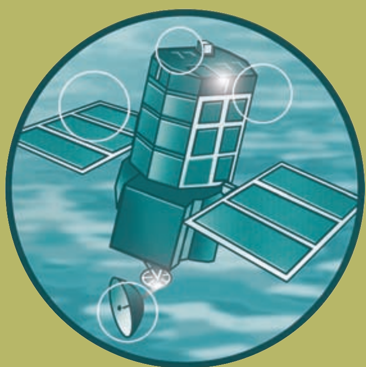
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Sand dune processes and management for flood and coastal defence

Part 1: Project overview and recommendations

R&D Technical Report FD1302/TR



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Part 1: Project overview and recommendations

R&D Technical Report FD1302/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

1.1 Report scope and purpose

This report summarises work undertaken under R & D Project FD1302 which 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

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

1.2 Report structure

The final 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.

1.3 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 and broader-scale, longer-term methods of dune management.

1.4 Coastal dune systems in England and Wales

A total of 112 coastal dune 'sites', comprising 158 dune individual dune localities, have been identified for the purposes of this report (Table 1.1 and Figure 1.1). Only dune localities on the mainland and islands connected to the mainland by roads (e.g. Anglesey, Holy Island) have been 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 report 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).

1.5 Significance of dunes for coastal flood defence

Although coastal flood defence is an extremely important aspect of coastal dunes (Plates 1.1. & 1.2), 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 (Figure 1.2; Plates 1.3, 1.4, 1.5 & 1.6). 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.

Figure 1.3a shows a schematic situation where the level of the hinterland lies above storm surge level and 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 (Figure 1.3b). Where the level of the hinterland lies below normal high tide level, the dunes have relatively higher flood defence significance (Figure 1.3c; Plates 1.1 & 1.2). 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 this report).

Figure 1.4 provides a summary of the geographical distribution of dune systems with varying degrees of flood defence significance in England and Wales. 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 (Figure 1.5). 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 (Figure 1.6).

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 Graff, 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.

1.6 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.

1.7 Dune system and dune morphology / mobility

Two aspects of morphology have been 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. The inter-relationships between these factors are shown in Figure 1.7.

1.7.1 Dune system morphology

For the purposes of this report, 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 this report).

1.7.2 Dune morphology

Individual dune forms have been classified in this report 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.

The mobility of wind blown sand, dune forms, and even entire dune systems, is also strongly influenced by the factors summarised in Figure 1.7. 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.

1.7.3 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 morpho-stratigraphic 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.

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 (e.g. Plates 1.7 & 1.8). 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.

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 (e.g. Plate 1.9 and Figure 1.8) 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.

1.7.4 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 this 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 (Figure 1.1) 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.

1.8 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.

1.8.1 Aeolian transport 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 (briefly reviewed in Part 2), 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.

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.

1.8.2 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.

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 discussed in Part 2.

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.

1.8.3 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.

1.9 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. 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.

1.10 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. 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. 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).

1.11 Conclusions and recommendations

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 reprofiling 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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1.13 Glossary

ATM	Airborne Thematic Mapper
avulsion	rapid movement in position of the coast
backshore	the part of the beach between MHW and HAT
barchan	crescent-shaped mobile dune with horns pointing downwind, usually composed of bare sand, formed when the wind blows predominantly from one direction
barrier island	elongate shore-parallel feature separated from the mainland by saltmarsh, mudflats or lagoonal areas
barrier spit	elongated accumulation of sand and/or gravel projecting into the sea, usually where the line of the mainland coast changes direction, formed by longshore drift
bay-fill	progradational beach ridge and/or dune development within an embayment setting leading to infilling of the bay
bay-head barrier	a barrier located near the head of a bay, but separated from it by a lagoonal area
bay-mouth barrier	a barrier that partially encloses a bay at its entrance
beach nourishment	artificial addition of sediment to the beach to raise beach levels
benchmark	fixed point of reference used in topographic surveying
bimodal	grain size distribution with two modal size fractions
blowout	depression or hollow formed by wind erosion on an existing sand deposit
BP	before present, relating to dates before the present day
Bruun Rule	two-dimensional cross-shore model that predicts the amount of shoreline displacement erosion as a result of rising sea levels

C3 grasses	plants which photosynthesize using the simple C3 method of carbon dioxide fixation, including the main dune building species
CASI	Compact Airborne Spectrographic Imager
cell	a length of coast that is relatively self-contained as far as the movement of sand and shingle is concerned
climbing dune	a dune formed by sand blown inland up a slope towards an area of higher ground
cliff-top dune	a dune located at the top of a coastal cliff formed either by sand transport up the cliff from the beach under moderate to high wind energy conditions or as a result of marine erosion of a climbing dune
composite dune system	dune system formed within more than one geomorphological setting alongshore
coppice dune	isolated mound formed as sand is trapped around a bush or clump of vegetation
deflation	reduction in sand dune volume by wind scour
Devensian	the last glacial stage in Britain lasting between *c.* 70,000 years BP to *c.* 10,000 years BP
dissipative beach	a beach on which, under average conditions, all wave energy is dissipated by interaction with the bed
dissipation rollover model	mode of coastal dune response to sea level rise in which dune height decreases with time, as sediment is lost from the system
do nothing option	strategic management approach in which no coastal engineering or other management measures are undertaken
Drift Potential (DP)	maximum sand moving capacity assuming all winds above the threshold velocity can transport sand
dune	aeolian bedform usually composed most commonly of sand which develops where the transporting capacity of the wind is reduced

dune nourishment	artificial addition of sediment directly to dunes to enlarge the volume of sand
dune site	term used in this report mainly referring to a single dune system, but in some instances to a group of adjacent systems grouped together on the basis of their physical setting or genesis
dune system	an area of aeolian sand accumulation composed mainly of dunes, which displays morphological or functional integrity.
D-values (D_{10}, D_{50}, D_{90})	particle size values corresponding to the tenth, fifteenth and ninetieth cumulative percentiles of the distribution
D_{90}-D_{10} range	the range (in microns) between the 10^{th} percentile and the 90^{th} percentile of a grain size distribution, with lower values indicating a better-sorted material
dynamic preservation	strategic management option involving maintenance of the coastline position whilst permitting the coastal zone to be dynamic
echo dune	a dune formed by accumulation of sand on the upwind side of a cliff or escarpment
embryo dune	small, often ephemeral sand mound usually found on the backshore, which may develop into a new foredune
equilibrium rollover model	mode of coastal dune response to sea level rise in which the dune height and width remains constant but is located further inland
fetch	distance over which a wind acts to generate waves
fixed dune	dune with a surface fixed by vegetation and which is not mobile
Flandrian	the postglacial period, which began *c.* 10,000 years ago
foredune	continuous or semi-continuous ridge of sand orientated parallel to the coastline and located nearest to the sea
foreshore	part of the beach between MLW and MHW

