located between the Mersey and Ribble estuaries and is transitional between open coast and estuarine regimes, being influenced by processes in the eastern Irish Sea and in the Ribble and Mersey estuaries (Pye, 1990; Figure 5.2). At its widest point, near Formby Point, blown sands extend inland almost 4 km from the shore, but high dunes are restricted to the most seaward 2 km. The dune belt is narrowest near Hightown, and there is another low/narrow point on the south side of Formby Point between Albert Road and Range Lane which may represent a former course of the River Alt. An artificial flood bank was constructed within the dunes in this area during the 1970’s to provide additional flood defence. Landward of the dune barrier lies an extensive area of low-lying agricultural land which forms the West Lancashire Plain (Figure 5.3). Much of this area was originally mossland with several shallow meres. Drainage during the past 250 years has resulted in subsidence of the land, with the result that much of the area now lies well below storm surge level. There are major urban developments at Formby, Ainsdale, Southport and Hightown which depend partly on the dunes for coastal flood defence.

The Sefton coast experiences a macrotidal regime, the mean spring tidal range being >8 m, resulting in exposure of a large intertidal zone at low tide. Offshore tidal currents can be strong, and there is significant potential for sand transport. The coast is exposed to prevailing south-westerly and westerly winds but wave energy is moderate due to the confined nature of the Irish Sea, and waves from the southwest are restricted by the shelter provided by Anglesey and the North Wales coast. The largest waves approach from the west-northwest, which is the direction of greatest fetch. Storm surges of up to 2 m can raise high tidal levels above 6.0 m ODN, and storm waves combined with storm surges result in severe dune erosion every few years (Pye, 1991).

5.2.2 Historical development and broad-scale morphology

The Sefton dunes probably originated as a barrier island system (Pye & Neal, 1993) but they are now attached to the mainland and the morphology has been profoundly affected by transgressive sand movement over the back-barrier deposits during the Little Ice Age. Consequently, for the purposes of this study they have been classified as an open coast transgressive system. Elements of open coast and estuarine fringing dunes also occur, particularly south of the River Alt and north of Southport.

Dune formation first began on the Sefton coast approximately 5,600 years ago and has continued episodically until the present day. Soil horizons buried within the dunes testify to periods of aeolian sand movement which have alternated with phases of dune stabilisation. Pye & Neal (1993) recognised four dune morpho-stratigraphic units in the eroding dune cliffs at Formby Point. Each unit is defined at the top by a peat or humic horizon. At the base of the profile is an intertidal and supra-tidal mud unit which contains *in situ* alder (*Alnus*) roots that have given a minimum radiocarbon age of 3230 ± 80 ^{14}C years BP. Unit 1 lies directly on this mud unit and is a podsolized dune sand capped by an organic A_1 horizon containing oak stumps and roots dated at 2510 ± 120 ^{14}C years BP (Pye, 1990). Optically stimulated luminescence (OSL) dating of the podsol A_2 horizon from this unit is in broad agreement with the radiocarbon dates which bracket this sample. This period of soil development corresponds with the onset of the Sub-Atlantic period, which was a period of climatic deterioration following the post-glacial climatic optimum (Neal, 1993). Widespread stability, with localized dune reactivation, continued until the Middle Ages, when increased storminess caused rapid coastal erosion and instigated extensive sand movement, forming dune Unit 2. Optical dating of a sample from C horizon dune sands in a section inland of the town of Formby indicates extensive aeolian activity during this period, with mean age estimates ranging from AD 1310 to AD 1620 (Pye *et al*., 1995). Dune instability has continued intermittently up to the present day, and Unit 3 has been dated between AD 1600 and AD 1900, corresponding with the cooler, wetter and more stormy period of the little Ice Age (AD 1430 to 1850). The fourth unit locally rests on all three older dune units and is related to the onset of erosion around Formby Point after 1900, which resulted in extensive transgressive sand sheet and rollover foredune ridge development (Neal, 1993; Pye & Neal, 1994).

Several dune morphological types are present in the Sefton system, including foredune ridges, hummocky dunes, blowouts, parabolics and sand sheets. Embryo dunes are present where accretion is occurring to the north of Ainsdale and around Range Lane, south of Formby Point (Plate 5.1). Blowouts are present both in the foredunes and in the hind dunes, the largest being the trough-shaped Devil’s Hole at Ravenmeols (Plate 5.2).

Erection of sand fencing on the upper beach between 1880 and 1914 was responsible for the development of a series of sub-parallel dune ridges, notably at Freshfield and Ainsdale and to the north of the River Alt mouth. At Ainsdale, the belt of ridges was several hundred metres wide at its maximum, but erosion has since truncated some ridges (Pye, 1990).

Most of the shoreline experienced seaward progradation during the nineteenth century, but around 1900 erosion set in at Formby Point and has continued to the present day (Gresswell, 1937, 1953; Pye & Neal, 1994; Figures 5.4 & 5.5). The erosion has been greatest to the north of Wicks Lane due to wave focusing on this part of the coast, and the coast here has retreated by over 500 m in 100 years. At Lifeboat Road, at the centre of Formby Point, the present shoreline lies almost in exactly the same position as during the late eighteenth century, having advanced seawards and then retreated again by over 300 m. The northern erosion limit has extended northwards towards Southport and now lies just north of Fisherman’s Path. Much of the dune frontage between Fisherman’s Path and Lifeboat Road is cliffed due to wave erosion (Plate 5.3), and back-barrier silts are widely exposed on the foreshore (Plate 5.4). The southern limit of erosion has fluctuated but in recent decades has also shown a tendency to move northwards, now lying near Alexandra Road on the south side of Formby Point. Between Albert Road and Alexandra Road the high water mark presently lies 100 to 200 m seaward of its position in the 1890’s, and a zone of well-vegetated hummocky dunes separates a former promenade from the sea.

There is a littoral sediment transport divide between Lifeboat Road and Victoria Road, resulting in transport of sand both northwards towards the Ribble estuary and southwards towards the Mersey estuary. The beach and foredune sediment budgets between Birkdale and Southport, between Albert Road and the River Alt, and north of Seaforth container terminal are strongly positive, resulting in foredune building and environmental problems associated with inland movement of blowing sand (Plate 5.5). At Formby Point the natural trend for marine erosion of the dunes is exacerbated by heavy visitor pressure (Plate 5.6).

Several factors apparently contributed to the onset of erosion after 1900, including changes in the wind/wave climate and the effects of dredging and training wall construction in the Mersey and Ribble estuaries on sediment transport, nearshore bathymetry and wave regime (Pye & Neal, 1994). Foredune erosion was also accelerated during the twentieth century by the abandonment of beach and foredune management practices implemented in the late nineteenth century, and by increasing visitor pressure from the 1920’s onwards.

5.2.3 Sediment characteristics and sources

The beach and dune sediments on the Sefton coast are predominantly composed of fine to medium, well-sorted to very well-sorted sands which show only limited variation along the coast (Pye, 1991; Kavanagh, 1997; Jay, 1998). There is a slight fining tendency towards the north and some pockets of mud occur in runnels towards Southport pier. Mud and fine sand has also accumulated within the high intertidal zone of the Alt estuary.

There are no significant differences in the mean grain size or sorting between the beach and foredune samples, reflecting the fact that aeolian transport is not selective when the source beach sediments are fine grained and well sorted. On average, the frontal dunes are slightly coarser and less well sorted than the dunes further inland, but these differences are not statistically significant.

The dune sands are mainly composed of silica (mostly >90%) with minor contributions from other major oxides and trace elements. The calcium oxide content is low, between 1 and 3%, reflecting a generally small shell fragment component south of Southport pier. The CaO content increases in the beach and dune sediments along the Ribble estuary, reflecting high biogenic productivity in the estuarine tidal flats.

The main source of sand is the offshore zone in the adjoining south-eastern Irish Sea. Much of the sea floor in this area is covered by sand derived from tidal current and wave reworking of relict glacial deposits. Little sand is transported to the coast by the Rivers Mersey and Ribble, or derived from cliff exposures along the North Wales coast.

5.2.4 The role of storms in dune erosion

Studies by several authors (Parker, 1975; Pye, 1991; Jay, 1998) have demonstrated the importance of storms as causes of frontal dune erosion at Formby Point. Damage is especially severe when strong westerly or north-westerly winds and large waves coincide with high water levels (especially those above 5.5 m O.D.). Under these conditions soaking of the dune toe leads to slumping of sand, in addition to the direct physical effect of waves which undercut the toe and cause collapse (Parker, 1975; Pye, 1991). Since 1991 tides at Liverpool have reached or exceeded 5.5 m ODN on at least eight occasions (Figure 5.6). During the 1990's major frontal dune erosion induced by storms occurred in February 1990, February 1997 and January 1998 (Figure 5.7). The February 1990 event was particularly severe on account of the fact that strong westerly winds were sustained over several consecutive high tides (Figure 5.8).

Tide gauge records suggest a slight upward tendency of mean sea level at Liverpool over the past century and a half, and especially over the last 70 years (Figure 5.9). In part this may be associated with increased storminess and frequency of surge components, but there is as yet no conclusive evidence that this has been a significant factor in changing the coastal and nearshore morphology.

