9 Coastal Dunes

S. M. ARENS,[1,2] P. D. JUNGERIUS[1,3] AND F. VAN DER MEULEN[4]

[1]*Netherlands Centre for Geo-Ecological Research ICG, University of Amsterdam, The Netherlands*

[2]*Bureau for Beach and Dune Research, The Netherlands*

[3]*Bureau G & L, The Netherlands*

[4]*Ministry of Transport, Public Works and Water Management, National Institute for Marine and Coastal Management, The Netherlands*

COASTAL DUNES AS A DYNAMIC SYSTEM

INTRODUCTION

In essence, the coastal dune environment can be seen as a system: a working system of elements, biotic and abiotic by nature and interacting with each other and their environment. For the purpose of this book it is necessary to define the steering processes of that system. Once knowledge has been obtained about the steering processes, the manager can choose to take that knowledge into account. Management activities can then be applied in such a way that the manager is working with nature rather than against it.

Knowledge of the processes in dunes and the application of that knowledge for their management has become increasingly customary. This chapter discusses recent studies of coastal dune processes and, using examples from various landscapes, illustrates the problems faced and the lessons learned. We emphasise the Dutch situation, but at the same time also try to extrapolate to the European situation.

THE COASTAL DUNE SYSTEM

The physical setting is essential in every natural system. It also determines its main abiotic processes. For example, is the system mainly aquatic, marine or terrestrial? Are the processes predominantly geomorphological or biological in character (in other words, are processes with wind and water as agents determinant) or is the production of biomass and vegetation structures predominant? In the former case, the system is likely to be very dynamic; in the latter case it is probably a more stable system where plants and animals build up complex and long-living communities.

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Figure 9.1 presents a simplified model of the coastal dune system as seen from a sedimentary perspective. Note that, from a systems approach, dunes do not stop at the beach, nor do they stop at the inner dune ridge. The offshore zone, beach and dune should be seen as one interconnected landscape entity. Ideally this entity should be managed as such. In practice, the entity is often divided into many parts and managed as many (often even separate) parts.

The coastal dune system consists of three main subsystems: an offshore zone, a transit zone and a resting zone. In Figure 9.1 these are seen from left to right. The coastline itself, the transition from land to sea, lies in the middle from top to bottom.

The Offshore Zone

This is the marine part of the dune system. The offshore zone is the sediment bank. When there is a positive sediment budget, more sand is transported

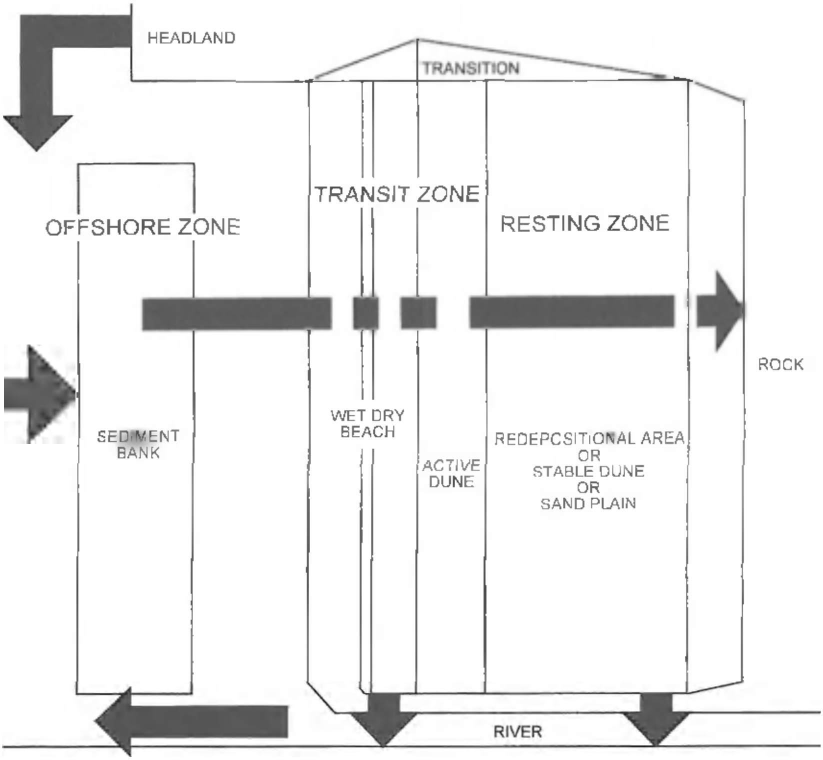

Figure 9.1. The coastal dune system (from Van der Meulen 1993).