fringing dune system	dune system morphological type consisting of a narrow dunebelt with a width of up to 200 m for at least 90 % of the dune system length
frontal dunes	dunes located immediately adjacent to the beach or those at the most seaward margin of the system
geochemical composition	abundance of chemical elements and oxides within a sample
ground survey	surveys of the intertidal and supratidal zones usually undertaken using a theodolite or Total Station (Electronic Distance Measurer, EDM)
habitat creation	the creation of new or extended ecological habitats either by direct or indirect intervention measures
HAT	highest astronomical tide
headland bypass dune system	dune system morphological sub-type where aeolian material accumulates in adjacent bays and moves inland, bypassing the headland separating them, so that they may eventually coalesce
heavy mineral	mineral of high specific gravity
hedgehogs	vegetated, isolated mounds of sand created by non-uniform aeolian erosion
hind dunes	dunes located landwards of the frontal dunes that owe their position either to coastal progradation or to landwards movement of the dunes under the influence of the wind
hinterland	area inland of the coastal zone
hold the line	strategic management option involving holding the current coastline position, which may require the implementation of defences in order to maintain the position
Holocene	the last 10,000 years in the geological timescale (equivalent to the Flandrian period in Britain)
hummocky dunes	continuous terrain of irregularly shaped mounds of sand, usually mainly vegetated
impeded dunes	dune morphological type in which vegetation plays an important role in preventing rapid movement

Index of Drift Potential including Precipitation (I_{DPP})	maximum sand moving capacity assuming all winds above the threshold can transport sand calculated for a wind regime using the Fryberger & Dean (1979) equation but also taking into account climatic wetness (precipitation factor)
Index of mobility/stability	the degree of mobility/stability of a dune system calculated using the percentage of bare sand or percentage coverage of different vegetation communities
inductively-coupled plasma atomic emission spectrometry (ICP-AES)	technique used to determine the chemical composition of sand and other materials
internal dynamism	strategic management option involving controlling the degree of system mobility/stability to achieve conservation and flood defence objectives
intertidal zone	the zone influenced by regular tidal action, commonly taken to be between MHWS and MLWS
isostatic adjustment	movement of the land in response to the application or removal of overburden (e.g. ice cover or water)
lacustrine	lake environment
laser granulometer	instrument which uses the principle of laser diffraction to determine the particle size distribution of samples
LAT	lowest astronomical tide
lee slope	the downwind side of a dune
lidar	light detection and ranging. An airborne remote sensing technique which generates a digital elevation model of the earth's surface
linear dune	a dune ridge where the crest is orientated almost parallel (at an angle of 0-15° to the resultant sand transport direction)
links	level areas of blown sand or gently undulating areas of low dunes, often used as golf courses
Little Ice Age	a period of climatic cooling in the Northern Hemisphere between the mid-16th century and the mid-19th century

longshore drift	movement of beach sediments approximately parallel to the shoreline
lower beach	the beach seaward of MLW
lunettes	small crescent-shaped dunes that occur on the downwind margins of lakes
macrotidal	mean spring tidal range of greater than 4 m
major element	an element which is present in concentrations higher than 0.1 %, or one of the ten elements which by convention is quoted in terms of the abundance of its oxide (Si, Al, Fe, Mg, Ca, Na, K, Ti, P, Mn)
meals, meols	an old english term for sand dunes, used mainly in parts of northern England
mesotidal	mean spring tidal range of between 2 and 4 m
MHW	mean high water
MHWS	mean high water spring
microtidal	mean spring tidal range of less than 2 m
mid beach	beach between MHW and MLW
MLW	mean low water
MLWN	mean low water neap
MLWS	mean low water spring
mobile dune	dune with an open plant community or bare of vegetation which tends to change position or extent (also known as a shifting dune)
morphodynamics	changes in form, shape and position of landforms
morphometric parameter	parameter involving the measurement of form
morpho-stratigraphic	a term summarising the relationship between landforms and stratigraphy (geological sequence of deposition)
multiple shore-parallel ridges	a series of dune ridges parallel to the shore with intervening troughs or slack areas

nearshore	area of the seabed below MLWS and above storm wave base
nebkha	isolated mound formed by trapping of windblown sand around a bush or clump of vegetation
negative feedback	system behaviour where the effect of a change is to counteract the impact of the initial alteration
neotectonics	crustal movements that have occurred in the Earth's recent past and are continuing at the present day
ness	a promontory of land, usually composed of marine sediment, projecting into the sea
non-climbing dunes	dunes which are restricted to the foot of a cliff or upland area, or which have not climbed over and buried older dunes
North Atlantic Oscillation (NAO) Index	a measure of large-scale fluctuation in atmospheric pressure between the subtropical high pressure system located near the Azores in the Atlantic Ocean and the sub-polar low pressure system near Iceland
oblique dune	dune ridge with crest aligned at angle of 15-75° to the resultant sand transport direction
ODN	Ordnance Datum Newlyn
offshore	area seaward of the nearshore zone below the wave base of normal storm waves
optically stimulated luminescence dating (OSL)	dating technique based upon the ability of minerals to store energy in the form of trapped charge carriers and release it when exposed to ionising radiation from a laser source
palaeoecological	the relationship between fossil organisms and their palaeoenvironments
palaeosol	an ancient soil horizon or buried fossil soil
parabolic dune	crescent-shaped mobile dune with ‘arms’ pointing upwind, formed by the centre of the dune being moved downwind faster than the sides which are usually partly fixed by vegetation

particle size distribution	the range of particle sizes present in a sediment sample
pedogenic processes	process involved in soil formation
plant succession	the process by which one plant community gives way to another in an orderly series from colonisers to climax
Pleistocene	geological period extending from around two million years to 10,000 years before present.
podsol	a type of soil formed in cool, seasonally humid climatic conditions where leaching is a dominant process
precipitation ridge	a type of transverse transgressive dune with a large slip face on the landward side
primary mode	the most abundant modal grain size fraction in a sample where two or more modes can be differentiated
progradation	seaward advance of the shoreline
rare earth elements	trace elements with atomic numbers between 57 and 71
RDP/DP	the ratio of Resultant Drift Potential to Drift Potential, used as an index of the directional variability of the wind
reflective beach	a beach on which, under average conditions, part of the incident wave energy may be reflected back out to sea
remnant knobs	vegetated, isolated mounds of sand formed as a result of aeolian erosion, particularly between two adjacent blowouts
Resultant Drift Direction (RDD)	the net trend of sand drift under the influence of winds from different directions
Resultant Drift Potential (RDP)	the net sand transport potential when winds from various directions interact
ridge and runnel morphology	beach morphological type, consisting of a series of shore-normal troughs (runnels) and ridges found in the intertidal zone

