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

Sand dune processes and management for flood and coastal defence

Part 4: Techniques for sand dune management

R&D Technical Report FD1302/TR

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Part 4: Techniques for sand dune management

R&D Technical Report FD1392/TR

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Statement of use

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

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Executive summary

Background

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

Project objectives

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

Results

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

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

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

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

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

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

Conclusions and Recommendations

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

Contents

4.1 Introduction

From an engineering and geomorphological perspective, coastal sand dune management has traditionally been concerned with three main problems: (1) wave/tide overtopping, with resultant coastal flooding; (2) dune erosion, leading to land loss and possible flooding caused by dune breaching; and (3) sand drift, which may cause problems to property and infrastructure through blowing of loose sand and invasion by mobile dunes. More recently, there has also been growing interest in the 'engineering' of dunes in order to enhance their nature conservation and recreational value. There has also been a move internationally towards integrated coastal dune management which seeks to combine the various interests in coastal dunes and to develop a long-term strategic framework within which day-to-day operational decisions can be taken.

Dune management can be implemented at several different spatial and temporal scales (Figure 4.1). The level of decision-making responsibility is a function of the scale of the project. Local-scale management measures, such as the stabilisation of a single blowout, are usually implemented by individuals or groups and are generally intended to provide a short-term solution to a specific problem. Large-scale management strategies, relating to such issues as areal extent of active and stabilised dunes, morphological modification and dune habitat creation, requires a broader view and consideration of various engineering, land use and conservation priorities defined at regional or national level.

Traditionally, the dominant management approach to coastal sand dunes has concerned the stabilisation of mobile sand. Sand encroachment has affected settlements and agricultural land in many coastal and inland parts of Europe, Australia and North America, partly as a result of natural climate changes, and partly due to poor land management practices. Techniques such as fencing and vegetation planting have been adopted to combat sand drift for hundreds, if not thousands, of years. More recently, dune stabilisation has also been viewed as desirable in terms of maintaining the flood defence value of dune systems, and during the late nineteenth and twentieth centuries stabilisation programmes and access control measures were initiated in many places primarily for this purpose. The frontal dunes came to be seen as a 'battleground' between land and sea, and much 'restoration' (i.e. stabilization) work was focused in this area. Creation of new dunes on the backshore was also seen as an effective method of encouraging land 'reclamation' from the sea (e.g. Case, 1914; Carey & Oliver, 1918).

Since the 1980's, however, it has become increasingly recognised that over-stabilised dune systems are detrimental to nature conservation and biodiversity objectives, since there is a close link between geomorphological dynamics and ecological diversity. Moreover, it has been recognised that a policy of 'hold the line' in the context of frontal dune management is likely to be unsustainable in the face of rising sea levels and global climate change. Consequently there has been a move internationally towards integrated coastal dune management which takes into account the flood defence, conservation, recreational and other interests in coastal dunes and designs intervention strategies which are appropriate to the management objectives. In part this change in approach has resulted from new legislation, including the European Habitats Directive of 1994, which requires that sites of ecological importance are to be maintained and diversified and, where necessary, new habitats created to compensate for losses elsewhere. Correspondingly, there has been a growth of interest in 'dynamic dune management' operated within a strategic framework at regional and national level.

4.2 Critical dune management issues

Sand dunes are naturally dynamic environments which are constantly changing in extent and form due to fluctuations in natural environmental forcing factors (wind, waves, tides, sediment supply, rainfall, etc.) and human activities (land-use, recreational pressure, etc.). In most circumstances, the nature and extent of dune habitats is dependent on the balance of these factors, only some of which can be controlled by management intervention.

As pointed out in Part 1 of this report, coastal dune systems serve several functions, including flood defence, conservation and recreation, the requirements for which are often conflicting. The central task of integrated coastal dune management is therefore to balance these interests and to ensure that dunes are managed within a broader framework which also takes into account other aspects of the physical, biological and human environment. Sand dunes cannot be viewed in isolation, but must be considered together with adjoining beaches, tidal flats, saltmarshes and other related environments.

4.2.1 Human impacts on dunes with regard to their flood defence function

Human activities which have an impact on dunes can be categorised into four types, and the degree to which they affect the flood defence value of the dunes can classified as major, intermediate or minor (Table 4.1). Type one, *conversion*, includes uses that change the dune vegetation or the form of the dune. Urban developments on or behind dunes have a major impact on their flood defence and coast protection value, with the value decreasing as a result of levelling and narrowing of the dunes, but perhaps increasing as the asset value of the land behind rises as a result of construction. Urban or industrial development of the hinterland will increase the need to maintain a high level of defence (i.e. a high, wide belt of dunes), and will also increase the need to stabilise both the position of the dunes and the sand surface to prevent hazards of blowing sand. If construction occurs directly on a dune system, the landform features and habitats are permanently lost. Alternatively, conversion to land uses such as golf courses and forestry may alter the dynamics and ecology of the dune system but potentially there is a possibility to restore at least some of the former features.

Type two, *removal*, includes removal of sand for use in industry or to provide sea views for coastal property developments. The impact of these activities on the flood defence value provided by the dune system will depend upon the scale and location of the extraction within the system, as well as on the physical attributes of the system including its dimensions and the rate of sediment supply. Lowering of the crest height of a frontal dune in itself may not pose a serious problem if the residual height remains significantly above storm surge level, and if the sand removed is placed at the rear of the dune belt to increase its width or to raise the level of the land behind.

Type three, *use*, includes activities which utilise the dune resource, such as sun-bathing, horse-riding, driving of off-road vehicles, and military activities. Pedestrians, horse riding and off-road vehicles can potentially cause serious damage to dune vegetation, leading to sediment mobilisation, the scale of impact being dependent upon the degree of use. The effects of trampling densities and the impacts on dune vegetation are well documented (e.g. Boorman & Fuller, 1977). In countries such as The Netherlands, where sand dunes are important for water supply, over abstraction can cause water table levels to fall and give rise to saline intrusion, again leading to damage to the vegetation and promoting sand movement (e.g. Geelan *et al*., 1995). In most cases these uses have only a minor impact on the flood defence value of dune systems, but in cases of extreme pressure major blowouts may develop and in narrow systems may destroy the lateral integrity of the flood defence (Hesp, 1988a, b; Short & Hesp, 1982).

Type four, *external*, includes indirect activities that influence the dune system. Interruption of longshore transport of sediment by structures such as groynes and jetties, and the losses to the coastal sediment budget via beach mining, offshore dredging and cliff protection, all reduce or inhibit the sediment supply to the dune system, potentially leading to decay of the system and a major negative impact of the flood defence.

Natural changes in dune systems can also pose a serious threat to the flood defence value of coastal dunes. The most widespread threat is provided by marine erosion, which occurs in any situation where the net beach sediment budget becomes negative. This may occur due to a reduction in sediment supply from offshore or alongshore, an increase in wave energy due to stronger or more frequent winds or a change in nearshore bathymetry, or a longer term change in tidal levels. However, other factors may also have a significant effect, including changes in climate which may not directly alter the beach sediment budget. Changes in precipitation, temperature, humidity and wind speed and direction affect vegetation growth both directly through transpiration rates and indirectly through water table levels. Any significant reduction in vegetation vigour can significantly affect surface sand mobility and the potential for the development of blowouts.

Key tasks of the coastal engineer are therefore to (a) monitor the condition of a dune system, most importantly that of the frontal dunes within *c*. 100 m of the shore, and (b) where necessary, control human activities in this critical zone. Traditionally, frontal dune condition has been monitored using a combination of ground surveys and aerial photogrammetry. Ground measurements are time-consuming and labour intensive, therefore they are usually made at relatively long time and spatial intervals, leading to low resolution data. More recently airborne Light Detection and Ranging (lidar) has been used to gather elevation data with higher spatial resolution (typically 1 or 2 m). This technique has been used to study dune morphodynamics and volumetric changes in sand dunes (Andrews *et al*., 2002; Woolard & Colby, 2002), and to identify critical relationships between beach and frontal dune morphology and erosion/accretion status (Saye *et al.,* 2005; see also Part 5 of this report). Assessments of dune vegetation cover can be made by ground quadrat surveys, which are rather time-consuming, and using colour air photography or digital multi-spectral remote sensing instruments such as the Airborne Thematic Mapper (ATM) and Compact Airborne Spectrographic Imager CASI) (e.g. Shanmugam & Barnsley, 1997; Lucas *et al*., 2002).

4.2.2 Maintenance of habitat diversity

From an engineering standpoint, a dense cover of a single vegetation type, such as marram, sea buckthorn or coniferous forest, might be considered sufficient to maintain the stability of a coastal dune sea defence. However, such mono-specific vegetation cover and landscape stability is undesirable from the biodiversity, recreational and aesthetic points of view. Under most natural conditions, coastal dune environments contain a range of vegetation types and habitats whose distribution and extent is continually changing in response to sediment movement and mobility of the landforms. Many species have evolved and adapted specifically to these conditions and are dependent on the existence of a mosaic of habitats for their survival. Many of these species and associations are now legally protected by a variety of conservation designations, and consequently the coastal engineer must today adopt a more sophisticated strategy than in the past, when planting with marram or with pines was often all that was required to create a stable defence.

Plant succession occurs naturally in dune systems, and spatial variations in plant communities occur in response to variations in sand mobility/stability, which is partly a function of distance from the shoreline and system age. The major communities which occur on sand dunes are: strandline, mobile dune, semi-fixed dune, fixed dune grassland, sand sedge dominated fixed dune, dune slacks and dune scrub and woodland (Salisbury, 1952; Ranwell, 1972; Malloch, 1989). Wherever possible, coastal dune management, including that undertaken for flood defence purposes, should seek to maintain the existence of these community types and a suitable balance between them appropriate to the environmental conditions at the site in question.

The maintenance of habitat diversity in sand dune systems often requires human intervention. Natural vegetation succession often leads to stabilisation of the dune system with age and to a decrease in the range of habitats present, except where levels of human disturbance are high. However, practices such as scrub clearance and grazing management to improve biodiversity often require coastal engineers to work in partnership with local authorities and landowners in order to develop an integrated approach to coastal dune management.

4.3 Local scale dune management methods

Local scale techniques, such as vegetation planting, thatching and sand fence erection, have been adopted in many parts of Europe, Australia, Asia and North America for centuries to stabilise and fix sand dunes to prevent sand encroachment into settlements and onto agricultural land. Marram planting has been undertaken in Britain since at least the seventeenth century (Ashton, 1909; 1920), and pine plantations have been used for at least as long to stabilise dunes in several European countries including France, Denmark, Scotland, England and Wales.

Techniques for dune creation and stabilization using fences and vegetation planting are well described in the literature and several dune management guides. The British Trust for Conservation Volunteers first published a practical handbook illustrating local-scale management techniques in 1979, and this has periodically been updated (Brooks & Agate, 2005). A guide detailing stabilisation techniques was also produced by the Institute of Terrestrial Ecology (Ranwell & Boar, 1986) and more recently Scottish Natural Heritage (2000) commissioned a guide which describes practical methods for managing marine erosion of dunes in Scotland from a conservation perspective. Elsewhere, during the late 1970’s and 1980’s the Beach Protection Authority of Queensland, Australia, produced a comprehensive set of guidance leaflets on all aspects of local-scale management options and how to implement them (Barr, 1983). The US Army Corps of Army Engineers also produced a series of technical publications during the 1960’s and 1970’s which described methods suitable to the barrier island dune systems of the eastern and southern United States (Savage, 1963; Savage and Woodhouse, 1969; Woodhouse, 1978). Sherman & Nordstrom (1994) provided a useful summary of methods available to deal with hazards associated with blowing sand and mobile dunes (Table 4.2). Other useful sources of information about specific techniques include Adriani & Terwindt (1974), Gares *et al*. (1979), Guilcher & Hallégouët (1991), Feilberg & Jensen (1992), Barrère (1992), Favennec & Barrère (1997), Bruun (1998) and US Army Corps of Engineers (2004). A number of case examples of the applications of these techniques, from which further information can be obtained, are listed in Table 4.3.

4.3.1 Hard protection methods

Hard protection methods are used to reduce the risks of coastal erosion and marine flooding where dunes defend residential property, industrial buildings and low-lying agricultural land, and where the dune belt is narrow, low and/or shows a natural tendency to erode. Various types of hard protection have been employed in England and Wales, and elsewhere, including concrete walls and stepped revetments (Plate 4.1), concrete-filled steel sheet piling and masonry walls (Plate 4.2), pre-cast concrete block revetments (Plate 4.3), rock armour (Plate 4.4), cobble-filled gabions (Plates 4.5 & 4.6), rows of old railway sleepers (Plate 4.7), revetments composed of construction rubble (Plate 4.8), rock groynes and offshore breakwaters (Plate 4.9).

Sea walls constructed from concrete effectively protect the dune toe from wave erosion but, due to their impermeable nature, wave reflection often induces scour and lowering of the fronting beach. A high concrete wall or stepped revetment may also prevent or reduce the transfer of windblown sand from the beach to the dunes. Walls with a gradual seaward slope reduce these effects. The use of honeycomb revetment ('Seabees') on the seaward side of the frontal dune provides some toe protection whilst permitting a degree of wind blown sand accumulation and inland transfer to the frontal dune. Marram can be planted in the interstices to promote dune growth, or it may become naturally established.

Gabion revetments can be effective in preventing small waves from attacking the dune toe, but larger waves can either overtop or undermine the gabion revetment, and they are generally not suitable for moderate to high energy environments. Broken gabions can be a public safety hazard and a source of beach contamination if the contents spill out.

Rock armour, especially if it consists of large boulders placed along the dune front, creates an effective physical barrier which dissipates wave energy and protects the dune toe but which does not entirely prevent the transport of windblown sand from the beach to the frontal dunes. However, in very severe storms even very large rock blocks can be undermined and moved by scour unless they are initially emplaced well below normal beach level. In west Wales and southwest England many dune systems have a natural protective revetment comprised of cobbles which accumulate along the dune toe during periods of strong swell and moderate storms.

