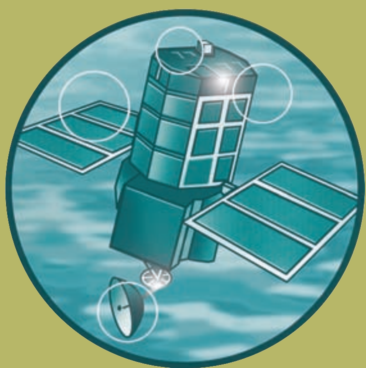
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Sand dune processes and management for flood and coastal defence

Part 2: Sand dune processes and morphology

R&D Technical Report FD1302/TR



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Sand dune processes and management for flood and coastal defence

Part 2: Sand dune processes and morphology

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

2.1 Introduction

There are two basic requirements for the formation of sand dunes: (1) a supply of sand and (2) wind energy to transport it. Vegetation is not essential for the formation of dunes but its presence can have a profound effect on dune morphology and the rate of dune movement (Pye, 1983). In simple terms, a large supply of sand and high wind energy result in the formation of extensive, and sometimes large, sand dunes. In the absence of vegetation and topographic obstacles, sand may be blown large distances inland from the source in the form of sand sheets or rapidly migrating dune forms such as barchans. Vegetation cover acts to impede sand movement and, depending on the vegetation characteristics, may encourage the development of large, high dune forms.

From a flood defence perspective, both the potential for aeolian sand transport and the nature of dune forms present in an area are important, since flood defence significance is related to the height and width of a dune belt, and also to the stability of the dune forms. If the frontal dunes are highly unstable and display a high rate of inland movement, the flood defence value may be rapidly reduced unless there is a steady supply of new sand from the beach.

Coastal dunes and aeolian processes cannot be considered in isolation from beach morphology and marine processes, since the latter are largely responsible for determining the availability of sediment for wind transport, and also whether the frontal dunes experience net erosion or net accretion (vertical or lateral). The effectiveness of a sand dune barrier as a coastal flood defence is dependent both on the morphology of the barrier and on the nature of marine processes (tidal heights, wave energy, storm surge magnitude and frequency). Beach-dune interactions are complex in nature with several different processes and possible morphological responses operating on a range of timescales (Sherman & Bauer, 1993; Arens *et al*., 2001; Aargard *et al*., 2003).

2.2 Aeolian processes

A considerable amount of research has been undertaken since the 1930's relating to the physics of blown sand and its relation to dune development (O'Brien & Rindlaub, 1936; Bagnold, 1941; Kuhlman, 1958; Horikawa & Shen, 1960; Kawamura, 1964; Kadib, 1966; Owen, 1966; Horikawa *et al*., 1986; Sherman & Hotta, 1990), and there have been numerous field studies of rates of sediment transport on natural beaches (Svasek & Terwindt, 1974; Bressolier & Thomas, 1977; Sarre, 1987, 1988; Nickling, 1988; Jackson & McCloskey, 1997). However, the results of such studies are of relatively limited value for the purposes of predicting long-term changes in dune morphology and designing / managing dunes for coastal flood defence. Accurate and truly representative aeolian sand transport data are difficult to obtain, partly owing the variable efficiency of different sand trap designs (Horikawa & Shen, 1960; Leatherman, 1978; Illenberger & Rust, 1986) or other types of sonic sampler (e.g. Jackson & McCloskey, 1997), and most studies have found wide discrepancies between measured transport rates in the field and those predicted by theoretical equations. In part this arises from the fact that theoretical predictive equations relate to potential transport, whereas actual transport in the field is governed by a whole array of factors such as fetch distances (related to tidal range, beach width and wind direction relative to the shore), sand grain size, moisture content, compaction and crusting, and the presence or absence of bedforms and surface debris such as pebbles and litter on the beach surface (Pye, 1980; Nordstrom & Jackson, 1992; Arens, 1996a; Davidson-Arnott & Law, 1996; Bauer *et al*., 1996; Davidson-Arnott *et al*., 1997; Gomes *et al*. 2002).

Aeolian sand transport within a dune system is even more difficult to predict than that from the beach to frontal dunes owing to the spatially variable effects of vegetation (Wasson & Nanninga, 1986; Buckley, 1987; Sarre, 1989; Willetts, 1989; Arens, 1996b) and also small-scale differences in wind shear stresses which arise from variations in the dune topography. Attempts to model airflow and aeolian sand transport over dunes have had some success with relatively simple forms, such as transverse dune ridges and isolated hills (e.g. Jackson and Hunt, 1975; Rasmussen, 1989; Arens *et al*., 1995; van Boxel *et al*., 1999; van Dijk *et al*, 1999), but have been relatively unsuccessful when applied to complex, vegetated dune terrain. Even with simple, bare dune forms, available models have been unable to predict accurately the nature of near-surface air flow and sand transport (Frank & Kocurek, 1996). In the case of more complex three-dimensional forms such as blowouts and parabolic dunes, flow patterns and shear stresses show great spatial variability and are difficult to predict accurately (Hesp & Hyde, 1996; Jungerius & van der Meulen, 1997; Fraser *et al*., 1998).

Partly for these reasons, many workers have preferred to estimate average aeolian sand transport rates using routine wind and other weather data collected at standard meteorological stations (e.g. Hsu, 1987; Chapman, 1991). Such wind data can be used to estimate daily, monthly, annual and long-term sand drift potentials and resultant transport directions (Fryberger & Dean, 1979; Pye, 1982, 1985). However, such methods only provide an estimation of potential sand transport at a relatively coarse scale, and within individual bays there may be considerable variations in actual rates owing to such factors as topographic exposure, variations in beach width, and differences in beach sediment characteristics (e.g. Harris, 1974). On developed urban coasts, the presence of high rise buildings may also have a significant local influence of aeolian sand transport rates and directions (Nordstrom & Jackson, 1998). However, monitoring of changes in average wind parameters at standard locations is frequently sufficient to predict and/or explain changes in major dune morphological features and sand mobility (Jungerius *et al*, 1981; Jungerius *et al*., 1991).

2.3 Dune morphology

Coastal dune morphology is influenced by several different factors (Figure 2.1) and the scale and form of dune development behind beaches shows considerable variation at national and global scales. Dune systems and individual dune forms can be classified in several different ways, including on the basis of the environmental setting in which they occur, the broader-scale landform units of which they are a part (Table 2.1), their basic size and shape, and their genesis (Table 2.2). At the simplest level, dunes may form a single vegetated ridge at the back of a beach (Figure 2.2), while at the most complex level several different types of transgressive and impeded dunes may be exist together as part of an extensive dune system which may extend a considerable distance inland, or form a thick vertical sequence which extends below current sea level.

Blowing sand is likely to be deposited wherever there is a reduction in wind speed or a significant increase in surface roughness. This may occur, for example, in the lee of a topographic obstacle (Plate 2.1), where there is a change in the particle size or bedform roughness of the surface (Plate 2.2), or a change in roughness due to vegetation (Plate 2.3). Development of embryo dunes on the backshore of a beach can occur in the absence of vegetation if there is a large amount of litter along the drift line, or if the beach is backed by a wave-cut dune cliff which favours the development of echo dunes (e.g. Pye, 1991). However, development of embryo dunes, and their transformation from ephemeral to permanent features, is favoured by vegetation establishment and succession (Plates 2.4 & 2.5). Pioneer vegetation species must normally have a degree of tolerance to saline influence, and be able to withstand relatively high rates of sand deposition (Ranwell, 1972; Kent *et al*., 2001). Once vegetation is established, it exerts a profound influence on the morphology of the foredune which subsequently develops (Hesp, 1988a, 1888b, 1989).

The nature of the frontal dune morphology on any beach is strongly influenced by the nature of beach-dune sediment exchange (Figure 2.3) and in particular by the balance between the beach and frontal dune sediment budgets (Psuty, 1988, 1992; Martinez & Psuty, 2004; Figure 2.4). If the beach sediment budget is generally negative, embryo dunes will not form and the foredune will undergo net erosion. In extreme circumstances, the foredune will become disrupted by blowouts, leading to the development of transgressive sand sheets and dunes. On the other hand, if the beach sediment budget is positive, the frontal dunes will either grow vertically or prograde seawards though development of new embryo dunes and foredune ridges.

On many sections of coast, there is a longshore variation in wave energy conditions and beach/dune sediment budget which is reflected in the dune morphology (Short & Hesp, 1982; Short, 1988). Figure 2.5 provides a schematic illustration of the longshore variation in dune morphology which can be expected in an area of unidirectional net littoral drift.

The nature of changes which take place in the frontal dune morphology over time are strongly dependent on the balance between beach and dune sediment budgets. Figure 2.6 illustrates a number of possible changes in dune cross-sectional morphology which can arise under differing conditions of beach sediment budget. If there is little or no net gain of loss of sediment from the beach or frontal dune, the profile is likely to show little change over time (situation a in Figure 2.6). If the dune sediment budget is slightly positive, then the dune is likely to grow slowly in height but maintain lateral stability over time (situation b). If the beach and frontal dune sediment budget are both positive, the dune system may be expected to grow seawards over time by development of new embryo dunes and foredune ridges (situation c). If the amount of sand removed from the beach by aeolian and/or marine processes is greater than the supply of new sand, the dune can be expected to move landwards over time due to foredune erosion and possible landward movement of transgressive dunes, either maintaining constant height (situation d) or reducing in height (situation e). Examples of stable foredunes are shown in Plates 2.6 & 2.7, while examples of prograding systems are shown in Plates 2.8 & 2.9.

As noted above, the morphology of individual dunes is often related to the broader environmental framework within which they occur. Saye (2003) developed a classification of dune system types which extended the ideas originally presented by Ranwell & Boar (1986). At the first level of classification, dune systems can be classified on the basis of environmental setting as *open coast*, *embayment* or *estuarine* types, At a second level of classification, the dune systems can be classified in terms of the major landform type on which they occur (e.g. *barrier island*, *spit*, *tombolo*), and various sub-types can be identified on the basis of other characteristics, such as whether or not the system is climbing or non-climbing (Table 2.1). This scheme has been used to classify each dune system in England and Wales (summarised in Part 3 of this report). The plan view and cross-sectional characteristics of the major types recognized are illustrated in Figures 2.7a to 2.7c.

In the context of coastal flood defence, the morphology of foredunes is often of particular significance. Arens & Wiersma (1994) classified Dutch foredunes into *progressive*, *stable* and *regressive* types, depending on whether they showed morphological evidence of seawards accretion, vertical accretion, or landwards movement over time. A similar foredune morphological classification scheme (Figure 2.8), developed from a model originally proposed by Pye (1990), was used in the present study to classify foredunes as *stable*, *eroding* or *accreting,* based on assessments carried out during field visits.

2.4 Dune responses under storm conditions

Dune morphology can be considered to reflect the balance between constructive aeolian processes, which are responsible for dune building, and marine processes, which may be either constructive or destructive, depending on the direction of net sediment transport (Figure 2.9). During storms, destructive waves erode sand from the beach, causing levels to fall, and may also erode the seaward face of the dunes (Figure 2.10). Increasing storm severity and/or duration results in progressively greater impact on the dune system (Figure 2.11). Under extreme conditions, a dune system may be eroded altogether, over-topped and flattened, or selectively breached at low points in the dune ridge (Leatherman, 1979).

Dunes which are protected by artificial structures, such as sea walls and revetments, behave differently during storms to dune frontages which are unprotected. In the former case, a severe storm may cause lowering of the beach in front of the protection works to the point where it is undermined and experiences catastrophic failure; no sand can be released from the dunes to replenish the beach until after the failure has taken place (Figure 2.12). In the second situation, unprotected dunes release sand which slows the rate of beach lowering; this acts to limit wave energy and slows the rate of frontal dune erosion. During subsequent periods of fair weather, constructive waves transport sand back on to the beach and aeolian transport processes then rebuild the frontal dunes. Under ‘ideal’ circumstances, therefore, a dune frontage provides a naturally dynamic sea defence which requires little or no initial capital investment and subsequent maintenance. In practice, of course, intervention may be required to rebuild the dune after a major storm event, or a series of smaller events which occur close together in time, preventing full natural recovery of the dune.

Storm damage to dune systems often shows considerable longshore variation which may reflect variations in the beach and nearshore bathymetry, degree of wave focussing (Healy, 1987) or in the dune morphology (especially crest height and width; Figure 2.13). Erosion also need not be restricted to the period of the marine storm event alone; several significant mechanisms of post-storm erosion exist, including slumping and wind scour from exposed sand faces (Figure 2.14). Intervention measures may be required to prevent or minimise the effects of these processes, for example by infilling low points in the frontal dune crest line, or by thatching bare sand surfaces created during a storm.

If counter-measures are not undertaken, exposed sand areas can quickly develop into blowouts and incipient mobile parabolic dunes. Blowouts can develop either at low points in the frontal dune ridge, which act as wind gaps through which airflow is funnelled, or near the crests of high points where bare sand has been exposed by cliffing and/or slumping (Jungerius & van der Meulen, 1988; Plate 2.10). Once initiated, blowouts often enlarge through a positive feedback mechanism. The existence of a depression creates additional turbulence and wind scour which erodes sand from the edges and bottom of the blowout (e.g. Hesp & Hyde, 1996). Evolution of the blowout into a parabolic dune (Plate 2.11) further serves to concentrate the airflow and to accelerate it as it moves up the windward slope of the dune, further enhancing downwind sand transport (Pye, 1982).

The rate of erosion of unprotected frontal dunes during storms is governed by several factors including tidal height, wave energy, dune height, duration of storm and particle size of the sand. Erosion almost always results in cliffing of the seaward side of the frontal dune (Plates 2.12 to 2.15).

Edelman (1968) found the rate of frontal dune recession in The Netherlands during storms was inversely related to the dune height, assuming that sand released was uniformly distributed over the foreshore and not immediately lost offshore. Parker (1975) noted that erosion of the dunes at Formby Point on the Sefton coast was most rapid when high tidal levels gave rise to standing water at the dune foot, causing sand saturation and slumping, in addition to the effect of wave and wave-induced current scour (Figure 2.15). Erosion was found to increase from *c*. 1.5 m per tide at a tide height of 9.60 m above Liverpool Bay Datum (LBD) to 4.5 - 6 m at levels of 9.75 m LBD. The main factors determining the height of wave run-up were found to be beach slope, beach width, dune stoss slope angle, deepwater wave height, wave period and magnitude of the storm surge component.

van de Graaff (1994) concluded from experimental investigations that the rate of dune erosion during storm surges is largely dependent on six main factors: (1) maximum surge level; (2) significant wave height during (the maximum of) the surge; (3) particle diameter of the dune material; (4) shape of initial profile (including dune height); (5) storm surge duration; and (6) occurrence of squall oscillations and gust 'bumps' during the storm. The volume of eroded sand and retreat distance as a function of time and other boundary conditions are shown in Figures 2.16 to 2.19.

Several computational models have been developed to predict the rate of dune erosion during storm surges. In the model developed by Vellinga (1982, 1983, 1986) the input parameters required are: (1) the coordinates of the initial profile; (2) significant deep water wave height; (3) median grain size diameter of dune sand and its corresponding fall velocity for a given water temperature; and (4) maximum water level during the storm surge. Three outputs are obtained from the model: (1) the recession of the dune front; (2) the erosion quantity above storm surge level; and (3) the beach profile after the storm surge. This model has been widely used in the safety assessment and design of Dutch frontal dunes that are required to protect the low-lying hinterland.

