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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: FD1302
2. Project title: Sand dune processes abd management for flood and coastal defence
3. Contractor organisation(s): Royal Holloway University of London; Kenneth Pye Associates Ltd
4. Total Defra project costs (agreed fixed price): £ 290000
5. Project: start date .... 01 July 1999
   end date .... 31 March 2007

6. It is Defra's intention to publish this form.
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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

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 Bay, 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.48km^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 - 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.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);
- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

Project scope and purpose

This project began as a shared cost research project funded by the Department of Environment, Food and Rural Affairs (DEFRA), Royal Holloway University of London (RHUL) and the Natural Environment Research Council (NERC). Work on the project was undertaken in conjunction with a NERC PhD CASE Research Studentship held by Samantha Saye and supervised by Professor K. Pye. Additional resources for further data processing and preparation of the final report were subsequently provided by Kenneth Pye Associates Ltd (KPAL) and DEFRA.

The project rationale was based on two main factors:

(a) a recognition that the overwhelming majority of existing information relating to coastal dunes in England and Wales relates to ecology, habitat conservation and visitor management, while geomorphological, sedimentological and engineering aspects have been relatively neglected

(b) changes in general coastal management philosophy during the 1990s, away from traditional hard engineering solutions towards ‘softer’ approaches which aim to work with natural processes, led to increased interest in understanding the behaviour of coastal dune and beach systems with a view to identifying management options which are more cost-effective, environmentally friendly, and sustainable in the face of future changes in climate and sea level. As part of this process, there has been a move away from rigid concepts of "flood defence" and "coast protection" towards more adaptive strategies such as "coastal flood risk management".

The initial objectives of the project were:

(i) to review the current geomorphological, sedimentological and management status of coastal sand dune systems in England and Wales, with particular reference to their role in coastal flood defence and wider shoreline management, and to record this information in a database format suitable for updating, expansion and information dissemination

(ii) to review current methods available for the management of coastal dune systems, including those currently used in Europe, North America and other parts of the world

(iii) to evaluate the effects of predicted climate change and its effects (sea level rise, increased storminess, nearshore steepening) on dunes and associated beach systems, and to assess the likely effects of removing hard defences to recreate more dynamic dune systems

(iv) to examine a number of case studies around the coast of England and Wales to identify the problems faced and to evaluate the options for future management

(v) to identify best practice for dune management within the context of coastal flood risk management and to identify requirements for further research

All of the objectives were achieved.

The approaches defined in the research plan were:

(i) a review of published and unpublished literature, maps and air photographs relevant to the scientific objectives

(ii) site visits to each of the major dune localities where there is a significant flood defence / coast protection interest, with more detailed field appraisals to be undertaken at locations identified as problematic or otherwise important from a demonstration point of view

(iii) site visits to coastal dune localities in other parts of Europe and North America which provide examples of alternative dune management strategies / methods

(iv) discussions with engineers and dune managers at key organizations in the UK and overseas

(v) laboratory analysis of sediment samples collected from each of the major dune localities in England and Wales

(vi) analysis of background data relating to dune processes (including meteorological and shoreline change data)

(vii) development of a preliminary database containing summary information relating to the major coastal dune systems in England and Wales

Final Report structure and content

The final main scientific report consists five parts. Part 1 provides an overview of the project rationale, objectives, major conclusions and recommendations for further action, together with a glossary of scientific terms used. Part 2 reviews the nature of coastal sand dune processes and morphology relevant to coastal dune management, particularly from the perspective of flood risk management. Part 3 provides summary information relating to each of the main dune sites considered in the report, together with summary tables which compare selected attributes for all sites. Part 4 reviews the principal methods available for the management of sand dunes, while the problems and management options at five case study sites (Sefton coast, Spurn Peninsula, Brancaster Bay, Studland Bay and Kenfig Burrows) are discussed in Part 5. The report is available in both paper and electronic (PDF) formats. Additional background environmental and laboratory analytical data are held by Kenneth Pye Associates Ltd, from whom further information can be obtained