4.3.2 Access management

Access management measures are implemented to control public access on the backshore, frontal dunes and hind dunes. They can be implemented to prevent or reduce dune erosion and to protect restoration work, or to prevent undue damage to pioneer vegetation on the backshore.

In the simplest case, a row of wooden stakes can be erected along the beach a few metres from the dune toe in order to limit damage by vehicles (Plate 4.10). Barbed wire connecting the posts can be used if the intention is also to prevent people entering the frontal dune area (Plate 4.11). Accretion of sand to widen the frontal dune ridge can be encouraged by the placing of wattle fences within the fenced off area (Plates 4.12 & 4.13).

Behind the frontal dune ridge, chestnut paling fencing or ranch style fencing and boardwalks can be used to restrict pedestrian access and to prevent undue sand erosion along paths (Plates 4.25 & 4.26). Conventional post and barbed wire fencing is usually sufficient to restrict the movement of grazing animals. The surfacing of paths through dunes with materials which are comfortable to walk on, such as bark chippings, encourages their use and keeps people to one route. The Beach Protection Authority of Queensland (1978) recommended that board and chain walkways are used at the beach end of access tracks where the frontal dune slopes are between 17° and 31° to prevent lowering of the dune and the development of blowouts. The spacing of boards depends on the dune slope with steeper slopes requiring greater spacing. Way-marking with posts can be used to guide people through the dune system to ensure they keep to designated paths. High dunes are often attractive to visitors as they provide good viewpoints but trampling can damage the dune slope causing avalanching and instability. If wooden viewing platforms are provided, with easy access, many people are deterred from climbing to the top of other dunes.

4.3.3 Public awareness

Signs and information boards can assist greatly in gaining public co-operation. Signs used within dune systems fall into two categories: prohibitive and informative. The former request/instruct people to keep out of certain areas or keep to the paths (Plate 4.25), whilst the latter explains the purpose of access management and stabilisation works. The success of management schemes can be greatly improved through public understanding of the significance of sand dunes and their associated flora and fauna. Public education through guided walks, public talks, on-site display boards, notices and interpretative leaflets forms an integral part of most dune management strategies.

4.3.4 Morphological modification

Several techniques can be employed to modify the morphology of the frontal dune to enhance the level of flood defence provided. Fencing can be used to trap sand within the frontal dune thereby promoting lateral and vertical growth (e.g. Plates 4.13 to 4.18). The success of fences is dependent upon three main factors: (1) the supply of blown sand, which is determined by sand availability on the beach, wind speed, direction, beach slope, grain size, compaction and sand moisture content; (2) the number, position and height of fences; and (3) the fence type and porosity (Beach Protection Authority of Queensland, 1978).

Fences can be constructed from a variety of materials including chestnut palings, brushwood, Christmas trees and synthetic mesh. Solid fencing can promote scour, especially if large posts are used, and porous fences with small posts are preferable. A fence with less than 20% porosity essentially behaves like a solid obstacle to the flow, and much of the sand will be deflected along the beach parallel to the fence rather than accumulating in a shadow zone behind it (Pande *et al*., 1980). Fencing materials with porosities of 30% to 50% create optimum conditions for sand deposition (Brooks & Agate, 2005). Plastic mesh can be very effective but has the disadvantage that most types are not biodegradable. Natural fibre of biodegradable geotextiles are preferable in this respect, but may be less robust under extreme wind conditions.

The porosity of the material used for fencing affects both the amount of sand trapped and the shape of the dune. Fences with around 50% porosity accumulate most sand within a distance twice the height of the fence either side of it (Manohar & Bruun, 1970). Low synthetic fencing with a high density of small holes, tends to create a wide, low-angled even dune, whilst chestnut palings with large porosities tend to create steep dunes with notches caused by scour around the pales. Brushwood creates an intermediate dune form in terms of slope but irregularities arise as a result of variation in brushwood density (Figure 4.2).

Build up of sand eventually buries the fence and sand reverts to being unhindered. The volume of sand trapped by a fence varies as a function of the square of its height, thus the effective life of a 2 m high fence is four times that of a 1 m high fence (Kerr & Nigra, 1952). In order to trap further sand new fences must be erected and the positioning of sequential fences will determine the dune form. Dune width can be enhanced using fences 1 m in height placed 4 m or more apart, whilst dune height can be achieved with fences 2 m high (Ranwell & Boar, 1986; Figure 4.3).

Optimum trapping capacity is achieved using fences at 90° to the dominant wind direction. However, fences used to promote foredune growth are generally positioned on the backshore zone parallel to the dune front irrespective of dominant wind direction so that growth follows the existing coastline. Short spur fences perpendicular or at a 45° angle to the frontal dune help to maximise sand catch on the seaward side of the foredune ridge where cross winds occur (Figure 4.4a). Spur fences are normally 10 to 15 m long and spaced at 10 to 20 m apart, although their actual length will be dependent upon fence height (Ranwell & Boar, 1986). To rebuild blowouts in the frontal dunes a grid of fencing is required due to the complex wind patterns within these features (Figure 4.4b). Fences positioned across the frontal dune stoss slope can be used but are inherently unstable on steep slopes. In such circumstances it may be better to lay wooden slat fencing parallel with the sand surface or at a low oblique angle (Plate 4.19), or to use low (<30 cm), flexible fencing (Plate 4.21). Single or multiple rows of brushwood fencing up to 1 m high can, however, often be used successfully to trap sand within blowouts which have slopes of up to 20^{o} (Plate 4.22).

Trapping of blown sand on the upper beach to raise the level of the backshore, and possibly to encourage the growth of a new embryo dune, can be achieved by planting rows of brushwood or old Christmas trees (Plate 4.20). These can be planted either parallel or perpendicular to the dune toe as a series of spurs, depending on the directional variability of the wind.

Some forms of fencing are designed to reduce wave attack of the dune toe as well as trap sand introduced both by waves and by the wind (Plate 4.15). This type of fencing has also been used on the top of low dunes on the North Norfolk coast in combination with gabion revetments and groynes for added protection. Fences arranged in a zig-zag formation trap a greater volume of sand but this may not provide sufficient justification for the extra costs involved (Savage, 1963).

The success of fencing in modifying the morphology of existing dunes or creation of new dunes is largely dependent upon the available sand supply and wind energy; where either is deficient, dune growth is likely to be slow or may not occur at all. Fencing placed on the upper beach can be easily washed away under storm tide conditions, and may cause problems of pollution and damage to vessels and fishing nets (Wheeler *et al*., 1993).

Additional methods of morphological modification include bulldozing of existing sand to form new sand mounds, infill blowouts etc., and importation of sand from elsewhere which can then be profiled to create the desired form. Sand can be bulldozed from the mid beach to raise the level of the upper beach and to increase the width of the frontal dune, but on relatively steep, narrow beaches the effect may be only temporary, as waves subsequently re-work the material to recreate a more natural beach profile. Re-profiling of the dunes themselves is relatively easy to achieve, but usually needs to be combined with other measures such as fencing, brushwood laying and marram planting.

4.3.5 Sand stabilisation

The main techniques used in dune stabilisation are fencing, thatching, mulching and planting. They can be implemented separately, although planting is usually used in combination with fencing. Other methods include the placement of gravel and spraying with mud, bitumen or artificial chemical mix. These methods have been more widely used in arid regions than on humid temperate coasts (e.g. Watson, 1985), and their long-term effectiveness is variable under wet and windy conditions.

Thatching involves placing branches of brushwood or bundles of straw directly onto the sand surface in order to increase the surface roughness and provide a physical barrier to the wind (Plate 4.28). It is an effective method of stabilising sand that is often used in conjunction with marram planting. Brushwood is more environmentally friendly than synthetic mesh as it gradually breaks down within a year or two, adding organic matter to the sand, and generally presents a lesser hazard to wildlife which can sometimes become ensnared in plastic mesh or geotextiles. The placement of the brushwood is critical and must be done evenly to avoid localised wind scour. The advantages of thatching listed by the Beach Protection Authority of Queensland (1978) are: (1) it enables vegetation to establish and grow; (2) the material can withstand strong winds; (3) the original dune shape is retained as a uniform thickness if wind blown sand is trapped and eventually buries the brushwood; (4) skilled labour is not required in the placement of brushwood; (5) seed or seedlings can be planted and fertilised prior to the placement of the brushwood; (6) the brushwood traps sand which covers seeds during germination and protects seedlings from wind and sand blast; and (7) the decaying brush adds organic matter to the sand increasing moisture retention. Two problems with brushwood thatching are that it is labour intensive and can only be implemented where there is a readily available supply of brushwood.

Suitable natural materials for use as a stabilizing surface mulch or thatching include hay, bracken, and straw. The mulch is spread mechanically or manually and pushed into the sand surface using tractor tyres or a roller. Surface stability can be achieved if mulch is applied at a rate of 5 to 6 tonnes per hectare (Beach

Protection Authority of Queensland, 1978). It is more suited to the stabilisation of less exposed hind dunes. A mulch containing grass and legume seeds, binder cellulose filler, fertiliser and water was sprayed onto eroding dunes within the Hayle Towans, Upton Towans and Gwithian Towans system in Cornwall in 1990 but germination was unsuccessful, although the mulch minimised the movement of windblown sand for several months (Lewis, 1992).

Chemicals sprayed onto dune surfaces to stabilise them are easier to apply than mulches or the placement of thatching. The function of a chemical spray is to initially stabilise the sand and prevent wind erosion for a sufficient period of time to allow plants to establish that can more permanently stabilise the dune surface. It is clearly important that the chemicals used do not inhibit seed germination, seedling establishment or plant growth. In Queensland, Australia two types of chemical sprays have been utilised: a bitumen emulsion and a polyvinyl acetate emulsion (Barr & McKenzie, 1976; Beach Protection Authority of Queensland, 1978).

Marram grass (*Ammophila arenaria*) is the most commonly planted grass due to its ability to withstand high sand burial rates (Plates 4.23 & 4.24). Marram has a virtually unlimited capacity for horizontal and vertical growth and can survive annual sand accretion rates of up to 1 m (Ranwell & Boar, 1986). Plants are usually planted at a depth of 0.15 to 0.20 m in a domino five formation, with a spacing of 0.3 to 0.9 m (Ranwell & Boar, 1986). However, the exact spacing will be dependent upon the degree of damage, the dune slope angle and wind exposure. Where the frontal dune is inherently unstable, uneven and/or steep, mechanical re-profiling has been necessary to create a more stable configuration prior to marram planting. This operation was carried out at Lifeboat Road on the Sefton coast and involved the replanting of two hectares of bare sand with 300,000 marram plants over a two-year period (Wheeler *et al*., 1993). Re-profiling has also previously been undertaken at the Hayle Towans, Upton Towans and Gwithian Towans system in Cornwall where steep sided blowouts caused wind turbulence ensuring the continuation of undercutting and erosion (Lewis, 1992). Re-grading created a gently convex slope of 30° to 35° to allow the wind to pass over with a smooth airflow. Marram planting has been used to stabilise artificially created dunes on many parts of the Dutch and Danish coasts.

Stabilisation has also been achieved using other vegetation types such as scrub and coniferous woodland (mainly Scots pine). In the past, sea buckthorn was introduced at sites such as Braunton Burrows in Devon to control instability caused by intensive military use in the Second World War. However, the invasive nature of this species means that it is now controlled by clearance more often than planted. Coniferous plantations provide effective shelterbelts, reducing wind strength by up to 25 times their height (Ranwell & Boar, 1986). Large-scale afforestation using pine trees to stabilise the landward margins of dune systems in many parts of England and Wales, including Holkham, Ainsdale, and Newborough Warren, was carried out in the late nineteenth and early twentieth century. Afforestation is no longer being implemented as a dune stabilisation technique in England and Wales, although commercial forestry remains an important activity in some areas.

4.3.6 Sediment budget modification

An important factor for the sustainability or enhancement of the flood defence value of frontal dunes is the supply and retention of sediment. The sediment budget of the frontal dunes can be modified directly via dune management techniques and indirectly via beach and nearshore management methods.

Beach nourishment can be used to raise beach levels in order to reduce wave attack of the frontal dune and also to promote aeolian deflation and frontal dune growth (Plate 4.27). Nourishment material can also be placed directly in the foredune area to raise the level of low spots (Plate 4.28), or behind the frontal dune ridge to create a secondary line of defence. On exposed, windy shores, nourishment material can usually be placed on the upper beach, allowing natural aeolian processes to transport it into the dunes (Plate 4.29). Deflation is enhanced if the nourishment material is placed as multiple small mounds on the mid and upper beach (Plate 4.30). This creates instability in the local wind field and greater turbulence to entrain and transport the sand. In situations where little or no dune ridge exists, it may be possible to construct an entire washover dune or low barrier dune system by large-scale beach nourishment and re-profiling using heavy machinery (Plate 4.31).

The sedimentological characteristics of the nourishment material applied to the beach and/or dunes can influence aeolian transport rates and thus beach levels and dune development. van der Wal (1998a,b; 2000) demonstrated that aeolian transport from nourished beaches in The Netherlands was lower than from unnourished beaches as a result of the more poorly sorted and coarser nature of the nourishment material compared to the native sand, indicating the need to consider the grain size distribution characteristics of nourishment material.

Beach nourishment to enhance dune defences has been widely employed in The Netherlands, Denmark, Portugal, USA and elsewhere (e.g. Møller, 1990; Matias *et al*., 2005) but so far only on a small scale in England and Wales. In fact, aeolian transport from nourished beaches in the UK has usually been viewed as undesirable due both to the loss of beach volume and the environmental problems which are sometimes created by blowing sand in built-up areas.