sand sheet	aeolian sand deposited by aeolian processes with either a flat surface or covered with small, scattered dune forms
sediment budget	a description of the inputs and outputs of coastal sediments
shadow dune	a dune formed in the lee of vegetation or other obstacle
significant wave height	the average height of the highest one-third of waves during a given event or time period
skewness	degree of symmetry or distortion to one side of a distribution average (in this report applied to grain size distribution)
slack	area within a dune system where the surface is near or at the ground water level. May be formed by wind deflation during dry weather, or as a result of seawards growth of successive foredune ridges
snowball rollover model	model of coastal dune response to sea level rise in which dune height above high water increases as the dune moves landwards
sorting	the dispersion of the particle size distribution of a sample, with lower values indicating a better-sorted material. The standard deviation is often used to represent dispersion
storm surge	a local change in the elevation of the ocean along a shore due to a storm, normally associated with a decrease in atmospheric pressure and 'wind piling' of water
stoss slope	the upwind slope of a dune, usually steeper than the lee (downwind) slope
strandline	high tide line on the beach where debris collects
stratigraphic dating	dating method based on the relative spatial and temporal arrangement of rock strata
Sub-Atlantic	phase of cooler and wetter climatic conditions in NW Europe commencing about 3200 BP
sub-cell	a division of a sediment cell based on best available knowledge of large scale processes within that cell

Sub-Boreal	phase of cooler and drier climatic conditions in NW Europe between about 5200 BP to 3200 BP
supratidal	coastal zone above the level of mean high water springs
threshold velocity	the critical wind velocity at which aeolian transport is initiated
tidal range	the vertical difference between high and low water levels
tombolo	an accumulation of sediment that links an island to the mainland or to another island
towan	a term for dune, widely used in Cornwall
towyn or tywyn	a term for dune, widely used in Wales
trace element	an element that occurs in small but detectable quantities in minerals and rocks, usually less than 0.1 %
transgression (marine)	an advance of the sea to cover new land areas, due to a rise in sea level relative to the land
transgressive dune	a mobile dune which moves inland over time
transgressive dune system	a dune system morphological type which is normally hundreds of metres to kilometres wide, formed by sand being transported in the direction of the resultant sand drift. The system may not be mobile under the current wind regime
transverse dune	a dune ridge aligned almost perpendicular (0-15°) to the resultant sand transport direction
trickle feeding	the artificial addition of sediment to the beach at a gradual rate which maintains a stable beach while allowing for losses alongshore, offshore or inland
unimodal	a grain size distribution which has a single mode
upper beach	part of the beach above MHW
washover dune	a low dune ridge which is regularly affected by storm wave overwash

washover rollover model	mode of coastal dune response to sea level rise in which dune height and dune width decrease considerably with time, leading to a high risk of washover and breaching

Tables

Table 1.1 List of the major coastal dune localities in England and Wales considered in this report.

SITE	SITE NAME	SUB-SITE	SUB-SITE NAME
1	Cocklawburn to Goswick	1a	Cocklawburn Beach
		1b	Cocklawburn Dunes
		1c	Cheswick Links
		1d	Goswick Links
2	Holy Island		
3	Ross Links and Budle Bay	3a	Ross Links and Budle Bay west
		3b	Budle Bay east
4	Bamburgh to Seahouses	4a	Bamburgh
		4b	Redbarns Links
		4c	St Aidan's Dunes
5	Annstead Dunes		
6	Beadnell Bay	6a	Tughall Mill Links
		6b	Newton Links
7	Embleton Bay		
8	Sugar Sands to Seaton Point	8a	Sugar Sands
		8b	Howdiemont Sands
		8c	Boulmer
9	Alnmouth Bay	9a	Alnmouth
		9b	Buston Links
		9c	Birling Links
10	Amble to Hauxley	10a	Amble Links
		10b	Hauxley Links
11	Druridge Bay		
12	Snab Point to Beacon Point	12a	Cresswell Dunes
		12b	Lyne Sands
13	Beacon Point to Newbiggin Point		
14	Newbiggin Bay		
15	North Seaton to North Blyth	15a	North Seaton
		15b	Cambois to North Blyth
16	South Blyth to Seaton Sluice		
17	St Mary's Island to Tynemouth	17a	St Mary's Island
		17b	Whitley Links
		17c	Long Sands
18	South Shields		
19	Whitburn Bay		
20	Hart Warren Dunes		
21	Hartlepool to Marske-by-the-Sea	21a	Carr House Sands and Seaton Dunes
		21b	Coatham Sands
		21c	Redcar to Marske-by-the-Sea
22	Spurn Peninsula		
23	Cleethorpes and Humberston		
24	Horse Shoe Point		
25	Somercotes Haven to Mablethorpe	25a	Somercotes Haven to Saltfleet Haven
		25b	Saltfleet Haven to Mablethorpe
26	Sutton on Sea to Chapel St Leonards		
27	Seathorne to Gibraltar Point		
28	Old Hunstanton to Holme Dunes		
29	Brancaster Bay		
30	Scolt Head Island		
31	Holkham Bay		
32	Wells-next-the-Sea to Morston	32a	East Hills
		32b	Stiffkey Meals
		32c	Morston Meals
33	Blakeney Point		
34	Northeast Norfolk Coast	34a	Happisburgh to Winterton Ness
		34b	Winterton Ness to Hemsby
		34c	Caister-on-Sea to Great Yarmouth
35	Suffolk Coast	35a	Gunton Denes and Lowestoft Denes
		35b	Kessingland
		35c	Covehithe Broad
		35d	Southwold
		35e	Walberswick
		35f	Minsmere to Sizewell
		35g	Thorpeness
36	Sandwich Bay		
37	Romney Sands		

Table 1.1 continued.