Previous studies

There is a large international scientific literature dealing with coastal dunes, although the great majority of published papers and books have been concerned primarily with dune ecology and conservation management issues (e.g. Salisbury, 1952; Ranwell, 1972; Boorman, 1977; Gimingham *et al*., 1989; van der Meulen *et al*, 1989; Carter *et al*., 1992; Packham & Willis, 1997; Ovesen, 1998; Arens *et al*., 2001; Doody, 1985, 1991, 2001; Houston *et al*., 2001; Martinez & Psuty, 2004). A number of publications have given greater attention to geomorphological aspects, including aeolian sediment transport processes and beach-dune interaction (e.g. Pye, 1983a; Psuty, 1988; Pye & Tsoar, 1990; Nordstrom *et al*., 1990; Bakker *et al.*, 1990; Nordstrom, 2000), and a number of practical guides have been produced which describe techniques for sand dune restoration (e.g. Ranwell & Boar, 1986; Scottish Natural Heritage, 2000; Brooks & Agate, 2005). However, there is only a relatively limited literature, much of it in the form of conference proceedings, dealing with the engineering design and management of dunes primarily for coastal flood defence, including the nature of dune erosion under storm conditions, post-storm recovery, and the impacts of sea level and climate change in the medium to longer term (e.g. Case, 1914; Vellinga, 1986; van de Graaff, 1986, 1994; Bruun, 1998). Works which discuss practical dune management measures aimed both at flood defence / coast protection and habitat biodiversity / nature conservation are even fewer in number (e.g. Favennec & Barrere, 1997). This lack of previous attention is reflected by the fact that the publication *Coastal Defence and the Environment, A Guide to Good Practice* (MAFF, 1999) contained only four pages of information relating to coastal sand dunes. Similarly, while the Coastal Engineering Manual (CEM) produced by the U.S. Army Corps of Engineers (2004) contains a detailed discussion of methods available to calculate wind blown sand transport, it contains only limited information about coastal dune morphodynamics.

Results of the project

The nature of coastal dune systems in England and Wales

A total of 112 coastal dune 'sites', comprising 158 dune individual dune localities, was identified for the purposes of this study. Only dune localities on the mainland and islands connected to the mainland by roads (e.g. Anglesey, Holy Island) were included in the study. Significant areas of dunes also occur on the Isles of Scilly, the Isle of Man and the Channel Islands, but have not been considered. Very small areas of dunes on the mainland (< 0.1 km^2), and some areas of vegetated blown sand without dune topography, were also excluded, since such systems are frequently ephemeral in character and / or are generally of very limited importance from a coastal flood defence perspective.

The dune ‘sites’ identified in this study mostly represent a single locality, although in some instances a ‘site’ is composed of a number of separate localities which occur in close proximity or share a common physical setting and mode of genesis. Systems within the same bay, estuary, or section of open coast have been grouped where they experience a similar process regime or have other features in common (e.g. where they evolved historically as part of one morphological system but have since been broken into parts by urban or industrial development). An example is provided in North Wales, where a once almost continuous system of barrier spit dunes existed between Abergele and Point of Air (Site 104), broken only by the outlet of the River Clwyd, but where urban development during the nineteenth and twentieth centuries has now divided the dunes into three main parts, each with differing character, centred on Kinmel Bay, Rhyl to Prestatyn, and Gronant to Talacre.

Although some systems have been grouped for the purposes of consideration in this report, it is important to recognize that the individual components may need to be considered separately for specific management purposes.

Dune systems are concentrated in six main areas of England and Wales: (1) northeast England; (2) eastern England between the Humber estuary and north Norfolk; (3) southwest England; (4) south Wales; (5) northwest Wales including Anglesey; and (6) northwest England between the Ribble and central Cumbria. Elsewhere, dune systems have a scattered distribution and are generally much smaller, although locally they may have high coastal flood defence significance. Some sections of coast have virtually no coastal dune development, for example between the Tees and the Humber, and along the shores of the Outer Thames estuary. In general, dunes are poorly developed on the coasts of southeast and southern England. The main reasons for this are a lack of suitable accommodation space for the accumulation of extensive coastal sand deposits, a local dominance of muddy or gravelly coastal sediments, and limited exposure to onshore winds on some sections of shoreline owing to the coastal orientation and the effects of topography.

Estimates of the area of different dunefields were taken from the *Sand Dune Vegetation Survey of Great Britain*, commissioned by the Joint Nature Conservation Committee and based on work undertaken between 1986 and 1991 (Radley, 1994; Dargie, 1995). These area estimates were based on examination of Ordnance Survey maps, air photographs and field surveys, and are inevitably subject to errors associated with these sources. However, they provide a useful indication of the relevant magnitude of dune areas which remain of conservation and potential coastal flood defence importance today. In the case of Welsh dune sites, additional area estimates were obtained from a survey undertaken on behalf of the Welsh Office by Posford Duvivier (1996). These estimates were also based on analysis of Ordnance Survey maps and local site visits carried out during 1993 to confirm system boundaries. Owing to the fact that some dune sites were classified or combined differently in these two reports and the present study, are area information cited is not exactly the same for every site.

In total, coastal dunes and associated areas of windblown sand in England and Wales have a total area of approximately 200 km^2 at the present time. The area was once considerably larger, but significant stretches of dunes have been levelled and built on for residential and industrial development during the nineteenth and twentieth centuries. For this reason, the areas of blown sands shown on maps published by the British Geological Survey are in some cases considerably larger than the area values cited in the *Sand Dune Vegetation Survey* and the Posford reports.