If there is an interval of several years between major storm events, and if wind scour of the cliffed dune face is not too severe, vegetation may naturally recolonise the eroded dune slope and begin to trap new sand blown from the beach (Plate 2.16). The rate of natural advance of the dune front will depend strongly on the availability of sand for aeolian transport (i.e. on the rate of natural beach recovery). This may take several years or not occur at all if intervention measures are not undertaken (Plate 2.17). In The Netherlands and on the German North Sea coast, beach nourishment and bulldozing are widely used to encourage beach and dune recovery following storms (e.g. Draga, 1983). Recovery is also assisted by fencing to keep pedestrians off the dune front while vegetation becomes re-established (alternative methods of fencing for different purposes are discussed in Part 4 of this report).

2.5 Assessment of the flood defence value of coastal dunes

The most important attributes of coastal dunes in terms of flood defence are the crest elevation above mean sea level and the surge level, the geometric shape and width dimension. The geometries and dimensions of dunes required for adequate protection are determined by storm surge and wave characteristics (Bruun, 1998). Dune systems which have the greatest flood defence value are both wide and high. In the context of England and Wales, a relatively narrow dune system, 30 to 40 m wide, can have high flood defence value if the dunes are above 10 m in height, although clearly such a system is at significant risk from erosion, which on exposed sections of coast can cause 10 m or more of dune recession during a single severe storm. Narrower systems (~16 m) can provide a medium level of flood defence where they are above 5 m in height. Dune systems which are only a few metres high but relatively wide (>50 m) can also provide a significant flood defence. Composite dune systems, such as those on the northern and southern Lincolnshire coast, comprising multiple dune ridges of low to moderate height, fronted by saltmarsh, also form a valuable natural flood defence (Plate 2.18). However, very low, narrow ridges and aeolian sand platforms have very low flood defence value. Dune systems <5 m wide and / or <2 m high can be considered to have no flood defence value since it is easily possible for such dunes to be eroded or severely overtopped in a single storm.

In The Netherlands, much greater dune system widths and heights have been prescribed in order to provide an acceptable level of flood defence (Rijkswaterstaat, 1990). Based on observed events, assessments have been made of the magnitude of dune recession, and risk of both breaching and overtopping, which is likely to occur during storm surges with estimated recurrence intervals of up to 10 000 years (Figure 2.20). On this basis, minimum widths have been prescribed for dune barriers which reflect local physical conditions (Figure 2.21). In part, the high level of concern with the factors of satefy provided by dune barriers reflects the great impact which the 1953 storm surge had in the Netherlands, and the large area of the country which could potentially be flooded again during a similar or larger event.

In addition to width and height, the longshore integrity of dune systems is vital in determining the flood defence value. Continuous dune ridges provide the greatest flood defence value; blowouts and other low or narrow points in the crest represent areas of weakness.

Traditionally, height, width and sand volume in frontal dunes has been monitored using a combination of total station 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. However, the more recent availability of kinematic gps has increased the speed and frequency with which data can be gathered with a spatial and vertical resolution of only a few centimetres (e.g. Rebelo *et al*., 2002). Airborne Light Detection and Ranging (lidar) also provides an effective method of monitoring large areas at moderate spatial resolution (typically 1 to 2 m) and relatively good vertical resolution (typically 15 – 20 cm in non-wooded terrain). This technique has been widely used to study dune morphodynamics and volumetric changes in sand dunes (Andrews *et al*., 2002; Woolard & Colby, 2002; Saye *et al*. 2005; see also Part 5 of this report).

The degree of vegetation cover on dunes is also an important attribute affecting their flood defence value since it influences dune resistance to both wind and marine erosion. In general, a frontal dune system which is well-vegetated with healthy marram or similar vegetation is desirable to effectively trap sand and to bind the sand together by way of the root systems. Assessments of dune vegetation cover can be made using colour air photography or digital multispectral remote sensing instruments such as Airborne Thematic Mapper (ATM) and Compact Airborne Spectrographic Imager CASI) (e.g. Shanmugam & Barnsley, 1997; Lucas *et al*., 2002), or by ground surveys using standard procedures (JNCC, 2004). The vigour of vegetation on coastal dunes is affected by several environmental and biological factors, including wind stress, rates of new sand deposition, nutrient status, moisture availability and pedestrian pressure, all of which should be monitored, and where necessary controlled, to ensure healthy vegetation growth (Salisbury, 1952; Ranwell, 1959, 1960, 1972; Willis, 1989; Moore, 1996)

2.6 Potential dune degradation processes

Dune ‘degradation’ can arise naturally due to natural factors (e.g. increase in wind stress, reduction in precipitation) or due to the effects of human activities. Deflation by wind action usually occurs when the vegetation cover declines and this can arise naturally due to disease, drought, lack of nutrients or overgrazing by rabbits (Ranwell, 1960; Rutin, 1992). Human activities such as pedestrian trampling, vehicles, sand extraction, groundwater extraction and excessive livestock grazing, can exacerbate vegetation damage (Boorman & Fuller, 1977; Anders & Leatherman, 1987; Andersen, 1995). The result is frontal dunes and hind dunes composed of irregular hummocks, knobs and blowouts (Plates 2.19 & 2.20). Transgressive sand sheets can develop where the vegetation cover is very low. Blowouts and severe dune dissection by human trampling of vegetation occur at systems subject to intense visitor pressure

Internal sand deflation is generally not as damaging to dune systems as marine erosion since it does not usually result in a net loss of sand, which is merely redistributed within the dune system. However, significant instability and loss of sand from the near-frontal dunes can significantly reduce the effectiveness of these dunes for flood risk management. Consequently, from this point of view it is preferable to allow blowouts and other areas of bare sand, which may be advantageous from a nature conservation perspective, to develop some distance inland within the hind dune system, rather than in the frontal dunes. If located more than 100 m from the shoreline, they are unlikely to have any significant impact on present or near-future shoreline recession rates.

In the past, drifting sand and migrating dunes have posed significant problems to residential areas and infrastructure, and there remains a need to ensure than internal dunefield mobility is not allowed to recreate such problems. Negative impacts of sand drift and dune migration include erosion of soils, abrasion damage to crops and paintwork, blocking of roads, railways and canals, infilling of wells and reservoirs, and burial of buildings and industrial installations.

2.7 Dune responses under different sea level scenarios

Sea level change exerts an important control on dune system behaviour and morphology at a regional scale over time periods of centuries to millennia, since it changes the nature of the equilibrium coastal profile and may cause the redistribution of coastal sediments. Sea level change can also affect ground water table levels which in turn determine the base level for deflation within the dunefield.

Five simple scenarios of dune development under constant sea level conditions may be envisaged (Figure 2.22). Model A represents vertical dune accretion, which occurs where the beach sediment budget is positive and total aeolian removal occurs landwards leading to an increase in dune height and volume thus the flood defence value is increased. Model B shows seawards coastal progradation which occurs when the beach sediment budget is positive and only a part of the sand supplied is removed landwards by wind action. Multiple dune ridges are formed where lateral accretion is rapid. The flood defence value of the system increases as it becomes wider, even though the maximum dune height may remain constant. Model C is similar to Model B but reflects the situation when saltmarsh areas separate multiple shore-parallel dune ridges. Such combined systems of sand dunes and saltmarsh forms a wide flood defence barrier but one which is generally less effective than one composed of beach - dune ridges alone. Coastal progradation often occurs in accordance with this model as a result of long-shore growth of dune-capped spits. Model D shows a transgressive dune system which arises where the beach sediment budget is negative and more material is blown from the beach than is supplied by marine processes. Under such conditions, beach lowering, steepening and cliffing of the dune toe are likely to occur, accompanied by the development of blowouts and relatively high frontal dunes which gain height as they move landwards. Despite the receding shoreline, the flood defence value of such a system increases due to the increase in dune height. Model E illustrates a further possible situation where the beach sediment budget is again negative but where there is little or no aeolian transport from the beach Dune cliffing occurs as a result of wave attack, but owing the poor efficiency of aeolian processes the dune height and width decrease over time, eventually leading to breaching and washover.

Under conditions of rising sea level a number of other modes of dune system evolution are possible, as shown schematically in Figure 2.23. In Model A, which represents a situation of ‘equilibrium rollover’, shoreline recession occurs as sea level rises and the beach sediment budget is strongly negative, whilst the dune sediment budget is positive. Dune height above high water level and dune width essentially remains constant and thus the flood defence value of the system is maintained, although the positioned of the barrier has shifted landwards. In Model B, which represents a case of ‘snowball rollover’, shoreline recession occurs during sea level rise, the beach sediment budget is strongly negative, but the dune sediment budget is strongly positive due to high wind energy. Dune height above high water increases as the dune moves landwards, leading to improved flood defence effectiveness. In Model C, which represents a situation of 'dissipation rollover', shoreline recession again occurs as sea level rises but in this case the dune sediment budget is neutral or only slightly positive. Dune height decreases with time as sediment is lost from the system, and consequently the flood defence value also decreases. In the case of Model D, 'washover rollover', shoreline recession occurs as sea level rises and both the beach and dunes have a negative sediment budget. Dune height above high water and dune width both decrease significantly with time. The flood defence value is reduced and there becomes a high risk of washover and / or breaching of the barrier. While these are conceptual models intended for illustrative purposes only, they illustrate that not all dune systems can be expected to behave in the same way, and that assessment of the likely response of any given dune system to sea level rise should take careful account of the beach and dune sediment budgets.

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Tables

Table 2.1 Classification scheme for shoreline and riverbank dune systems (after Saye, 2003).

GEOMORPHOLOGICAL SETTING	DUNE SYSTEM MORPHOLOGY	
1. OPEN COAST	(a) Barrier island dunes	
	(b) Barrier spit dunes	i) Single
		ii) Multiple
	(c) Tombolo dunes	
	(d) Fringing	i) Non-climbing
		ii) Climbing
		iii) Cliff-top
	(e) Transgressive dunes	i) Non-climbing
		ii) Climbing
		iii) Cliff-top
	(f) Ness dunes	
2. PROTECTED MAINLAND COAST	(a) Barrier spit dunes	i) Single
		ii) Multiple
	(b) Fringing	i) Non-climbing
		ii) Climbing
		iii) Cliff-top
	(c) Transgressive dunes	i) Non-climbing
		ii) Climbing
		iii) Cliff-top
3. EMBAYMENT	(a) Bay-mouth barrier dunes	
	(b) Bay-head barrier dunes	
	(c) Tombolo	
	(d) Fringing	i) Non-climbing
		ii) Climbing
		iii) Cliff-top
	(e) Transgressive dunes	i) Non-climbing
		ii) Climbing
		iii) Cliff-top
		iv) Headland by-pass
	(f) Bay-fill	
4. DELTAIC	(a) Barrier spit dunes	i) Single
		ii) Multiple
	(b) Fringing (non-climbing)	
	(c) Transgressive dunes (non-climbing)	
5. ESTUARINE	(a) Barrier spit dunes	i) Single
		ii) Paired
	(b) Tombolo dunes	
	(c) Fringing	i) Non-climbing
		ii) Climbing
		iii) Cliff-top
	(d) Transgressive dunes	i) Non-climbing
		ii) Climbing
		iii) Cliff-top
6. OFFSHORE ISLAND DUNES	(a) Barrier spit dunes	i) Single
		ii) Multiple
	(b) Tombolo dunes	
	(c) Fringing	i) Non-climbing
		ii) Climbing
		iii) Cliff-top
	(d) Transgressive dunes	i) Non-climbing
		ii) Climbing
		iii) Cliff-top
	(e) Composite sand island dunes	
7. LACUSTRINE SHORELINE	(a) Barrier island dunes	
	(b) Barrier spit dunes	i) Single
		ii) Multiple
	(c) Tombolo dunes	
	(d) Fringing	i) Non-climbing
		ii) Climbing
		iii) Cliff-top
	(e) Transgressive dunes	i) Non-climbing
		ii) Climbing
8. RIVERBANK DUNES	(a) Fringing	i) Non-climbing
		ii) Climbing
		iii) Cliff-top
	(b) Transgressive dunes	i) Non-climbing
		ii) Climbing
		iii) Cliff-top

Table 2.2 Classification of the main morphological types of coastal dune (Pye, 1983)

COASTAL DUNES	
IMPEDED DUNES	**TRANSGRESSIVE DUNES**
Echo dunes	Blowouts
Embryo/shadow dunes	Parabolic dunes and elongate parabolic dunes
Foredunes	Transverse ridges (including precipitation ridges and oblique dunes)
Multiple shore-parallel dunes	
Hummocky dunes	Barchans
Isolated mounds (knob, nebkhas, hedgehogs)	Transgressive sand sheets (including long-walled transgressive dunes)
Lunettes	