SITE	SITE NAME	SUB-SITE	SUB-SITE NAME
38	Camber Sands		
39	Littlehampton	39a	East Beach
		39b	West Beach
40	East Head, West Wittering		
41	Sinah Common, Hayling Island		
42	Poole Harbour Entrance	42a	Sandbanks
		42b	Studland
43	Exe Estuary	43a	The Maer, Exmouth
		43b	Dawlish Warren
44	Bigbury Bay	44a	Thurlestone Sands
		44b	Leas Foot Sand
		44c	Yarmouth Sand
		44d	Bantham Ham
		44e	Cockleridge Ham
		44f	Bigbury-on-Sea
		44g	Burgh Island
		44h	Challaborough
		44i	Ayrmer Cove
		44j	Westcombe Beach
45	Par Sands		
46	Kennack Towans		
47	The Towans, Mullion		
48	Praa Sands		
49	Marazion		
50	Whitesand Bay		
51	St Ives Bay	51a	Lelant Towans
		51b	Hayle Towans, Upton Towans and Gwithian Towans
		51c	Godrevy Towans
52	Porth Towan		
53	Perran Bay		
54	Holywell Bay		
55	Crantock Bay		
56	Fistral Bay		
57	Berryl's Point to Trevose Head	57a	Mawgan Porth
		57b	Constantine Bay
58	Camel Estuary	58a	Harbour Cove
		58b	Rock to Daymer Bay
59	Widemouth Bay		
60	Bude		
61	Taw Estuary	61a	Northam Burrows
		61b	Instow Sands
		61c	Braunton Burrows
62	Croyde Burrows		
63	Woolacombe Warren		
64	Berrow and Brean		
65	Weston Bay		
66	Sand Bay		
67	Merthyr-mawr Warren		
68	Swansea Bay	68a	Kenfig Burrows
		68b	Margam Burrows
		68c	Baglan Burrows
		68d	Crymlyn Burrows
		68e	Black Pill Burrows
69	Oxwich Bay	69a	Pennard Burrows
		69b	Penmaen Burrows
		69c	Nicholaston Burrows
		69d	Oxwich Burrows
70	Port-Eynon Bay		
71	Rhossilli Bay	71a	Rhossilli
		71b	Hillend Burrows
		71c	Llangennith Burrows
72	Burry Holms to Whiteford Point	72a	Broughton Burrows, Delvid Burrows and Hills Burrows
		72b	Whiteford Burrows
73	Pembrey Burrows		
74	Laugharne Burrows and Pendine Burrows		
75	The Burrows, Tenby		

Table 1.1 continued.

SITE	SITE NAME	SUB-SITE	SUB-SITE NAME
76	Lydstep Haven		
77	Manorbier Bay		
78	Freshwater East		
79	Stackpole Warren		
80	Linney, Brownslade and Broomhill Burrows	**80a**	Linney Burrows and Brownslade Burrows
		80b	Gupton Burrows, Broomhill Burrows and Kilpaison Burrows
81	The Burrows, Whitesands Bay		
82	Newport Bay		
83	Teifi Estuary	**83a**	Poppit Sands
		83b	Towyn Warren
84	Ynyslas		
85	Aberdovey to Tywyn		
86	Mawddach Estuary	**86a**	Fairbourne spit
		86b	Barmouth
87	Morfa Dyffryn and Llandanwg	**87a**	Morfa Dyffryn
		87b	Llandanwg
88	Dwyryd-Glaslyn Estuary	**88a**	Morfa Harlech
		88b	Morfa Bychan
89	Morfa Abererch		
90	Pwllheli and Traeth Crugan		
91	Abersoch	**91a**	The Warren, Abersoch
		91b	Morfa Gors
92	Tai Morfa		
93	Morfa Dinlle		
94	Newborough Warren		
95	Porth Twyn-mawr		
96	Tywyn Aberffraw		
97	Tywyn Fferam and Tywyn Llyn	**97a**	Tywyn Fferam
		97b	Tywyn Llyn
98	Tywyn Trewan		
99	Tywyn-gywyn		
100	Tywyn-mawr		
101	Dulas Bay and Lligwy Bay	**101a**	Dulas Bay
		101b	Lligwy Bay
102	Red Wharf Bay		
103	Conwy Bay	**103a**	Conwy Morfa
		103b	Deganwy and Llandudno
104	Abergele to Point of Ayr	**104a**	Kinmel Dunes
		104b	Rhyl to Prestatyn
		104c	Gronant Dunes and The Warren, Talacre
105	Wirral Peninsula	**105a**	West Kirby to Leasowe
		105b	Leasowe to New Brighton
106	Sefton Coast	**106a**	Seaforth to Hightown
		106b	Hightown to Marshside
107	Fylde Coast	**107a**	Lytham to Blackpool
		107b	Fleetwood to Pilling
108	Walney Island	**108a**	South End Haws
		108b	North End Haws
109	Duddon Estuary	**109a**	Sandscale Haws
		109b	Askam in Furness to Dunnerholme
		109c	Hodbarrow
		109d	Haverigg Haws and Kirksanton Haws
110	Esk Estuary	**110a**	Eskmeals Dunes
		110b	Drigg Dunes
111	Seascale to Braystones		
112	Maryport to Grune Point		

Table 1.2 Summary of the frontal dune erosion/accretion status at dune systems in England and Wales as recorded during field visits between 1999 and 2001.

EROSION/ACCRETION STATUS	**NUMBER OF SITES**			
	ALL	**EAST ENGLAND**	**SOUTH ENGLAND**	**WALES & WEST ENGLAND**
TOTAL NET MARINE ERODING	40	12	1	27
TOTAL NET ACCRETING	27	11	2	14
TOTAL NET STABLE	46	11	8	27
VARIABLE STATUS	37	10	3	24
MARINE ERODING ONLY	3	3	0	0
PROTECTED ONLY	3	0	0	3
MARINE ERODING & PROTECTED ONLY	3	0	0	3
ACCRETING ONLY	5	4	1	0
STABLE ONLY	16	1	2	13
NET MARINE ERODING	19	7	1	11
NET PROTECTED	5	2	0	3
NET MARINE ERODING & PROTECTED	7	0	0	7
NET ACCRETIING	22	7	1	14
NET STABLE	30	10	6	14