5.2.5 Beach and frontal dune morphology and morphodynamics

Work by Gresswell (1937, 1953) indicated that the onset of frontal dune erosion at Formby and Ainsdale was preceded by narrowing and steepening of the beach. A narrowing of the upper beach (especially the backshore) was identified as being of particular importance since it allowed wave run-up during even moderate storms to reach the dune toe. Analysis of topographic beach profile data obtained by Sefton Council subsequently confirmed that changes in beach morphology provide a useful early warning indicator of the onset of frontal dune erosion (Pye & Neal, 1994). Consequently, lidar data flown in March 1999 were analysed in this study to quantify more precisely the morphological relationships between beach morphology, dune morphology and frontal dune erosion/accretion status at different points along the coast. A digital terrain model was constructed from the data and cross-sections obtained at 78 locations between Crosby and Southport (Figure 5.10).

The large tidal range results in the formation of a relatively wide foreshore which is characterized by multiple ridge and runnel development. The individual ridges and runnels lie at a slight oblique angle to the coastline. The foreshore on average becomes wider and flatter in a northerly direction towards the Ribble estuary, and southwards from Formby Point towards the main approach channel of the Mersey estuary. It is currently narrowest and steepest between Formby Point and Freshfield (transects 30 to 45 shown on Figure 5.10) where dune erosion is most rapid.

The height of the frontal dunes shows an inverse relationship with beach width, the highest dunes being located on the eroding section of coast which is fronted by the narrowest and steepest beach (Figure 5.11). This is because on this relatively high wind energy coast a high proportion of the eroded sand is reworked landwards, and the frontal dune ridge grows in size in the manner of a ‘rolling carpet’ or ‘snowball’ during coastal recession (Pye, 1990). Exceptions to this rule occur where the sand cover on the beach is thin and kept permanently wet by a perched groundwater table on top of the underlying Holocene silts, and where sand is funnelled inland through low gaps in the dune topography. This is most notably the case near Massam’s Slack and Dale Slack Gutter between Victoria Road and Fisherman’s Path.

The position of HAT has recently retreated by 2.4 m per annum near transect 39 and by 3.4 m per annum near transect 43 (close to Fisherman’s Path; Figure 5.5). However, there appears to have been no associated steepening of the beach above MLWN. At the same time, the beaches and dunes near Altcar (south of transect 30) and near Ainsdale (north of transect 50) have been accreting (e.g. transect 64), reflecting the longshore transfer of sand from the eroding section at Formby Point towards the north and south. A green beach with embryo dunes, initiated by *Puccinellia* colonization and subsequently followed by *Leymus* spp. and *Ammophila* spp. invasion, has developed in front of the existing foredune between Ainsdale and Birkdale.

Analysis of the lidar data (Figures 5.10 to 5.13; see also Saye *et al*., 2005) allowed four sections of coast to be distinguished. South of the River Alt (transects 1 to 14), the foredune is generally stable (partly fronted by rubble) or accreting, with the exception of a short stretch near Blundellsands Sailing Club, opposite Hightown, where it is still eroding. The highest part of the foredune varies from 6.5 to 11.4 m ODN. The River Alt runs almost parallel to the coast, and the beaches landward of the course of the Alt are about 150 m wide (measured between ODN and HAT), sloping gently at 1 to 2°. Holocene silts and peats are extensively exposed in this area, or are covered only by a thin veneer of sand. The foredune is lowest at transect 8 where its maximum height is just 1.3 m above HAT. Behind the eroding dunes at Hightown lies an area of recent residential development, but at present the width of dunes is sufficiently large that the risk of storm surge flooding is fairly low.

North of this area, but still south of Formby Point, there are accreting foredunes (transects 15 to 26) which are slightly higher (7.4 m to 12.0 m ODN) than those in the River Alt region and are fronted by wide (831 m to over 1419 m) beaches. In the 1970’s there was concern that a storm breach might develop where the dune belt was narrowest near Range Lane, and an earth flood bank was constructed to provide additional protection. Since that time the foredunes in this area have prograded by more than 50 m and the dunes have also increased in elevation through natural processes. Slightly further to the north, the large Devil’s Hole blowout has continued to increase in size and sand tongues have advanced landward, but this currently poses no direct threat to property.

Transects 29 to 50 represent the eroding section of Formby Point. The foredune is high (up to 18.9 m ODN) and extensively cliffed, retreating at an average rate of 3 m per annum over the past 40 years. However, both the frontal dunes and hind dunes further inland contain a substantial sand volume, and there is currently no serious erosion or flood risk to the main settlements of Formby and Freshfield, although a number of isolated properties and caravan parks could be affected in the relatively near future. Truncation of the former artificial shore-parallel ridges near Massam's Slack and Fisherman's Path has resulted in the formation of a large transgressive sand sheet fronted by a foredune which had a maximum height only 2.5 m above HAT in 1999, rendering it vulnerable to marine incursion during major storms. However, since 1999 this foredune has increased in height, largely through natural processes as sand blown along the beach has found its way into the gap and has been trapped by vegetation.

North of Fisherman's Path lies the fourth, accreting section of coast which extends towards Southport (transects 54 to 78). Frontal dune volumes and maximum crest heights diminish towards the north, reflecting higher rates of lateral progradation, in accordance with the model predictions of Pye (1990). At transect 76 the maximum foredune crest height is low, being only 1.3 m above HAT, although higher dune crests occur further inland. The beach fronting these dunes is wide (530 to 2131 m) and the average slopes (measured between ODN and HAT) are low (0.1 to 0.6°). These beaches are highly effective in dissipating tidal and wave energy, and the large width of dunes means that there is virtually no risk of flooding to property and infrastructure between Ainsdale and the southern end of Southport. In recent years flood risk at Southport itself has been substantially reduced by construction of a new sea wall which extends southwards to Weld Road, Birkdale.

Field monitoring between October 1996 and August 1998 (Jay, 1998) showed that foredune sand accretion was limited to the coast south of transect 26 and north of transect 49 (Figure 5.14). The intervening section lost sand from the frontal dunes, corresponding with a landward movement of HAT (Figure 5.15). A relatively good correlation (R^2=0.52) was evident between changes in upper beach volume and foredune volume over this period (Figure 5.16).

The foredune and beach sediment volume changes recorded by Jay (1998) have been compared with the morphometric parameters extracted from the lidar data in the present study (Figure 5.17). No clear relationship is evident between frontal dune height or volume and the foredune sand erosion/accretion recorded by Jay (1998). However, a weak relationship is indicated between beach width and beach slope and observed foredune sand erosion/accretion. Eroding, often cliffed, foredunes are almost invariably associated with narrow and steep beaches, whereas accreting foredunes are associated with wide and flat beaches. Similar relationships, with a slightly higher correlation coefficient, were found between the vertical erosion/accretion rate of the upper beach and foredune height, beach width and beach slope, respectively (Figure 5.18). Using these data, it is possible to identify critical values of beach width and slope which can predict the onset of net foredune erosion or accretion, although inevitably any such average relationship can be affected in the short-term by severe storm surges (Saye *et al*., 2005).

5.2.6 Management issues and practices

The Sefton dune system is important for nature conservation and recreation in addition to serving an important flood defence function. The dune system has been affected by a range of past activities, including asparagus cultivation, sand mining and military maneouvers (Atkinson & Houston, 1993), but by comparison with many other systems in England and Wales the Sefton dune system retains many natural features. The whole area is covered by several nature conservation designations (see Part 3 of this report), and the site is of major international importance for wildlife conservation. It is also nationally important as a geomorphological and geological system identified in the JNCC Geological Conservation Review (May, 2003a). A major task of coastal managers is therefore to strike an appropriate balance between these diverse interests which, in some instances, may be conflicting.

A high priority is to ensure the integrity of the sand dune belt as an effective flood defence barrier in the medium to long term, taking into account the possible effects of increasing sea level and storm surge frequency. From a coastal engineering point of view, a high standard of flood defence can best be ensured by a high, wide and generally stable coastal dune system fronted by wide, high beaches (as discussed in Part 2). In the case of the Sefton coast, there is limited opportunity for very large-scale set-back of the flood defence line since the nearest high ground lies more than 10 km inland, and the low-lying plain of west Lancashire and north Merseyside contains a high concentration of urban and industrial development, as well as high-grade agricultural land. The presence of property and infrastructure relatively close to the coast also acts as a constraint on the scale of active sand blowing and dune migration which can be permitted.

As recently as the 1970's, blowing sand and mobile dunes posed a significant problem for the coast road near Ainsdale, and for the Liverpool to Southport railway line. Consequently, the strategy adopted during the later 1970's, 1980's and 1990's placed considerable emphasis on sand stabilization and a 'hold the line' approach to the management of the frontal dunes at Formby Point. More recently, it has been recognised that a more sustainable strategy is to allow controlled retreat at Formby Point, with continued efforts to manage visitor pressure in this area, and to allow the system to evolve naturally in accordance with natural processes, taking advantage where possible to encourage new dune growth in areas of natural accretion. Nature conservation interests have also made a strong case for a higher degree of sand movement and dune mobility within the area in order to maintain biodiveristy, and especially to allow dynamic development of the habitats necessary to sustain priority species. Much of the Sefton Coast is designated as a Special Area of Conservation (SAC) which brings obligations to conserve and protect Annex I habitat types and Annex II (flora) and Annex IV (fauna) species. Amongst the other priority habitats and species identified in the Habitats Directive are fixed (grey) dunes (fixed dunes with herbaceous vegetation) and dune heath (Eu-Atlantic fixed dunes) and individual species including petalwort, great crested newt, natterjack toad and sand lizard (Rooney, 2001). These species require significant areas of bare, mobile sand and wet slack habitat in order to thrive and breed.