There are a number of alternative sand deposition strategies for dune enhancement, and selection depends on the existing morphological character of the beach and dunes, and on the scheme objective. Sand can be placed on the seaward side, landward side, dune crest area or all three (Figure 4.5). An entire length of frontal dune may be reinforced, or only selected parts. The latter may include low points within the frontal dune ridge which may represent a blowout or a depression (slack or swale) between two parallel dune ridges which has been intersected as a result of coastal erosion. An entirely new dune ridge may also be created behind or in front of the existing dune ridge, depending on the specific requirements and opportunities at a particular site.

The construction or re-establishment of dunes requires careful design. The Beach Protection Authority of Queensland (1978) produced guidelines for the design of artificial dunes and identified five main criteria for consideration: (1) material; (2) cross sectional area; (3) height and width; (4) slopes; and (5) location. The material used to construct the dune should be sand free of clay or other binding material that could alter the drainage properties. The grain size of the sediment should not be too coarse, as this may affect the ability of the dune to support vegetation growth due to loss of nutrients and poor water retention. The origin of the nourishment material will affect the chemical composition of the sand. Dredged sand initially has a high salinity that can affect vegetation establishment, and the material normally has to undergo a desalination process prior to use to prevent freshwater lakes within the dunes from becoming contaminated with salt (van de Graaff, 1994). Adriaanse and Coosen (1991) provide further discussion of dune nourishment methodologies and the environmental issues involved.

The volume of sand within an artificial dune should be sufficiently large to provide adequate flood defence and to accommodate erosion during storm events. The height and width of the dune should be sufficient to prevent overtopping and breaching by waves during major storms (Figure 4.6). Loss of sea views may be a consideration in some circumstances and require a lesser height. The slopes of the constructed dune should be shaped to permit vegetation establishment and the long-term maintenance of a stabilised dune form. The Beach Protection Authority of Queensland (1978) recommended that the initial dune profile should have an aerodynamic shape with a seaward slope of about 1 in 5 and a landward slope of about 1 in 3. Consideration of the location of an artificial dune is important for the longevity of the feature. The location of dunes seaward of the current coastline could result in failure unless beach nourishment is implemented to increase beach levels and reduce wave attack of the newly constructed dune. In the construction or re-establishment of dunes, planting with native dune vegetation is important to stabilise the dune form. In general, it is desirable for aesthetic as well as practical reasons to design an artificial dune which has a natural profile rather than the appearance of an embankment (Figure 4.6).

At Freshwater East, Pembrokeshire, an artificial foredune ridge was constructed seaward of the existing eroding dune frontage and stabilised with marram grass in the late 1980’s to early 1990’s. This ridge is now well established and not visibly artificial. In several places around the coast, including Sizewell and Minsmere in Suffolk and Sea Palling in Norfolk, artificial earth embankments have been constructed and then buried with sand which has been shaped to provide the appearance of a natural dune.

4.3.7 Habitat creation/recreation

EU legislation states that priority dune habitats and designated nature conservation sites must be maintained in ‘favourable condition’, which has been widely interpreted to mean that the existing range and relative abundance of habitat types and intrinsic species should be maintained. Where, for overwhelming practical reasons, this is not possible, compensatory habitat must be created to offset any loss. Maintenance of the existing habitats requires careful management, while creation of new or replacement habit requires novel interventionist approaches.

A number of dune management policies designed to maintain or enhance biodiversity have potential implications for the maintenance of sand dunes as a sea defence. These include clear-felling of coniferous woodland, reactivation of blowouts, wet slacks and mobile dunes, and the creation of tidal saline lagoons through artificial breaches in the frontal dunes.

4.3.7.1 Tree felling

Plantations replace natural dune habitats, encourage scrub growth, reduce sand mobility, acidify the soil and can affect the dune hydrology, influencing vegetation outside of the woodland (Smith, 1999). Particular concerns have been expressed that in some areas, including Newborough Warren, Anglesey, falling water tables have led to a reduction in wet/damp slack habitat, and it has been suspected that in part this may be due to the growth of coniferous plantations. It has been suggested that these effects can be reversed by tree-felling. The view has also been expressed that extensive woodland contributes to overall reduction in sand/dune mobility through an effect on the local wind climate. A reduction in tree cover should therefore promote higher wind velocities and greater sand movement.

Since 1992 part of the coniferous woodland at Ainsdale Sand Dunes National Nature Reserve, Sefton, originally emplaced to stabilise the system and prevent inland sand drift, has been removed to encourage sand mobility and reintroduce open dune grassland habitats (Sturgess, 1991, 1993; Simpson & Gee, 2001). Despite initial concerns, to date there have been no noticeable effects on rates of frontal dune recession, although the situation is being monitored. Similar action is currently under consideration at a number of other English and Welsh sites, including Newborough Warren, Anglesey, and Whitesands Bay, Pembrokeshire, and is being undertaken at many places overseas (e.g. Lemauviel & Roze, 2000).

4.3.7.2 Reactivation/creation of blowouts

Artificial reactivation of blowouts can help to restore natural dynamics of coastal dunes (van Boxel *et al*., 1997). Experimental work on the reactivation of blowouts has been undertaken in inner dunes near Haarlem in The Netherlands (van Boxel *et al*., 1997). Branches used to stabilise the blowouts in the 1970s were removed as was vegetation and the soil that had developed. Monitoring of the blowout demonstrated that small adjacent areas that had been reactivated were spontaneously restabilised, whilst reactivation of the main blowouts was relatively successful, slowly increasing both their area and depth. Blowouts have been artificially excavated in the first dune ridge landward of the frontal dune at Kenfig Burrows, South Wales, to encourage dune dynamics (see Part 5 of this report). Features such as blowouts can become wet slacks when the wind scours sand to the water-table creating an important habitat for rare species such as the Natterjack Toad. At Sefton, wet slacks have been artificially maintained as part of a breeding programme for this species (Simpson, 1992;

Smith, 1999). However, blowouts can become stabilised by a number of natural processes and such works are often in vain if natural conditions are not favourable (van der Meulen & Jungerius, 1989).

4.3.7.3 Artificial breach creation

Concern about a lack of dynamism in the heavily-engineered coastal sand dune systems of The Netherlands led in the late 1990's to a number of experiments designed to increase their environmental diversity and conservation value. The foredune near Schoorl was artificially breached in 1997 to create new habitats such as wet slacks and a tidal lagoon (van Bohemen, 1996; Arens *et al*., 2001; Plate 4.32). The foredune has been abandoned in this area as the primary flood defence and a new defence zone defined landward of the area influenced by the breach. The sea has periodically entered the gap and inundated the area behind. The long-term success of the project is currently still under evaluation. This approach can only be adopted where the dune system is not critical for flood defence or where the system is sufficiently wide so that hind dunes still offer protection.

4.3.7.4 Creation of new land

New dune areas can potentially be created on land reclaimed from the sea. In The Netherlands the extension of the Rotterdam harbour facilities into the North Sea included 850 ha designated for the creation of new nature habitats. Loffler & Veer (1999) identified three ways in which new dunes could be created: (1) anthropogenic – placement of sand on the new land and shaping into a dune form to create an instant but unnatural dune; (2) geomorphic – sand placed to create a beach and dunes allowed to form naturally; and (3) geological – sand deposited on the foreshore leaving natural processes of tides, currents and winds to potentially create a dune landscape. A combination of ecosystems is being created including intertidal areas, dunes and 'slufters' (small saltmarshes within areas of dry dune). It is believed that the creation of these habitats seaward of the existing coastline will increase the resilience of the entire coastal system as well as adding to its ecological value particularly where a narrow dune ridge is currently the only form of defence (Arens *et al*., 2001).

Creation of new land, with or without dunes, using marine dredgings and/or tipping of material from land sources, has been undertaken in many parts of the world, including the UK.

4.4 Large-scale long-term strategic management

Large-scale, long-term strategic management of dune systems requires a knowledge of the morphological and sedimentological characteristics of a dune system, an understanding of the processes governing the system, and prediction of future changes in factors which influence the process regime and sediment balance.

As discussed in Part 2, the sediment budgets of the beach and frontal dunes, and their relative balance, have a highly important influence on the erosion/accretion status, morphology and mobility of a dune system. The beach and foredune sediment budgets at any time are controlled partly by geological influences which determine the regional availability of sediment, partly by the balance of natural environmental forcing factors (wind, wave, tides, sea level), and partly by the nature of human interventions which may affect the system (sand extraction, groyne construction etc.). All of these factors, which are summarised in the following sections, can change on timescales of 10 to 100 years or longer.

4.4.1 Sediment supply

4.4.1.1 Sediment sources

Much of the coastal sediment around the coast of England and Wales is derived from Pleistocene geological deposits which were reworked by marine processes during, and following, the Holocene marine transgression. In some areas sediments derived from these deposits are still available in the offshore zone and are being reworked landwards by marine processes (e.g. parts of the eastern Irish Sea), but in many places the supply of marine sediment is nearing exhaustion or has already ceased. Supplies of sandy sediments from rivers are relatively insignificant in England and most of Wales, and the only other major potential source is provided by erosion of soft cliffs in some parts of the country (e.g. Holderness, East Anglia, Isle of Wight, Dorset). Over the course of the past century, large sections of soft cliffs have been protected by coastal engineering works, reducing the sediment input to the coastal zone (Clayton, 1989). Moreover, only a proportion of the eroded sediment is retained within the beach and nearshore system, and much of that eventually finds its way into large depositional sinks such as The Wash. Sand (and mud) continues to accumulate towards the down-drift ends of some littoral drift systems (e.g. Gibraltar Point, Lincolnshire), but the number of such sites is small. The majority of dune systems in England and Wales are now essentially fossilised, cut off from significant supplies of new sediment, and morphological and sedimentary changes are being brought about mainly by the reworking of existing beach and dune deposits (e.g. the transfer from Formby Point towards Southport and Crosby on the Sefton coast).

4.4.1.2 Effects of changes in sediment supply

Changes in the sediment supply, due to either natural or anthropogenic causes, can influence the erosion/accretion status and the morphology of the dune system. Sediment supply changes can be direct via dune management techniques or indirect via beach-dune interactions and nearshore modifications.

Humans have indirectly influenced the supply of sediment to dune systems by interfering with sources and their pathways. The beach volume fronting dune systems can be directly reduced by beach mining and increased by the addition of industrial waste or nourishment material for management purposes. Beach material has been extracted for a variety of commercial purposes including quartz sand for glass-making, carbonate sand with seaweed for use as a fertiliser, gravel for use in the construction industry and large pebbles for facing residential properties. Although the material removed may not be of a suitable grade for aeolian transport, the selective removal of certain size fractions will alter the character of the remaining beach. In addition to the physical volumetric loss, the beach gradient and sorting may be altered, affecting wave activity and aeolian transport, and thus coastal stability may be compromised. Similarly, artificially introduced material, depending on its grain size and composition, may also alter the character of the beach and not be suitable for aeolian transport.

A reduction in sources of beach sediment can arise from the protection of eroding cliffs or coastal deposits and offshore or channel dredging. The intentional impediment of longshore drift by the implementation of groynes to limit erosion in one area often leads to sediment starvation downdrift. Interruption of longshore drift is also caused by structures such as breakwaters, channel training walls, harbour walls, jetties, piers and pipelines. In addition to changes in the bathymetry of Liverpool Bay, training walls and dredge spoil dumping in the Mersey Approaches also have had a direct effect on sediment supply to the coastline. The deterioration of the Formby Channel is thought to have decreased the amount of sediment moving south to north by the ebb flow thereby reducing the sediment supply to Formby Point on the Sefton coast where the frontal dune has been eroding since c.1900 (Pye, 1977; Pye & Neal, 1994).

The sediment supply from cliff erosion to beaches at Dawlish Warren, Devon, was curtailed by the construction of the main London to Penzance railway line along the cliffs to the west of the spit in 1849. A continuous sea wall between Langstone Rock and Teignmouth now protects this railway. In addition, a stone breakwater at Langstone Rock intercepts the longshore transport of sediment. Beach and dune erosion of about 1 m per annum (although beach erosion of up to 7 m per annum was recorded between 1949 and 1962) along Dawlish Warren spit has been attributed to the cutting off of the sediment supply (Kidson, 1964). However, the rate of erosion during the century prior to the construction of the railway was of a similar magnitude. Kidson (1964) concluded that the phase of coastal retreat in the first half of the twentieth century was a normal stage in a cycle of growth and decay of such features. At the present time more sediment is being transported offshore onto sand banks than is being supplied alongshore and erosion is expected to continue, at least in the short to medium term (Sims, 1998).

Breakwaters on either side of the mouth of the Tees estuary have influenced the erosion/accretion status of the adjacent dune systems. To the south of the estuary is the Coatham Sands dune system which, although classified as an open coast system, experiences processes akin to an embayment system due to the existence of the South Gare breakwater. Dune accretion is occurring in the shelter of the breakwater, but more exposed areas further away are eroding. North of the estuary, the North Gare breakwater divides the Seaton Dunes system into two parts. In the sheltered area behind North Gare, the dune frontage is stable or accreting, whilst on the more exposed section to the north of the breakwater the dunes are eroding, exacerbated by visitor pressure.

4.4.2 Sea level change and its likely effects on shoreline erosion and dune mobility

Sea level change is an important control on dune systems at a regional scale on timescales of centuries to millennia, since it exercises a control on the wave base (and therefore on nearshore sediment movement) and the height at which waves break. A number of alternative models which predict the possible effects of changes in sea level are discussed in Part 2. A decision regarding which, if any, is applicable to a particular dune system can only be made after a detailed evaluation of the geological and sea level history in an area, the sediment supply conditions, and the nature of the environmental forcing factors which are operative.