Based on the available data, Coastal Cell 9, as defined by Motyka & Brampton (1993), has the largest total area of dunes and associated windblown sand (47.87 km^2), followed by Cell 11, Cell 8 and Cell 1. Approximately 50% of the 124 systems for which area data are available can be classified as small and medium sized (with areas ranging from 0.1 to 1 km^2). There are relatively few systems larger than 5 km^2, the largest of all being the Sefton dune system in northwest England (19.56 km^2).

Significance of dunes for coastal flood defence

Although coastal flood defence is an extremely important aspect of coastal dunes, and is the main focus of this report, it is important to bear in mind that there are several other important interests, including nature conservation, recreation and leisure, forestry, stock grazing, military training, and archaeological heritage. All decisions relating to the management of coastal dunes for coastal flood defence must therefore take into account the other potential interests.

There are some situations where dunes are important from a coast protection point of view, for example where they occur to seaward of a man-made defence or soft cliff-line, thereby forming a buffer zone which protects the structures or cliffs behind from wave attack and potential erosion. However, the principal significance of dunes lies when they act as a barrier to marine flooding. The importance of dunes in this regard depends partly on the relative relief of the land behind the dunes, on normal high tide and storm surge levels, and on the land-use and asset value of the hinterland area.

In a situation where the level of the hinterland lies above storm surge level, a belt of coastal dunes has little or no flood defence significance under the prevailing sea level conditions. The dunes could, however, be of significance for coast protection if the land is composed of ‘soft’ geological formations which are susceptible to wave erosion. It should also always be borne in mind that mean sea level and storm surge levels could change significantly over time. In situations where the level of the hinterland lies just above normal high tide level, but below storm surge level, the dunes may be considered to have moderate flood defence significance under the prevailing conditions. Where the level of the hinterland lies below normal high tide level, the dunes have relatively higher flood defence significance. The degree of ‘high’ significance will vary with the asset value of the land behind, generally being highest in areas of dense urban and industrial development or international habitat importance.

Dunes may also be of high flood defence importance if the area behind consists of open water rather than land, since dunes and associated beaches may form a barrier which impedes the movement of storm surges and tidal waves into estuaries and coastal lagoons. Globally, there are many examples where coastal dune barriers provide a vital flood protection function against hurricane-induced surges and tsunamis. Good examples are found along the Gulf of Mexico and Atlantic barrier coasts of the United States. Closer to home, the dune-capped barriers of the Spurn Peninsula and Studland Peninsula are important in restricting the passage of storm surges and open sea waves into the Humber estuary and Poole Harbour, respectively (see Part 5 of the main report).

Sites with high coastal flood defence significance are widely distributed but there is a high concentration in eastern England (especially Lincolnshire and Norfolk), northwest England (especially Merseyside and Lancashire) and north Wales. For example, the Sefton coastal dune system provides an important flood defence barrier for a large area north Merseyside and the West Lancashire Plain which lies below 5 m ODN. Dunes between Lytham St. Annes and Blackpool are also important for the flood defence of the southern Fylde. These areas contain significant urban and industrial developments as well as high grade agricultural land. Other important examples are provided in east Lincolnshire and north Norfolk, where dunes form an important flood barrier for extensive areas of reclaimed marshland which is of considerable value for agriculture.

Outside the UK, coastal dunes are extremely important for coastal flood defence in The Netherlands and parts of the North Sea coasts of Denmark, Germany and Belgium (e.g. Rijkswaterstaat, 1990; van de Graaff, 1994). The littoral dunes in these countries have been heavily engineered to provide an adequate standard of flood defence, and the experiences of these countries provide a useful source of information. However, the practices adopted in these countries have not been without environmental disadvantages and are not necessarily applicable in the UK.

Dune system ages

Virtually all of the coastal dune systems in England of Wales have formed since the last Ice Age, and the vast majority are of very late Holocene age. This contrasts with the situation in many other parts of the world, such as Australia (Pye, 1983b), New Zealand, South Africa, Brazil and several parts of the United States (Cooper, 1958; 1967), where very large dune systems have evolved over tens or hundreds of thousands of years. Even within northwest Europe, several countries have much larger coastal dune systems which have formed over a longer time period, for example in southwest France (Clarke *et al*., 1999; Saye & Pye, 2000), The Netherlands and Denmark (Landsberg, 1956; Clemmensen *et al*., 2001; Saye *et al*., 2006).