There is a long history of human intervention and dune management at Sefton, with the first recorded marram planting to control mobile sand in the seventeenth century (Ashton, 1920). Prior to the First World War, sand fencing, marram planting and coniferous forest planting was undertaken on a wide scale, but these activities declined at the outbreak of the First World War. Between the wars, a range of activities, including sand mining, military training and uncontrolled recreational pressures lead to widespread deterioration of the dune environment, with widespread vegetation destruction and blown sand instability. This situation essentially continued until after the Local Government reorganization of 1974, which created Sefton Metropolitan Borough Council within the overall structure of Merseyside Metropolitan County Council. A Sefton Coast Management Scheme was formally established in 1978 to protect and restore the dunes and to encourage a long-term strategic view for the management of the coast (Houston & Jones, 1987). This initiative was followed by the appointment of a full-time Coastal Management Officer under the auspices of the Sefton Planning Department, working in close liaison with the Technical Services (Engineering Department) and local landowners. Subsequent developments have included a European Commission-funded Life-Project and formation of the Sefton Coast Partnership to encourage discussion amongst stakeholders and to maximise the opportunities to manage the dunes in a sustainable manner from flood defence, nature conservation and other perspectives.

The Second Review of the Sefton Coast Management Plan 1997-2006 identified seven main management aims:

1) to encourage and support appropriate land-use, sustainable economic development, investment and employment consistent with the natural character and conservation importance of the coast;

2) to conserve, protect and enhance the natural beauty and biodiversity of the coast, including its characteristic terrestrial, littoral and marine flora and fauna, geology, geomorphology, landscape and heritage features of architectural, historical, cultural and archaeological interest;

3) to facilitate and enhance the enjoyment, understanding and appreciation of the coast by improving and extending opportunities for quiet recreation, education, sporting and tourist activities that draw on, and are consistent with, the natural character and conservation value of the coast;

4) to support the need to protect life, property and habitats by appropriate coast defence strategies, and to maintain the sea defence function of the beaches, sand dunes and saltmarshes, consistent with the natural character and conservation importance of the coast;

5) to liase with the competent agencies for the control of activities at sea to ensure that they are aware of the high amenity and conservation value of the Sefton coast and the impact their activities may have on terrestrial sites, and to work with others to promote the conservation and management of marine resources;

6) to protect and enhance the environment by reducing pollution and promoting public heath;

7) to adopt a systematic and open approach to the delivery and monitoring of Plan outputs.

The multiplicity of land ownerships and uses on the Sefton coast has both created a variety of habitats and presented particular challenges for the integrated management of the whole dune system and achievement of sometimes conflicting management objectives. Both managers and the general public have often perceived there to be a conflict between conservation objectives and other functions of the dune system, including recreational use and maintenance of an effective flood defence. Some previously afforested dune areas have been felled to restore open dune habitat for important species such as the natterjack toad and sand lizard, but local people have raised concerns about the impact of the project both on perceived aesthetic quality of the landscape and on potential coastal erosion (Simpson & Gee, 2001). The woodlands were considered by many nature conservationists to pose a serious threat to these sensitive species and biodiversity more generally by their stabilising, sheltering and drying effects, but the importance of bare sand and the negative impacts of trees on natural dynamic processes were found to be poorly understood by the general community (Edmondson & Velmans, 2001). Despite these difficulties, in order to meet statutory obligations, land at risk has been purchased, practical management work is being undertaken to restore and create favourable conditions for particular species, and sustainable management strategies are being developed and kept subject to regular review.

The importance of the beach-dune system for flood defence has been recognized in the Shoreline Management Plans for this section of coast, and a policy of management recommended which will maintain this role while at the same time preserving the nature conservation interests. Monitoring is a key measure which has been long employed at Sefton and which will be extended in the future to provide an early warning of possible future changes and allow refinement of existing management strategies. For the time being, the policy is generally one of no major intervention on the undeveloped sections of coast while at the same time upgrading standards of defence as part of wider environmental improvement schemes along the more developed frontages at Southport and between Crosby and Hightown.

5.2.7 Possible future changes and recommendations for strategic dune management

In the medium term erosion is likely to continue at Formby Point, with associated coastal progradation on the Birkdale to Southport and Altcar frontages as eroded sand is transported both to the north and south by littoral drift, supplemented from other offshore sources. In the longer-term, erosion rates at Formby Point may accelerate if the rate of sea level rise accelerates in accordance with global climate change predictions, and/or there is an increase in storminess and storm surge magnitude/frequency. However, since much of the dune belt is relatively wide, there is no immediate serious risk of flooding at Formby, and land loss through erosion poses only a limited threat. The system is also large enough to provide scope to recreate new areas of mobile dunes and wet slacks. However, there will remain a need to manage such areas, together with visitor pressures, in order to ensure that property and infrastructure do not again become threatened.

Dune area losses at Formby and Freshfield are likely to be offset, at least in substantial part, by embryo dune, foredune, and dune slack habitat gain at Birkdale and Altcar unless there is a dramatic change in sea levels, storminess and sediment transport regime. The development of new dune ridges at Birkdale and Southport will reduce flood risk in these areas, and the requirement for additional or improved artificial defences will be focused on a relatively small number of areas such as Hightown. Continued monitoring should allow any early warning signs of change to be identified before they begin to pose a major problem.

5.3 Spurn Peninsula

5.3.1 Location and physical environment

The Spurn Peninsula forms a tapering piece of land which projects into the Humber estuary from Holderness. The southern part of the Peninsula comprises a narrow, curving sand and shingle spit which terminates at Spurn Point (Figure 5.19). The whole area was designated as a Heritage Coast area in 1988 and its overall management is now the responsibility of the East Riding of Yorkshire Council.

Geologically, the northern part of the Spurn Peninsula consists largely of glacial till which overlies Chalk. An area of low ground between Kilnsea and Easington is formed mainly of marine and estuarine silts and reclaimed marsh deposits, overlain in the east by a thin cover of blown sand. A further area of low-lying marine/estuarine alluvium separates two areas of glacial till to the south of Kilnsea. Much of the coastal frontage in this area consists of made ground and rubble mounds derived from building demolition. Low dunes were once present in this area (Kilnsea Warren) but have now been largely eroded or buried. Today significant dunes are found only along the sand and shingle spit to the south of the Visitor Centre.

At its narrowest point the sand and shingle spit is only about 50 m wide but near Spurn Head it attains a maximum width of approximately 300 m (Figure 5.20). The Peninsula is important from a flood defence point of view in that it acts as a barrier which impedes the progression of storm surges and waves into the Humber estuary. The spit is also of importance as a base for the Humber Pilots, the Associated British Ports Vessel Traffic Control Centre and the RNLI lifeboat station. In earlier times the spit also served as a strategic location for a gun battery which protected the approaches to the ports of Hull, Immingham and Goole. The spit is identified as a geomorphological feature of national importance in the JNCC Geological Conservation Review (May, 2003b), and has numerous other nature conservation and environmental designations, including NNR, SSSI and AONB (see Part 3 for further information).

Spurn experiences a macrotidal regime with a mean spring tidal range of 5.7 and is exposed to winds from almost all points of the compass, although the prevailing winds are from the southwest. Resultant Drift Potential and Resultant Drift Direction calculated from Met Office wind data for Donna Nook on the Lincolnshire coast indicate relatively low net aeolian transport (RDP = 117 vector units) in an offshore direction (128°). However, the Drift Potential is high (1672 vector units), reflecting the variable wind regime. The wind energy on Spurn Peninsula is higher than at Donna Nook in view of its more exposed location, and westerly and south-westerly winds have greater relative importance, but the overall regime is still directionally variable. This has led to the formation of foredune ridges on both sides of the spit and encourages southerly littoral drift of sediment on the North Sea side and northward transport on the Humber estuary side.

5.3.2 Historical development and broad-scale morphology

The Spurn dune system can be classified as an estuarine single barrier spit system. On the North Sea side there is a single foredune ridge at the northern end and multiple shore-parallel ridges near the southern end, indicating progradation in this area. On the estuary side of the spit there is a low cliff cut in glacial sediments along the northern section, but along the central and southern parts a hummocky foredune ridge with small blowouts is present. The dunes are generally well vegetated, largely by marram grass and sea buckthorn.

The spit has formed as a result of the net longshore drift of sediment in a southerly direction under the influence of dominant north-easterly waves, and modified by constructive swell waves from the south-east (Motyka & Beven, 1986). The sediment supplying the spit is mostly derived from the eroding cliffs of the Holderness coast, which are composed of glacial till. Wave refraction around Spurn Head results in northerly movement of sand bars along the shore of Spurn Bight (Figure 5.20; Phillips, 1963, 1964; Institute of Estuarine and Coastal Studies, 1992, 1994).