Figures

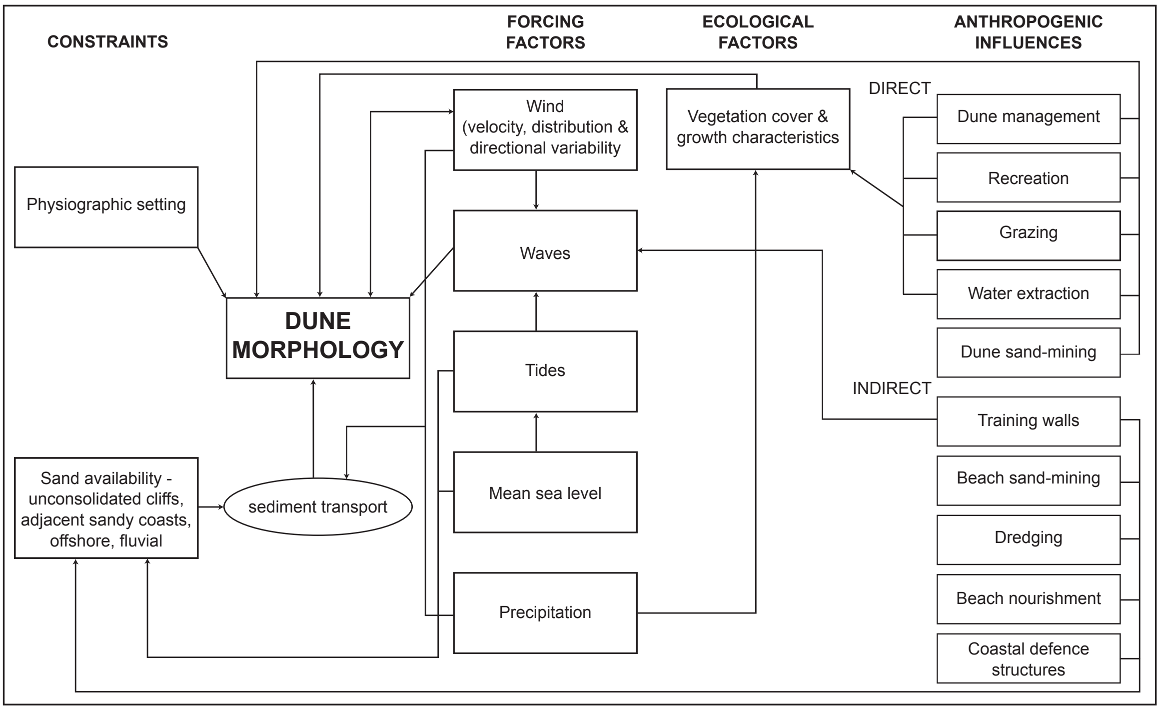


Figure 2.1 Factors controlling dune morphology

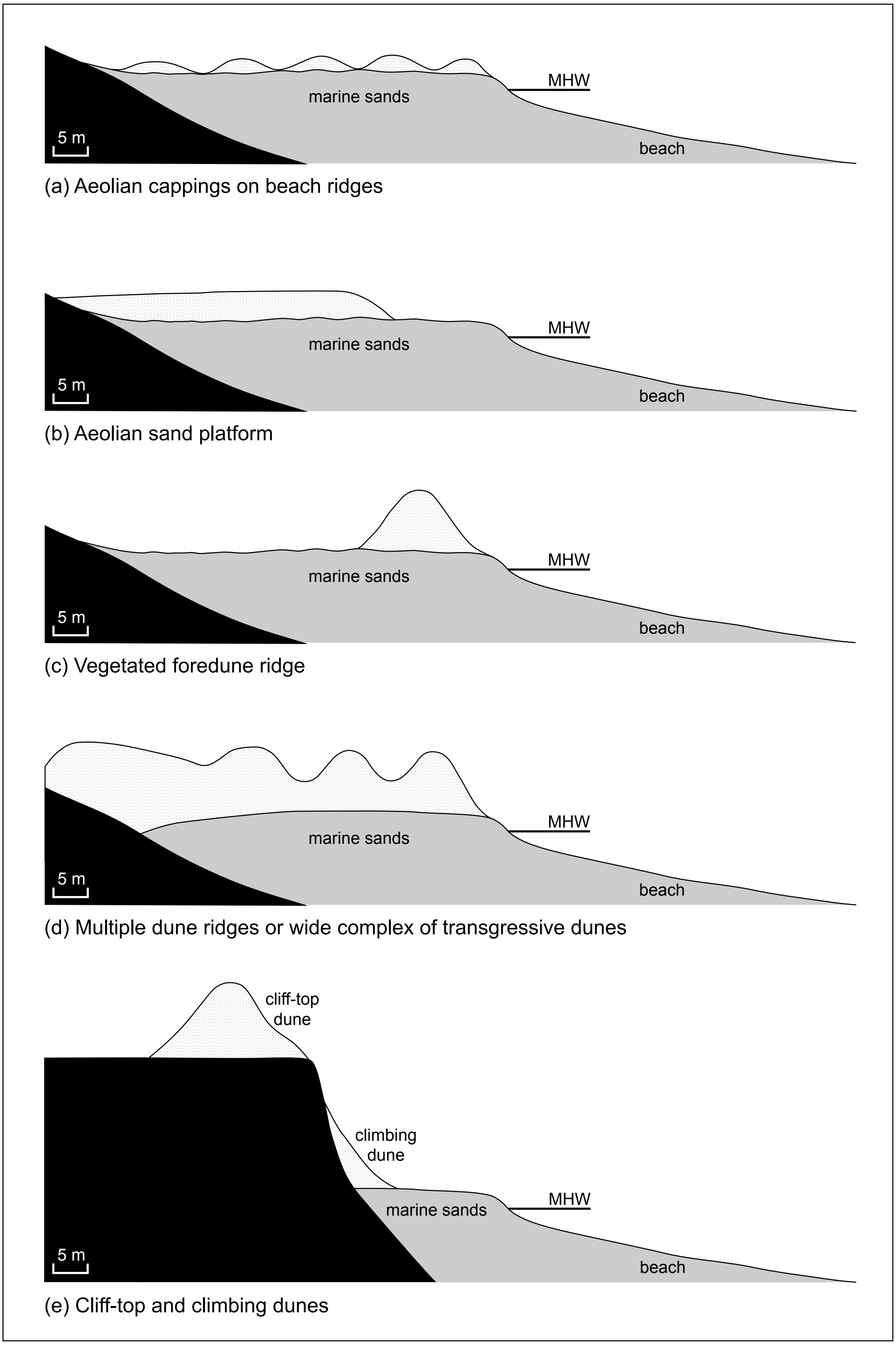


Figure 2.2 Variable scales of dune development behind sandy beaches

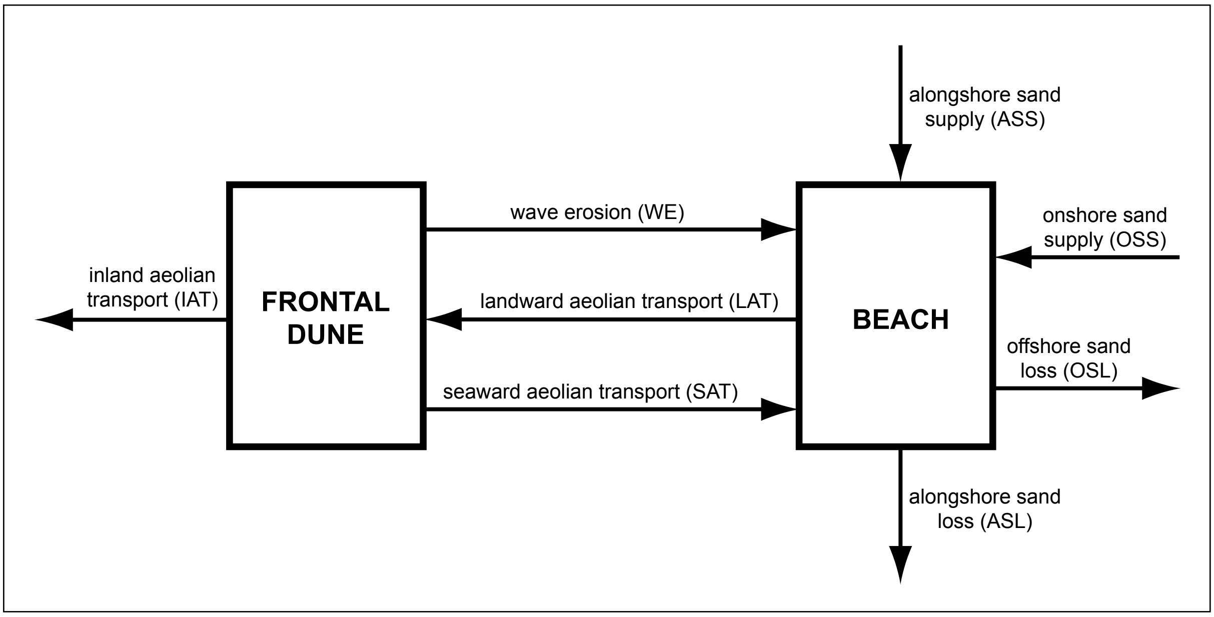


Figure 2.3 Conceptual beach-dune interaction model

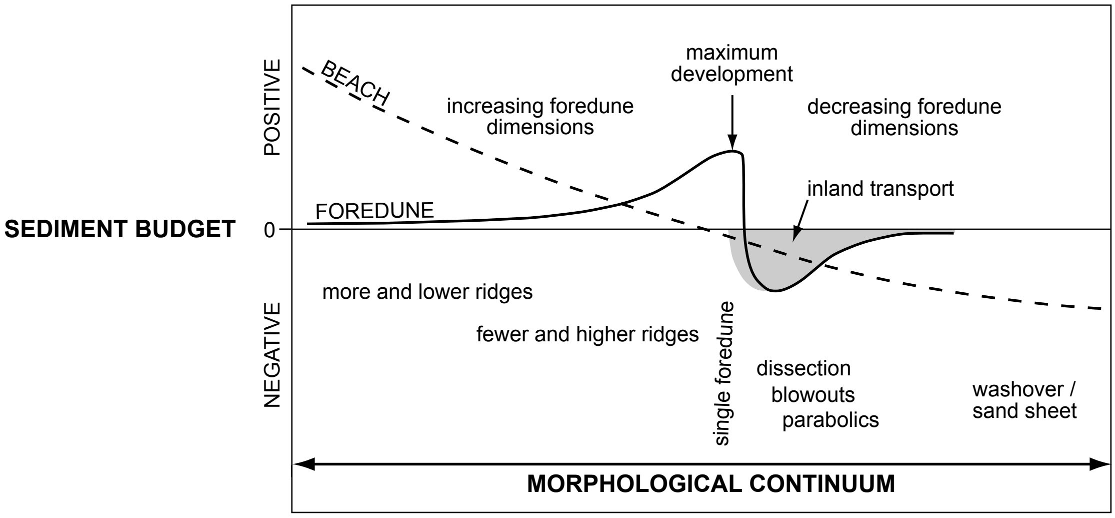


Figure 2.4 Conceptual model of the relationship between beach sediment budget, foredune sediment budget and frontal dune morphology (after Martinez and Psuty, 2004). The heavy black line indicates the situation which maximises foredune development. The grey shaded area indicates the situation where inland sand transport is maximised, favouring the development of transgressive parabolic dunes and sand sheets. Under conditions of a strongly negative beach sediment budget, sand supply to the frontal dunes is insufficient to maintain their integrity, leading to break-down and washover.

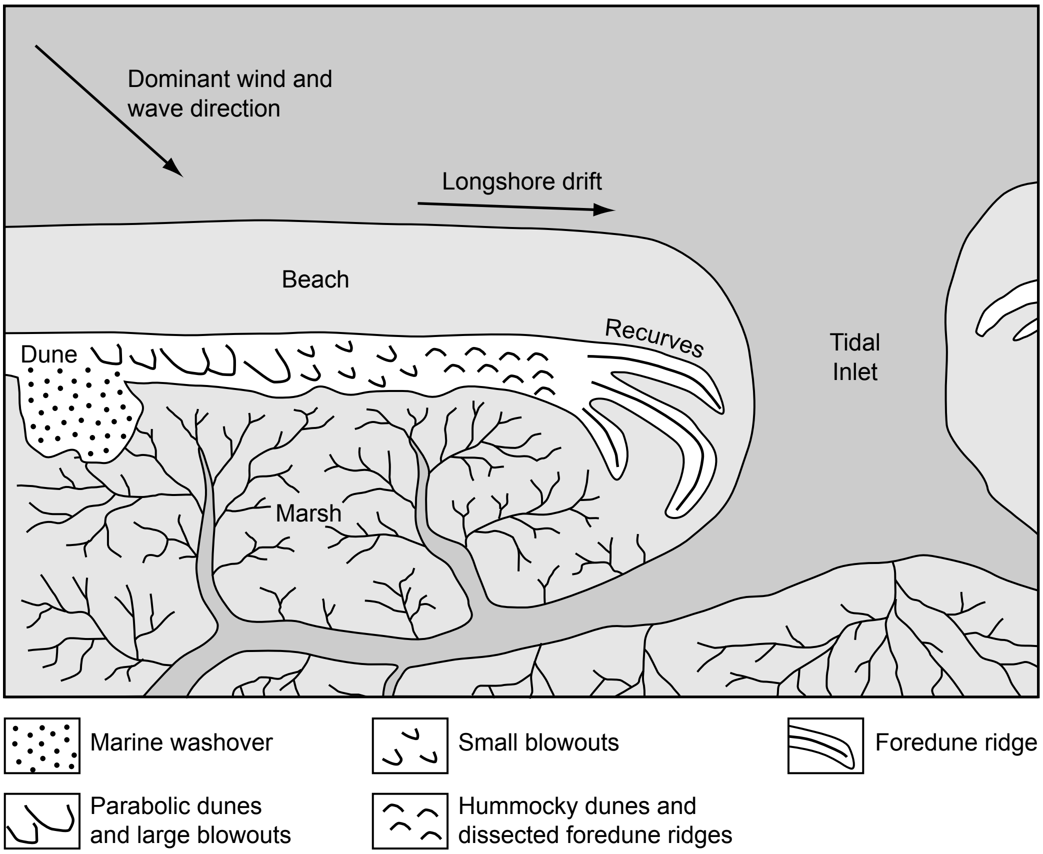


Figure 2.5 Schematic diagram showing longshore variations in frontal dune morphology resulting from differences in the sediment budget of the upper beach. At the up-drift end of the system the beach sediment budget is negative, resulting in frontal dune erosion and blowout development. At the down-drift end of the system new spit recurves form, capped by low foredune ridges. In the intervening area of balanced sediment budget hummocky dunes and/or high foredune ridges are likely to form. This type of system is exemplified in several places on the North Norfolk coast.

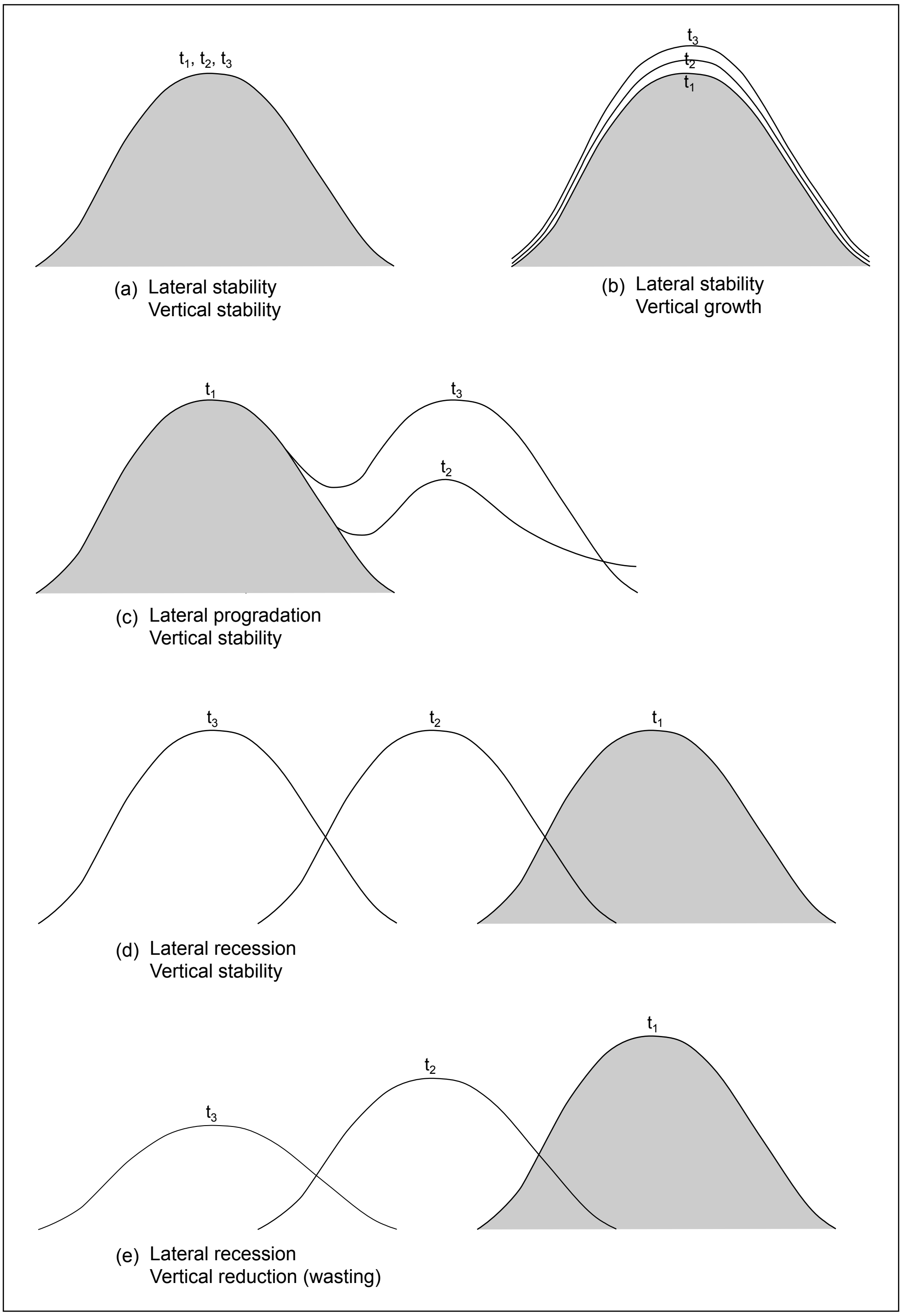


Figure 2.6 Different medium to long-term changes in dune morphology (t_1, t_2 and t_3 are successive time intervals).