Figures

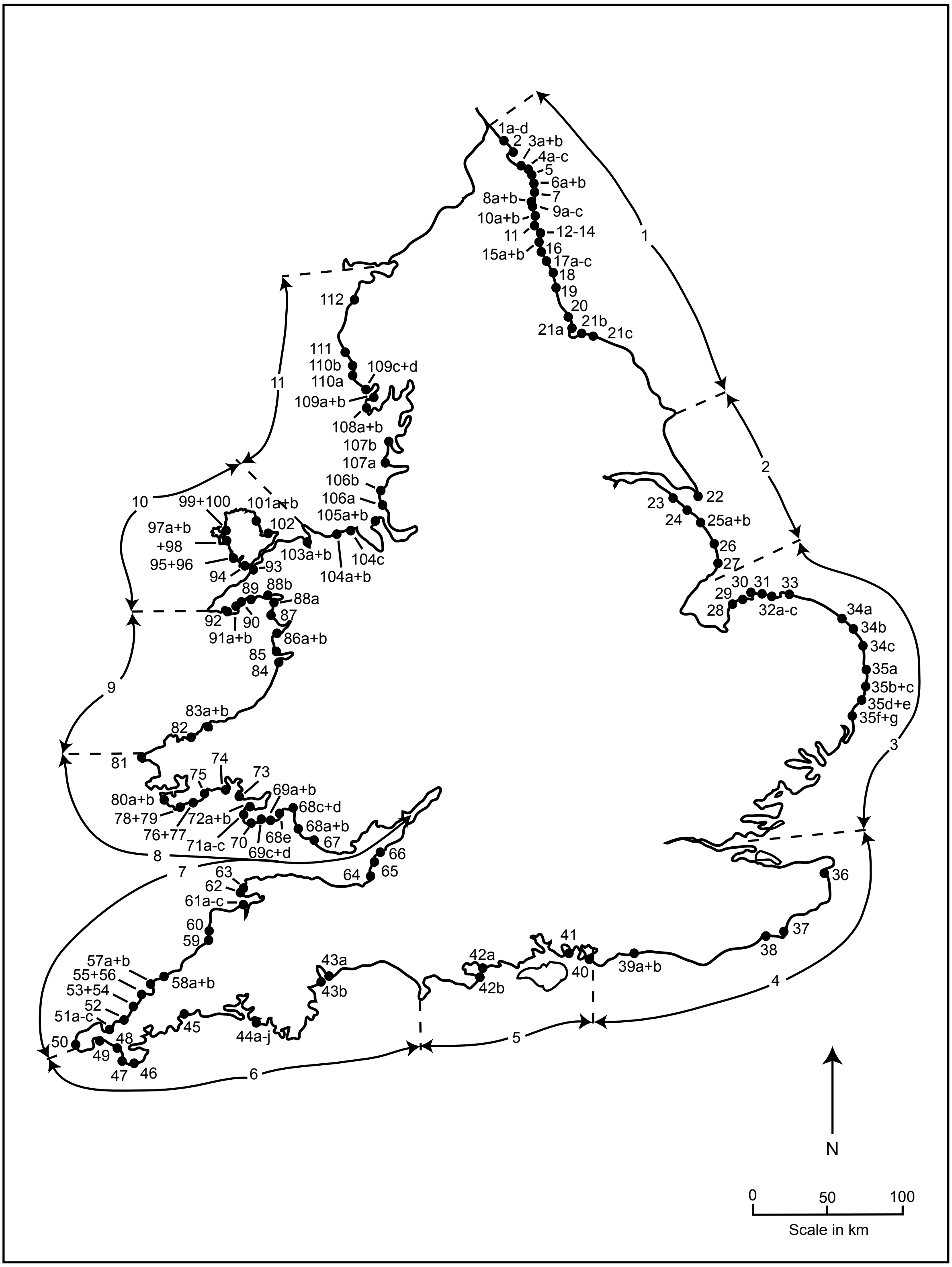

Figure 1.1 Location of the major coastal dune systems in England and Wales. Coastal process cells (as defined by Motyka & Bramptom, 1993) are also shown.

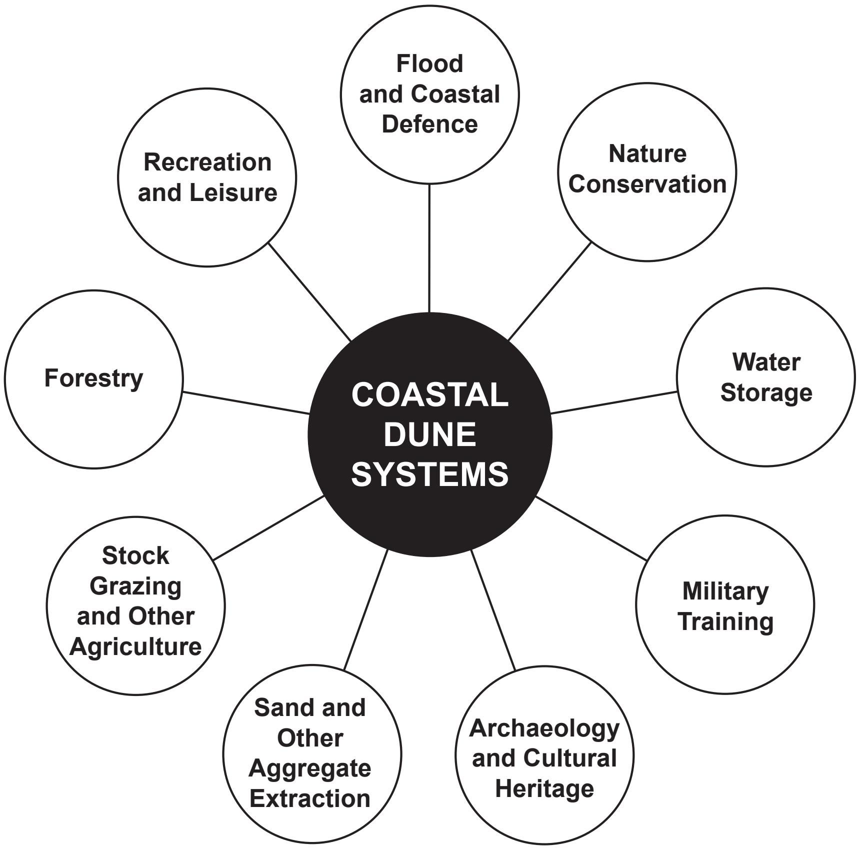

Figure 1.2 Human interests in coastal dune systems.