It was suggested by De Boer (1964, 1981) that the evolution of the spit has been cyclical on a timescale of *c*. 250 years, but there is only limited evidence to support this hypothesis. As the spit extends in length due to longshore drift, the neck of the spit becomes narrower, increasing the risk of overwashing and/or breaching. In historical times the northern part of the spit has been breached on several occasions, with the last series of breaches occurring between 1849 and 1856 (De Boer, 1964). In the later nineteenth and twentieth centuries the northern end of the spit was protected by groynes, wall construction and ad-hoc dumping of rubble (Plate 5.7), but in places along this section the dunes are still only 1 to 2 m high and 5 to 20 m wide (Plate 5.8). Parts of the dune frontage are cliffed and slowly eroding, despite the existence of dune toe protection (Plate 5.9). Further south, along the central and southern parts of the spit, the beach and foredune sediment budget are positive, resulting in foredune accretion and/or growth of new embryo dunes (Plates 5.10 & 5.11). There has also been recent growth of a new foredune ridge on the western side of the spit near the lifeboat station (Plate 5.12).

5.3.3 Sediment characteristics and sources

The beaches (especially in the north) contain a significant proportion of gravel intermixed with sand (Ciavola, 1997), although the surface sediments show considerable spatial and temporal variation in response to fluctuations in wind, wave and tidal conditions.

The foredunes are composed of medium, moderately sorted, unimodal sands. The mean size is on average finer on the east side of the spit but on both sides the grain size decreases towards the south. In this study, the mid beach was found to be consistently coarser than the upper beach and the frontal dunes, while the upper beach was coarser than the frontal dunes with the exception of the first sampling point on both the east side and west side. The frontal dunes are generally finer, better sorted and more finely skewed than the beach, indicating that aeolian transport is selective in transporting finer sizes.

The dune sands are largely composed of silica (mean 74.34%, SD 10.44%), have low contents of metal oxides denoting the presence of feldspars (sodium, potassium, aluminium) and a low calcium oxide content (less than 2.19%), indicating a low content of shell and/or limestone and chalk. The iron oxide content and the concentration of several trace elements, including cobalt, chromium, copper, nickel, scandium, yttrium, vanadium, zinc, zirconium, barium and the rare earth elements lanthanum, cerium and neodymium, are higher at Spurn relative to other sand dune systems on the east coast of England, indicating the importance of a localised sediment source (Saye, 2003). Geochemical trends alongshore in the frontal dunes at Spurn are evident with a southerly decrease in most trace elements and oxides accompanied by an increase in silica, sodium oxide and potassium oxide. Calcium oxide and strontium do not vary significantly alongshore. The geochemical trends observed are probably due to dilution with distance from the main sediment source which is provided by the glacial till cliffs of Holderness.

The Holderness cliffs have been eroding at a long-term average rate of 1.8 m per annum (East Riding of Yorkshire Council, 2002), potentially supplying 0.63 $\times 10^6$ m^3 of sand per annum (O'Connor, 1987). However, Ciavola (1997) estimated from volumetric changes in beach transects that only 6% of the total longshore drift travels along Spurn and is subsequently deposited on the shoals (the Binks) to the east of its southern end, the remainder being transported offshore. The permanence of the spit's attachment to the shoreline is dependent upon this sediment supply (Institute of Estuarine and Coastal Studies, 1994).

Tide gauge records for Immingham only extend back to the early 1960's, but there is no evidence of a significant rise in annual mean sea level over this period (Figure 5.21), or that changes in sea level or storminess have had a major effect the rate of sediment supply on this timescale.

5.3.4 Beach and frontal dune morphology and morphodynamics

Lidar data flown in May 1999 were used to construct a digital terrain model of the spit and to derive a number of morphological parameters relating to the dunes and adjoining beach (Saye *et al*., 2005; Figure 5.22). Ground surveys carried out by East Riding of Yorkshire Council between 1997 and 1999 were also analysed to provide additional information about the beach morphology and to provide a cross-check on the lidar data (Figure 5.23).

The protected section of dune frontage along the northern part of the spit on the North Sea side (transects 12 to 21) is characterised by low foredunes (maximum crest height of 5.6 to 8.9 m ODN), with a steep dune front, indicated by the distance between HAT and the dune crest (Figure 5.24). At transects 18 to 21 the dunes have a maximum crest height of no more than 2 m above HAT. The beach is relatively narrow and steep in the north (the distance ODN to HAT is 30 to 54 m, with a slope of up to 7° for transects 17 to 21) and wider along the central part of the spit, close to Chalk Bank (with a width of nearly 80 m at transect 11).

Further south, the foredune height increases to 13.7 m ODN and the dune front becomes less steep. The dune complex becomes more developed, achieving the greatest sediment volume at Spurn Head. However, the beach narrows (to just over 40 m) and steepens (to over 5°) towards the south, becoming slightly wider again at the very tip of the spit (transects 1 and 2).

The width of the beach between MLW and MHW is up to 124 m in the north, with an average slope of 2.0° (transect 21), decreasing to 43 m in the south (transect 3) with an average slope angle of 5.6°. Those parts of the upper beach which are backed by significant dunes, both on the North Sea side and the Spurn Bight side, are convex.

A strong negative relationship was found between foredune height and beach width, defined as the distance between MLW and MHW. As on the Sefton coast, higher foredunes were found to be associated with narrower beaches (Figure 5.25). No clear relationship was found between foredune height and the width of beach between ODN and HAT.

In this case, dune sand volume and erosion/accretion status do not appear to be related simply to beach width since the accreting southerly section is fronted by a narrower beach than the eroding section. The variation may be related partly to sediment supply and the grain size of the sediment on the beach, and partly to longshore variations in storm wave exposure. In the northern area, the beach sediments are coarser and more poorly sorted; consequently aeolian transport is limited and the dune volume is smaller. Littoral drift of the finer sediments is significant and the beach sediment budget lies close to a state of dynamic equilibrium in which alongshore transport is much greater than onshore transport. Further south, the beach sediment budget is positive and onshore transport to the upper beach and dunes has a greater magnitude than in the north. The sand fraction of the beach sediments is finer and therefore more easily transported by wind. In the extreme south, sand transport from the beach is achieved by winds from a wider range of directions than further north.

5.3.5 Management issues and practices

The development of the Spurn Peninsula has been intimately linked with the erosion of the glacial till cliffs on Holderness. These cliffs may have receded by as much as 2 km since Roman times, and during that period the spit has experienced a natural tendency to retreat landwards into the Humber estuary. Historical evidence suggests that Spurn has undergone several periods of breaching and self-healing, reflecting a fluctuating balance of sediment supply from the cliffs to the north and longshore drift of material from the northern end of the spit towards the south. Attempts to protect the Holderness cliffs from erosion in the past century have served to reduce sediment supply to the spit. Continued southward drift of material along the spit has led to loss of volume in the north, increasing the risk of overtopping and/or breaching. A breach in 1849 was filled and reinforced by construction of two chalk banks in 1855 and 1870, thereby rejoining the main island of Spurn Warren near the end of the present spit system to two smaller islands (De Boer, 1981). The most recent breach, which occurred near the neck of the spit, was closed in 1956, and since then the eastern side of the spit has been protected by a variety of ‘hard’ sea defences. On the east side, the seaward side of the frontal dune is currently protected between the northern end and the area of Chalk Bank (transect 11 in Figure 5.22). The defences comprise a combination of timber groynes and concrete/rubble revetments. On the western shore, the dunes are protected by a concrete and masonry wall in the vicinity of the lifeboat station. The concrete revetment was constructed during the Second World War to protect the railway and concrete road leading towards Kilnsea. These defences are currently in a state of disrepair.

The most critical management issue identified in the Spurn Heritage Coast Management Strategy 2003 (East Riding of Yorkshire Council, 2003) concerns the risk that the neck of the spit will be breached by the sea, severing the road link to the Humber Pilots facilities and RNLI lifeboat station. A consequence of the defence works undertaken since the last century is that the central part of the spit has been fixed, preventing the retreat required to maintain an equilibrium plan shape with the Holderness coastline. In the opinion of some geomorphologists, the present morphology of Spurn is in serious disequilibrium, analogous to a ‘coiled spring’ which could release its stored energy in a sudden morphological readjustment at any time (Institute of Estuarine and Coastal Studies, 1992, 1994).

A stated aim of the Heritage Coast Management Strategy 2003 is “to secure for the Spurn Peninsula a sustainable future based upon a return to the natural processes of erosion and deposition, whilst protecting both the valuable habitats and the socio-economic needs of the local community and the visiting public”. In order to achieve this broad aim, adopted policies include support for the approach of non-intervention in natural processes and to return the Peninsula to a more natural coastal system by non-replacement and removal of coastal defence structures, and to employ soft engineering methods to restore natural processes when opportunities arise. These policy objectives are broadly in agreement with those recommended in the local Shoreline Management Plan (Posford Duvivier, 1998) and Coastal Management Strategy (East Riding of Yorkshire Council, 2002).

Rock armour placed along the cliff toe between Dimlington and Easington in 1999 to protect the BP gas terminal at Easington could have serious consequences for Spurn. Further reductions in sediment input following these protection works could increase the risk that the narrow neck of land at the northern end of the spit will be breached again. The risks will also be enhanced by accelerated sea level rise and/or increased storminess, if predictions of the implications of global climate change prove to be correct.

A large part of the Spurn Peninsula is owned by the Yorkshire Wildlife Trust and managed as a National Nature Reserve with the assistance of English Nature who have designated the area as a Site of Special Scientific Interest (SSSI). The feature also falls within an Area of Outstanding Beauty (AONB). Spurn is also popular with bird watchers and for other forms of recreation, with approximately 65,000 visitors a year. The future management of Spurn must therefore achieve a balance between maintaining access to important infrastructure and protecting the nature conservation and recreational value of the site.