With the exception of parts of Cornwall (e.g. James, 1992), the oldest documented coastal dunes in England and Wales are approximately 5000 to 6000 years old. An intra-dune peat layer at Ainsdale National Nature Reserve on the Sefton coast was dated at 5110 ± 70 ^{14}C yr BP, indicating that some dunes existed on this coast at least by 5200 years ago, around the time when the post-glacial marine transgression reached approximately its present level (Pye & Neal, 1993). Archaeological evidence suggests that other dunes in southwest England and parts of South Wales were also initiated around the same time (e.g. Higgins, 1933; Harding, 1950; Lewis, 1992). Dunes had formed at several locations in northeast England, including St. Aidan's dunes, by 3500 to 4000 years ago (Orford *et al*., 2000). Dune-capped barriers of comparable age may also have existed along the shores of Lincolnshire and North Norfolk around this time, but they lay to seaward of the present shorelines. The presence of a thick (>10m) back-barrier sequence of intertidal muds, saltmarsh sediments and freshwater peats along the coasts of North Norfolk and Lincolnshire suggests the possibility of a significant marine barrier to seaward throughout much of the later Holocene. However, the barriers may have taken the form of low islands, locally dune-capped, and surrounded by extensive sandy intertidal flats, rather than high dune-capped barriers. The oldest recorded sedimentary evidence suggests that the present dunes in Lincolnshire began to accumulate after the eighth or ninth century AD, and mainly from the thirteenth century onwards. In North Norfolk, dating evidence suggests that parts of Scolt Head Island and other sand/shingle barriers were probably in existence more than 3000 years ago, but most of the modern dunes are less than 600 years old (Orford *et al*., 2000; Andrews *et al*., 2000). There were no dunes at Winterton Ness and many other places on the East Anglian coast before the beginning of the eighteenth century (Steers, 1964). This largely reflects the fact that most of the East Anglian coast has experienced long-term erosion and under such conditions depositional geomorphological features can only be transient.

Dune system and dune morphology / mobility

Two aspects of morphology were considered in this study: (1) the morphology of a dune system as a whole; and (2) the morphology of individual dunes within the system. Both dune system morphology and individual dune morphology are influenced by a number of controlling variables, including: (a) the nature of forcing processes; (b) available sand supply; (c) vegetation characteristics; (d) water table levels; and (e) land-use and recreational pressures.

For the purposes of this study, the dune system morphological classification scheme described by Saye (2003) was adopted. At the first level of classification, coastal aeolian accumulations can be classified according to the geomorphological setting in which they occur. With respect to coastal dunes in England and Wales, three types of setting are of importance: (a) *open coast*; (b) *embayment*; and (c) *estuarine*. The boundaries between the three types are clearly gradational, and some dune systems occur in more than one setting. In such cases, the predominant setting has been used for classification purposes in this study. At a second level of classification, dune systems can be classified according to the type of major landform feature on which they occur, or which they form. The main feature types relevant to England and Wales are: (a) *barrier island*; (b) *barrier spit*; (c) *tombolo*; (d) *mainland fringing*; (e) *mainland (or inland) transgressive*; and (d) *ness*. Various sub-types can also be recognized (for further information see Part 2 of the main report).

Individual dune forms were classified in this study using a slightly modified version of the classification scheme proposed by Pye (1983a). This scheme makes a basic distinction between *impeded dunes* (i.e. dunes which are essentially stationary) and *transgressive dunes*. Impeded forms include *embryo dunes*, *foredunes*, *multiple shore-parallel ridges*, *hummocky dunes*, and *isolated mounds*. Transgressive forms include *blowouts*, *parabolic dunes* and *transgressive sand sheets*. Again, various sub-types can be recognized. Photographic examples of the most common types present in England and Wales are provided in Part 2 of the main report.

The mobility of wind blown sand, dune forms, and even entire dune systems, is also strongly influenced by both environmental factors and human activities. In general, stable (non-migrating) dunes are favoured by low to moderate wind energy, high precipitation, high water table levels, high vegetation growth rates, low rates of sand supply, and limited human disturbance. Mobile (transgressive) dunes and sand sheets are favoured by high wind energy, dry conditions, patchy vegetation cover, high rates of sand supply, and high levels of human disturbance. Changes in the balance between these factors may be brought about by natural changes in climate and sea level or by anthropogenic activities.

Temporal variations in dune system mobility and attitudes towards management

A great deal of sedimentary and historical documentary evidence indicates that sand blowing and dune migration occurred on a large scale occurred during the Little Ice Age, and especially between the early thirteenth and mid seventeenth centuries. Landward movement of aeolian sand sheets and transgressive dunes during this period has been documented at many sites in Cornwall (Harding, 1950), South Wales (Higgins, 1933), Anglesey (Bailey *et al.,* 2001), northwest England (Pye & Neal, 1993) and northeast England (Orford *et al*., 2000). This corresponded with the development of shifting sands in some inland areas of England such as the Breckland**,** and in many parts of continental Europe including the Netherlands (Koster *et al.*, 1993) and western Denmark (Møller, 1985; Clemmensen *et al*., 2001). The large scale of aeolian sand transport at this time was probably influenced partly by human activities but was driven mainly by an increase in storminess, especially the frequency, magnitude and duration of strong winds, which lead to widespread coastal erosion, destruction of dune vegetation, and inland movement of sand. A lowering of the wave base (the depth at which waves disturb sediments on the sea bed) may also have contributed in some areas to increased landward movement of sand. This, combined with littoral drift of sediment derived from sections of eroding coast, led to accumulation at the down-drift ends of coastal sediment transport cells, resulting in spit elongation and the blockage of many small harbours and estuary entrances around this time.