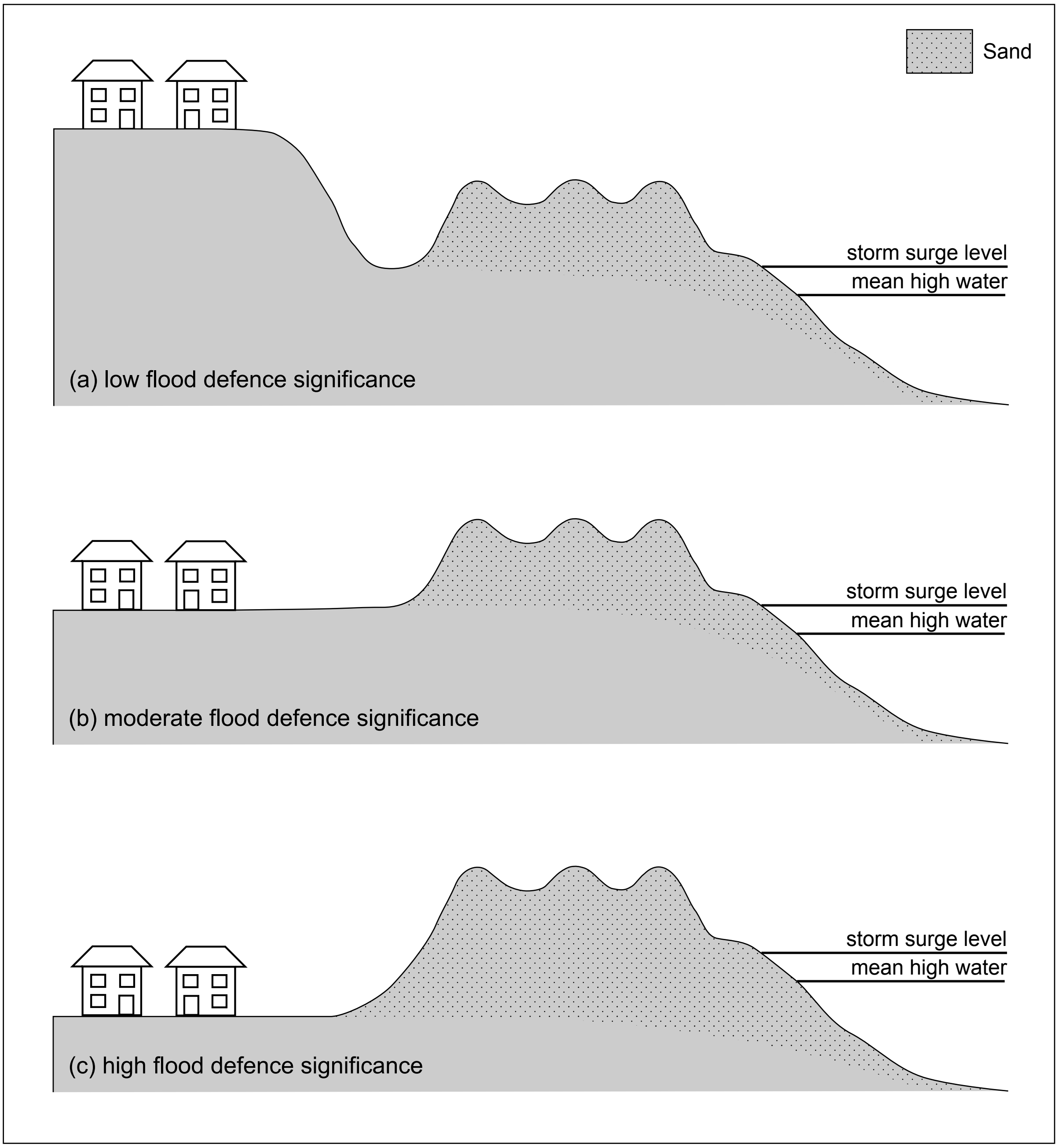

Figure 1.3 Schematic diagram showing degrees of significance of dunes for coastal flood defence.

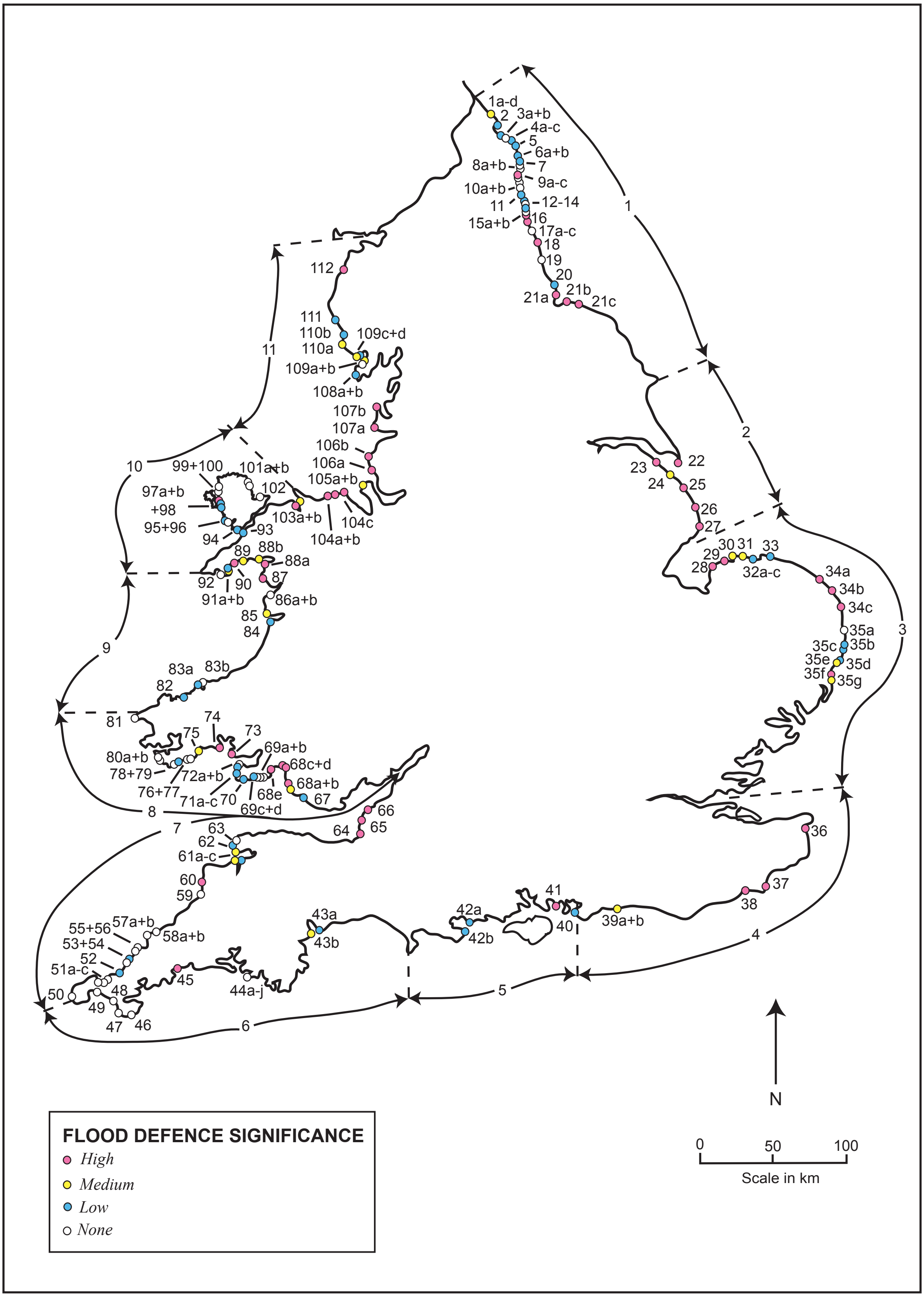

Figure 1.4 Flood defence significance of dune sites in England and Wales. See text for full definitions of each status type.