5.3.6 Options and recommendations for strategic management

Major changes in the form of the Spurn Peninsula could have adverse effects on the hydrodynamic regime of the Humber estuary. A breach in the narrow neck of Spurn would expose the mudflats on the north bank of the Humber to potential wave attack. Destruction of these mudflats would leave the flood banks of the north bank of the Humber and the urban areas behind open to direct wave attack. Tidal levels throughout the estuary could also be affected. This could have consequences for the habitats within the Humber estuary that are of national, European and international importance (Environment Agency, 2000).

At the present time erosion is only a significant problem at the northern end of the spit, and consequently this is the area where the risk of a breach is greatest. As in many other similar situations, four main management options are available for consideration: (1) do nothing, (2) removal of defences, (3) hold the line, and (4) dynamic preservation. 'Advance the line' is clearly not a viable option for this area of long-term net erosion. Under a 'do nothing' scenario, or with removal of existing defences, there is significant risk that breaching will occur under storm conditions within a relatively few years. The third option, of hold the line, could be achieved in the short to medium term by construction of new hard defences, but only at major economic cost and with serious environmental impact, and there would remain a risk that the solution and might not be sustainable in the longer term. The fourth option might be viable in the short to medium term using a combination of soft engineering measures, including beach recharge combined with artificial dune construction employing some of the techniques discussed in Part 4 of this report. Using such methods the general form of the spit could be maintained whilst permitting some dynamic realignment of the system. However, the longer-term effectiveness and sustainability of such a scheme would require careful assessment, especially in the light of a potential further reduction in sediment supply, rising sea level, and increased storminess. The costs and benefits would require evaluation alongside those of a full assessment of the consequence that a major breach might have on the margins of the Humber estuary more generally.

From the perspective of dune management, the critical question is whether an effective dune barrier could be created and maintained along the narrow neck of the Peninsula. Consideration of the sediment supply and grain size characteristics of the beaches on this part of the coast, together with the nature of the wind energy regime in the area, suggests that a self-sustaining barrier dune system is unlikely to develop of its own accord. Left to its own devices, this part of the coast is likely to evolve according to the manner predicted by the *dissipation washover model* discussed in Part 2 in this report, and the existing dune barrier, which currently provides a low to moderate level of flood protection, is likely to deteriorate until is serves no flood defence value. Intervention would be required to create and sustain a dune barrier of medium or high flood defence value. Such intervention would require importation of sand and the formation of an artificially profiled dune, followed by vegetation planting and 'trickle feeding' of fine-grained sand to the beach and dunes. As discussed in Part 4, such techniques have been used successfully in many places on the coast of Denmark and elsewhere, normally with the objective of creating a stable rather than a dynamic feature.

While creation of such a 'fixed dune barrier' feature along the northern end of Spurn would be technically and environmentally feasible, especially if maintained by periodic beach nourishment, development of a self-sustaining landward-migrating dune barrier would probably not be feasible, given the small magnitude of the onshore wind transport vector at this site. To stand any chance of success, large quantities of fine sand, easily transported by wind, would need to be introduced, and a carefully balanced programme of dune vegetation management enforced. A dynamic (laterally mobile) dune defence at this location also would be incompatible with the maintenance of a hard surfaced road leading to the installations at Spurn Head.

5.4 Brancaster Bay

5.4.1 Location and physical environment

The dunes of Brancaster Bay form part of a barrier island and barrier spit system which extends along the north Norfolk coast between Hunstanton and Cley next the Sea. The barriers protect extensive saltmarshes, which have been partly reclaimed for arable and pastoral agriculture, and a number of coastal villages and towns including Wells and Blakeney. The Brancaster Bay barrier specifically provides protection for the villages of Thornham and Brancaster, and the important RSPB Reserve at Titchwell. The barrier system consists of a low foredune ridge with development of higher hummocky dunes at the eastern and western ends, adjacent to the entrances to Thornham and Brancaster Harbours. Part of the dune frontage in the central to eastern section of the bay, close to the Royal West Norfolk Golf Club club-house, is protected by a variety of hard defences (Plate 5.13), but the remainder is mostly unprotected.

This part of the north Norfolk coast experiences a macrotidal regime, with the tidal range increasing from east to west (mean spring tidal range in Brancaster Bay is *c*. 5.5 m). The level of HAT is almost 4 m ODN, but storm surges may raise high water levels well above 5 m ODN (Steers *et al*., 1979). Wave energy along much of the coast is low to moderate (Halcrow, 1988). Dominant waves approach from the north-north-east (corresponding with the greatest fetch), whilst the prevailing wind direction is south-westerly. In terms of wind transport of sand from the beach, north-westerly and westerly winds are most important, but easterly and north-easterly winds are also significant (Pye, 1992; Bristow *et al*., 2000).

Brancaster Bay and adjoining areas contain several ecologically important sites which have numerous conservation designations, including Site of Special Scientific Interest (SSSI), Area of Outstanding Natural Beauty (AONB), Special Area of Conservation (SAC), Special Protection Area (SPA), Ramsar site, and Heritage Coast, which place restrictions on the management options available.

5.4.2 Historical development and broad-scale morphology

The Brancaster Bay dune system consists of a single foredune ridge in the western and central parts and up to twelve spit recurves in the east. No well-developed blowouts are currently present within the system which is fairly well vegetated, predominantly by marram grass, although active sand deposition is occurring on, and behind, the main frontal dune ridge as it retreats landwards by ‘rollover’. Parts of the dune frontage are cliffed, especially to the east of the Golf Club, and have been eroding at least since the 1930’s (Plate 5.14).

The barrier and adjoining back-barrier system developed during the mid to later Holocene as sea level rose. The present sand barrier deposits overlie saltmarsh and tidal flat deposits which extend to at least -6 m ODN (Figure 5.27; Funnell &

Pearson, 1989; Andrews *et al*., 2000). The landward limit of the coastal sediment sequence is defined by higher ground which is underlain by Chalk.

Luminescence ages of 313 years BP (error range 357-269 years) and 252 years BP (error range 286-218 years) have been reported from the dunes at the eastern and far eastern end of the Brancaster Bay (Orford *et al*., 2000), indicating that the modern dune topography is relatively young. Wave-formed beach ridges provide the core of the younger aeolian ridges at the eastern end of the bay. These recurves result from longshore transport of sediment along the beach towards Brancaster Harbour. Further west, between Titchwell and Thornham, the present dune forms are only a few decades old, and are being continually reworked as the shoreline moves landwards.

5.4.3 Sediment characteristics and sources

Both the beach and dunes are composed of fine to medium well-sorted sand (mean size 210 to 250 microns). The frontal dune sediments become slightly finer and significantly better sorted in the direction of net transport towards the west (Saye, 2003; Figure 5.33). The dune sediments are mainly composed of silica (mean 93.05%, SD 0.64%) with minor contributions from other major oxides and trace elements. The calcium oxide content is low with a mean value of 1.24% (SD 0.11%), indicating that shell is a minor component.

The cliffs between Weybourne and Happisburgh, composed of glacial till, Tertiary sediments and Chalk, are eroding by wave action at an average rate of 0.9 m per annum and supply an estimated 400×10^3 m^3 per annum of sediment to the coastal zone, the majority of which (some 260×10^3 m^3per annum) is transported eastwards and southwards along the east Norfolk coast (Clayton, 1989). Potential westwards longshore transport of material along the North Norfolk coast was estimated by Clayton to be 60×10^3 m^3per annum. However, Vincent (1979) noted that the lack of sandy sediment in the Blakeney area suggests that this potential transport is not realised. Geochemical differences in the composition of the dune sediments between North and East Norfolk suggest that the two areas are supplied by different sediment sources. The sediment supplied to the North Norfolk coast by the small rivers draining the till-capped hinterland is negligible (Andrews *et al*., 2000), and the main source is probably the sea bed off North Norfolk and Lincolnshire (Pye, 1992). The recent pattern of accretion and erosion along this coast suggests that supplies of new sediment from offshore are limited and that sediment transport mainly involves recycling of material within the system.

5.4.4 Beach and frontal dune morphology and morphodynamics

There is substantial spatial variability in the morphology and frontal dune erosion/accretion status of the frontal dunes within Brancaster Bay. Dunes are higher towards the eastern and western ends of the bay and lowest in central part which has been subject to periodic washover and breaching for much of the last century (Figure 5.28; Plates 5.15, 5.16 & 5.17). Comparison of Ordnance Survey map editions of differing dates indicates a marked landward movement of the coast in the central part of the bay after 1904, although lateral growth of recurves has continued at the ends of the system (Figure 5.29). During this period Scolt Head Island continued to grow in a westerly direction, forcing the Brancaster Harbour channel closer to the shore. These changes were accompanied by significant changes in the bathymetry of the offshore zone which included a steepening of the sea bed profile in the central Brancaster Bay (Figure 5.30). Major storm surges in 1938, 1949, 1953 and 1978 were also responsible for major shoreline recession and offshore movement of sediment. In the past 15 years further severe erosion and flooding has been caused by surge tides in 1993, 1995, 1997 and 2005 (Figure 5.31).