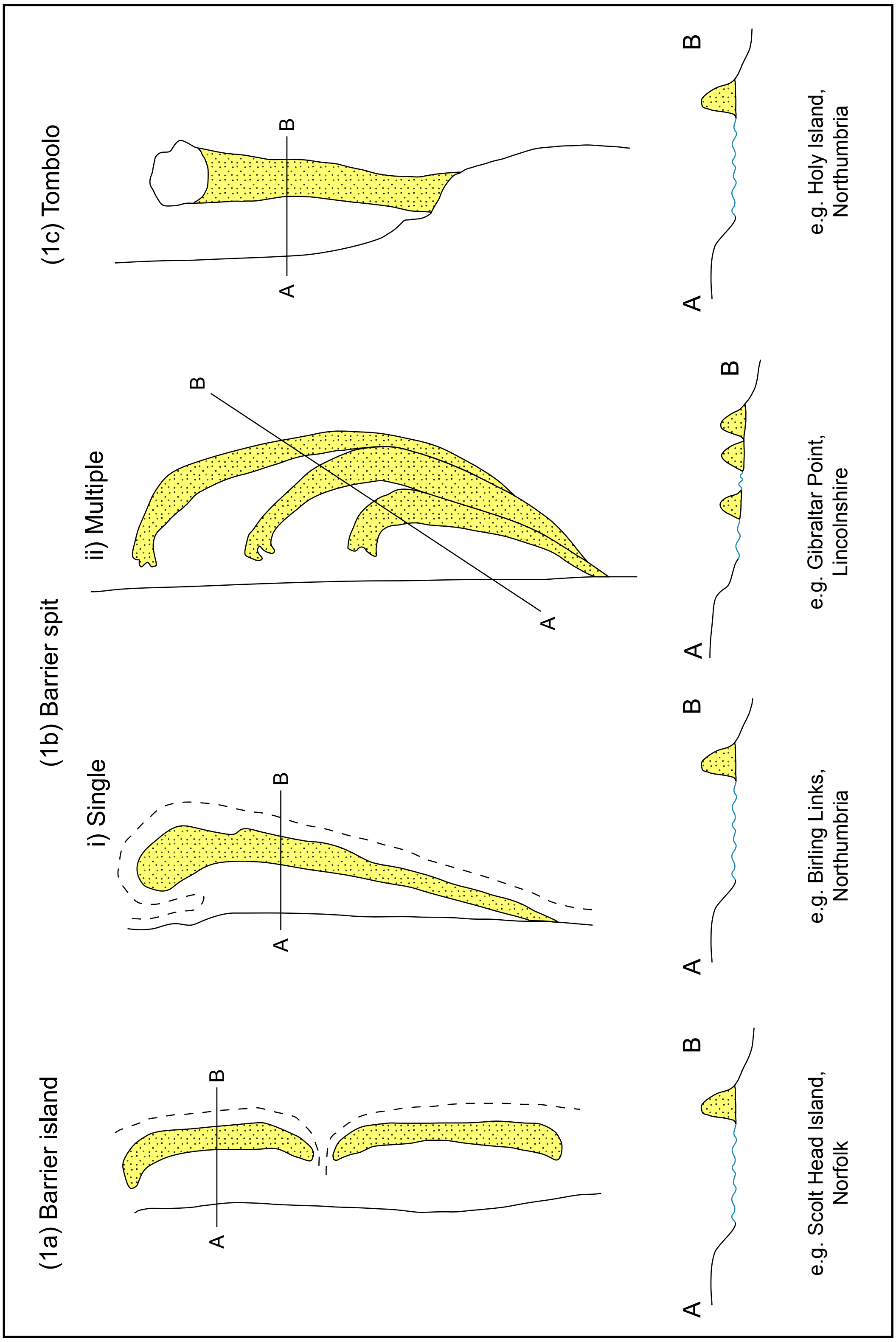


Figure 2.7a Open coast dune system morphological types.

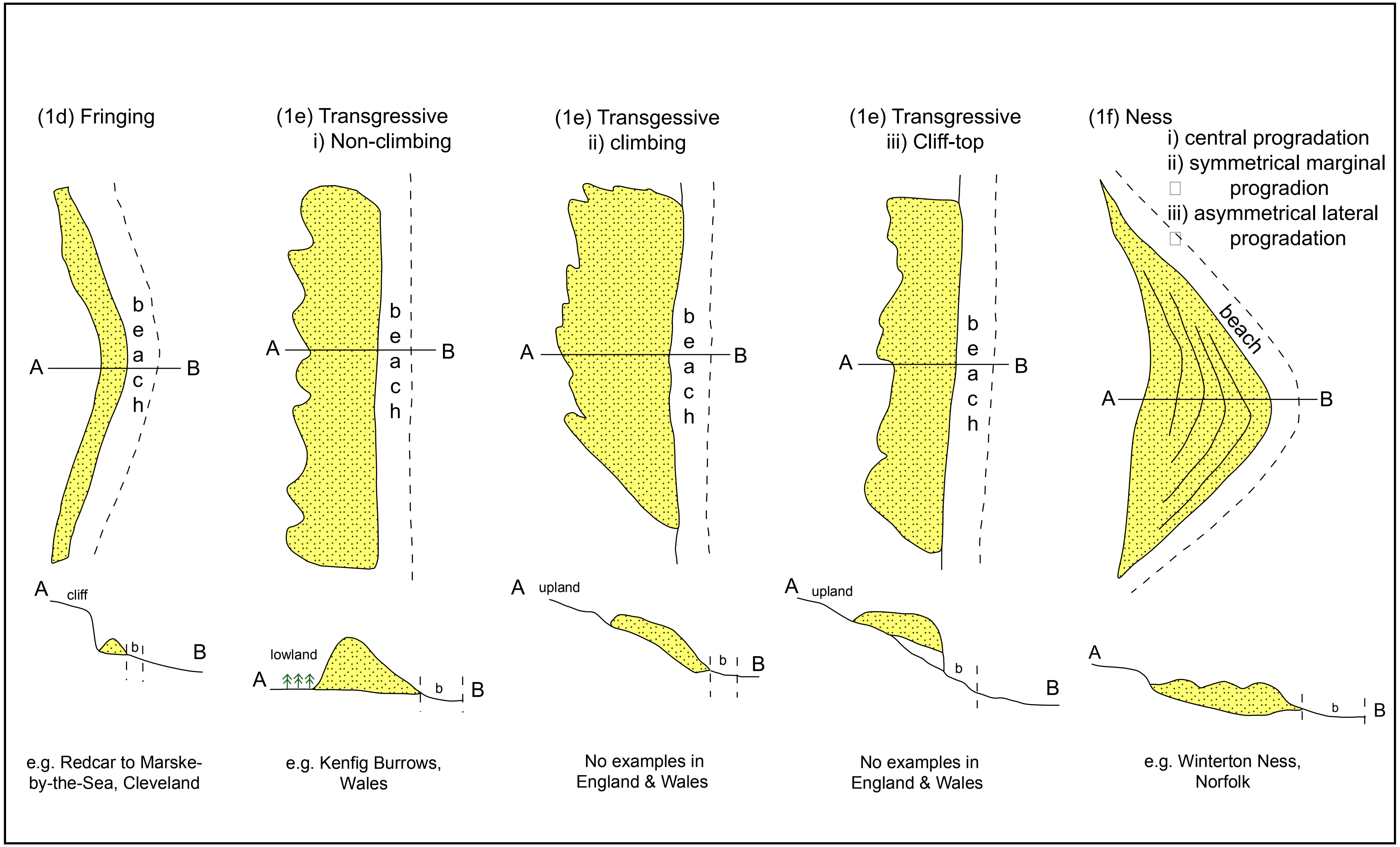


Figure 2.7a continued. Open coast dune system morphological types.

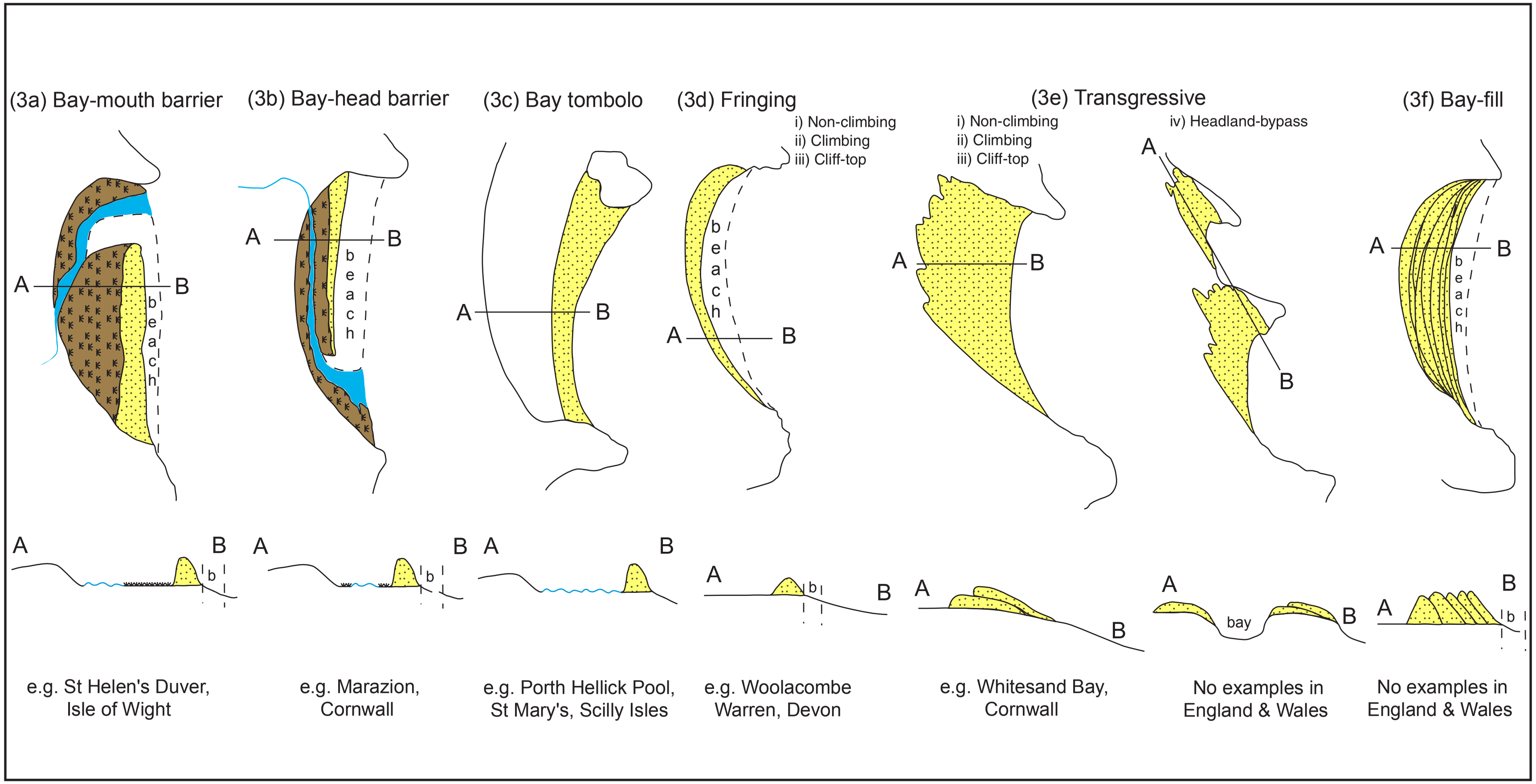


Figure 2.7b Embayment dune system morphological types.

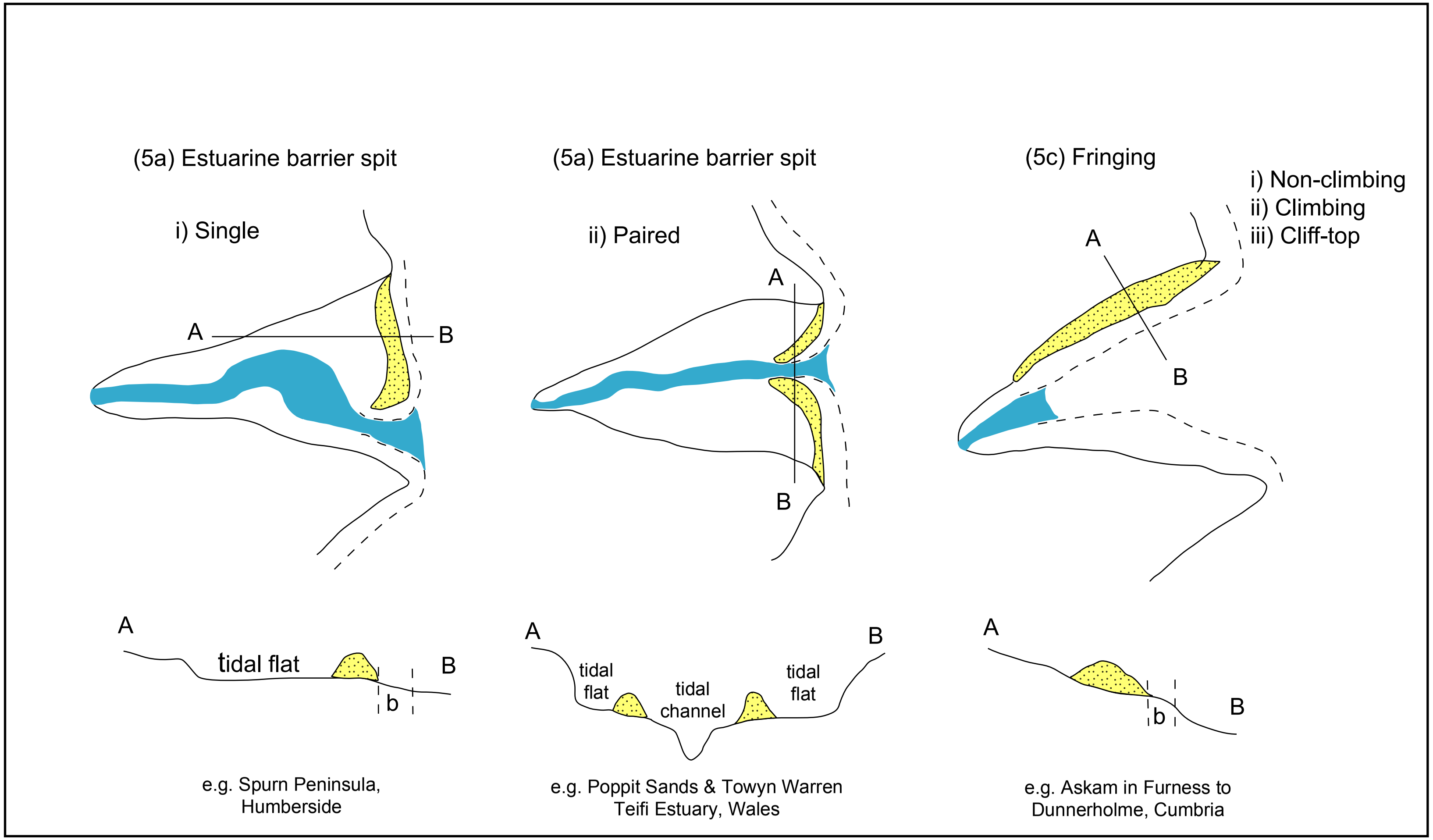


Figure 2.7c Estuarine dune system morphological types.