4.4.2.1 Late Quaternary sea level change

Although there have been marked geographical variations, the general form of global sea level change during the Holocene was a rapid rise between 15,000 and 6,000 years ago, at an average rate of 10 mm per annum, after which rates slowed to 0.5 mm per annum between 6,000 and 3,000 years ago, and 0.1 to 0.2 mm per annum over the last 3,000 years (Church *et al*., 2001). The total magnitude of variation in global mean sea level during the last 6,000 years is likely to have been less than 0.3 - 0.5 m. However, in the British Isles, patterns of relative sea level change during the Holocene varied significantly due to local isostatic and neotectonic effects. Lambeck (1992) simulated sea level changes during the Holocene using geomorphological and palaeoecological evidence to validate predictive geophysical models. He found that in central and western Scotland and northern Ireland sea level reached a maximum around 6,000 years BP and has subsequently fallen by up to 8 m. Conversely, along the East Anglian coast, the Channel coast and the Bristol Channel, sea level rose rapidly between about 14,000 and 6,000 years BP, since when it has continued to rise at a slower rate of approximately 2 to 3 mm per annum. In northwest England relative sea level rose almost continuously between about 13,000 and 6,000 years BP and has subsequently varied by no more than ±1 m.

4.4.2.2 Tide gauge records and future predictions

Most tide gauge records in the UK show a positive tendency in mean sea level of up to 1 to 2 mm per annum over the last century (Woodworth *et al*., 1999). The very few available long-term records suggest that the average rate of sea level rise was greater during the twentieth century than during the nineteenth century, although no significant general acceleration in the rate of sea level rise during the twentieth century was identified by Woodworth *et al*., (1999) and Church *et al*. (2001). The Fourth IPCC Scientific Assessment predicts that by 2090 to 2099 global mean sea level may rise by between 0.18 and 0.59 (the full range for the different scenarios considered), relative to the period 1980 to 1999 (Solomon *et al*., 2007; Table 4.4). The exact magnitude of future rise, and its rate over time, are uncertain, but are likely to be significant. Updated DEFRA Guidance issued in October 2006 advised relevant operating authorities to allow for a sea level rise of 2.5 to 4.0 mm per annum between 1990 and 2025, 7.0 to 8.5 mm per annum between 2025 and 2055, 10.0 to 12.0 mm per annum between 2055 and 2085, and 13.0 to 15.9 mm per annum between 2085 and 2115 (DEFRA, 2006).

As a consequence of mean sea level rise, the frequency of extreme high water levels will be likely to increase. Climatic warming may also result in an increase in the frequency and severity of storms, which will further enhance the frequency of high water levels and periods of strong wave activity.

4.4.2.3 Relationship to shoreline erosion

Rising sea level can be expected to have a direct effect on coastal processes by raising the plane of activity from which waves operate (Carter, 1991). Since sandy beaches and dunes are composed of relatively low-strength materials which respond quickly to perturbations in forcing energy, erosion rates will probably be proportional to sea level rise.

Bruun (1962) proposed a simple two-dimensional cross-shore model which predicts the amount of erosion as a result of rising sea levels. This model uses the principle that adjustment to sea level rise will be achieved by dispersal of the eroded volume across the nearshore and inner shoreface, thereby maintaining an optimum depth of water in the nearshore zone.

This can be mathematically represented as follows:

$$W = \frac{XS}{Y}$$

where W is the width of beach erosion, X is the horizontal length from the shore to a limited depth of sediment transport (closure depth), S is sea level rise, and Y is the vertical length of profile, with all terms given in metres.

This simple model has been widely used to predict future shoreline movements due to sea level rise. However, the model is based on a number of questionable assumptions and has been criticised as inappropriate for practical use (Cooper

& Pilkey, 2004). Realistically, three-dimensional redistribution of sediment is likely to occur with material being transported into deeper water, onshore or alongshore (Carter, 1991). In addition, some eroded material will move landward, returning to the dune system, especially on high wind energy coasts. Therefore it is likely that the foredune will move both upwards and landwards as sea level rises (Carter, 1991). Where the vegetation is absent or ineffective due to engulfment, transgressive dunefields may evolve. The increased frequency and severity of storms associated with climate change may lead to the formation of new ridges which subsequently act as nuclei for further growth. Alternatively, storms may cause blowouts initiating landward migration of the dune system. However, the effect of further rise in sea level on coastal dunes is likely to vary spatially and temporally. Erosion in one area may result in sediment accumulation in another area downdrift. The presence of coastal protection structures such as sea walls and revetments will also cause variations in response.

4.4.2.4 Effects of sea level rise on groundwater hydrology

Rising sea level is also likely to have a significant effect on the groundwater hydrology of dune systems, which may in turn have knock-on effects on vegetation growth and dune mobility (van der Meulen, 1990; Pye, 2001). There are two possible effects which operate in opposite directions. Firstly, coastal erosion as a result of rising sea level may initially cause lowering of the groundwater level in the frontal dunes due to the narrowing of the dune belt and steepening of the groundwater table surface. The previously wet sub-surface dune sand will become dry and vulnerable to deflation to a deeper level. However, the rise in sea level may also act to impede land drainage, leading to a rise in regional water table levels. This may be sufficient to offset and reverse the initial decline, leading to the creation of a series of shallow lakes within the dunes (Carter, 1991). The balance between these two effects will depend on the characteristics of each individual dune area, the amount of erosion and the degree of sea level rise (van der Meulen, 1990).

4.4.3 Climate change and its potential impacts on coastal dune systems

Changes in climate can occur without any significant change in sea level, although the two may go hand in hand. From the perspective of dune processes, changes in wind strength and direction can have a direct effect on rates of aeolian sand transport and dune migration, and an indirect effect via wave energy and erosion on the frontal dunes and via vegetation transpiration rates (Pye, 2001). Changes in temperature and precipitation can also have a small but significant effect on aeolian transport rates and a major impact on vegetation growth and the potential for dune stabilization. The biggest effect, however, is likely to be via changes in the frequency and magnitude of major storms and storm surges which exert a major control on the medium term sediment budget of beach and frontal dune systems, and which may act as a trigger for major inland transgressive dune activity (see Part 2 of this report).

4.4.3.1 Climatic changes in the late Holocene

The climate of western Europe has changed significantly over the course of the last 4,000 to 5,000 years, with alternating periods of warmer and wetter conditions corresponding with phases of dune stabilisation and soil development, followed by cooler and dryer phases with dune development. The most recent of these cool periods, the Little Ice Age, occurred between AD 1300 and 1850 (700 to 150 years BP), and especially between *c*. AD 1350 and *c*. 1650. Episodes of extensive aeolian sand accumulation during the Little Ice Age have been documented at a number of locations in northwest Europe, indicating the regional scale of activity and the likelihood of a common forcing mechanism (Klijn, 1990; Tooley, 1990; Pye & Neal, 1993; Clemmensen *et al*., 1996, 2001a; Orford *et al*., 2000). The short-term climate shifts during the Little Ice Age are thought to have created conditions conducive for dune development on both the east and west coasts of Britain (Wilson *et al*., 2001). Stratigraphic dating and archaeological evidence suggests that phases of dune development in many areas of northwest Europe coincided with cool periods prior to the Little Ice Age. There is limited evidence of the climatic conditions during cool phases prior to the Little Ice Age, but they are considered to be Little Ice Age type events characterised by increased storminess (Meese *et al*., 1994; Lamb, 1995; Bond *et al*., 1997). However, the absence of extensive dune development on the east coast of England during these earlier cool periods suggests that the climate and/or morpho-sedimentary conditions of the Little Ice Age must have been significantly different in order to generate dunes in this area (Wilson *et al*., 2001).

4.4.3.2 Changes in wind and wave regime

Shorter-term changes in wind speed and direction can have a significant impact on dune morphology and mobility. The wind regime is a key factor controlling the extent of aeolian transport. During the twentieth century changes in wind strength and direction have been documented as the primary cause of morphological changes of a large dune at Råbjerg Mile, Denmark (Anthonsen *et al*., 1996) and a contributing factor to erosion/accretion status along the Sefton coast in Merseyside (Jay, 1998). In addition, wave height increases exponentially as wind velocity increases, leading to greater frontal dune erosion. A change in the direction of prevailing winds can alter the focus of waves on the coast and alter longshore drift patterns.

Bacon & Carter (1991) combined the evidence from visual estimates and instrumental measurements (Shipborne Wave Recorder) to demonstrate that the mean wave height over the whole of the North Atlantic has increased by approximately 2% per annum since the early 1950's, though the physical cause has not been identified. However, Bacon & Carter (1993) did identify a correlation of the increase in wave height with the gradient in sea level pressure between the Azores and Iceland. Data are more limited for the North Sea and it is still uncertain whether the mean wave height or extremes have increased significantly, or whether there has simply been short-term variation. The available data show that the mean wave height increased from about 1960 and peaked around 1979-1980, though in 1984 the height was 13% lower (Bacon &

Carter, 1991). However, severe conditions have occurred in the southern Norwegian Sea and northern North Sea during some winters (particularly 1988-1989). The partially enclosed nature of the North Sea results in a limited fetch in all directions except to the north, thus local meteorological conditions have a more dominant effect on wave conditions than in the open ocean. A similar scenario occurs in the Irish Sea. In both areas the wave data has been obtained some distance offshore thus does not necessarily represent the nearshore wave climate.

Wave direction is also of great importance but insufficient data exist to establish trends. Wave direction can be altered by changes in bathymetry or the direction of prevailing winds. Modelling undertaken by Neal (1993) suggested that there had been a change in wave direction on the Sefton coast, with a significant increase in wave focusing on Formby Point since 1847. This effect on wave refraction was attributable to the changing offshore bathymetry. However, wave focusing appears not to have been the major initiator of dune erosion on this coast at the turn of the twentieth century, since the main bathymetric changes which led to the focusing postdate the onset of erosion.

4.4.3.3 Recent and possible future changes in global temperature and precipitation

The global average surface temperature has increased by 0.6 ± 0.2ºC since the late nineteenth century and the current best estimates of future rise under differing scenarios by 2090-2099 range from 0.6 to 4.0ºC (Table 4.4), mainly as a result of increasing concentrations of greenhouse gases in the atmosphere (Solomon *et al*., 2007). Globally averaged water vapour, evaporation and precipitation are projected to increase during the 21st century based on global model simulations for a wide range of scenarios. At a regional scale, both increases and decreases in precipitation are likely, with a predicted increase in winter over northern hemisphere mid-latitudes. Over northwest Europe a small increase in winter precipitation is projected which is quantified as an average change of between 5 and 20% (Church *et al*., 2001). In summer no change (-5 to +5%) or a small decrease (-5 to -20%) is projected for the same region. Climatic warming is likely to increase the frequency and severity of storms (Houghton *et al*., 2001, Solomon *et al*., 2007).

4.4.3.4 Changes in the North Atlantic Oscillation

Atmospheric circulation variability over the North Atlantic region is largely controlled by the North Atlantic Oscillation (NAO). The NAO influences wind speed/direction and storms, and is also associated with wave climate, winter precipitation and changes in air-sea fluxes (Osborn *et al*., 1999). The NAO is said to be positive when air pressure is unusually high over the Azores but uncharacteristically low over Iceland. The mode is negative when both centres are poorly developed and the pressure gradient is weakened. The difference in normalised sea level pressure between the Azores region and over Iceland is known as the North Atlantic Oscillation Index and is used to describe the conditions upwind of the British Isles.

Much of the atmospheric circulation variability arises from internal atmospheric processes (Osborn *et al*., 1999). Variation in the NAO correlates well with changes in the stratospheric vortex (Baldwin & Dunkerton, 1999), sea surface temperature (Stocker *et al*., 2001) and high latitude snow cover (Watanabe & Nitta, 1999). Changes in these parameters resulting from natural variation or anthropogenic influences on climate are likely to have an impact upon the NAO.

Currently, the effect of future predicted climate change on the NAO index is inconclusive (Cubasch *et al*., 2001). Recent studies using coupled models have shown that climate change, due to increased greenhouse gases, would cause an increase in the NAO index (Ulbrich & Christoph, 1999; Paeth *et al*., 1999). However, Osborn *et al*., (1999) showed that after an initial small increase in the NAO index, a decrease occurred during the remainder of the simulation. Current climate models have failed to reproduce recent trends in the NAO index therefore these model predictions are unlikely to be reliable (Cubasch *et al*., 2001).

If the NAO index was to exhibit positive change, then an increase in the frequency of westerlies would occur, leading to increased precipitation, storminess and wave heights. When the NAO index is positive the resulting impacts will be greater on the west coast of the British Isles due to the approach of cyclonic activity. Conversely, when the NAO index is negative a strong pattern of blocking is present, resulting in cyclones being deflected further to the north and south. A consequence of this blocking is that more airflow from the north, south and east occurs over the British Isles. A lower frequency of westerlies occur, thus precipitation and storminess would be less frequent on the west coast of the British Isles, whilst the east and south coasts are likely to experience greater precipitation and onshore winds. It is uncertain how any changes in the NAO index will affect the magnitude of storminess, precipitation, windiness and wave heights, which may have a greater influence on dune dynamics than the frequency of these factors.

4.4.3.5 Effects of changes in storminess and precipitation

Studies have shown that most frontal dune erosion occurs during storms, and especially when strong winds and destructive waves coincide with high spring tides and storm surges (e.g. Pye, 1991). During the last 50 years, episodes of frontal dune erosion on the northwest coast of England have been found to correspond with periods of increased storminess associated with positive NAO index values (e.g. Jay, 1998). The seaward margin of dune systems will experience the greatest effects of an increase in storm event frequency, as wave erosion is more likely to occur. Instability of the frontal dunes will lead to shoreline recession and thus a decrease in the flood defence value of narrow dune systems. As recession occurs it is important to identify for management purposes whether the sand volume will (a) remain as part of a frontal dune rolling landwards, (b) dissipate inland, losing form integrity, or (c) be lost from the system entirely via offshore and/or longshore transportation.