A variety of measures has been employed to protect the frontal dunes around the golf course and Brancaster West Marsh. The clubhouse itself is protected by steel sheet piling, reinforced concrete and rock armour (Plate 5.13). To the east of the clubhouse triangular shaped sand-retention structures have been placed along the dune front for a length of 600 m (Plates 5.17 & 5.20). These structures, constructed from vertical pine poles draped with geotextile, provide a more flexible form of defence, aiming to reduce wave attack on the foredune whilst trapping and temporarily storing sand which is later available to replenish the beach during severe storms. The sand surface within these structures has been stabilised with brushwood and in places marram grass has become established on the newly accumulated sand. The remains of a degraded groyne system are also visible on the lower beach in this area, but have been buried by emplacement of nourishment sand on the upper beach. Immediately to the west of the clubhouse there is a 100 m section of gabion revetment (Plate 5.18) and ad-hoc protection formed of rubble-filled sacks, old concrete blocks and wooden fencing (Plate 5.19). Such materials are unsightly and can present a safety hazard, although in this case attempts have been made to restrict access using wooden paling fencing.

As part of this study, lidar data flown in March 1999 were obtained and used to construct a digital terrain model of the area (Figure 5.32). Environment Agency beach and nearshore profile data were also examined, and a sediment survey undertaken to establish trends in sediment transport within the Bay. The results of this latter study provided evidence that there is net east to west transport of sediment, resulting in fining and improved sorting towards the western end of the Bay (Figure 5.33). Analysis of the profile data indicated a deepening of parts of the nearshore zone, and a narrowing of the upper intertidal zone, between the golf club and Titchwell Reserve between 1996 and 2003 (Figure 5.34). Such changes have acted to increase wave energy at the high water mark and to increase the risk of overtopping and/or breaching of the unprotected frontal dune ridge at Titchwell.

Longshore variations in beach and dune morphological parameters, derived from the lidar data, are shown in Figure 5.35. The maximum dune crest height occurs along the eastern part of the golf course frontage where the dunes have been eroding for more than 70 years but have moved only a few metres inland from their original position. Between transects 4 and 11 the dune crest lies only 1 to 2 m above the level of HAT, and below storm surge level. The most vulnerable section lies around transects 4 and 5 where the distance between HAT and the dune toe is at a minimum, and where the frontal dune sand volume is small. Overall beach width (between ODN and HAT) is lowest near the golf clubhouse (transect 13), where the clubhouse buildings are protected by hard defences which form a salient (Plate 5.13).

Spatial variations in the rate of shoreline advance and retreat have been attributed to the influence of the tidal channel entrances to Thornham and Brancaster Harbours (Halcrow, 1988). The development of ebb tidal deltas at the entrances to these harbours has favoured progradation and dune development on adjoining parts of the barrier. By contrast, the mid part of the barrier has experienced landward movement of nearshore bathymetric contours, leading to increased wave activity and frontal dune erosion.

5.4.5 Management issues and practices

In terms of flood defence significance, the Brancaster Bay dunes provide storm surge protection for the mainland coast between Thornham and Burnham Deepdale, and for the freshwater and brackish habitats present on the RSPB Titchwell Reserve. Further erosion and/or serious overtopping of the dunes would significantly increase the risk of saline flooding to Titchell Reserve and the coastal road linking the village settlements. Concerns have been raised in recent years about the sustainability of the freshwater interests on the Reserve, and adjustment measures are currently being planned by the RSPB. It is likely that these will involve breaching of the embankment surrounding one of the lagoons, thereby re-introducing saline influence. A managed realignment scheme, involving re-introduction of tidal waters and re-establishment of saltmarsh, has already been undertaken at Brancaster West Marsh by the Environment Agency.

There is also serious concern about the long-term sustainability of the Royal West Norfolk Golf Club course, and especially whether the club-house can be maintained in its present position. To date, however, the adopted approach has been to defend the golf club using a combination of hard and soft engineering measures.

5.4.6 Options and recommendations for future strategic management

Owing to the relatively narrow nature of the dune barrier and the active nature of the salt marshes behind, there is limited opportunity to reposition the golf course further inland. The only practical options are therefore either to abandon the course or to attempt to ‘hold the line’ using a combination of soft and hard engineering measures. At the present time there is a reluctance to adopt the first of these options, but if erosion becomes more serious as a result of global climate change then a hold the line policy may become impossible to sustain on technical, economic and / or environmental grounds. In such circumstances it may become necessary to relocate the entire golf course to a more inland location and to allow the coast to respond naturally.

Whether or not erosion of the golf course frontage continues will be dependent partly on movements of the Brancaster Harbour channel, which is in turn linked to the progressive westward development of Scolt Head Island, and partly on the nature of changes in sea level or storminess over the nest few decades. Even without any significant change in forcing factors, it is likely that the erosional trend of the last 70 years will be maintained. If the rate of sea level rise accelerates, or there is a significant increase in storminess, the pressure on the shoreline will be likely to increase.

Although potential rates of aeolian sand transport are moderate on this coast, large scale beach nourishment using fine to medium sand would be required in order to allow the development of a dynamic, landward moving dune barrier which also provides an effective flood defence A suitable source of fine sand would need to be identified, and it is uncertain whether the economic or environmental benefits would justify the economic costs of a scheme on the scale which would be required. In the absence of significant beach nourishment, it is likely that the dunes in the central part of the bay will continue to dissipate as they move landwards, with washover events becoming more frequent. This will increase pressure on the embankments which surround the Titchwell Reserve, and will increase the risk of flooding to the coastal road and adjoining properties. However, there could also be environmental gains in the form of more extensive washover dune and temporary saline lagoon habitats.

5.5 Studland (South Haven Peninsula)

5.5.1 Location and physical environment

The Studland dunes form part of the South Haven Peninsula, a complex spit feature located on the south side of the entrance to Poole Harbour (Figure 5.36). The Peninsula comprises a series of shallow lakes and dunes which are mainly vegetated with marram grass and heather. The surface features have developed partly on the site of a former shallow sea since the seventeenth century (Diver, 1933). At the southern end of Studland Bay, the dunes and beach abut soft cliffs composed of Tertiary Bagshot Beds.

The area experiences a micro-tidal regime, the mean spring tidal range being only 1.6 m. Due to its aspect and position, the coast is relatively well protected from westerly and south-westerly wind waves generated in the English Channel. Maximum fetch lies to the southeast, south of the coast of the Isle of Wight. Relatively short-term tide gauge records are available for Poole Town Quay and Bournemouth. Although they provide a useful record of recent storm surges and resultant high tide levels, they are little value as an indicator of recent sea level tendency in the area. A somewhat longer, though broken, tide gauge record is available for Portsmouth, where a significant upwards trend in annual mean sea level is evident (Figure 5.38).

The Studland dunes are recognized as being of ecological and geological conservation importance (May, 2003c). Studland has the second largest area of dune heath in England and Wales, and parts of the area have designations as a National Nature Reserve, Site of Special Scientific Interest, Heritage Coast, Ramsar site, Geological Conservation Review site and a Special Area of Conservation. The adjoining area of Poole Harbour also has a number of other designations including Special Protection Area. The Peninsula is highly popular for recreational purposes, attracting hundreds of thousands of visitors each year. The dune system protects a road leading to the ferry crossing between Shell Bay and Sandbanks Peninsula. In addition, the two peninsulas have a major influence on the tidal regime and wave climate within Poole Harbour, which is increasingly popular with boating enthusiasts. Following a recent capital dredging programme, the port of Poole is also expected to experience significant commercial expansion.

5.5.2 Historical development and broad-scale morphology

The dune system at Studland can be classified as an estuarine barrier spit complex. Although Poole Harbour has the plan form of an enclosed embayment rather than a typical estuary, it can be classified as an estuary based on the fact that several significant rivers drain into it and the water salinity shows spatial and temporal variations similar to those of many other estuaries.

The Studland (South Haven) Peninsula has formed as a result of northwards drift of sediment towards the Poole Harbour entrance (Robinson, 1955). The

Sandbanks (North Haven) Peninsula on the northern side of the entrance to the Harbour is also substantially composed of windblown sand overlying marine sediments derived mainly from the north, but is now largely built-upon.

Dunes on the South Haven Peninsula have formed mainly by deflation of beaches on the Studland Bay (eastern) side (Plates 5.21 & 5.22), although foredunes and hummock dunes have also formed partly by deflation of the sand from the north-east facing beach in Shell Bay (Plate 5.23).

To landward of the modern foredune ridge in Studland Bay lie three shore-parallel ridges which are separated from each other and the higher land composed on Tertiary sediments to the west by low-lying areas which contain heathland and freshwater marsh with scattered pools. The largest freshwater lake (the Little Sea) occurs along the western edge of the dune system (Figures 5.36 & 5.37). These successive dune ridges reflect eastwards growth of the system over time. The foredune towards the northern end of Studland Bay has an embryonic dune ramp which indicates that lateral accretion is still occurring in this area. Further south, embryo dunes are absent and the foredune ridge shows incipient blowout development due to visitor pressure. At the extreme southern end of the bay, near Knoll Beach car park, the frontal dunes on the National Trust land have experienced significant erosion in recent decades. Diver (1933) concluded that the dune system at Studland is relatively young, having formed during the last 400 years. The maps of Saxton (1575), Camden (1607) and Speed (1611) show the South Haven Peninsula merely as a narrow strip of land, called Plateau Heath. The west shore of the Little Sea formed the original coastline in Studland Bay and comprised a low cliff cut into Tertiary sediments, the continuation of which forms the current coastline southwards from Knoll House Hotel to Studland village. However, other cartographic and documentary evidence suggests that the South Haven Peninsula is in fact an older feature, and some dune ridges may have been present at the time of the Domesday Survey or even earlier (May, 2003c).