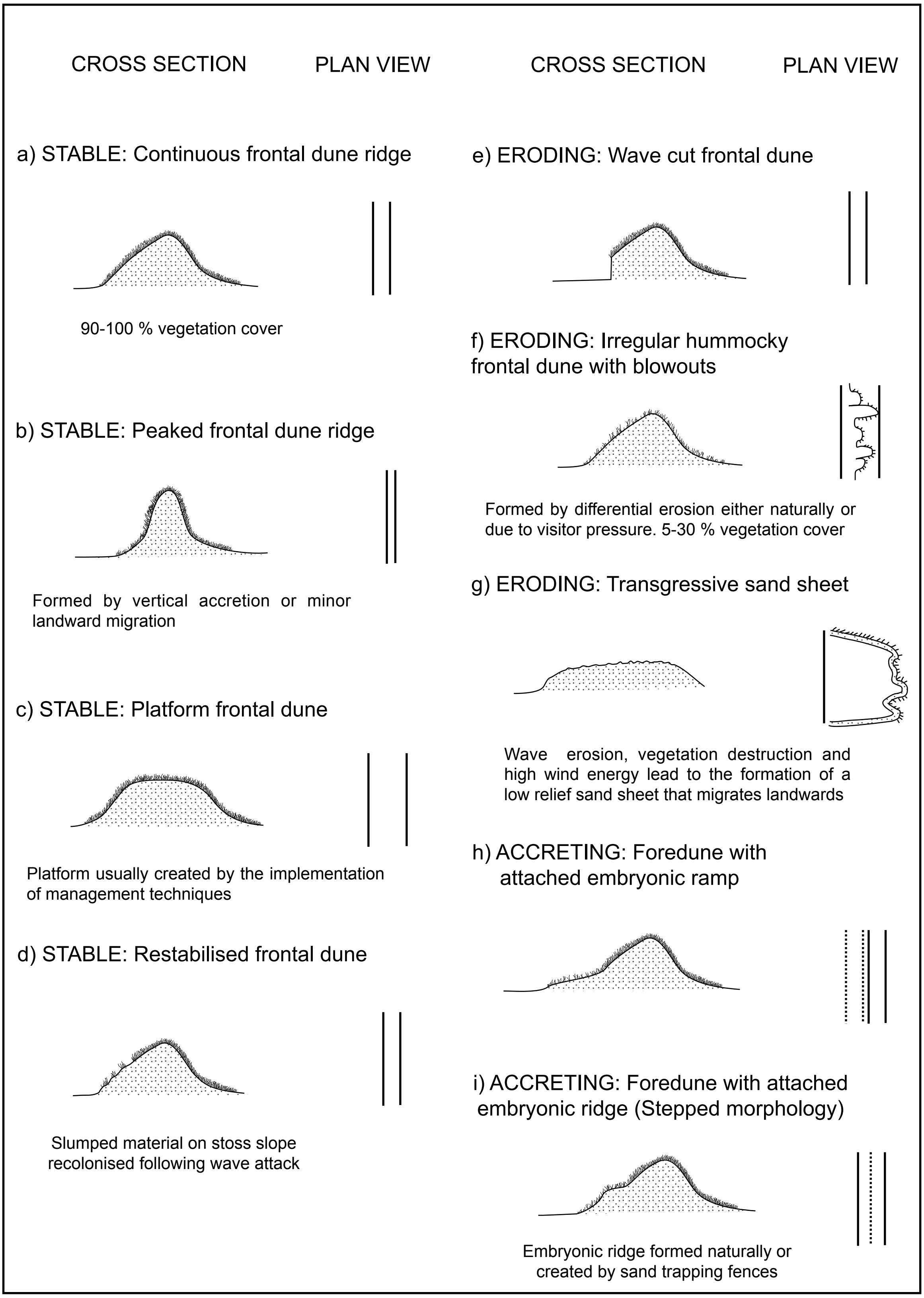


Figure 2.8 Classification scheme for frontal dune morphology.

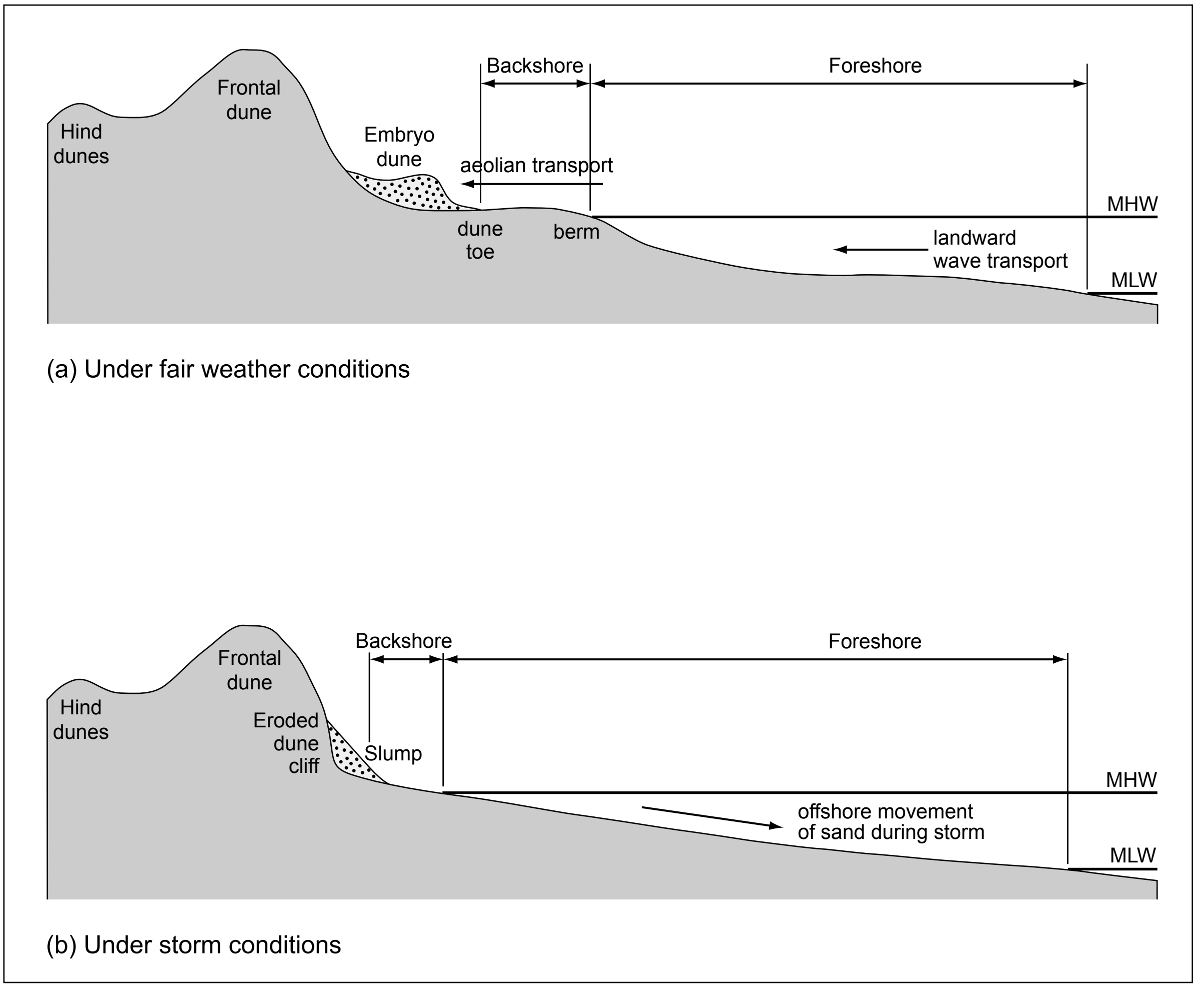


Figure 2.9 Schematic representation of sediment transport processes and morphology at the beach-dune interface (a) under fair weather conditions and (b) under storm conditions.

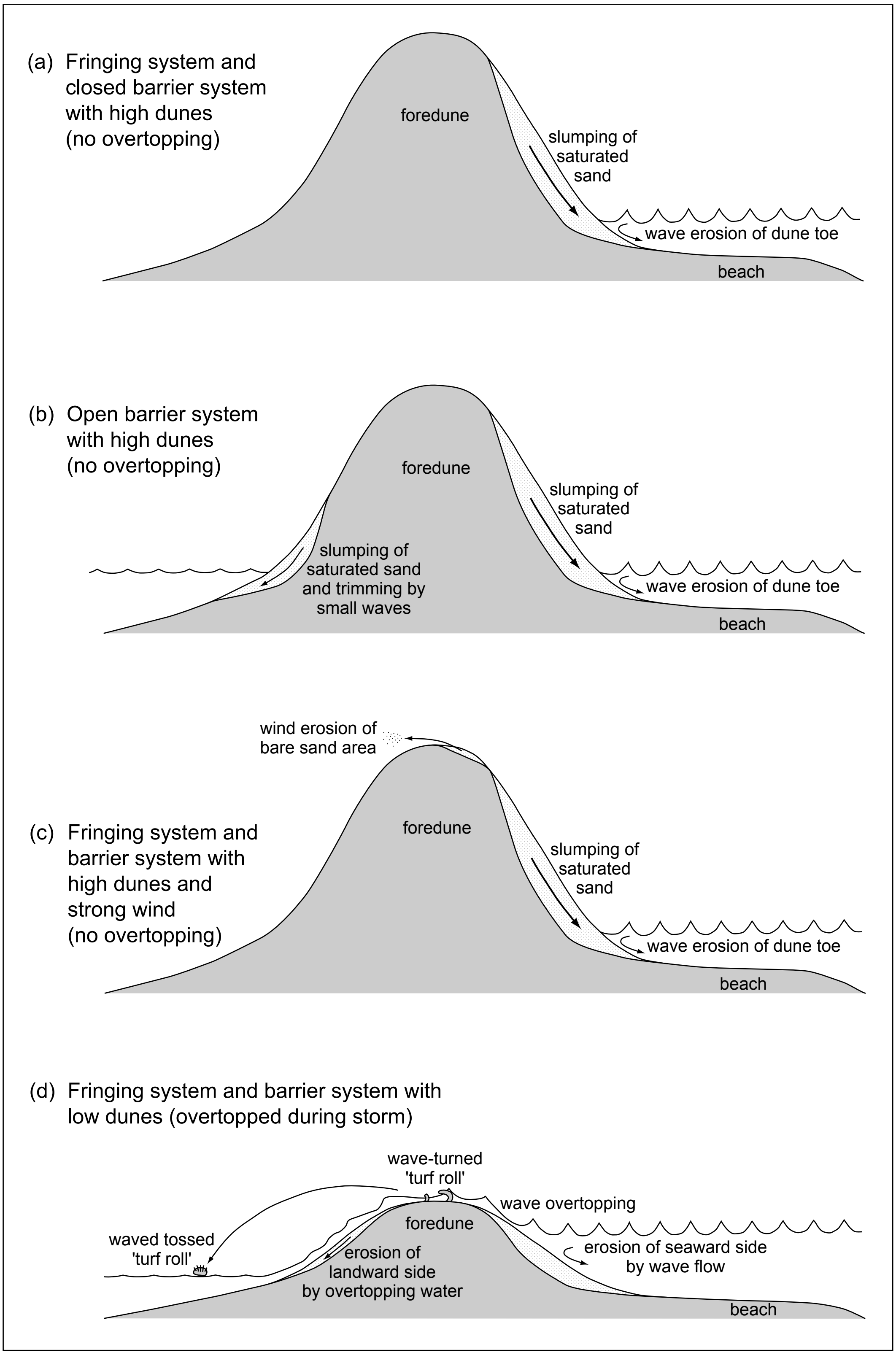


Figure 2.10 Processes of dune erosion under storm conditions.