Increased sediment transport by both wind-driven currents in shallow waters and aeolian transport onshore and alongshore would be anticipated as wind strength or duration increases. As a consequence, blowout development and dune migration rates are likely to be enhanced and damage to vegetation may occur. Large-scale transgressive dune development across western Europe during the Little Ice Age has been mainly attributed to periods of increased storminess (e.g. Clemmensen *et al*., 1996; 2001a; Pye & Neal, 1993). As demonstrated in Part 3 of this report, higher wind energy in England and Wales is correlated with the occurrence of larger and generally more transgressive systems; consequently an increase in mean wind speed could lead to the development of more extensive and more active dune systems. A recent analysis of factors which control the mobility and stability of dunes by Tsoar (2005) concluded that wind energy is of considerably greater importance than precipitation and evapo-transpiration. Under conditions of high wind stress plants find it difficult to stabilise sand, even in areas of extremely high precipitation.

The increased precipitation is likely to enhance dune stabilisation via the promotion of vegetation growth and increase in groundwater levels limiting the depth of aeolian transport. However, an increase in precipitation may not affect the dune systems substantially due to both the magnitude of the predicted change and the likely counteractive effect of the accompanying increase in temperature. A decrease in sand transport, increase in vegetation cover and increase in groundwater levels due to greater precipitation may be offset by the increase in temperature and thus potential evaporation.

The combined effect of increased storminess and precipitation is likely to lead to instability of the frontal dunes and stabilisation of the hind dunes. Slow rates of frontal dune erosion in the presence of a high vegetation cover will lead to a relatively stable dune system. However, an increase in windiness could remobilise the dune system. Rapid rates of lateral shoreline erosion will lead to dissipation of the system and ultimately the development of washover dunes of low flood defence value. Any rise in sea level will enhance the effects of increased storminess by raising the level at which waves operate.

4.4.3.6 Effects of changes in vegetation cover

Global warming and enhanced carbon dioxide levels are likely to have a direct impact on dune vegetation. The exact effect will depend on three main factors: (1) the metabolic response of dune plants to carbon dioxide enrichment; (2) plant competition; and (3) reaction of species to changes in physical conditions such as sand supply rate, precipitation and groundwater (Carter, 1991). Many plants grow better in a carbon dioxide enriched environment, although the main dune building grasses are C3 plants, which respond particularly positively to increased carbon dioxide levels. Production of dune grasses may be further stimulated by increased transport of wind blown sand associated with greater storm frequency and severity. The predicted increase in global precipitation would also promote the growth of many plant species. Enhanced plant growth would influence dune stability/mobility. More rapid spread and vertical growth of dune forming grasses may lead to greater sand accumulation in foredune areas, which in turn would limit the quantity of sand transferred to hind dunes, encouraging their stabilisation. On the other hand, predicted increases in the frequency and intensity of summer droughts would tend to have an opposite effect. The overall effect of climate change on coastal dune dynamics will be dependent upon the balance between the impact of changes in temperature, precipitation, wind strength, wave climate and sea level.

4.4.4 Bathymetric change

Bathymetric changes occur naturally as patterns of banks and channel shift in response to natural forces, but they may also result from human activities such as dredging and training wall construction. They can affect tidal flows and wave activity, and in turn, influence sediment transport dynamics, both locally and regionally. Changes in the wave direction and height as a result of bathymetric changes can profoundly affect the erosion/accretion status of a beach and frontal dune system, with higher waves more likely to cause erosion. Sediment eroded from the dunes is initially supplied to the beach, but if it is then moved offshore or alongshore it will become unavailable for later dune recovery.

For example, along the Lincolnshire coast between Skegness and Gibraltar Point, nearshore sandbanks limit the wave energy reaching the shore, which in turn reduces the longshore transport rate. In addition, sediment circulates between the sandbanks and beaches forming a semi-closed system. The spatial relationship and volumetric balances of the sandbanks is pertinent to the sediment regime of the coastline. An accretionary 'ness' has formed on the foreshore immediately south of where the Skegness Middle sand bank meets the foreshore. Dugdale & King (1978) found from analysis of Admiralty Charts that both the Skegness Middle bank and the foreshore 'ness' have migrated southwards since 1871. Between1910 and 1970 the bank had moved c. 4 km to the south (Scott Wilson Kirkpatrick, 1997). Consequently, the zone of foreshore and frontal dune accretion has also moved southwards, whilst the area to the north at Skegness has become exposed and has experienced net erosion in recent decades. However, significant further southerly migration of the bank and is unlikely as it is now beginning to encroach upon the Wainfleet Swatchway flood channel

Significant bathymetric changes have occurred in the offshore and nearshore zones in Liverpool Bay as a result of dredging and construction of training walls. Since 1890 the Mersey Approaches have been dredged to maintain a channel for navigation purposes. Between 1890 and 2003 approximately 780 million hopper tons of sediment were dredged with the greatest quantity of dredging per annum removed between the two World Wars (Smith, 1982; Blott *et al*., 2006). The dredge spoil was deposited in Liverpool Bay, mainly on Great Burbo Bank south west of Crosby Channel and offshore of Formby Point. Construction of the Mersey training walls began in 1909 and was largely completed by 1939, although further improvements were made up until 1957 (Cashin, 1949; O’Connor, 1987).

Pye & Neal (1994) and Blott *et al*. (2006) demonstrated from marine charts that training walls and dredge spoil dumping contributed to extensive shoaling in the Formby Channel and its virtual disappearance by 1965. These authors also found that Queen's Channel had deepened and an offshore bank, Taylor's Bank, had grown as a consequence of the works. Neal (1993) was also able to show that the works had led to the development of a new offshore bank, Jordan's Spit since 1932. Price & Kendrick (1963) also concluded that the training walls had concentrated the flow in the main channel, leading to the enhancement of flood-dominated transport, accelerated onshore transport of sand, and accretion on the intertidal banks and in secondary tidal channels.

As a consequence of the bathymetric changes, there was a significant increase in wave focusing onto Formby Point after 1847 (Neal, 1993; Pye & Neal, 1994). The three main factors for this increased wave focusing were identified as: (1) accretion in Formby Channel leading to increased focussing onto the north side of Formby Point; (2) deepening of Queen's Channel and growth of Taylor's Bank leading to increased refraction of westerly waves at the channel-bank interface northwards onto Formby Point; and (3) growth of Jordan's Spit causing wave orthogonals to be focused onto Formby Point.

Similar channel dredging and construction of training walls in the Ribble estuary had an impact on erosion/accretion trends along the Sefton coast (van der Wal *et al.,* 2002). Enhanced shoreline accretion at Southport was caused by the reduced ebb tidal current transport of sand in South Channel, located off Southport, which was a consequence of the works (Pye, 1977). Works in the Ribble estuary may also have influenced erosion at Formby Point. However, Pye & Neal (1994) concluded that although training works, dredging and spoil dumping in the Mersey Approaches and Ribble estuary contributed significantly to the erosion at Formby Point, they did not initiate the problem since erosion pre-dated most of the works.

4.4.5 Direct human disturbance

The nature and intensity of human activities influencing dunes, and the coastal zone as a whole, have shown a general increase in extent and variety over time. Any activities which have an impact on the vegetation type and density are also likely to have an important influence on dune stability / mobility and dune morphology.

4.4.5.1 Recreation

If not controlled, recreational activities, including walking, cycling, off-road vehicle driving, motorcycling, horse riding and golfing, can destroy vegetation cover and / or alter the plant species present. Off-road vehicles such as quad bikes and motor bike scramblers are especially damaging to dune vegetation and cause physical disruption to the surface. Anders and Leatherman (1987) found that even low-level off-road vehicle use severely damaged vegetation and within one year vegetation was essentially eliminated (<0.6%) within impact zones. The passage of horses and pedestrians also reduces the height and density of dune vegetation and increases soil compaction, which in turn reduces the level of oxygen around plant roots (Liddle, 1973). The destruction of vegetation reduced the aerodynamic roughness of the surface, potentially enhancing aeolian sand movement.

Ranwell & Boar (1986) concluded that pedestrian trampling has the most widespread impact on dune vegetation in England and Wales. Most dune localities are easily accessible to walkers, with the exception of areas that are fenced off or have dense scrub. Pressure is greatest on access routes to the shore and near caravan sites, beach huts, car parks and visitor centres. Sustained pressure reduces the vegetation density, height, capacity for regeneration and the rate of dune building (Ranwell & Boar, 1986). Boorman & Fuller (1977) estimated that 80 pedestrian passes per month would cause bare ground to appear, whilst 150 passes per year would lead to 50% bare ground. Research by Andersen (1995) in Denmark demonstrated that, although pedestrian trampling leads to a reduction in vegetation density and changes the floristic composition, it does not necessarily decrease species number or diversity and can result in greater diversity by preventing vigorous species from overgrowing those with a competitive disadvantage.

Walkers can also have a significant effect on other areas of the dune system, notably the strandline environment and embryo dunes. The main growing season of strandline vegetation is between June to July, coinciding with the start of the tourist season. Intensive trampling along the dune front at this time can destroy strandline vegetation and inhibit the growth of embryo dunes. Temporary fencing along the upper beach can help to alleviate this problem

Most golf courses utilise the natural dune topography to varying degree but modifications are often made to create fairways, tees and greens. The natural vegetation is usually modified on parts of the course to that three distinct vegetation communities are often present: an artificial sward on tees and greens, modified semi-natural sward on fairways, and unmodified rough grassland areas elsewhere. Actively blowing sand are usually seen as a problem if they impinge on the playing areas. Management measures are therefore usually undertaken to ensure stability of the system. Most golf courses in England and Wales are now subject to local management agreements between the clubs concerned and nature conservation organizations.

4.4.5.2 Military use

Past military training activities have caused substantial damage to the vegetation in many of the dune systems in England and Wales, with resulting impacts on the dune morphology. The scale of the impact has varied considerably. Some areas are, or have been, used only as rifle ranges, for weapons testing or the manufacture and storage of munitions, but others have been more seriously affected by use for infantry and tank training or as bombing ranges. Extensive system instability occurred during and following the Second World War at many sites, including Braunton Burrows, Camber Sands, and Newborough Warren. Stabilisation programmes, in the form of planting with marram, sea buckthorn and Corsican pine, were subsequently undertaken at many of these sites from the 1950's onwards (Doody, 1989).

A potential benefit is that military use often restricts or prevents public access, and such dune systems may be subject to less damage than those with free public access. Military ownership / management has also helped to protect a number of large dune systems from destructive urban and recreational developments in the past.

4.4.5.3 Sand extraction/removal

In the past sand has been removed from coastal dune systems for four main reasons: (1) for use as aggregate in the construction industry, (2) for use as a raw material in the glass and brick making industries, (3) for use as a soil improver on agricultural land; and (4) to improve the sea views of properties near the coast. Sand mining has taken place in several dune systems, including Formby Point and Ainsdale on the Sefton coast, Druridge Bay in Northumberland, Rock dunes in the Camel Estuary, Cornwall, and Aberffraw on Anglesey. Sand extraction has now ceased in most areas, although it still continues on a small scale at some sites. Over 80 ha of dunes were levelled during sand extraction between Hayle Towans and Gwithian Towans in Cornwall (Lewis, 1992). Extraction is nearing completion and the restoration of the frontal dune between Gwithian Towans and Godrevy Towans is being undertaken. Dune height, and in some cases volume, have been reduced to provide better sea views at many coastal resorts, including Lytham St Annes on the Fylde coast .

Removal of sand from frontal dune areas has an immediate effect on the physical integrity of the system as a flood barrier and may initiate or accelerate coastal erosion if disturbance to the vegetation is significant and there is an increase in the rate of transport of transport of windblown sand. Removal of sand from hind dune areas may also promote sand blowing and dune remobilisation, which may have both positive and negative implications.

4.4.5.4 Grazing

Grazing of dunes by domestic and wild animals (predominantly rabbits) can have a significant influence on dune mobility / stability and on vegetation composition. Overgrazing was a contributing factor to sand destabilisation in Denmark during times of increased storminess such the late Sub-Boreal and early Sub-Atlantic periods (Clemmensen *et al*., 2001b). Many dune areas in England and Wales have a long history of grazing but at present the grazing pressure is generally much less than in the past (Burton, 2001; Boorman, 1989a). This has led to a loss of species-rich grassland, the development of coarse grassland and the invasion of scrub (Ranwell, 1960; Rothwell, 1985; Boorman, 1989b). In some areas acidic dune heathland has been replaced with species-poor grassland (Leach, 1985).

Concerns regarding the over-stabilisation of dunes due to lack of grazing has initiated the introduction of grazing programmes at several systems including Braunton Burrows and Newborough Warren. However, the relationship between the nature and intensity of grazing and plant species diversity is a complex one (Ranwell & Boar, 1986). Different grazing regimes are required to achieve optimum species diversity in different dune habitats, but obtaining the appropriate degree of grazing is difficult as the response of the flora can vary in space and time (Boorman & Boorman, 2001). The rate of response to grazing varies according to the maturity of the plant community but generally the effects of new management regimes need to be assessed over long periods of time before the effects can be identified (Boorman, 1989a). The effects of grazing can largely be controlled and the future use of grazing management will depend upon findings from the various experiments in operation.

4.4.5.5 Afforestation

Partial afforestation was carried out to stabilise the dunes at several sites in the nineteenth and early twentieth century. At Ainsdale and Formby, the landowners planted pine trees between 1887 and the 1930s in response to the disruption to agriculture, tracks, buildings and the railway line from blowing sand (Smith, 1999). Large-scale state-financed afforestation has also taken place for commercial purposes since the 1930s at Pembrey Burrows and Newborough Warren.

Plantations provide effective shelterbelts, reducing the wind strength in their lee over distances up to 25 times their height (Ranwell & Boar, 1986). They directly reduce the extent of open dune habitats, and djacent dune areas can also be affected. On the Sefton coast several changes were observed, including lowered water tables, a decrease in light levels a reduction in temperature extremes, changes in soil properties, and self-seeding of pines into unplanted areas (Edmondson *et al*., 1993). Drying of dune slacks due to changes in the water table is believed to have caused a loss of species diversity and an increase in birch invasion (Atkinson, 1988). Soil acidity on the dunes has also increased due to the presence of pine needles (James, 1993). However, plantations themselves are also valuable habitats and on the Sefton coast are considered important for birds, the Red Squirrel and some plant species, most notably the Dune and Green-flowered Helliborines (Smith, 1999).