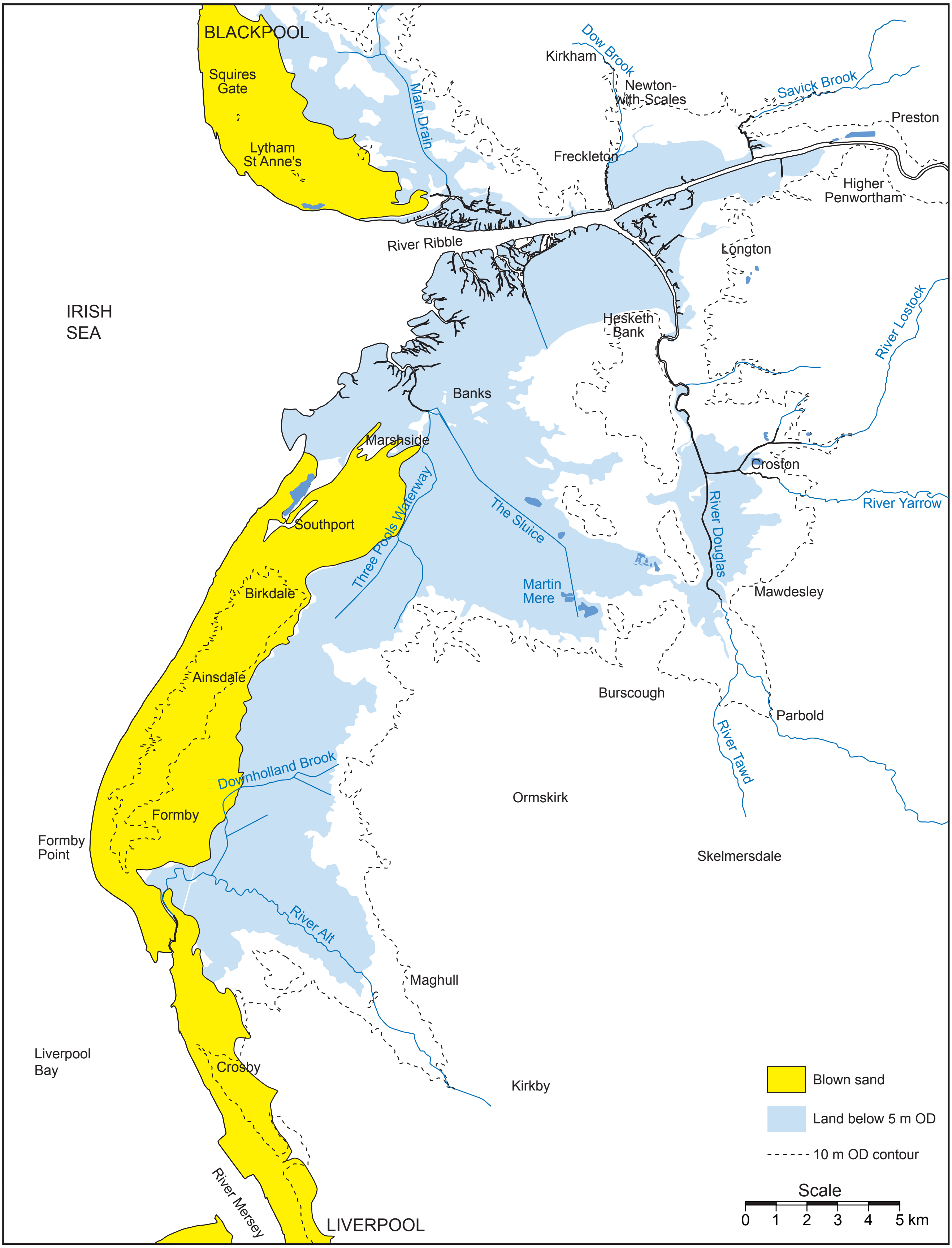

Figure 1.5 An example where dunes form an important flood defence barrier: the Sefton Coast and Southern Fylde, northwest England.

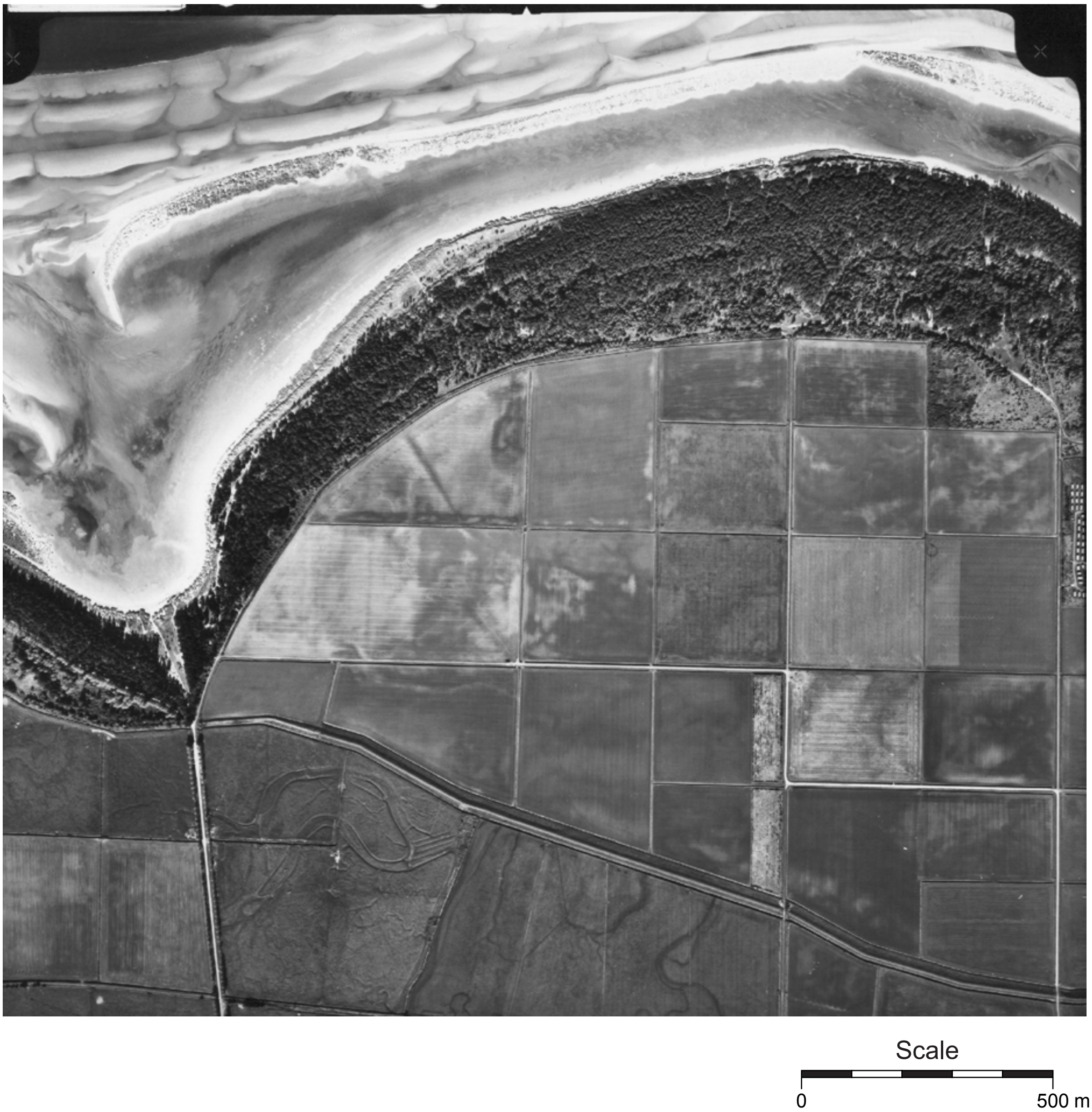

Figure 1.6 Vertical aerial photograph of the dune barrier (Holkham Meals) east of Holkham Gap, North Norfolk, with agricultural land on reclaimed marsh behind.