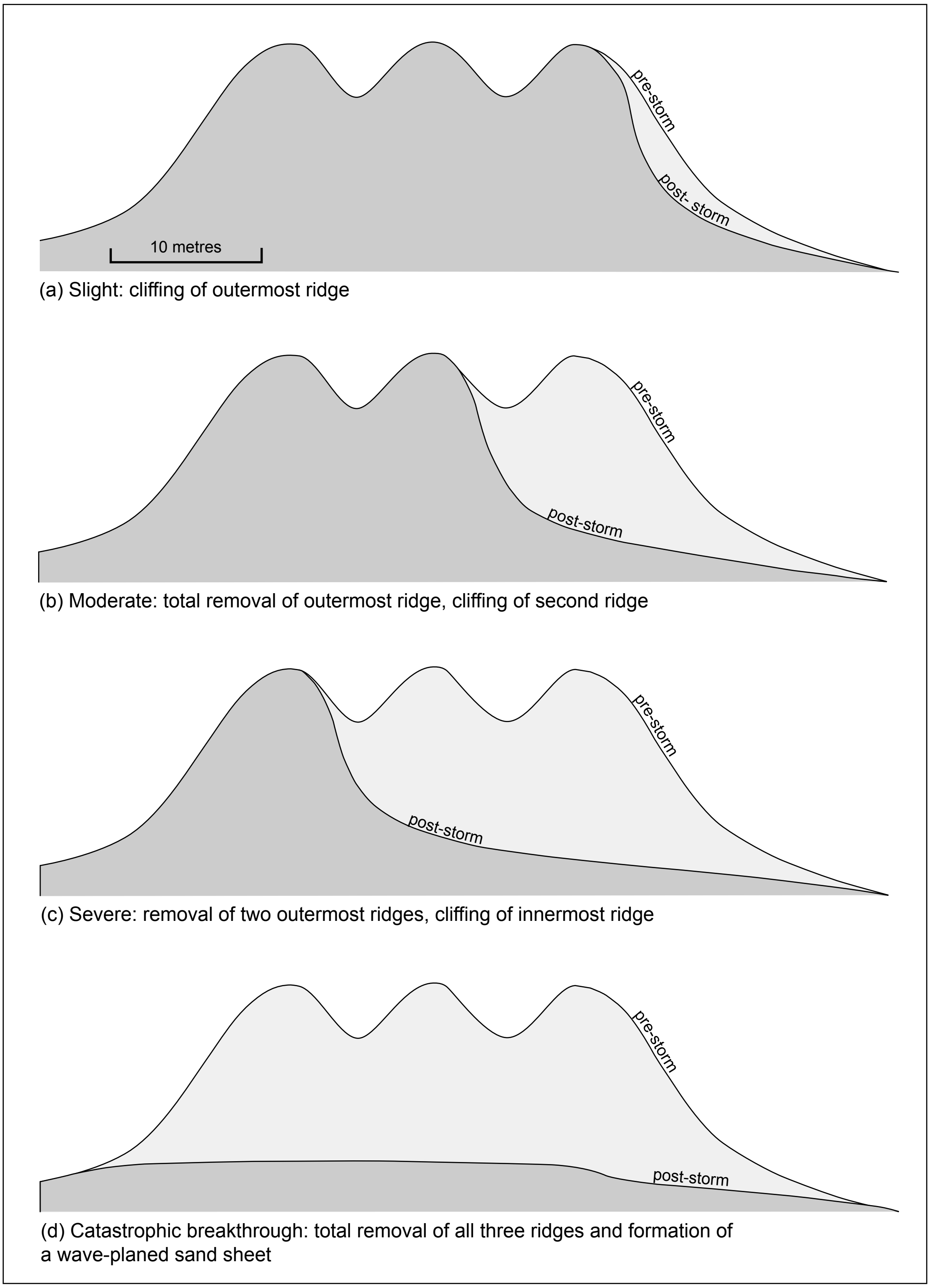
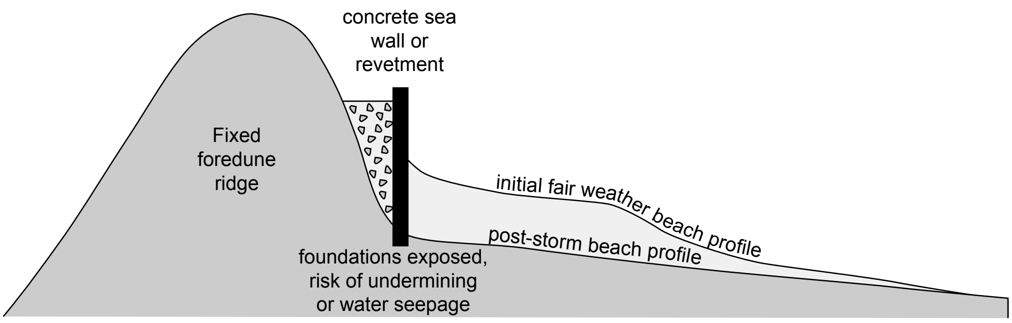
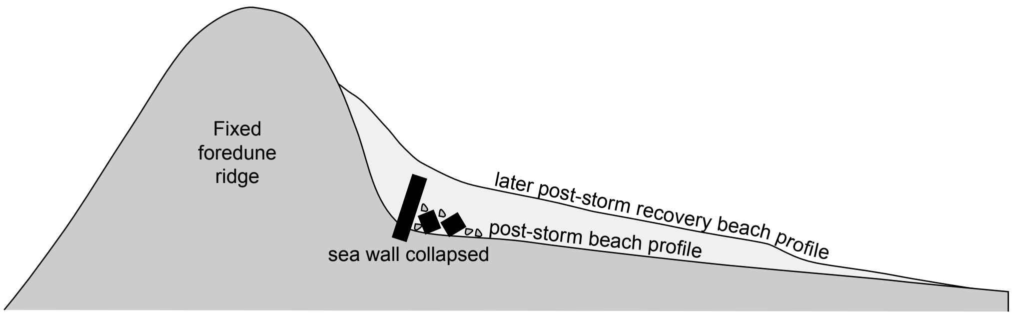


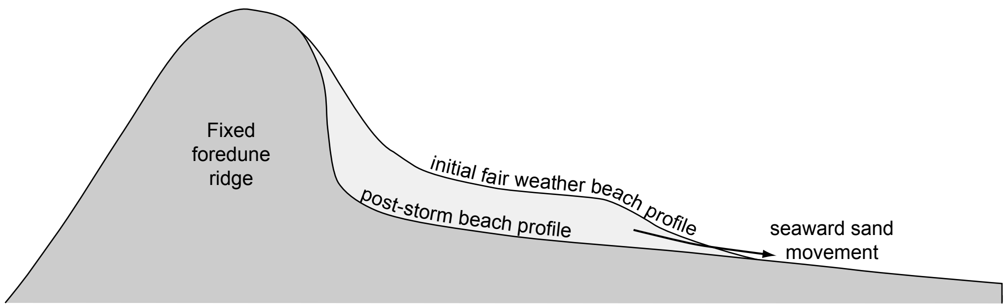
Figure 2.11 Impact of increasing storm severity and duration on dune morphology.



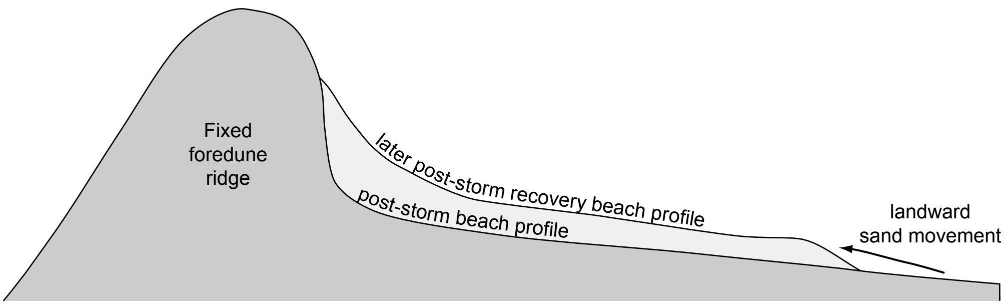
(a) Foredune ridge protected by a concrete sea wall or revetment before and immediately following a storm event, which results in exposure of the toe but no collapse.



(b) Foredune ridge protected by a concrete sea wall immediately following a storm event causing wall collapse and after a period of recovery: maintenance and rebuilding of the wall is a high coast option..



(c) Foredune ridge with no hard defences before and immediately following a storm event



(d) Foredune ridge with no hard defences immediately following a storm event and after a period of recovery: a low maintenance, low cost option.

Figure 2.12 Schematic illustration of changes at the beach / dune interface with and without hard defences present.

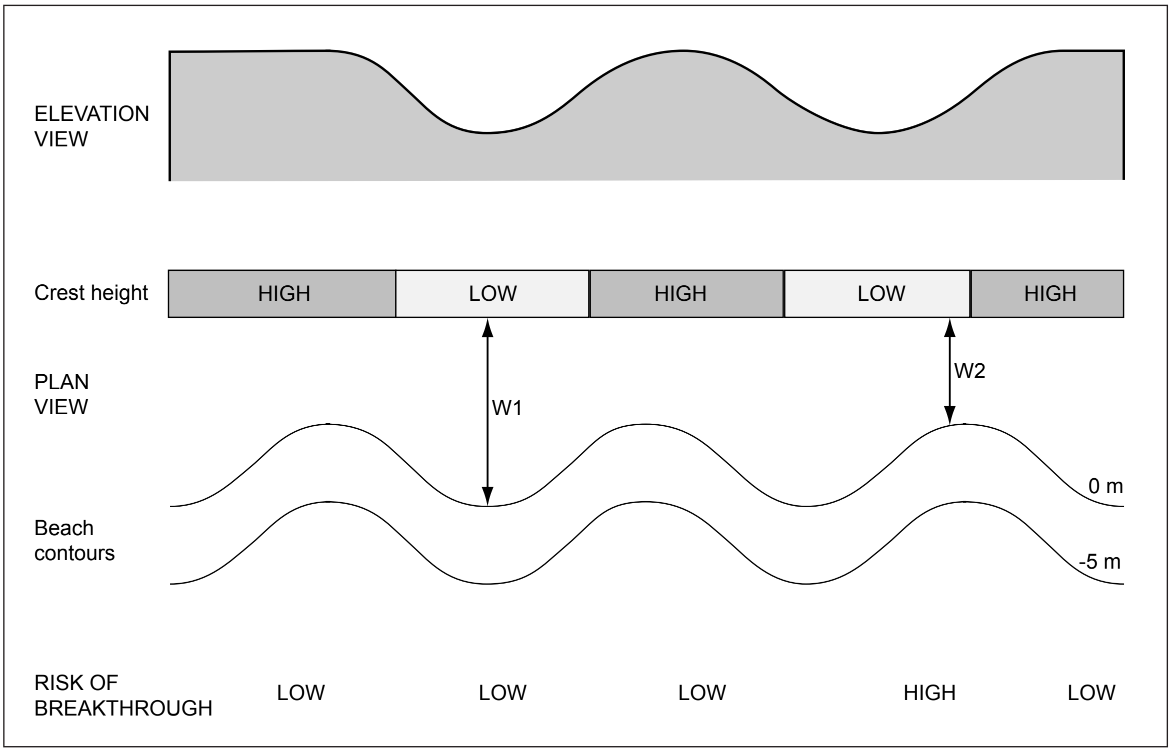


Figure 2.13 Effect of alongshore variation in dune crest elevation and nearshore bathymetry on the likelihood of dune overwashing and/or breakthrough. The highest risk occurs where low points in the frontal dune crest coincide with sections of narrow beach.

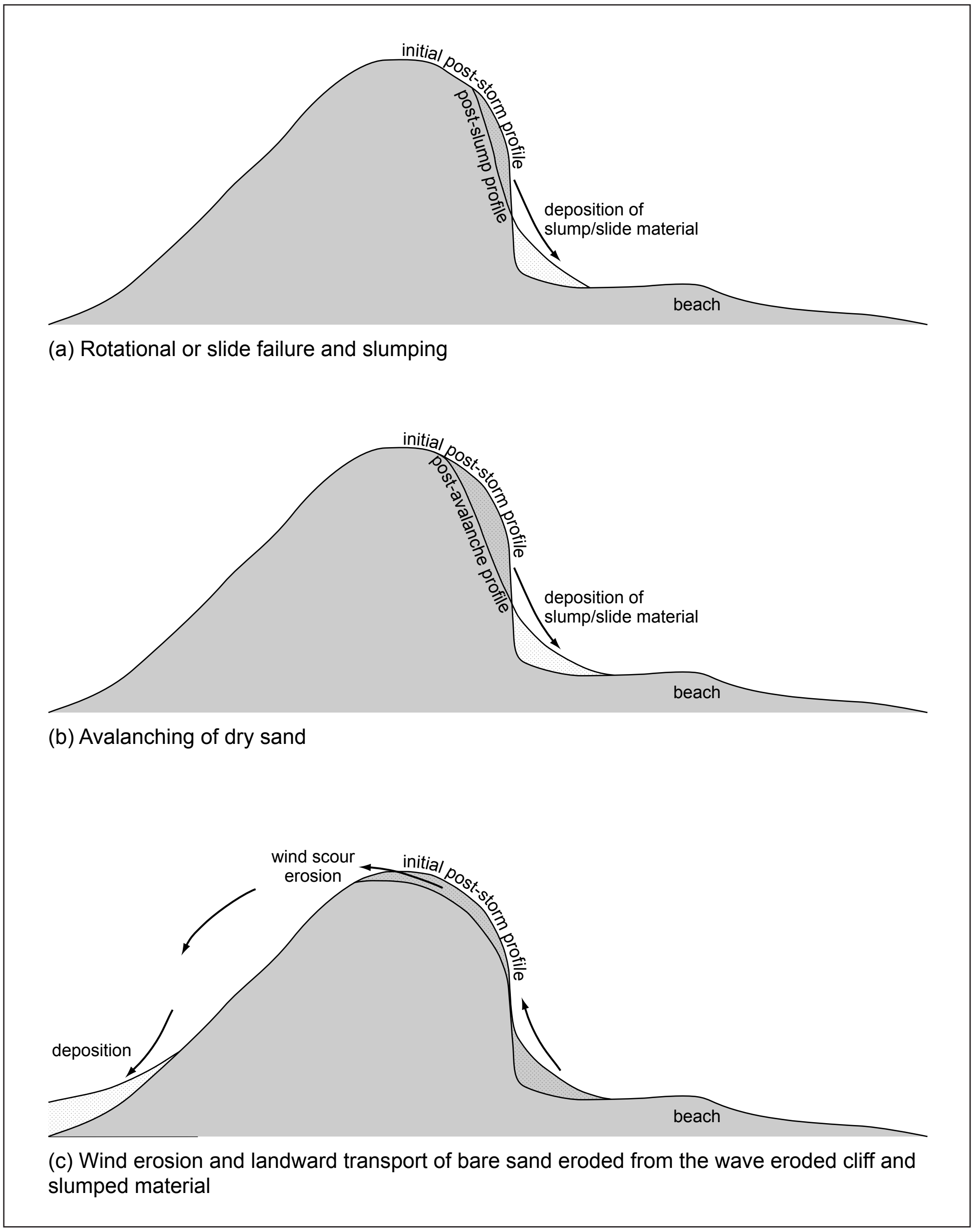


Figure 2.14 Post-storm erosion mechanisms.

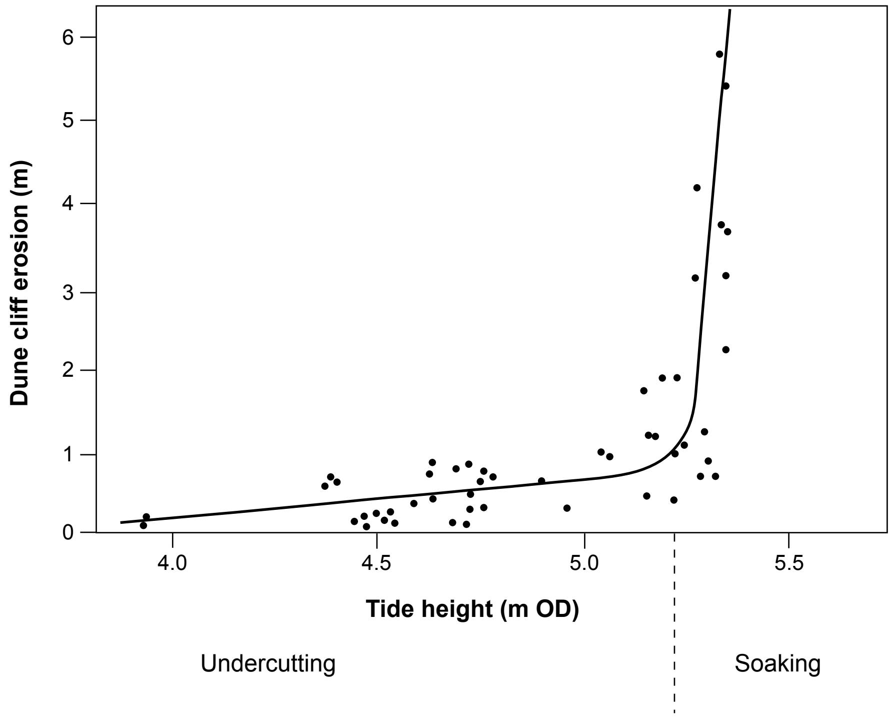


Figure 2.15 Relationship between erosion per tide and tide height (modified from Parker, 1975).

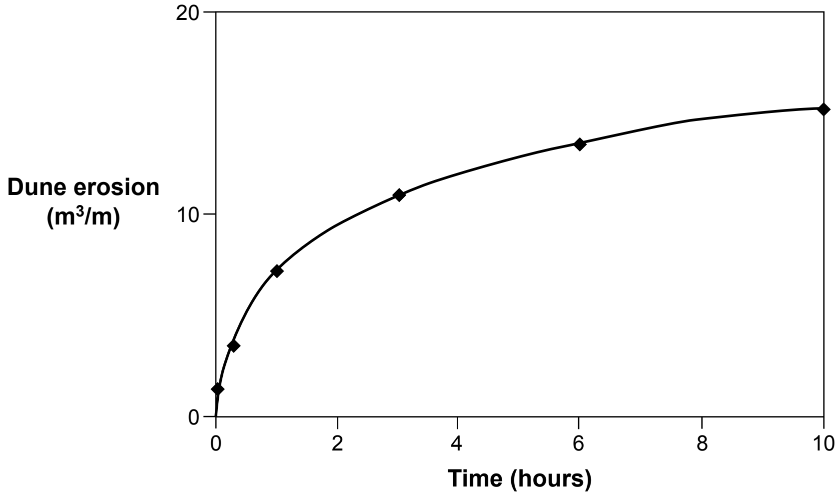


Figure 2.16 Eroded volume of sand as a function of time. After van de Graaff (1994).