Since 1992 parts of the pine plantations on the Sefton coast have been felled to restore open dune habitats (Simpson & Gee, 2001). However, whilst mobility may be easily re-initiated, restoring a diverse flora is not simple since the woodland substantially alters the ecosystem, both physically and biologically. Sturgess (1993) suggested that the low pH created by pine cover may prevent successful growth of many dune plants characteristic of young, calcareous dunes. The age of the plantation prior to felling is evidently an important factor in ecological recovery. Sturgess (1991) reported that many original dune species returned within ten years after the felling of a 30-year old plantation at Whiteford Burrows as the stand had not had enough time to cause too much change to soil conditions and the seed-bank had survived.

4.4.5.6 Nature conservation

Many dune systems consist of a wide variety of habitats rich in flora and fauna. Consequently, many dune sites in the UK have received conservation designations to protect and conserve the wildlife value of this environment (see

Parts 2 and 3 of this report). Such designations generally reduce the impact of human activities, although in the past difficulties have sometimes arisen from conflicts of interest between land owners, coastal engineers, nature conservationists and other users.

An important development in international wildlife legislation was the adoption in May 1992 by member states of the European Union of Council Directive 92/43/EEC on the Conservation of Natural Habitats and of Wild Fauna and Flora (the 'Habitats Directive'). The main aim of the Directive was 'to contribute towards ensuring biodiversity through the conservation of natural habitats and of wild fauna and flora in the European territory of the member states to which the treaty applies' (Article 2). This directive requires member states to designate and protect particular habitats and species as Special Areas of Conservation (SACs). These sites, along with Special Protection Areas (SPAs) designated under the 1979 Birds Directive, form sites known as 'Natura 2000 sites'.

This designation brings obligations to conserve and protect Annex I habitat types and Annex II (flora) and Annex IV (fauna) species. Loss of dune resources should be prevented and favourable conditions for habitats and species created to encourage expansion. On the Sefton coast, for example, a number of the habitats and species present are defined by the Habitats Directiveas being 'priority' habitats: fixed (grey) dunes (Fixed dunes with herbaceous vegetation) and dune heath (Eu-Atlantic fixed dunes) habitats, and species including petalwort, great crested newt, natterjack toad and sand lizard. To meet these obligations, land at risk has been purchased, practical management work is being undertaken to restore and create favourable conditions for particular species, and sustainable management strategies are being developed (Rooney, 2001).

The multiplicity of land ownerships and uses creates a variety of habitats, and a range of different intensities of use presents a challenge for the integrated management of the whole dune system and prevention of conflicting conservation objectives. A key concern at most dune systems is achieving wide public support for conservation management. Generally there is a poor public understanding of dune processes, coastal change and the need for management. Habitat restoration involving dramatic landscape change and the use of heavy machinery often causes public alarm and conflict between local communities and dune managers. An example is provided by the public debates which followed the proposed and subsequently implemented clear-felling of afforested dune areas on the Sefton Coast (Simpson & Gee, 2001). The importance of bare sand and the negative impacts of trees on sand dunes were evidently poorly understood by the local community who perceived that felling was destroying the woodland habitat whilst badly eroded dunes are usually restored by vegetation planting (Edmondson & Velmans, 2001).

Habitats and populations are subject to natural changes in response to a variety of factors, but under conservation legislation there is often pressure to maintain the status quo. In some circumstances this may lead to an artificial environment which is not in equilibrium with changed conditions, and which may be unsustainable in the longer term. It will be a major future challenge for conservations to devise and implement management strategies which can adapt to future changes in climate, sea level, coastal processes and morphology, and at the same time satisfy defined legal obligations.

4.5 Policy objectives for strategic management

A strategic approach to dune management involves consideration of the entire dune system in the context of the wider coastal environment, and requires clear definition of the medium to long-term management objectives. In the case of dune management for flood defence, the objectives may be site specific or governed by the national coastal management strategy. In some countries, such as The Netherlands, a national strategy has been in place for some years, but in England and Wales decisions have generally been based on local assessments by the relevant operating authorities (mostly District Councils and the Environment Agency), informed during the past decade by the recommendations of Shoreline Management Plans and constrained by requirements imposed by national and international nature conservation legislation.

4.5.1 Alternative strategies for frontal dune management

In principal there are five main strategic options relating to the management of coastal sand dunes primarily for the purposes of coastal flood defence:

(1) 'do nothing' : allow natural processes to take their course, possibly resulting in frontal dune erosion, blowout development and formation of transgressive dunes / sand sheets where the balance of forcing factors and human pressures favours this; allow accretion of new dunes to occur where favoured by forcing factors and sediment supply

(2) 'hold the line', or ‘static preservation’: undertake engineering works (hard or soft) to maintain the position of the beach-dune interface, and by raise the level and width of the frontal dunes where necessary to ensure they can withstand the impact of a severe storm (e.g. 1 in 200, 1 in 1000 or 1 in 10000 year event)

(3) ‘dynamic preservation’: maintain the general position of the coast but view the frontal dunes as a buffer zone within which limited change is permitted to take place during storms, and within which a degree of natural process instability is encouraged for the benefit of nature conservation

(4) 'managed retreat' or 'managed realignment': re-position the dune sea defence and create a second line of defence, inland of the frontal dune, using imported sand, re-profiling or existing sand and/or vegetation planting; alternatively allow or encourage the frontal dunes to roll back in a controlled manner in order to maintain the integrity of the defence; cease maintenance and possibly remove existing artificial defences and dune toe protection

(5) 'advance the line', by fence construction and planting of vegetation to seaward of the existing foredune ridge, encouragement of vegetation development in areas of natural potential accretion, by beach nourishment and / or creation of artificial dunes by bulldozing, planting and fencing

4.5.1.1 Do nothing

Although there is a long history of management intervention in the sand dune systems of England Wales, option (1) remained the most widely adopted until the 1970's. Many dune systems became degraded by visitor pressure, over-grazing, sand mining and military activities, resulting in extensive areas of freely blowing sand and mobile dunes. Many dune frontages experienced significant erosion during most of the twentieth century, and the lack of maintenance resulted in numerous breaches and episodes of marine flooding. The situation changed significantly from the 1970's onwards, when the 'do nothing' option widely became seen as undesirable. In the 1980's and 1990's it became the norm to undertake sand stabilization measures, both at the beach - frontal dune interface and in the hind dunes. This policy has, in some instances, been too successful, resulting in over-stabilization of many dunefields, sometimes to the detriment of biodiversity.

4.5.1.2 Static preservation

The aim of strategic static preservation is to maintain the long-term flood defence value of the dune system more or less in its existing position. The system can be treated as a sediment store whose volume can be controlled. The decision whether a dune frontage should be permitted to erode or not needs to be assessed in conjunction with a consideration of the potential impacts on the adjoining coastal areas as well as the immediate hinterland. Prevention of erosion at one location may simply move the problem elsewhere. Clearly, if there is major residential or industrial development in the hinterland, and the dune belt is relatively narrow, there is little scope to allow the dune ridge to erode and / or to move backwards. A high, robust frontal dune ridge with adjoining high beach to dissipate wave energy, and reduce the threat of wave attack, will be required. Provision and maintenance of such a defence may well involve beach nourishment, placement of rock armour and / or construction of offshore breakwaters in extreme cases. However, if the hinterland consists mainly of agricultural land, or is used for other 'mobile' purposes such as golf, other options may be viable.

4.5.1.3 Dynamic preservation

Dynamic preservation can only be considered in places where the dune belt is relatively wide (at least 500 m). The advantage of this option over static preservation is that repair works to the frontal dunes do not need to be undertaken after every storm or every year; allowance can be made for the fact that much natural recovery can take place between storm events, and emergency works are only required if the standard of defence is threatened (i.e. the dune belt is reduced to a defined critical width and / or height). In such areas it may be perfectly possible, and indeed desirable, to remove existing defences (groynes, gabions, revetments etc.) in order to allow the beach and frontal dune system to adopt a more natural profile. Following major storms, or after several years or decades with a net erosional trend, the condition of the beach and frontal dune system can be restored by way of a beach nourishment and re-profiling scheme.

In The Netherlands, a policy of static preservation was adopted after the serious loss of life which resulted from breaching of the dunes in many places during the 1953 storm surge. However, since 1990, there has been a change in policy towards dynamic preservation where the dune belt is wide enough. Elsewhere in Europe, a combination of static and dynamic preservation is still widely employed.

4.5.1.4 Managed retreat

In areas where natural processes favour frontal dune erosion, and where static or dynamic preservation ‘hold the line’ approaches are unsustainable or not cost-effective in the medium to longer term, some form of managed retreat provides the only realistic alternative. There are many such areas on the coast of England and Wales where the flood defence significance of the dunes can be classified as ‘low’ or ‘moderate’ and a few where the significance can be considered as ‘high’. In such circumstances, the key issue is to identify what form of managed retreat would be most appropriate. This will depend on such factors as the rate of coastal retreat, the potential for aeolian sediment transport in the area, the nature of the hinterland, and the availability of suitable sources of sediment for the construction of a secondary defence line. It is important to determine whether, if left to natural processes, the frontal dune will roll back, maintaining a more or less constant profile, or whether it will dissipate and lose volume or cross-sectional area as retreat takes place (see Part 2 for further discussion of alternative models). Such an evaluation should be undertaken before any decisions are taken to remove existing defence works.

4.5.1.5 Advance the line

Option 5 may be a viable option where natural processes favour progradation of the coast; e.g. where there is a positive beach and frontal dune sediment budget. The number of such locations in England and Wales at present is relatively small, mostly being restricted to the littoral ends of some littoral drift cells. In some such areas, minimal management intervention measures, such as the erection of rows of posts to exclude cars or pedestrians, can be sufficient to allow formation of new dunes (e.g. at Ainsdale North and Birkdale on the Sefton coast, and in several places between Cleethorpes and Mablethorpe on the Lincolnshire coast). Creation of new artificial dune ridges can also be achieved where large quantities of nourishment material are introduced to the beach, as has occurred at many locations on the North Sea coasts of Denmark and The Netherlands. To date, new dune ridge construction has not been a feature of beach nourishment schemes in England and Wales, although beach nourishment has been carried out to reinforce/enhance existing dunes where levels are low. Such schemes have sometimes employed bulldozing, but in most cases natural wind action has been relied upon to transport sand from the beach into the dunes.

4.5.2 Alternative strategies for hind dune management

From the perspective of coastal flood defence, the most important issue relating to the hind dune areas concerns the degree of blowing sand and dune mobility which should be allowed within the system. Traditionally, coastal engineers have considered it desirable to maintain a stable system, since this keeps as much sand as possible near the beach for as long as possible, and prevents problems associated with sand invasion at the landward margin. However, the internal dynamics of a dune system have a large influence on the dune habitats that develop and thus the range of vegetation communities and wildlife that exist. In general terms, a dynamic landscape favours biodiversity, although there can also be a risk that too much change may result in destruction of particular ecological features which are of importance for nature conservation. A strategic decision therefore has to be taken, both for flood defence and nature conservation reasons, regarding the degree and spatial distribution of mobility / stability which is desirable. Following from this, decisions need to be taken about land-use and access within the dune area, for example the grazing regime, extent of afforestation, recreational activities and visitor management. Specific actions to engineer the dune landscape for biodiversity and conservation objectives also need consideration (Rooney, 2001). Examples include options to create artificial breaches, washover areas and shallow saline lagoons within the frontal dune area, or the reactivation of blowouts and recreation of wet slack areas in the hind dune area. In the past decade a number of such experiments have been carried out in The Netherlands and in England and Wales, with variable reported degrees of success (Simpson & Gee, 2001; Rooney, 2001; Arens *et al*., 2004; Arens *et al*., 2005). All such decisions should be based on a detailed understanding of the natural process regime and geomorphology of the dune system as well as the flood defence and nature conservation requirements.

4.5.3 Possible removal of artificial dune defences

Dune systems deemed not to provide an adequate level of natural flood defence, or which would otherwise be eroding, are often protected with artificial structures such as sea walls, rock armour or revetments (e.g. the Spurn Peninsula, and between Happisburgh to Winterton Ness, northeast Norfolk). Such structures have a finite design life and usually require maintenance, such that on economic as well as environmental grounds it may be desirable to remove them if circumstances allow. On coasts where the beach sediment budget is strongly negative or where energy conditions are high, such protective works are often of limited value. The available choices in such circumstances are therefore to improve the defences, perhaps at considerable cost and with serious environmental impact, or to abandon the existing line of defence and to allow the frontal dunes to move back. In many circumstances a decision will depend on a full cost benefit analysis which takes into account the value of environmental assets, plus an appraisal of the environmental context of the dune system which will determine the sustainability of any particular course of action. Dune systems which protect low-lying densely populated areas will, in most cases, need to continue to be defended but possibly using additional methods such as beach nourishment and artificial dune construction. However, where sufficient accommodation space exists, it may be possible to allow a dune system to migrate landwards to some degree. Allowing greater dune mobility would increase habitat diversity without compromising the flood defence value of the system. However, consideration must also be given to potential undesirable effects which could arise from sand drift onto downwind land uses. The strategic management of future dune habitat resources should encompass the requirements identified by Habitat Action Plans (HAPs) that aim to recover endangered habitats and Coastal Habitat Management Plans (CHAMPs) which aim to balance habitat losses and gains likely to occur in response to ‘coastal squeeze’ by identifying the new habitats that will need to be created to offset the effects.