The presence of soil horizons within the dune sand sequences in many areas testifies to the fact that periods of dune sand movement and accumulation have alternated with periods of widespread sand stability and vegetation colonization. For example, Pye & Neal (1993) identified four dune morphostratigraphic units in the eroding dune cliffs and beach exposures at Formby Point, Merseyside. Similar buried soil horizons are present in many other dunefields (e.g. Orford *et al*., 2000). Some are clearly of only local importance, but there is also evidence that some periods of stabilization affected several dunefields around the same time, pointing to regional influences on stability / mobility. The relative importance of changes in natural forcing factors, including climate, sea level, sediment supply, and human activities, in bringing about these changes is discussed more fully in Part 4 of the main report.

There is considerable photographic and documentary evidence to show that windblown sand movement and dune migration occurred on a much larger scale in the early and mid periods of the twentieth century than in the period after the mid 1980's. Between the turn of the last century and the 1970's, coastal engineers were regularly faced with problems of migrating sand which invaded roads, railway lines, agricultural land and residential areas. Principal concerns were to stabilise the sand to prevent these problems and to limit rates of coastal erosion by trapping as much sand as possible on the upper beach and in the frontal dunes (e.g. Case, 1914). Large areas of dunes were planted with marram and conifers in order to create a 'stable' coastal defence. In many places these measures were supplemented by erection of fencing to trap sand and by protection of the dune toe using armourstone, gabions and sea walls. During the 1970's, 1980's and 1990's, coastal dune management emerged as an important topic, driven partly by a widely held view that areas of bare sand and patchy vegetation represented a form of environmental degradation that was detrimental to both coastal engineering and nature conservation interests. Dune 'restoration' work was widely undertaken and typically involved construction of fences, boardwalks and other visitor management measures, combined with vegetation planting. A brief review of these techniques is provided in Part 4 of the main report.

These management measures have had a dramatic impact on the great majority of coastal sand dune systems in England and Wales. Today, most are largely stabilised by vegetation, with areas of active blown sand restricted mainly to near-coastal areas where there is a strongly positive sediment budget or high visitor pressure which prevents re-vegetation of blowouts. In the last decade, concerns have arisen in the UK and elsewhere that over-stabilization of dune systems is undesirable from the standpoint of biodiversity and amenity/landscape scenic value, and that dune future management should seek to restore a greater degree of sand and dune mobility. Paradoxically, 'dune restoration' is now widely interpreted to mean a reduction in vegetation cover, reactivation of blowouts, and an increase in sand mobility to enhance habitat dynamism and diversity.

There is also growing concern that there could be a significant net loss of sand dune habitat during the next 50 to 120 years if rates of frontal dune erosion increase due to climate change and sea level rise but the landward dune limit remains fixed. Consequently, there is interest in the possibility of allowing active dunes to move landwards in order to compensate for the effects of 'coastal squeeze' and to allow a situation of 'no net habitat loss'. A preliminary assessment of the potential impacts of sea level rise and climate change on SSSI and SAC dune sites in Wales was completed in 2005 (Pye & Saye, 2005), but a comparable exercise relating to English dune sites has not yet been undertaken.

It has also become a matter of concern amongst engineers that it may not be possible to maintain present frontal dune defences if predictions of the accelerated climate change and sea rise prove to be correct. Revised Guidance to Operating Authorities issued by DEFRA in October 2006 (DEFRA, 2006) makes recommendations to allow for a much larger and more rapid rate of future sea level rise than hitherto. Under currently predicted climate change scenarios, some dune defences may become impossible to maintain within less than 20 years, and in the medium to longer term (50 to 115 years), there is a significant risk that certain dune systems could experience a 'catastrophic' readjustment which would have major implications both for coastal flood defence and nature conservation. However, the threat posed to different sites is variable, and some sites will probably be able to accommodate change without significant detrimental effects.

These issues are not limited to England and Wales, and there is now widespread international recognition of the desirability of increasing the degree of sand mobility and allowing dune systems to adjust in a more natural manner to changes in environmental forcing factors.