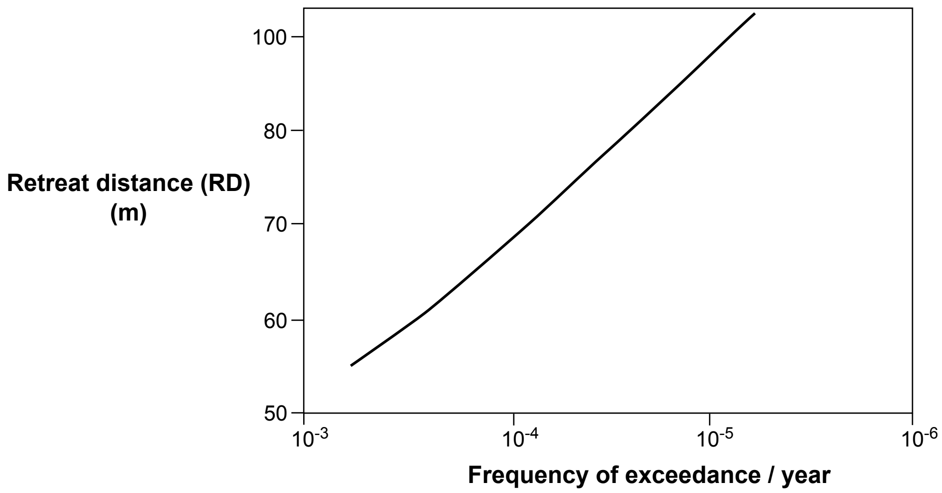


Figure 2.17 Retreat distance (RD) as a function of frequency of exceedance. After van de Graaff (1994).

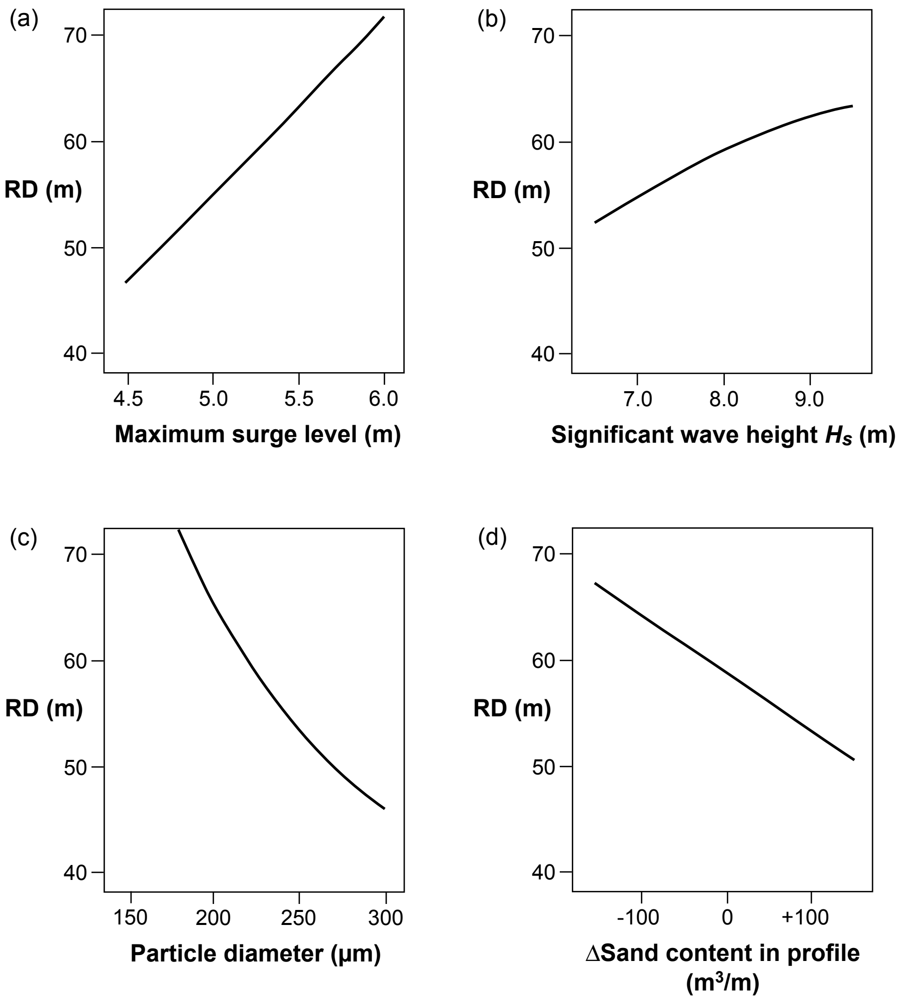


Figure 2.18 Retreat distance (RD) as a function of boundary conditions. RD is measured by the change in position of the dune foot before and after a storm. After van de Graaff (1994).

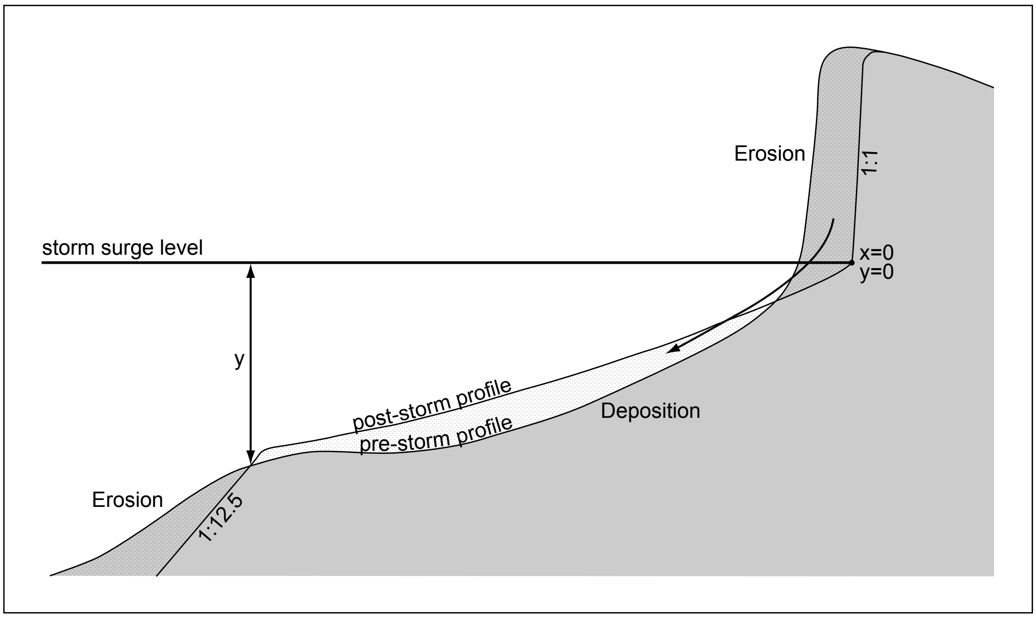


Figure 2.19 Principle of a computation model for dune erosion. Modified after van de Graaff (1994). See text for further explanation.

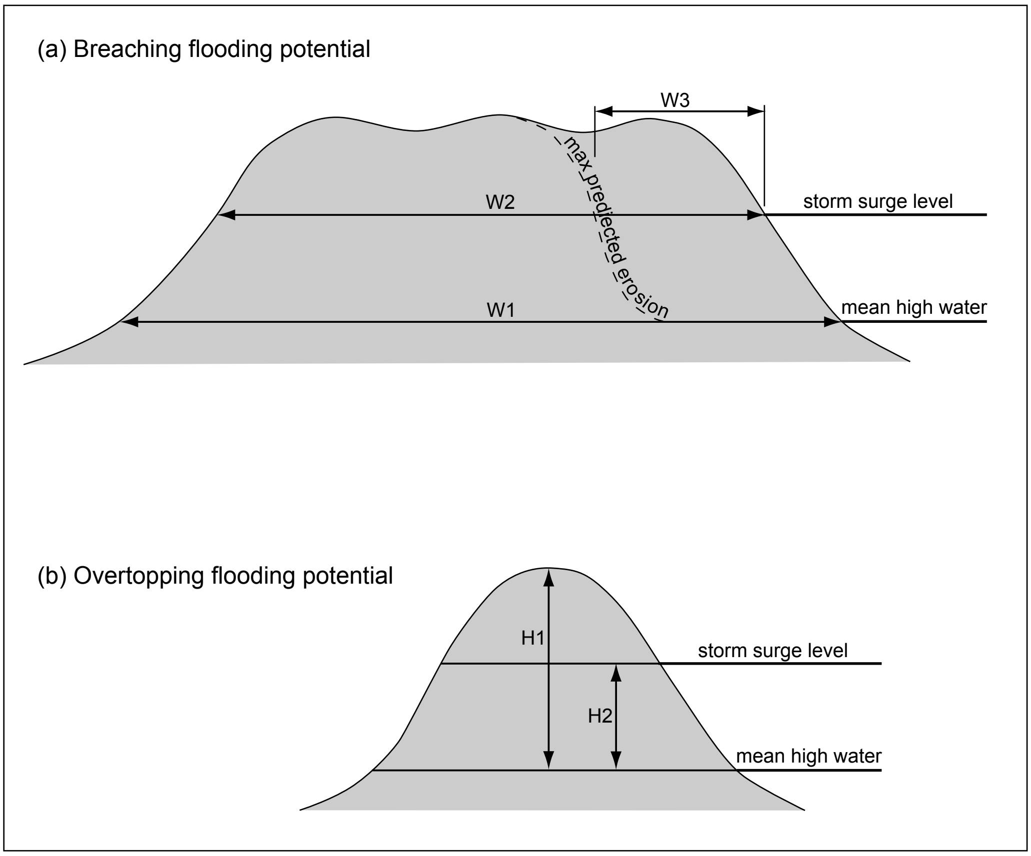


Figure 2.20 Effects of dune width and height on coastal protection. Modified after Rijkswaterstaat (1990). See text for further explanation.

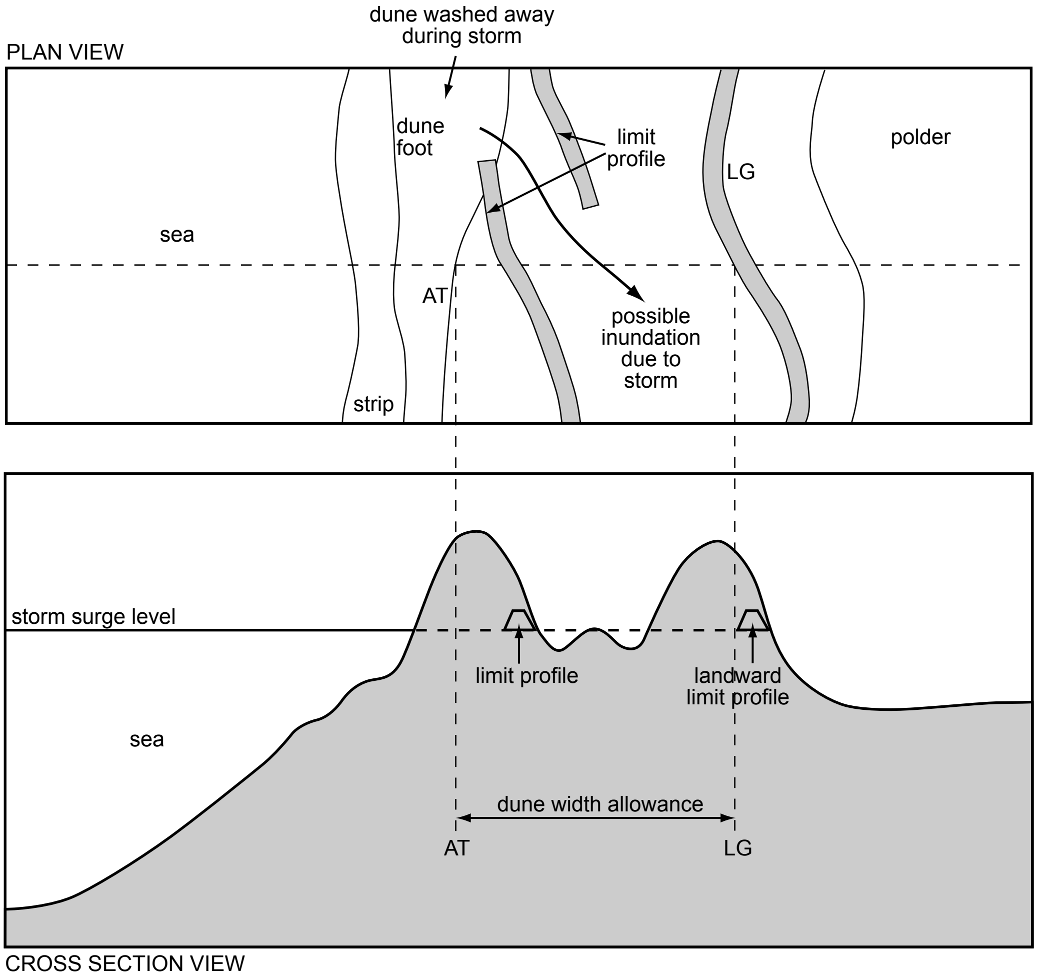


Figure 2.21 Safety of dunes in their function as water barriers. Modified after Rijkswaterstaat (1990).