In order to take account of the various interests relating to any given dune area, and to assist the development of an integrated dune management approach, it is advantageous if a formal management scheme, or partnership, is established. A good example is provided by the Sefton Coast Management Scheme, started in the late 1970's, which subsequently evolved into the Sefton Coast Partnership (Houston & Jones, 1987). Similar arrangements have been developed in several parts of the United States and elsewhere (Nordstrom & Psuty, 1980; Nordstrom, 2000; Nordstrom *et al*., 2002). Individual management plans are required for each dune area, since the nature of problems, objectives, and physical and human constraints will differ from area to area. Such plans provide a useful framework within which to undertake assessments of dune system ‘vulnerability’ (e.g. Williams *et al*., 1993, 2001; Williams & Davies, 2001), to plan and carry out monitoring of beach and dune morphology, vegetation and other aspects of flood defence/conservation interest (e.g. Rebelo *et al.*, 2002; Andrews *et al*., 2002), and to construct local databases of information relevant to local and regional dune management (e.g. Chapman, 1993).

4.6 References

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Tables

Table 4.1 Estimates of impact severity of different uses of dunes with respect to effectiveness of dunes as coastal defence structures. After French (2001).

Category of impact	**Implications for effective sea defence**	
CONVERSION		
Urbanisation	Major	Inability of dunes to remobilise/loss of sediment
Golf courses	Minor	Possibility of return to natural system
Arable	Minor/Intermediate	Possibility of return to natural system
Forestry	Intermediate	Tree felling required
Grazing land	Minor	Depends on degree of improvement
Competitor species	Minor	Depends on degree of invasion and species present
REMOVAL		
Mining	Major	Loss of sediment/dune stability
Development	Major	Loss of sediment; little possibility of increased mobility
USE		
Trampling	Minor	Varies according to degree of vegetation loss and blowout formation
Horse riding	Minor	Varies according to degree of vegetation loss and blowout formation
Sand yachting	Minor	Varies according to degree of vegetation loss and blowout formation
Off-road vehicles	Minor	Varies according to degree of vegetation loss and blowout formation
Water extraction	Minor/Intermediate	Depends on extent of extraction and impacts on water table
Conservation	Minor	Problems if rare species cannot be lost
Military	Minor	Does not involve change of use/as for trampling
EXTERNAL		
Reduced sediment supply	Intermediate/Major	Loss of ability of dunes to build and migrate
Sea defences	Major	Removes dunes from dune/beach interactions
Migration prevention	Major	Coastal squeeze

Table 4.2 Range of adjustments to wind-blown sand and migrating dunes. After Sherman & Nordstrom (1994).

Class of adjustment	Blowing sand	Migrating dunes
Affect the cause	Stabilize bare sand surfaces: plant vegetation; pave surface; increase sediment cohesiveness	Stabilise bare sand surfaces: plant vegetation; pave surface; increase sediment cohesiveness
Modify the hazard	Establish wind breaks: sand fences; vegetation line Channel wind flow: reshape up wind surface	Establish wind breaks: sand fences; vegetation line Channel wind flow: reshape up wind surface Reduce impact by sand removal: shovel; earth moving equipment
	Establish sand control programs: protect stabilizing vegetation; dune protection legislation; designate drift control areas; establish buffer zones	Establish sand control programs: protect stabilizing vegetation; dune protection legislation; designate drift control areas; establish buffer zones
Modify loss potential	Relocating activity or evacuating	Relocating activity or evacuating: remove structures; abandon property
	Change land use Design compatible structures: cover vulnerable surfaces Increase public awareness Forecasting and rescheduling	Change land use Design compatible structures: elevate buildings; reinforce walls Increase public awareness
Adjust to loss	Bear the loss Insurance and reserve funds	Bear the loss Insurance and reserve funds Disaster relief

Table 4.3 Specific studies and examples of local-scale coastal sand dune management techniques.

Country	Authors	Location	Type
UK	Burton (2001)	Cumbria	Grazing
	Boorman (1989a)	General	Grazing
	Houston & Jones (1987)	Sefton coast	Management Scheme
France	Favennec & Barrère (1997)	General	General
	Favannec (1996)	Aquitaine	General
	Guilcher & Hallégouët (1991)	Brittany	General
	Barrére (1992)	Gascony	Stabilisation
	Paskoff (2001)	Aquitaine	Artificial dune
The Netherlands	Adriaanse & Coosen (1991)	General	Beach and dune nourishment
	van Bohemen & Meesters (1992)	General	Beach and dune nourishment
Denmark	Skarregaard (1989)	Jutland	Afforestation
Egypt	Misak & Draz (1997)	General	Sand drift control
Senegal	Mailly et al. (1994)	Northern coast	Stabilisation and Afforestation
South Africa	Avis (1989)	Cape Province	Stabilisation
	Lubke & Hertling (2001)	Cape Agulhas	Stabilisation
Australia	Barr (1983)	Queensland	Stabilisation
New Zealand	Gagil and Ede (1998)	General	Stabilisation
USA	Dahl et al. (1975)	Texas	Stabilisation
	Marsh (1990)	Great Lakes	Dune nourishment
	Nordstrom & Psuty (1980)	General	Protection
	Reckendorf et al. (1985)	Oregon	Stabilisation

Table 4.4 Projected global average surface warming and sea level rise at the end of the 21st century. Source: Solomon *et al*. (2007).

	Temperature change (ºC at 2090-2099 relative to 1980-1999)		Sea level rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	Likely range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations	0.6	0.3-0.9	NA
B1 scenario	1.8	1.1 - 2.9	0.18 - 0.38
A1T scenario	2.4	1.4 - 3.8	0.20 - 0.45
B2 scenario	2.4	1.4 - 3.8	0.20 - 0.43
A1B scenario	2.8	1.7 - 4.4	0.21 - 0.48
A2 scenario	3.4	2.0 - 5.4	0.23 - 0.51
A1F1 scenario	4.0	2.4 - 6.4	0.26 - 0.59

Figures

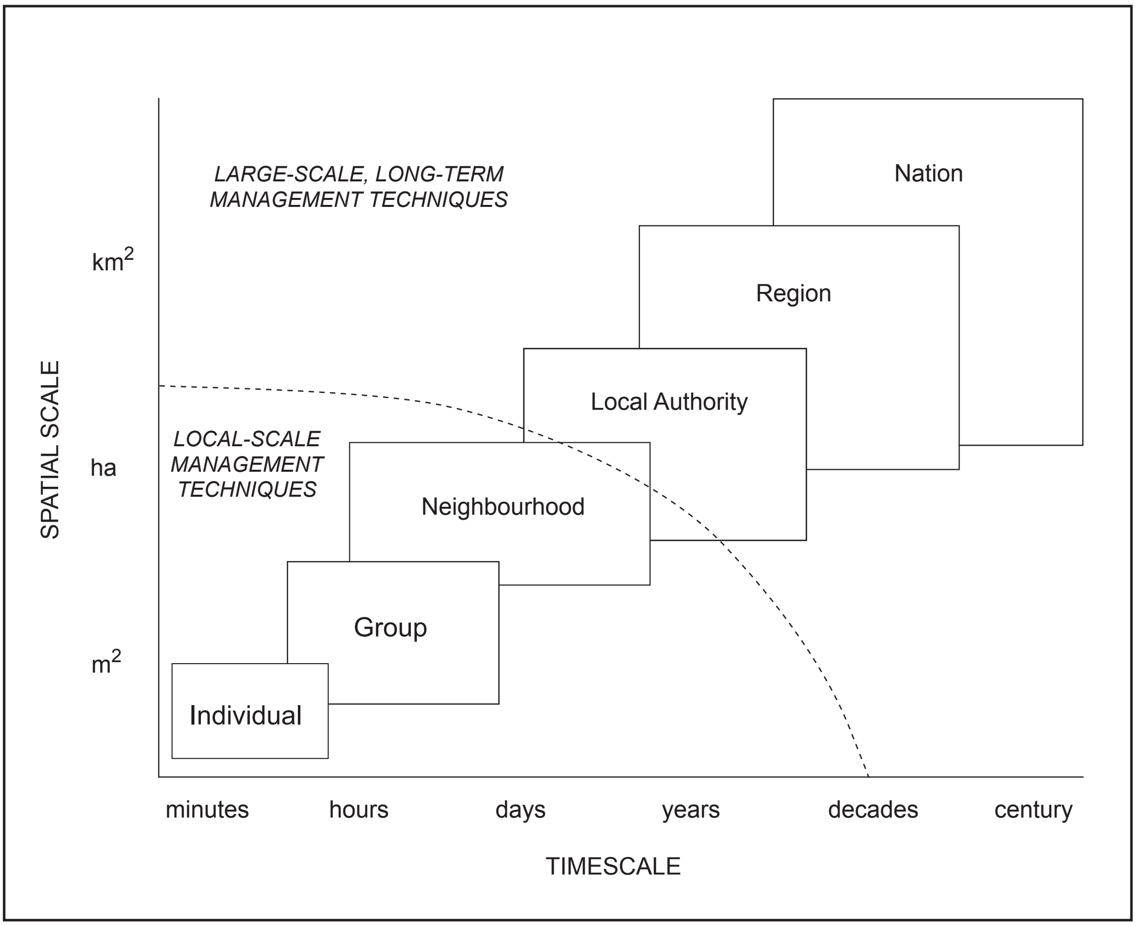

Figure 4.1 Spatial, temporal and management levels at which coastal sand dune management is implemented. Modified from Sherman and Nordstrom (1994).

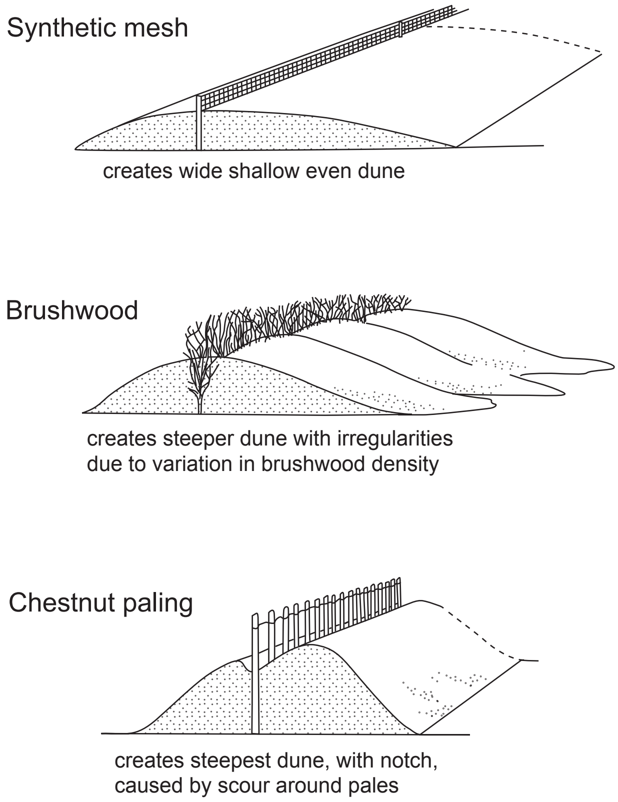

Figure 4.2 Different fencing materials used to trap wind-blown sand and their influence on dune shape. After Brooks & Agate (2005).

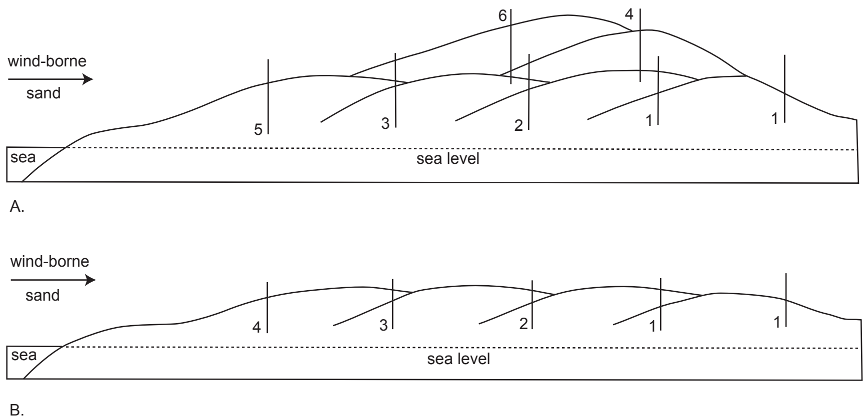

Figure 4.3 Placing of fences to A, gain height, and B, to increase width of coastal sand accumulations. After Adriani & Terwindt (1974).

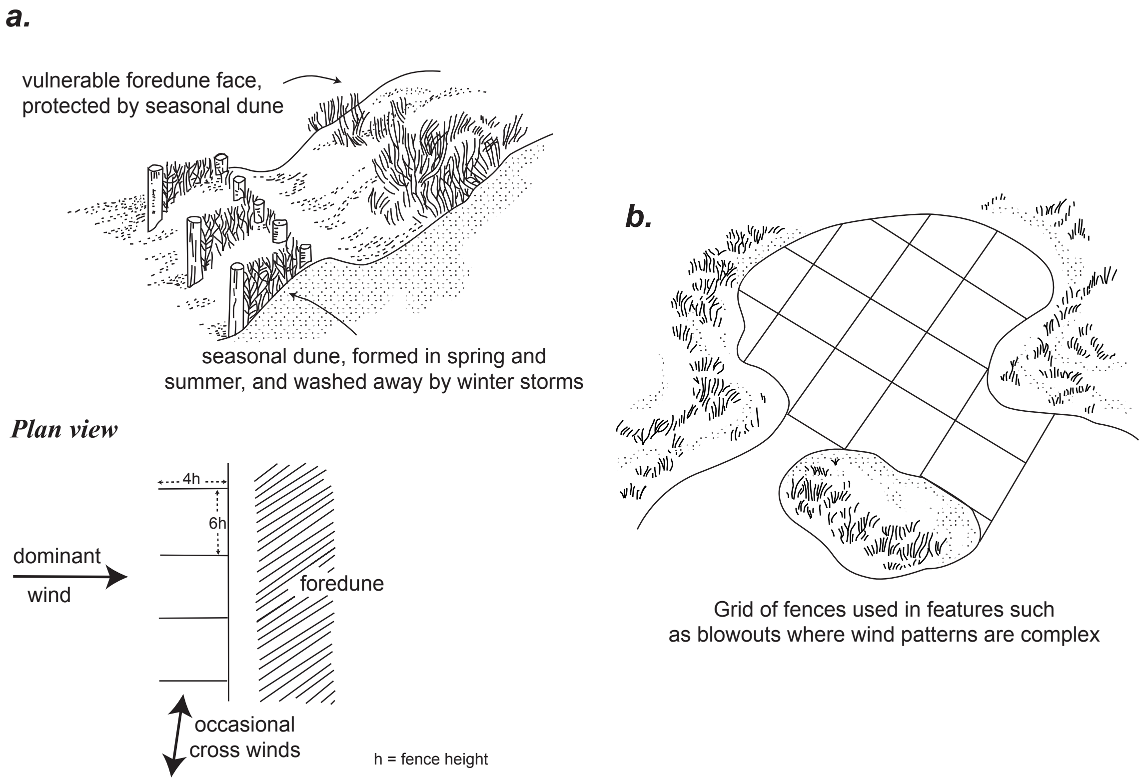

Figure 4.4 Placing of fences to trap sand a, where strong cross winds occur in addition to the dominant wind direction and b, where wind patterns are complex. After Brooks & Agate (2005).