Assessment of recent dune stability/mobility

The degree of mobility of individual dunes, and of dunefields as a whole, is dependent on two main factors: (1) erosion/accretion at the beach-dune interface, which reflects the sediment budget of the upper beach and the foredunes; and (2) the balance between vegetation cover and wind stresses across the dune system as a whole. Both aspects have been considered in this study. Where available, historical map, chart, air photograph and ground survey information has been evaluated to provide information about historical changes in shoreline position on decadal to millennial time scales. Inevitably, data coverage varies greatly between sites and some dune localities have been subject to more intense investigation than others. Additionally, the recent erosion/accretion status of all sites was assessed by field surveys carried out between June 1999 and August 2001, supplemented by further surveys at selected sites between 2002 and 2006. Such ground surveys provide a relatively short-term 'snap-shot' of shoreline and frontal dune erosion / accretion trends (averaging over periods of a few weeks to a few years), although longer-term (decadal) trends can to some extent be assessed by evaluation of the frontal dune morphology and vegetation character. The methods used, and the results obtained, in these surveys are described in Part 3 of the main report. Overall, approximately 35% of the total dune frontage in England and Wales was found to show evidence of recent stability, 30% showed evidence of recent net accretion, while the remainder either showed evidence of recent net erosion or is protected by defences. Coastal Cells 8 and 1 were found to have the greatest percentages of eroding dune frontage (42% and 37%, respectively). Cells 3 and 10 had the greatest percentage of net accreting frontage (46% and 42%, respectively), while Cells 2 and 3 had greatest percentage of protected dune frontage (27% and 21%, respectively).

The degree of overall dune system mobility / stability was assessed using information contained in the *Vegetation Survey of England Wales*. Amongst other factors, the nature of vegetation communities strongly reflects the time over which the community has evolved. Several different community / habitat types are identified in the *Vegetation Survey* and data provided for the area covered by each on a site by site basis. For the purposes of our analysis, *strandline*, *mobile dune*, *semi-fixed dune* and *bare* sand community types were taken to be indicative of dunefield mobility and change, while *Fixed dune grassland*, *other grassland*, *sand sedge*, *dry scrub and woodland*, *dry heath* and *plantations* were considered to provide a proxy measure of dunefield stability. The ratio of the areas covered by these two groups of habitats was then used to provide a simple index of the mobility / stability of each dune system. 'Stable' dune habitat types were found to represent almost 44% of the total dune area for which data were available, with 'mobile' dune habitats representing approximately 25%, giving an average mobility / stability index of 0.58. Similar patterns were observed in most coastal cells with the exceptions of Cell 3, 9 and 11 which had higher mobility/stability indices of 0.85, 1.01 and 0.86, respectively.

The area covered by a further broad habitat group, *dune wetland*, was also calculated and included *dune slack*, *wet heath and mires*, *swamps*, *wet mesotrophic grassland*, *wet woodland and scrub* and *open water* habitats. In general, a high percentage of dune wetland habitats corresponds with lower degrees of dune mobility, although exceptions exist.

Sand dune processes

Sand dune processes can be divided into two main types: (1) aeolian processes which concern the transport of individual sand particles by the wind; and (2) dune processes which concern the development and movement of dune bedforms, together with their morphological responses to changes in the processes and sediment budget at the beach-dune interface.

Aeolian processes

Wind is the essential driving force in aeolian sand transport, although other factors such as sediment grain size, moisture content, content of soluble salts and organic matter, can have an important influence. Although a considerable amount of research has been undertaken in the last 70 years to improve understanding of the physics of sand transport by wind (reviewed in Part 2 of the main report), accurate prediction of sand transport rates in the field on timescales of relevance to the coastal engineer remains very difficult, and little progress has been made in relating such information to the longer-term morphological evolution of entire dunefields. For practical purposes, it is considered more useful to undertake broad environmental assessments of aeolian processes and likely morphological responses using data from local or regional meteorological recording stations. In this study, available wind speed and direction data for stations across England and Wales were evaluated and estimates made of the potential for aeolian sand transport using previously published formulae. The results for different stations, and the implications for nearby dune sites, are summarised in Part 3 of the main report.

The prevailing winds across England and Wales are generally south-westerly, but the dominant winds on particular sections of coast are strongly dependent on coastal orientation and local physiography which determine the degree of shelter and fetch. For example, on much of the east coast, the prevailing south-westerly winds blow offshore, and may move sand from dune crests back onto the beach. The reverse situation occurs on the west coast of England and Wales. On north-facing sections of coast, such as that of North Wales, winds from the northwesterly to northeasterly quadrants are most important in terms of transporting sand from the beach to the dunes, but winds from other directions also play a part in redistributing sand within the dunes and in shaping the dune morphology. On the north Norfolk coast, northwesterly to northeasterly winds are again mainly responsible for transporting sand from the beaches, but southwesterly and westerly winds have played an important role in the development of blowouts and small parabolic dunes which face those directions. The relative balance of wind energy from different directions, especially onshore versus offshore, has a profound effect on the overall sand drift potential, dune mobility and dune morphology.