The Little Sea is shown on a map published in 1721 as a tidal inlet with a wide opening towards the east, partly enclosed by the oldest (most landward) dune ridge. The tidal inlet became a lagoon by the end of the eighteenth century and the second ridge had also developed. Sheringham’s map of 1849 shows the beginnings of the first (most seaward) dune ridge, although it was invaded by the sea during high spring tides. At this time an inlet was maintained behind the developing dune ridge into the Little Sea, but by 1886 had become virtually cut off from the sea (Canning & Maxted, 1979). The two sand accumulations became united shortly after 1900, causing the Little Sea to become landlocked. Eastern Lake represents part of the channel that formerly existed between the northern and southern dunes and was created between 1894 and 1900 (Canning & Maxted, 1979). The Little Sea has since become a freshwater lake fed by short streams, with two outlets taking overflow water into Shell Bay.

5.5.3 Sediment characteristics and sources

The dunes at Studland generally consist of fine sand (mean size typically 210 to 270 microns). During this study no consistent trends in mean size were found either in a shore-normal direction or alongshore (further information is contained in Saye, 2003). The dune sands are primarily composed of silica (mean 99.03%, SD 0.59%) with minor contributions from other major oxides and trace elements, notably aluminium. The calcium oxide content is very low (average 0.06%), creating acidic growing conditions which favour heathland vegetation communities. The Studland dunes have much higher aluminium / potassium and silica / aluminium ratios than any of the other dune systems sampled in this study (Figure 5.41). This difference reflects the importance of local Tertiary sediment sources which are rich in silica and kaolinite with relatively low concentrations of feldspars and micas (Saye, 2003).

At the southern end of Studland Bay slow recession of the Tertiary cliffs (Reading Beds, London Clay and Bagshot Beds) is still taking place, although supply of sediment to the beach is less important now than in the past. The dominant longshore drift direction is south to north along the Studland Bay frontage, but littoral drift from further west in Dorset is limited by the headlands of the Isle of Purbeck. Material eroded from the Tertiary cliffs in Poole and Christchurch Bays accumulates offshore in Studland Bay, and a proportion of this material also finds its way onto the South Haven Peninsula. These sediments form sub-tidal sand bars in Studland Bay which migrate shoreward and supply material to the beaches and dunes.

5.5.4 Beach and frontal dune morphology and morphodynamics

Seaward progradation of the dunes in the central part of Studland Bay continued during the first half of the twentieth century, but was reported to have essentially ceased by the late 1950’s (Wilson, 1960). Map evidence suggests that the foreshore extended seawards by up to 150 m between 1936 and 1970, in particular opposite the northern part of the Little Sea, where a new foredune, now up to 40 m wide, is still developing.

Surveys by the Nature Conservancy Council showed that between 1936 and 1970 there was erosion in Shell Bay, with some accretion of the foreshore in the centre of the bay (Canning & Maxted, 1979). Construction of a breakwater extension in 1924 may have had a significant effect on the rates and direction of sediment drift (Welsby & Motyka, 1991). Erosion of the dunes close to the Knoll Beach car park in Studland Bay has also occurred for several decades, especially where high recreational pressure has led to vegetation destruction and blowout development in the foredune.

For the purposes of this study, lidar data flown in March 1998 were processed to obtain a digital terrain model of the dune system (Figure 5.39). Analysis of the transects derived from the lidar data (Figure 5.40) showed that the most seaward dune ridge is relatively low (4.2 to 6.5 m ODN), but still lies 2.9 m to

5.3 m above the level of HAT, thereby forming an effective flood defence. The height of the most seaward dune ridge decreases slightly between transects 1 and 6, and is variable but generally increases again between transects 6 and 13. The width of the beach between ODN and HAT generally increases from Knoll Beach car park (17 m at transect 1) towards the north (70 m at transect 12). The relatively wide and flat beach at transects 8, 9 and 10 may be associated with the relatively sheltered conditions created by the training bank which fronts these transects. Frontal dune sand volume is relatively constant along the shore but shows a slight tendency to increase between transects 5 and 9.

With the exception of an anomaly at transect 9, the beach width increases and beach slope decreases towards the north. The beaches in Shell Bay are notably wider and less steep than those in Studland Bay: beach angles range from 4.1° (transect 1) to 1.0° (transect 13). The beaches often have a distinct berm formed by swell waves, especially in Studland Bay, but there is considerable temporal variation in response to wave and tide conditions.

5.5.5 Management issues and practices

From a flood defence perspective, the key importance of the dunes on the Studland Peninsula lies in the protection they provide to Poole Harbour, its port and industrial facilities, and the residential areas which surround it. Although the normal high tidal range in Poole Harbour is small, serious flooding at Town Quay and other locations can occur when strong southerly or south-westerly winds drive water through the Harbour entrance and cause wave set-up on the north-east side. It is therefore of importance to ensure the integrity of the dune barrier from a flood defence point of view. In addition, the high nature and geological conservation importance of the dunes requires that they be carefully managed.

A large part of the Studland Peninsula is now owned and managed by the National Trust, and the whole area attracts a large number of visitors, especially during the summer months. In the past, visitor pressures have caused serious damage to the dunes, especially in the Knoll Beach car park area. In recent years several areas have been ‘restored’ for conservation purposes, including the creation and protection of sand lizard habitat. Marram planting has been undertaken to stabilise the sand in areas of high visitor pressure and fences constructed to restrict access. Other management measures have included removal of scrub and juvenile woodland to preserve the heathland habitats. These activities have not posed any threat to the integrity of the dune barrier as a flood defence.

Erosion at the Knoll and Middle Beaches began to threaten infrastructure in the early 1990’s. Research commissioned by the National Trust from Bournemouth University in 1996 showed that the annual rate of erosion had significantly increased in recent years. The main causes of erosion were identified as an increase in easterly winds, an increase in stormy weather and a rise in sea level. Other factors included reduced local sediment supply to the system due to cliff protection measures at the southern end of the Bay, and interruption of littoral drift by the construction of groynes.

At Knoll Beach car park, close to the southern end of the dune system, 190 spaces were lost in 1998 due to erosion. The 2001 National Trust Studland Peninsula Management Plan for the period 2001 to 2006 proposed that an artificial dune should be constructed along the Knoll Beach car park frontage to act as a temporary sea defence and to provide time for managed retreat. The National Trust's long-term policy for the dune system is to permit natural processes to operate. At the present time, beach erosion is not a sufficiently widespread problem to require large-scale relocation of visitor facilities or other infrastructure, but this may be required in the future and it will be a wise precaution not to build new facilities close to the shore or in the frontal dunes.

5.5.6 Options and recommendations for strategic management

Large scale erosion of the sand dunes on Studland Peninsula could have very serious implications for extreme water levels and wave exposure within Poole Harbour, and especially on Brownsea Island. However, this would require loss of virtually all of the sand between Jerry's Point and South Haven Point, which is unlikely in the short to medium term. A more likely short-term scenario would be breaching of the dunes at the southern end of Studland Bay and recreation of a tidal inlet leading to the Little Sea. This feature would then revert to a brackish or saline tidal lagoon. Although this would have ecological consequences, the implications from a flood defence point of view would be relatively minor. However, dune width and sand volumes in this area are still relatively healthy and there is no immediate risk of a major breakthrough.

Given the relatively sheltered location of the site, and low rates of aeolian transport, it is unlikely that the frontal dunes in this area will roll back and maintain their present size, especially in the face of sea level rise. Rollover dissipation is more likely, ultimately leading to washover and breakthrough on a timescale of 50 to 100 years. Given the limited threat to property and infrastructure, and the variable implications for nature conservation, the best management policy for this area is considered to be "do nothing" other than limited maintenance measures to control the effects of visitor pressure. Creation of a substantial artificial dune would require the importation of a significant quantity of sand or its transfer from elsewhere within the system. Construction of such an artificial ridge would reduce local flooding risk in the short term but would not in itself solve the longer-term erosion problem. This would require beach nourishment on a continuing basis.

5.6 Kenfig Burrows

5.6.1 Location and physical environment

Kenfig Burrows is located between Port Talbot and Porthcawl at the southern end of Swansea Bay (Figure 5.42). The area is bordered by the Afon Kenfig (Cynffig) in the north, and the beach is confined by Sker Point in the south. Kenfig Burrows is one of the largest remaining intact dune systems in Wales, extending more than 3.2 km inland at its widest point. It was formerly part of a more extensive dune system fringing Swansea Bay which has become fragmented as a result of industrial and urban development.

Swansea Bay experiences a macrotidal regime which is accentuated by the funnelling effect of the Bristol Channel; the mean spring tidal range is 8.9 m. Tidal currents can be strong. Winds are predominantly onshore from the southwest. The site is exposed to swell waves from the Atlantic Ocean and more locally generated wind waves, but few large waves reach the shoreline because of the shallow nature of Swansea Bay and the Bristol Channel. The effect of storm waves on the frontal dunes can, however, be significant.