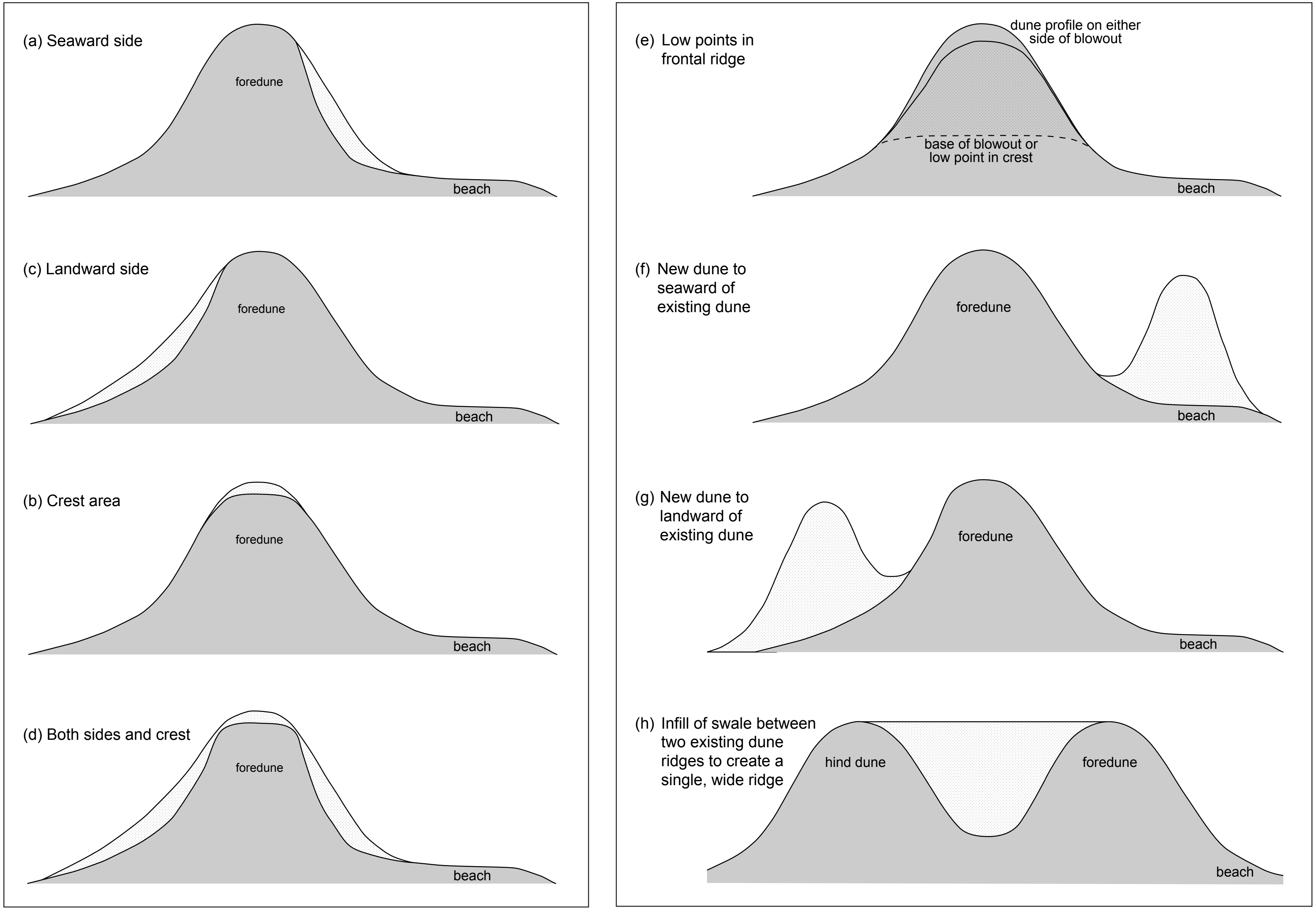

Figure 4.5 Alternative sand deposition strategies for dune enhancements.

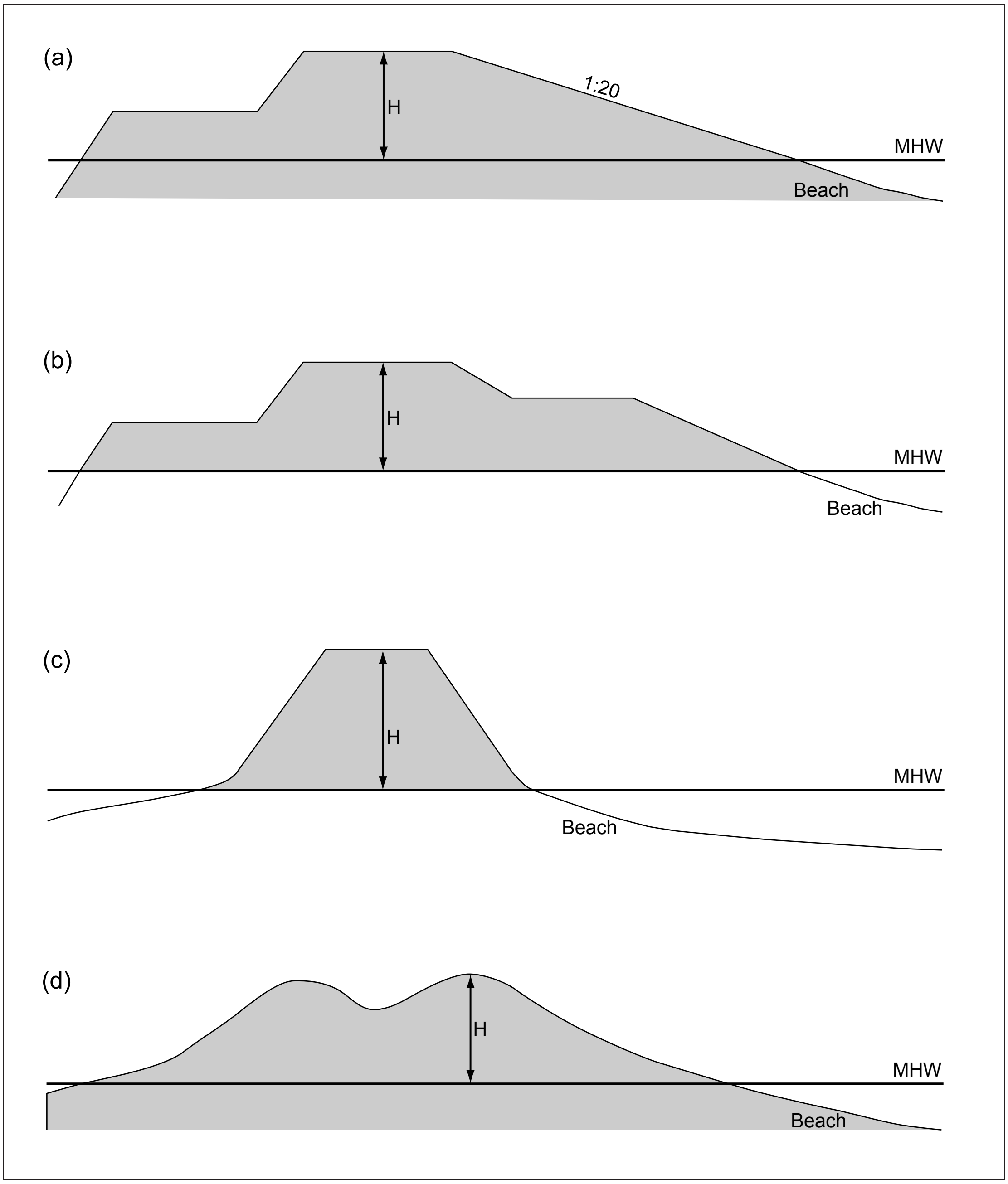

Figure 4.6 Artificial dune profiles. (a), (b) and (c) are effectively artificial embankments with a non-natural profile; (d) has a more natural profile.

Plates

Plate 4.1 Example of a dune frontage protected by a concrete sea wall and (in the distance) rock armour: east of Prestatyn, North Wales.

Plate 4.2 Dune toe protected by steel pilings, concrete, and masonry wall, south end of Llandanwg frontage, Wales.

Plate 4.3 Dune toe protected by placed concrete blocks. Note piles of 'placed' beach nourishment material designed to trickle-feed the frontal dunes with wind blown sand. The seaward face of the foredune ramp has been covered with a coarse-mesh geotextile and planted with marram. West coast of Jutland, Denmark.

Plate 4.4 Narrow frontal dune ridge protected by rock armour, Traeth Crugan, Wales. Pwllheli golf club to the left of the picture.

Plate 4.5 Dune frontage protected by cobble-filled gabions, Fistral Bay Cornwall.

Plate 4.6 Dune frontage protected by rock-filled gabions and low groynes, Old Hunstanton, North Norfolk.

Plate 4.7 Dune frontage protected by a wooden revetment constructed of old railway sleepers, Dundrum Bay, Northern Ireland. Royal County Down Golf Club to the left of the picture.

Plate 4.8 Dune frontage protected by an artificial beach composed of bricks and lumps of concrete from the demolition of Fort Crosby, between Hightown and Blundellsands, Sefton Coast.

Plate 4.9 Eroding dunes protected by an artificial rocky beach and offshore rock reefs, near Løkken, Denmark.

Plate 4.10 A row of timber posts placed to limit vehicle damage to embryo dunes, Ainsdale, Sefton Coast.

Plate 4.11 Barbed wire fencing designed to keep people out of the frontal dunes, Texel, The Netherlands.

Plate 4.12 Barbed wire fencing and planted rows of wattle fencing designed to trap sand on the seaward side of the foredune ridge, Texel, The Netherlands.

Plate 4.13 Wattle fencing placed both parallel and perpendicular to the beach and frontal dune toe in order to increase the width of the frontal dune, Texel, The Netherlands.

Plate 4.14 Single line of chestnut plaing fencing placed obliquely on the upper beach to trap sand and with the intention of creating a wet slack behind, Cabin Hill National Nature Reserve frontage, Sefton Coast.

Plate 4.15 Zig-zag arrangement of timber posts, chestnut palings and placed brushwood designed to trap sand transported to the upper beach both by wave action and aeolian processes, Brancaster Bay, north Norfolk.

Plate 4.16 Timber posts and brushwood fencing constructed transverse to the dune front in order to trap sand blown along the beach. Ploughing of the upper beach in this instance was undertaken primarily for racecourse training but also has the effect of enhancing aeolian transport to the dunes, Ainsdale, Sefton Coast.

Plate 4.17 Short lengths of wooden fencing placed in a line on the upper beach oblique to the dune toe but transverse to the dominant sand transport. Cocoa Beach, Florida.

Plate 4.18 Rows of plastic mesh fencing erected to trap sand on the seaward face of a foredune ridge, Aquitaine Coast, southwest France.

Plate 4.19 Wooden slats placed on the seaward face of an eroding dune to reduce sand loss by wind deflation, Cap Feret, southwest France.

Plate 4.20 Rows of dead Christmas trees placed on the upper beach to trap wind-blown sand, Formby Point, Sefton Coast.

Plate 4.21 Single row of plastic mesh fencing placed to control the rate of movement of bare sand, Cap Feret, southwest France.

Plate 4.22 Brushwood fence erected across the mouth of a large blowout to trap sand on the leeward side, Formby Point, Sefton Coast.

Plate 4.23 Fenced-off area being planted with marram, Penhale, Cornwall.

Plate 4.24 Artificially re-profiled dune recently planted with marram, Thy, Denmark.

Plate 4.25 Fenced-off area approximately 4 years after planting with marram, Morfa Dyffryn, west Wales.

Plate 4.26 Boardwalk constructed to control access through the dunes to the beach, Morfa Dyffryn, west Wales.

Plate 4.27 Removal of sand from the Aberdovey harbour area for recharge of the frontal dunes along the Aberdovey to Tywyn frontage, west Wales.

Plate 4.28 A recharged area of the frontal dunes north of Aberdovey, west Wales. Wind-deflation of the deposited sand is limited by emplacement of brushwood and gravel which is naturally present in the harbour dredgings.

Plate 4.29 An area of frontal dunes which has received new supplies of blown sand following nourishment of the adjoining beach, Gronant to Talacre frontage, north Wales.

Plate 4.30 Artificial piles of sand placed on the backshore to nourish the dunes behind, Bjerghuse, western Denmark.

Plate 4.31 Creation of an artificial 'washover dune' using sand dredged from Harwich Harbour, entrance to Walton Backwaters.

Plate 4.32 Artificial breach created in the frontal dune ridge to create an episodically tidal lagoon and wet slack, between Bergen Aan Zee and Schoorl, The Netherlands, view looking to seaward.

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