Useful measures of the potential for aeolian sand transport are provided by the *Drift Potential* (DP) and by the *Resultant Drift Potential* (RDP) which are calculated using formulae first proposed by Fryberger & Dean (1979). The Drift Potential provides a sum measure of the potential aeolian sand transport from all directions, while the Resultant Drift Potential (RDP) provides a more representative measure of the potential net transport capacity (taking into account that winds and sediment transport from opposing directions will cancel each other out). Calculated RDP values for stations near the east and south coasts of England are lower than those for stations elsewhere, with the highest RDP values recorded for stations on or near the coasts of Wales and northwest of

England. In short, other things being equal, there is greater potential for aeolian sand transport and dune growth / mobility on exposed parts of the coast in western England and Wales than in southern and eastern England. Actual sand transport will, however, also depend on other factors including sand availability and size characteristics.

Results of the analysis undertaken in this study indicate that other climatic factors such as temperature and precipitation total are likely to have only a minor effect on aeolian sand transport rates and dune mobility. This is consistent with the findings studies. Tidal range was also found to have only a small influence on the scale of dunefield development, or on recent frontal dune accretion/erosion status.

Dune processes

The morphology and mobility of frontal dunes is closely related to that of the adjoining beach and nearshore zone. A number of conceptual models of beach-dune interaction have been developed in the last 20 years which relate longshore and temporal variations in dune morphology and dynamics to coastal processes. The balance between local beach sediment budget and the adjoining foredune sediment budget has been recognized as critical in determining whether the dune frontage will experience erosion, progradation, or no change in position but with vertical accretion. Other factors of importance include whether the neighbouring beach is 'reflective' or 'dissipative' in terms of the incident wave energy, and the existence or otherwise of local wave focussing. These factors and their relationships to dune processes are discussed in more detail in Part 2 of the main report.

Although frontal dune erosion can be gradual, it is more commonly episodic with periods of major recession during severe storms alternating with periods of stability, or even recovery, during intervals of relatively non-stormy weather. The frequency and magnitude of storm events is therefore of critical importance.

Dune frontages which are protected by artificial defences behave differently during storms to unprotected frontages. Under favourable circumstances, a dune belt can act as a natural dynamic defence which absorbs storm wave energy and releases sediment to the beach during storms, and which is rebuilt by natural processes (wind action) during periods of fair weather. However, in order to serve this function the dune belt must be sufficiently wide and high, and it may be necessary to assist the rebuilding process following storms by intervention measures. Depending on circumstances, these may involve bulldozing of sand, beach nourishment, fencing and vegetation planting. In areas where the coast shows a medium to long-term trend of recession, dune barriers have the potential to migrate landwards and yet to maintain their morphology (height and width) and sand volume. Whether or not this occurs will depend on the efficiency of aeolian processes and the rate of coastal recession. A number of alternative models relating both to conditions of stable sea level and rising sea level conditions are also discussed in Part 2 of the main report.

The morphology and mobility of the hind dunes behind the shore is, to a large extent dependent, on the balance between wind energy and vegetation cover. While the former can effectively be considered as an independent variable governed by regional weather patterns, vegetation cover is influenced both by natural climatic factors and by human activities including vegetation management. Under prevailing climatic conditions in England and Wales today, there is a natural tendency for dunes at most sites to stabilise relatively quickly in the absence of factors such as high grazing or visitor pressure. Positive measures, such as planting and fencing, usually have to be taken to create and sustain mobile dunes until they reach a critical size where they can become self-sustaining.

Potential impacts of future climate and sea level change on dune processes and flood defence significance

The impacts of future climate changes on the dynamics of British dune systems remain a matter of uncertainty. Several potential impacts have been identified, but these may operate in opposite directions and the net effect is difficult to predict. A marked rise in sea levels is likely to raise water tables within dunefields, increasing the extent of wet slacks and decreasing the rate of sand movement. Warmer, wetter conditions would reinforce this effect, whereas colder, drier conditions would tend to counteract the effect, to varying degrees. However, the most significant factor would be a major change in wind regime (speed, duration and direction).

The nature of the impacts will depend to a significant extent on the rate of change in forcing factors, especially the rate of sea level rise, wind regime and storm surge frequency and magnitude. If change becomes increasingly rapid some beach and dune systems may not be able to adapt sufficiently quickly and there may be major changes in the size and morphology of some dunefields. It will be of crucial importance from a coastal flood defence perspective whether dune systems are able to move landwards and upwards in line with rising sea level, thereby maintaining a constant cross-sectional profile and sand volume, whether they grow in size as landward movement takes place, or whether gradual dissipation occurs, thereby progressively increasing the risk of overwashing and breaching. A number of schematic models illustrating these alternative modes of evolution are discussed in Part 2 of the main report.

Sediment composition

The vast majority of dune systems in England and Wales are composed of medium, well-sorted sand, although some sites, especially in the southwest, are composed of less well-sorted, coarser sand. The sands at most sites are overwhelmingly siliceous, being derived mainly from former glacial sediments which have been reworked by marine processes. Contributions from marine shell material are regionally significant only in the dune systems of Southwest England and southwest Wales.