5.6.2 Historical development and broad-scale morphology

The dune system is classified as being of *transgressive non-climbing* type. In the historical past, and especially during the Little Ice Age, sand sheets and mobile dunes extended inland beyond the present position of the M4 motorway. Even as recently as the 1960’s, there were extensive areas of mobile sand in the area. Today, however, more than 97% of the dune area is covered by vegetation (Figure 5.43). The modern dune topography comprises a series of dune ridges separated by slacks and stabilised parabolic dunes. Near the beach lies one or more shore-parallel ridges, widening towards the north, and dissected in places by blowouts and incipient parabolic dunes (Plate 5.24 & 5.27). In many places the frontal dunes are cliffed (Plates 5.25 & 5.26). The dune toe is partially protected by a high tide gravel beach (Plate 5.28). Further inland are a series of hummock dunes and eighteen large, but poorly defined, parabolic dunes whose long axes are oriented almost west to east, parallel with the resultant wind.

The formation of the dune system at Kenfig Burrows is thought to have commenced about 2000 to 2500 years BP (Carr & Blackley, 1977; Price & Brooks, 1980), although dunes may also have existed further to seaward earlier in the Holocene. The dune sediments largely rest on marine clay deposits, beneath which is a peat layer. Historical and archaeological evidence indicates that from the thirteenth to at least the seventeenth century the dunes were actively migrating on a large scale, and the mediaeval township of Kenfig had apparently been buried by blown sand by 1538 (Higgins, 1933).

Aerial photographs taken just after the Second World War show that extensive mobile dune areas and many active blowouts were still present, but at present aeolian processes are mainly confined to the first hundred metres landwards of the dune front (Jones & Etherington, 1989; Jones, 1996). The exact timing and causes of the stabilization of the Kenfig dunefield remain uncertain, although it is likely that both climatic and human factors have played a role.

Analysis of historical maps has shown that there have been only limited changes in the position of the frontal dune toe since 1876 (Pye & Saye, 2005; Figure 5.44), so it is unlikely that changes in shoreline position have had any significant impact on dune mobility over this period. Tide gauge records for the nearest recording stations at Milford Haven and Hinkley Point are short and discontinuous. There is some evidence of a significant recent increase in annual mean sea level (Figure 5.45), but nothing to suggest that such changes have yet had any impact on the stability of the beach and frontal dunes at Kenfig Burrows.

5.6.3 Sediment characteristics and sources

The dune sediments consist mainly of medium sand (mean size approximately 300 microns), although at the southern end the frontal dune sands are significantly coarser (mean size >500 microns). The mean grain size and sorting (D_{90}-D_{10} range) decrease inland from the foredune (or embryo dune, where present) to the first dune ridge (Figure 5.48). The parabolic and hummocky dunes further inland are relatively uniform in grain size, although there is slight fining and improved sorting in a landward direction. The significantly coarser frontal dune sand at the southern end of the system suggests a recent change in the nature of the beach sediments feeding the dunes in this area. The present beach is composed of coarse, slightly calcareous (shelly) sand, with an upper beach storm ridge composed of shingle in many places.

Compositionally, the dune sediments consist mainly of silica (mean 89%, SD 3.33%) with low percentages of other major oxides and trace elements (mainly aluminium, potassium and sodium associated with feldspars). The calcium oxide content is fairly low (mean 2.75%, SD 0.63%), indicating a small but significant calcium carbonate component. Most of the calcium carbonate represents shell material, although some limestone and calcareous sandstone grains are also present.

The Kenfig Burrows dune sediments are compositionally similar to those of other systems in Swansea Bay. They are derived from Pleistocene glacial and fluvio-glacial deposits on the seafloor which were reworked by wave action and transported onshore during the Holocene transgression. Much of the coastline of Cell 8, in which Kenfig Burrows lies, is composed of Carboniferous limestone and Devonian Old Red Sandstone which are resistant to erosion and provide little beach sand material. Swansea Bay is essentially a closed system which receives very little material from further offshore or neighbouring coastal sub-cells. In the past, sand was transported in large quantities to Kenfig Burrows, partly from the zone immediately offshore and partly from northern Swansea Bay via longshore drift. However, sand supply is now very limited and the dune front is stable or subject to slow recession. It is likely that the main phase of aeolian sand blowing during the Little Ice Age was triggered by increased storminess and coastal recession, in a similar manner to the Sefton coast. The sand was probably derived partly from nearshore sources but also by landward recycling of existing beach and dune deposits.

5.6.4 Beach and frontal dune morphology and morphodynamics

Lidar data acquired in November 1999 were analysed in this study to obtain a digital terrain model (Figure 5.46). Longshore plots of morphometric parameters derived from the DTM demonstrates that the seaward side of the Kenfig system comprises a foredune system which is widest in the north and which has been truncated by recent marine erosion along the central and southern parts of the system (Figure 5.47). There is a pronounced dune cliff along much of the dune frontage (e.g. Plate 5.25). In places, there is limited new growth of dune at the slumped dune toe, but these features are ephemeral. Rates of shoreline recession are low, however, and large-scale frontal dune ‘rollback’, of the type seen at Formby Point on the Sefton Coast, is not occurring.

The maximum height of the frontal dunes generally increases towards the north (from 8.8 m ODN at transect 2 to 16.1 m at transect 10; Figures 5.46 & 5.47). Their maximum height varies from 3.2 m above HAT (transect 2) to 10.5 m above HAT (transect 10). The width of the zone between HAT and the frontal dune crest varies but shows no significant overall change. Frontal dune sand volume (within 200 m of HAT) also shows no significant longshore trend.

The lower beach is generally of very low gradient, separated from a steeper upper beach by a marked break in slope. The width of the beach between ODN and HAT is quite uniform, decreasing slightly from *c*. 200 m in the north to *c*. 160 m in the extreme south. Correspondingly, the average beach slope (both ODN to MHW and ODN to HAT) shows a slight increase in the same direction.

5.6.5 Management issues and practices

Owing to the nature of the topography and landuse behind Kenfig Burrows, the dune system is of limited flood defence significance. However, the dunes are of considerable nature conservation importance, and the stability of the sand is also of concern with respect to potential threats posed to infrastructure (notably the M4 motorway).

Partly due to unresolved problems of land ownership and management responsibility, there was little management of the Kenfig dune system until the late 1970’s. Much of the area was designated as a Site of Special Scientific Interest in 1954 and the site was first proposed as a Local Nature Reserve (LNR) by Glamorgan County Council in 1956, but this initiative failed. During the 1950’s and 1960’s the area was subjected to heavy recreational pressure, uncontrolled grazing (by rabbits and livestock) and extensive extraction of sand and gravel for industrial purposes. LNR status was only achieved in 1977 under the auspices of Mid-Glamorgan County Council, and the site was subsequently declared a National Nature Reserve in 1989. The site is now owned by the Kenfig Corporation Trust and managed by Bridgend County Borough Council in consultation with a range of interested parties including the Countryside Council for Wales.

Management between 1977 and 1990 concentrated on visitor management and habitat management. Controls on human activities after 1977, including restrictions on visitor access and sand extraction, combined with a reduction in rabbit numbers, undoubtedly played a major part in allowing rapid vegetation colonization. Initially this involved grass species, but ecological succession soon presented problems of scrub invasion, as in the Sefton coast dune system. In the late 1980's and 1990's much attention was given to the control of sea buckthorn (*Hippophae rhamnoides)* and maintenance of open areas through a combination of controlled grazing and mowing. The site is grazed by sheep, the density of which has been increased from 100 to 500 ewes between the 1970s and the late 1990s. However, the Kenfig Corporation Trust controls all grazing and the sheep used are owned by local graziers. The site's designation as an urban common prevents the use of fenced enclosures and therefore grazing has generally been at a level too low for effective ecological management. In addition, the effects have been compounded by a continuing reduction in rabbit numbers due to myxamatosis. As a result, the dunes have suffered from over-stabilization (from an ecological point of view), and in recent years initiatives have been introduced to rectify the balance. Unconventional forms of destabilisation are being implemented at Kenfig Burrows. Blowouts have being artificially excavated in the first dune ridge landward of the foredune to encourage dune mobility (Plate 5.27). This destabilisation is, however, localised and on a small scale. As at Sefton, it has proved difficult to convince local communities that a return to a more mobile sand regime would be generally beneficial.

5.6.6 Options and recommendations for strategic management

The dune system at Kenfig is wide (>2 km) and relatively high (8.8 m to 16.1 m ODN). It is unlikely to be breached or seriously eroded in the immediate future, even if there is a significant increase in sea level or level of storminess. The key management issue is the degree to which destabilization of the dunes could or should be undertaken to enhance ecological benefits. At present, most of the dune frontage is stable and only slowly eroding. If destabilization of the frontal and near-frontal dunes is undertaken on a large scale, there is a risk of large-scale landward movement of sand and a significant increase in the rate of coastal erosion. Extensive destabilization further inland could result in the formation of active sand sheets which might threaten infrastructure at the landward limit, including the M4 motorway. Given these constraints, the most appropriate policy option is one of limited intervention with a localised and carefully monitored programme of small-scale de-stabilisation in the hind dunes, primarily for nature conservation purposes. It is likely that, if sea level rises significantly, the shoreline will respond naturally by rolling back with the development of higher foredunes in accordance with the ‘equilibrium rollover’ or ‘snowball rollover’ models discussed in Part 2 of this report.

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