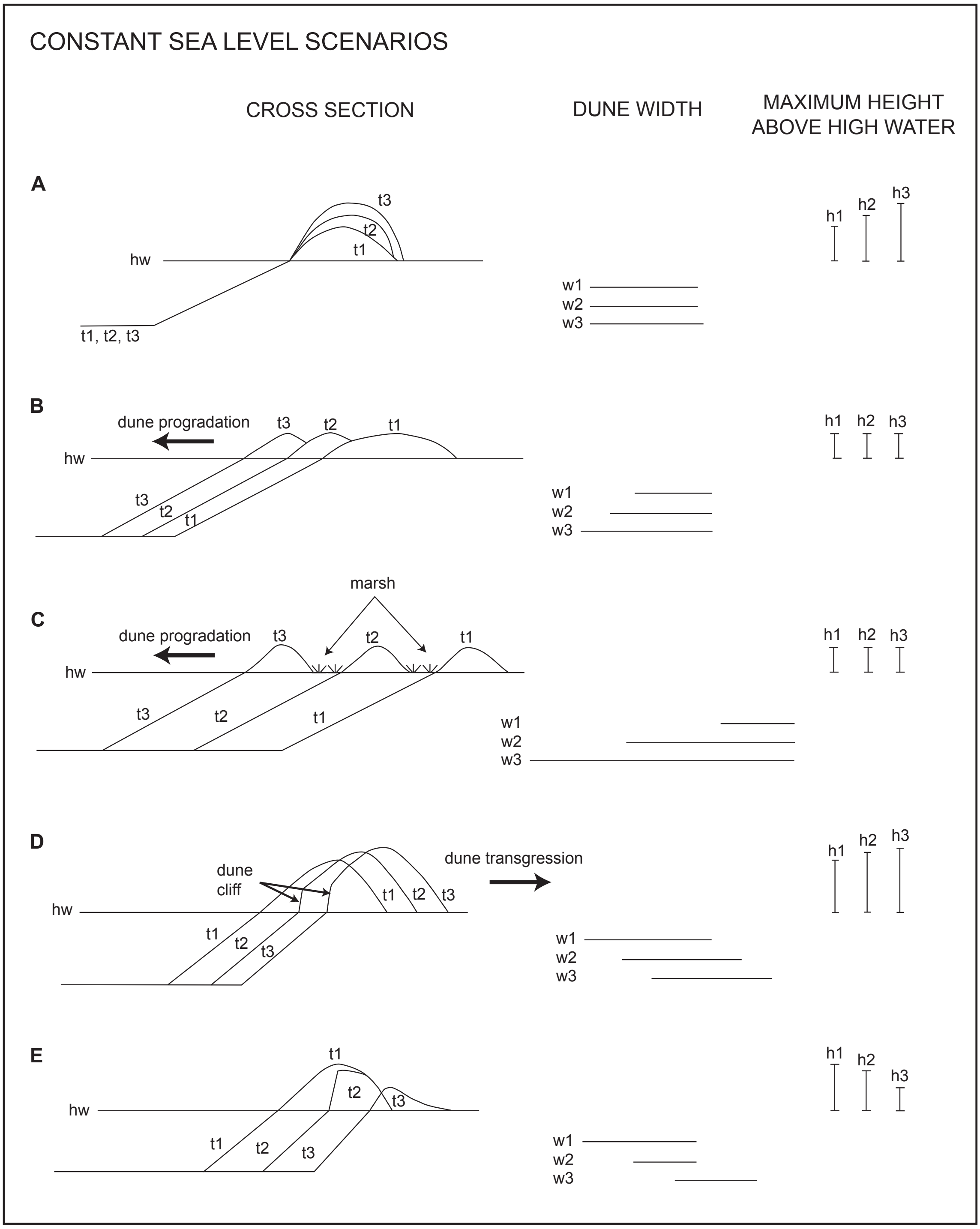


Figure 2.22 Schematic coastal dune development scenarios under constant sea level conditions. See text in Section 2.7 for further explanation.

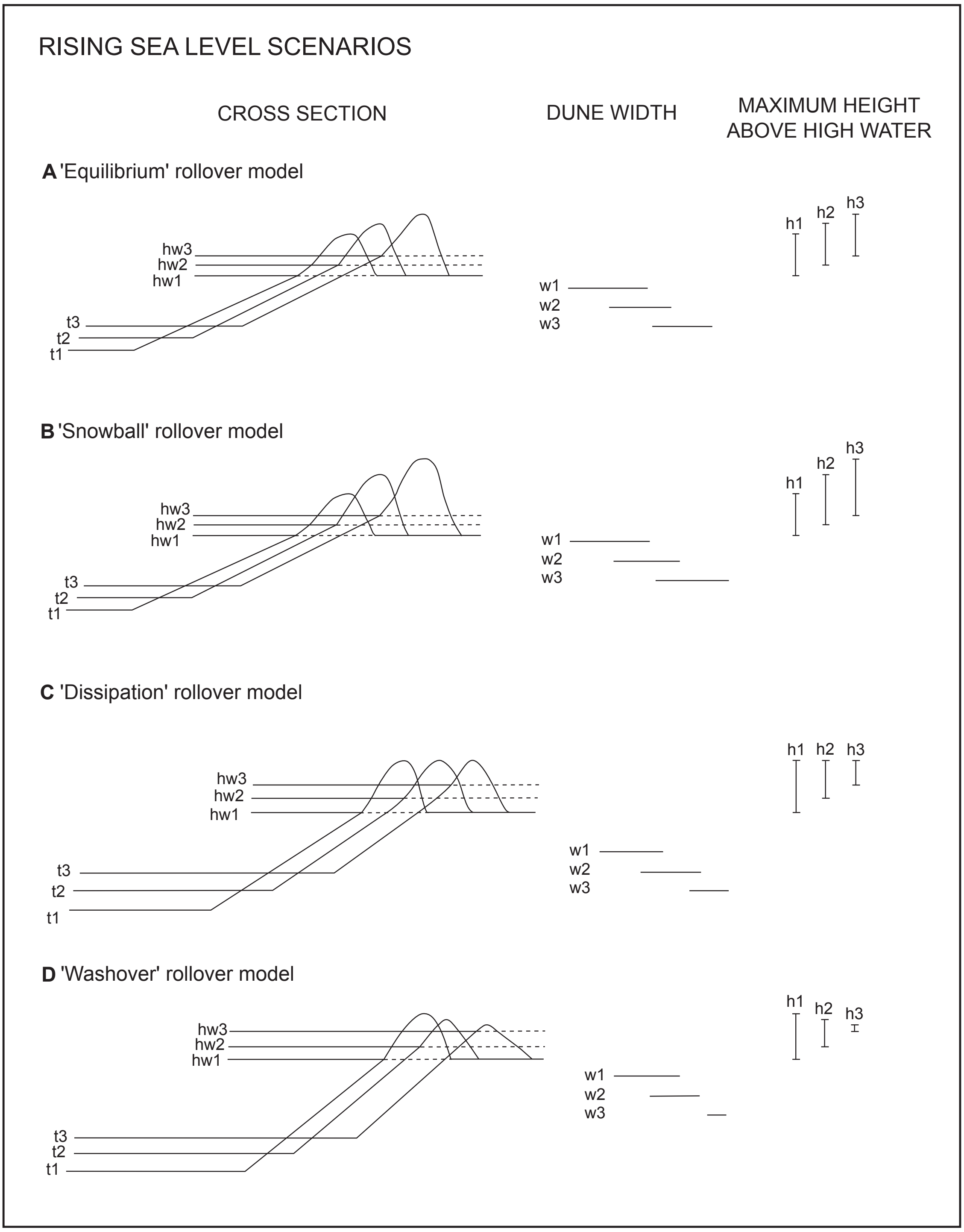


Figure 2.23 Schematic coastal dune development scenarios under rising sea level conditions. See text in Section 2.7 for further explanation.

Plates

Plate 2.1 Accumulation of sand transported in saltation on the upwind and downwind sides of a tyre. The pattern of sand accumulation is generated by a horse-shoe vortex around the obstacle. Wind flow from left to right.

Plate 2.2 Transverse barchanoid megaripples formed under the influence of strong westerly winds, Holkham, North Norfolk (view upwind).

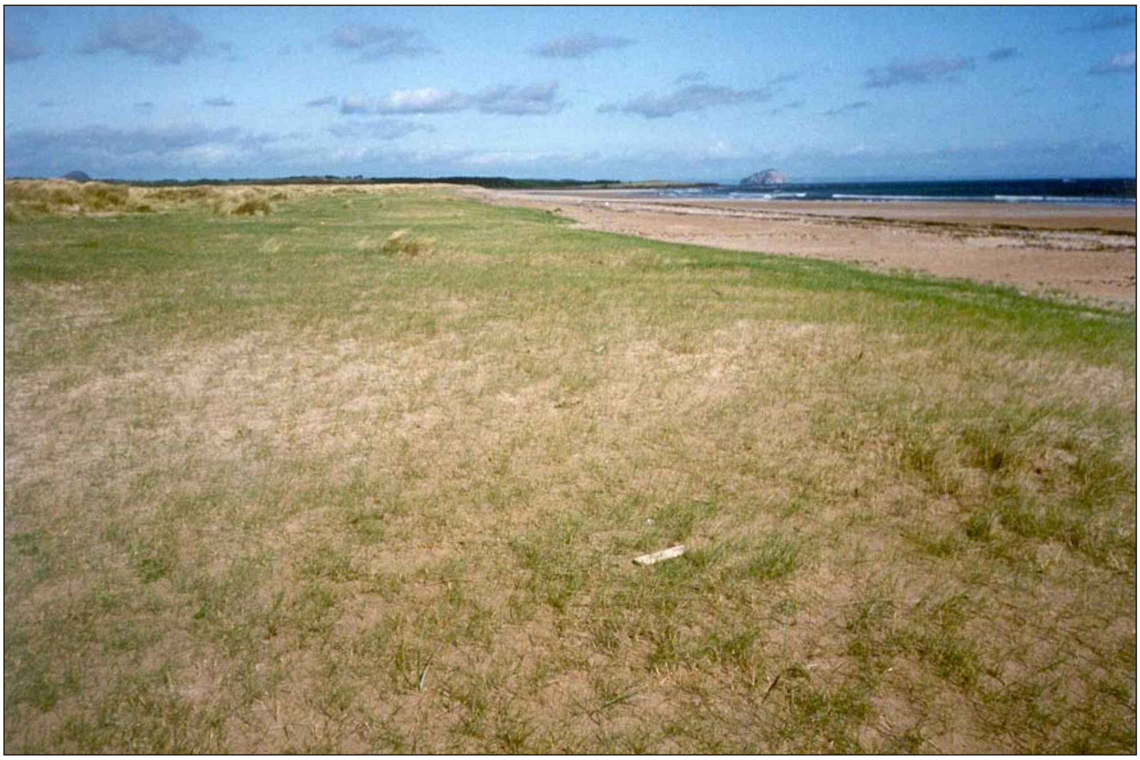


Plate 2.3 Trapping of wind-blown sand on the upper part of a wide sandy beach on which *Puccinellia* vegetation has become established. This type of accumulation results in the formation of a 'green beach' or low aeolian sand platform until such time as tussock-forming grasses become established. Belhaven Bay, Dunbar, Scotland.

Plate 2.4 Embryo dune developing in front of an established foredune ridge. Sand accumulation can occur in the absence of vegetation within the zone of low wind velocity at the dune foot, but is aided by pioneer plant species (in this case *Elymus arenarius*). Range Lane, near Formby, Sefton Coast.

Plate 2.5 Multiple embryonic dune mounds forming seaward of a foredune ridge, between Cassock Hill and Brea Hill, Padstow, Cornwall, looking north-north-west.

Plate 2.6 Foredune with peaked morphology indicating vertical accretion and gradual landward migration, Alnmouth Dunes, Northumberland, looking north.

Plate 2.7 Stable foredune with 'striation' morphology, Morfa Harlech, Gwynedd, looking north. The 'furrows' running perpendicular to the dune toe are formed by the combined effects of pedestrian trampling and wind-funnelling.

Plate 2.8 Accreting foredune fronted by an embryo dune ramp, southeastern end of Newborough Warren frontage, Anglesey, looking north west.

Plate 2.9 Multiple shore-parallel dune ridges on a prograding shore at Haverigg Haws, Cumbria, looking east-south-east.

Plate 2.10 Example of a trough blowout, The Devil's Hole, Ravenmeols, Sefton Coast, looking east-north-east.

Plate 2.11 A parabolic dune now completely stabilised by vegetation, Newborough Warren, Anglesey, looking north-east.

Plate 2.12 Wave cutting of the frontal dune toe, Hills Burrows, The Gower, looking east-south-east.

Plate 2.13 Eroding frontal dune with slumped blocks of vegetation, Kenfig Burrows, Swansea Bay, looking north east.

Plate 2.14 Wave-cliffing of the frontal dunes near Sizewell Nuclear Power Station, Suffolk.

Plate 2.15 Slumped clumps of marram lying along a wave-eroded dune cliff, Minsmere to Sizewell frontage, Suffolk.

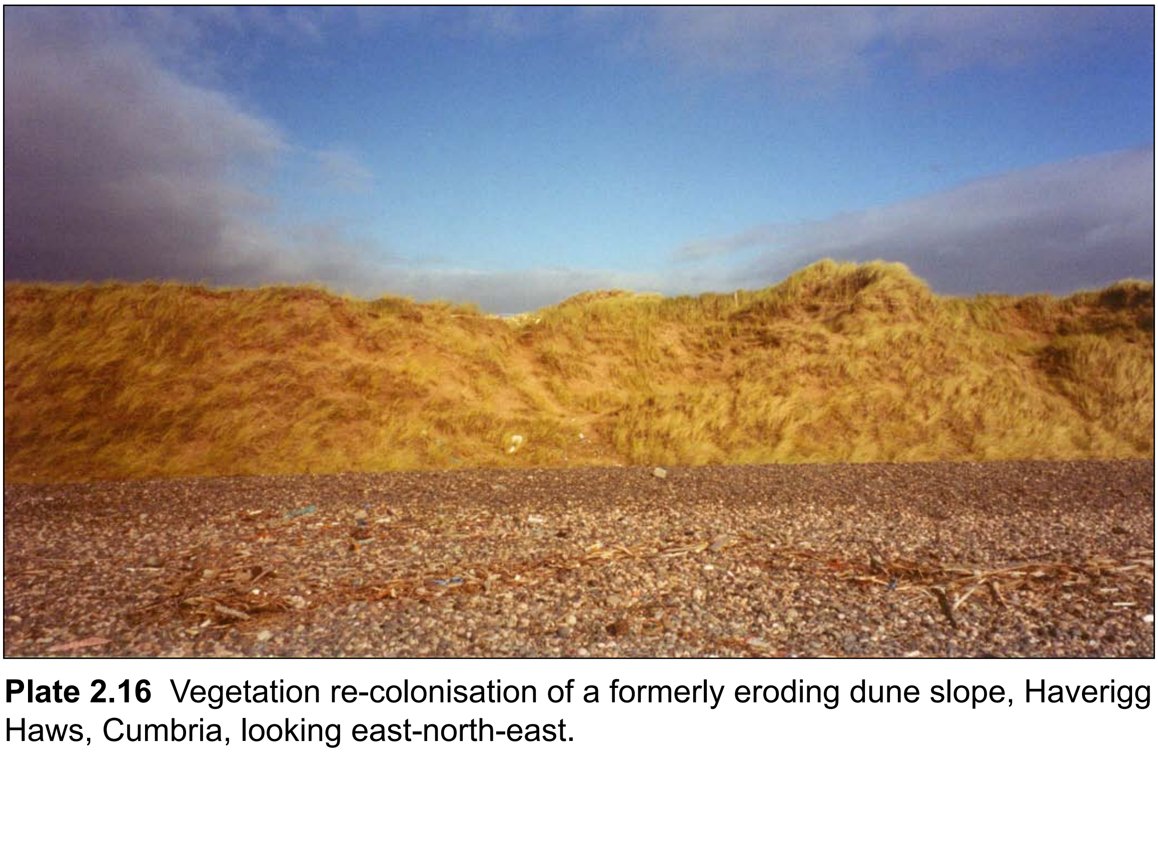


Plate 2.16 Vegetation re-colonisation of a formerly eroding dune slope, Haverigg Haws, Cumbria, looking east-north-east.

Plate 2.17 Low dunes forming at the site of a breach created during the 1953 storm surge, Scolt Head Island, North Norfolk.

Plate 2.18 Stabilisation of a formerly eroding frontal dune ridge caused by growth of saltmarsh to seaward, Stonebridge car park, near Donna Nook, Lincolnshire, looking north west. These dunes are now up to 1 km from the mean high water mark.

Plate 2.19 Hummocky hind-dune topography, Bamburgh, Northumberland, looking south east.

Plate 2.20 Remnant 'knob' formed by differential erosion, Hayling Island, Hampshire, looking east-north-east.

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