Detailed analysis of the major and trace element composition of the sands allows different provenance sources and sediment transport pathways to be identified. Although the beach and dune sediments in some coastal cells originate from well mixed regional 'pools' some dune sites show clear local chemical signatures which reflect the importance of local sediment sources. Further information is given in Part 3 of the main report. Geochemical and textural sediment fingerprinting provides a valuable tool for the definition of sediment sources, sinks and transport pathways which has so far been under-utilised in UK coastal management.

Land use, management and conservation status

There are few, if any, areas of entirely natural coastal dune landscape in England and Wales. Most dune areas have experienced a long history of many different types of land use, including livestock grazing, managed warrens, sand mining, forestry, military activities, golf courses and holiday camp development. Many of these activities continue today. Available information is summarised in Part 3 of the main report. The nature of the activities undertaken in an area, and the associated ownership, access and usage rights, exercise considerable constraints on the management strategies which can be implemented.

The great majority of dune systems in England and Wales have one or more nature conservation designations, and several are sites of international nature conservation importance. Details are given in Part 3 of the main report. In many dune systems, recent management policy has been governed to a significant degree by legal requirements to maintain designated habitats and species in 'favourable condition'. Local biodiversity action plans (LBAPs) or habitat action plans (HAPs) have been established for many sites, mostly led by local authorities with participation from local representatives of interested organizations (e.g. Natural England, Countryside Council for Wales, local Wildlife Trusts, Ministry of Defence). These plans generally aim to achieve local targets within the wider frameworks set by national and regional-scale initiatives including UK Biodiversity Action Plans (UKBAPs) and Coastal Habitat Management Plans (CHAMPs). Many of the Plans and other dune management initiatives are supported by web sites aimed at public awareness and participation (e.g. those sponsored by Sefton Council, the Sefton Coast Partnership, Cornwall County Council and Wirral Borough Council).

Conclusions and recommendations for further work / action

Coastal sand dunes are of considerable coastal flood defence significance in several parts of England and Wales, as well as being of importance for nature conservation, recreation and other reasons. If current predictions regarding acceleration of future sea level rise prove to be correct, the areal extent, and possibly the continued existence, of some systems (especially narrow, fringing and non-climbing systems) will be placed under severe threat.

Wherever possible, natural processes should be allowed to take their course so that dune systems can evolve to achieve a new equilibrium with the forcing factors. This may involve a reduction in dune area and loss / reduction of some important habitats in certain areas, but there is likely to be partial compensation by development of new dune habitat elsewhere. A reduction in the natural flood defence value of some dune systems is also likely unless remedial works are undertaken, including large-scale beach nourishment, dune re-profiling and vegetation planting, as has been done for many years in The Netherlands. Whether or not such action can be justified and considered environmentally acceptable will depend on local circumstances.

In order to provide a better basis for informed decision making, it is recommended that a *Geomorphological Evaluation Study* (GES) should be undertaken for each of the dune sites, or appropriate group of sites, identified in this report. These studies should seek to quantify more precisely the beach and dune sand volumes present above various datum levels, the rates of recent morphological change, the nature of the frontal dune vegetation and degree of sand mobility, the area at risk from flooding behind the dunes, the standard of existing flood defence provided by the dunes, and the standard of defence which is desirable given the commercial and environmental asset value of the protected land. These assessments should also consider the nature of morphology and process regime in the adjoining nearshore and offshore areas in order to develop predictive models of the likely three-dimensional evolution of each beach-dune system in the short, medium and long term. The GES for each dune site should be co-ordinated by the relevant authority responsible for flood and coastal defence. It should take into account other existing studies and plans, including Shoreline Management Plans (SMPs) and Local Biodiversity Action Plans (LBAPs), but its outputs seek to inform and guide the next generation of such plans, rather than be governed by them. The scale of study required will clearly vary from area to area, depending on such factors as the size of dune system, its present and potential future coastal flood defence significance, and habitat significance.

Monitoring of all dune systems should be seen as a high priority in order to provide early warning of potentially significant changes and to allow sufficient time to consider and design appropriate responsive strategies. Some dune systems are already covered by comprehensive physical and biological monitoring programmes (e.g. the Sefton coast), but this is not true everywhere and steps should be taken to improve the position where required. Lidar and kinematic GPS ground-based surveys provide now rapid and cost effective methods of acquiring the necessary physical information from large areas.

Monitoring data should be collected and stored in a standard and easily accessible format (e.g. Microsoft Excel files) which can be exported for centralised analysis. Many local authorities and other organizations concerned with sand dune management are now moving to establish databases which are able to store large amounts of environmental information which can be readily interrogated. This should be viewed as good practice which is to be encouraged. However, such local databases should be accessible so that relevant data can be exported in order to allow centralised analysis of regional and national trends. The possibility of creating a higher level, national beach and dune morphological database, similar to those operated in The Netherlands and Australia to inform both strategic and operational management planning, should also be explored.

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References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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