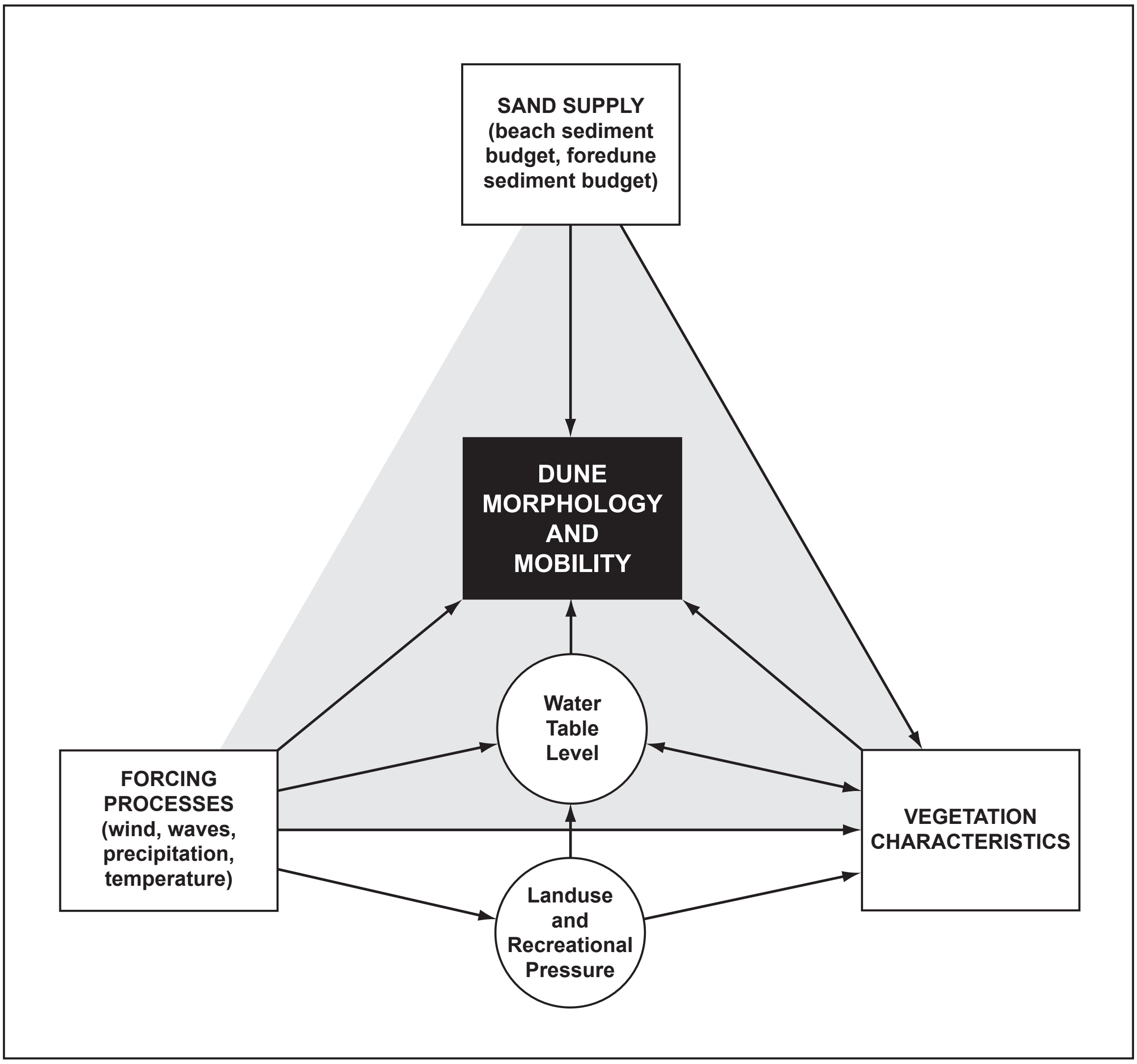

Figure 1.7 Schematic illustration of factors which influence the morphology and mobility of coastal dunes and which need to be considered in an assessment of alternative management strategies relevant to coastal flood defence.

Beach house sand storm

Russell Jenkins

A pensioner who lives beside the seaside has been warned that he faces a heavy fine for fly-tipping if he returns to the beach sand that has been blown into his garden.

Arthur Bulmer, 79, has long complained of sand drifting on to his property on the foreshore at Lytham St Anne's, in Lancashire, but this year's gales have exacerbated the problem.

When he asked Fylde Borough Council if it was permissible to return the sand, he was told that this would constitute fly-tipping. Instead, he should treat it as litter and take it to the municipal refuse tip.

The council added that it would happily clear sand deposited on a public highway but that once it landed on private property it became the responsibility of the owner.

The pensioner said that he had no alternative but to pay a specialist waste disposal firm to collect his unwanted sand and take it away.

Figure 1.8 Newspaper article from The Times, 11th March 2007.

Plates

Plate 1.1 Dune barrier providing flood defence for a low-lying residential area, Pwllheli, North Wales.

Plate 1.2 Single (partly artificial) foredune ridge, Sea Palling, Northeast Norfolk, looking south east. The dunes at this location were breached during storm surges in 1938 and 1953, resulting in loss of life and severe flooding of the agricultural land behind.

Plate 1.3 Recreational activities, Porth Towan, Cornwall.

Plate 1.4 Aberdovey Golf Club, Cardigan Bay, Wales.

Plate 1.5 Dune grassland, Traeth Crugan, North Wales.

Plate 1.6 Newborough Forest, Anglesey, with clear-felled area of dunes in the foreground.

Plate 1.7 Sand encroachment in Southport, northwest England, *c*. 1900. Source: Simpson (2001).

Plate 1.8 Oblique aerial view showing extensive inland invasion of blown sand between Woodvale and Birkdale, northwest England, in the 1930s. Southport. Source: Sefton Coast Database Archive.

Plate 1.9 Accumulation of blown sand on the promenade at Crosby, northwest England. Sand invasion poses a significant problem to properties located to the right of the picture.

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