towards the right of Figure 9.1 (i.e. from the offshore zone to the beach and subsequently to the dunes beyond the beach). An accreting coast can be the result. In the case of a negative sediment budget, more sand is transported from the beach, and perhaps also the dunes, to the offshore zone. This means erosion. So far, we have only mentioned movements along a transect perpendicular to the coast (on/offshore). But most coasts also have longshore currents such that sediment is transported from one part of the sediment bank to the next. Such transport may aggravate the transport movements that have just been outlined. Apart from the sources mentioned, sediments in longshore transport can enter the sediment bank, for example by erosion of a headland further down the coast (top of Figure 9.1) or by discharge of a river entering the sea (bottom of Figure 9.1) or from the deeper sea bottom (extreme left of Figure 9.1). Examples of coastal erosion caused by sediment starvation in rivers that have been dammed upstream are well known. This illustrates the fact that integrated coastal management is often equivalent to catchment management. We will not elaborate on this point here. Long Point peninsula in Lake Erie, Canada, is an example of a sandy coast where erosion of a headland occurs, causing growth of the coast further along the shore; but this co-acting erosion–accretion system moves along the coast, one process following another at any particular spot.

The Transitional Zone

This is the wet-dry beach and the active dune or, as we call it here, foredune. Sandy coasts with steep beaches and foreshores and low tidal differences have a narrow transitional zone. The opposite is found on gently sloping shores with great tidal differences. Once the sand is deposited on the beach by tides and waves, it can be transported by the wind. Depending on whether the prevailing winds are on- or off-shore, sand reaches the foredunes or not. The foredune is the first place where sand is effectively trapped by vegetation and where real dune formation can begin (Arens 1996). The evolution, ecological processes, aerodynamics and morphology of new foredunes on the upper beach has been reviewed by Hesp (1989). A boulevard (or worse, one with buildings) along the beach can cut off the active dune from sediment supply and thus remove its conditions for life. Depending on the intensity of development, foredunes have been manipulated in many ways, particularly for recreation and coastal defence. This kind of interference is drastic. For example, the Dutch foredunes have often been transformed into a high, straight sand dyke where wind activity and the formation of blow-outs is not allowed. Beyond the influence of water and waves, the transitional zone is dominated by aeolian processes. Natural vegetation, which is essential for trapping the sand, usually does not develop much beyond the pioneer stage.

The Resting Zone

This is the zone of inland dunes behind the foredunes. The resting zone can be up to several kilometres wide, as is the case on the Dutch mainland coast and along the French coast of Aquitaine (Paskoff 1994). In most cases, this zone is a depositional area inherited from the past. Wind activity is reduced to occasional blow-outs. Plants have stabilised the surface and various kinds of vegetation have developed. The vegetation succession in dunes with higher calcium carbonate contents and more nutrients leads to a mosaic of grasslands, shrublands and woodlands. Stabilisation measures have been carried out over many centuries. In the twentieth century, large-scale afforestation, mainly with pines, helped to stabilise this zone. Vegetation development is associated with soil development. When the soils have developed humic horizons the dune surface is more resistant to wind erosion. Since the influence of the wind has been reduced, we can characterise the resting zone as a subsystem where biological processes have become dominant over geomorphological processes. This theme is elaborated in the next section. On many parts of the European coast, for example northern France and Great Britain, the sand dunes meet solid deposits further inland, on which they often partly rest. Such deposits usually rise in height above the dunes, going inland. On low-lying delta coasts, like the Dutch mainland coast, which is essentially a coastal barrier system, dunes border former lagoonal areas, later filled in with clay and peat, and now turned into polders. The polders are lower than the sea and the dunes protect them from flooding.

THE STEERING PROCESSES

Seen at a general systems scale and looking at steering processes, the coastal system consists of a marine and a terrestrial part. The marine part is dominated by hydraulic processes. The terrestrial part is the visual dune landscape which is our main concern. This part is characterised by land forms and vegetation cover. The seaward zone is dominated by geomorphological processes. Their influence diminishes inland as biological processes become dominant. This means that every part of the dune landscape is determined by the interaction of geomorphological and biological processes, as shown in the model of Figure 9.2. The degree to which each of these processes dominates, at each location, is reflected in the soil profile.

The geomorphological processes operating in dunes are perhaps more dynamic than anywhere else. They comprise the action of wind and water. Essentially they lower the surface by erosion, or raise the surface by accumulation, thereby changing relief. There is little or no soil profile development as long as these processes keep the surface unstable. Biological processes result in

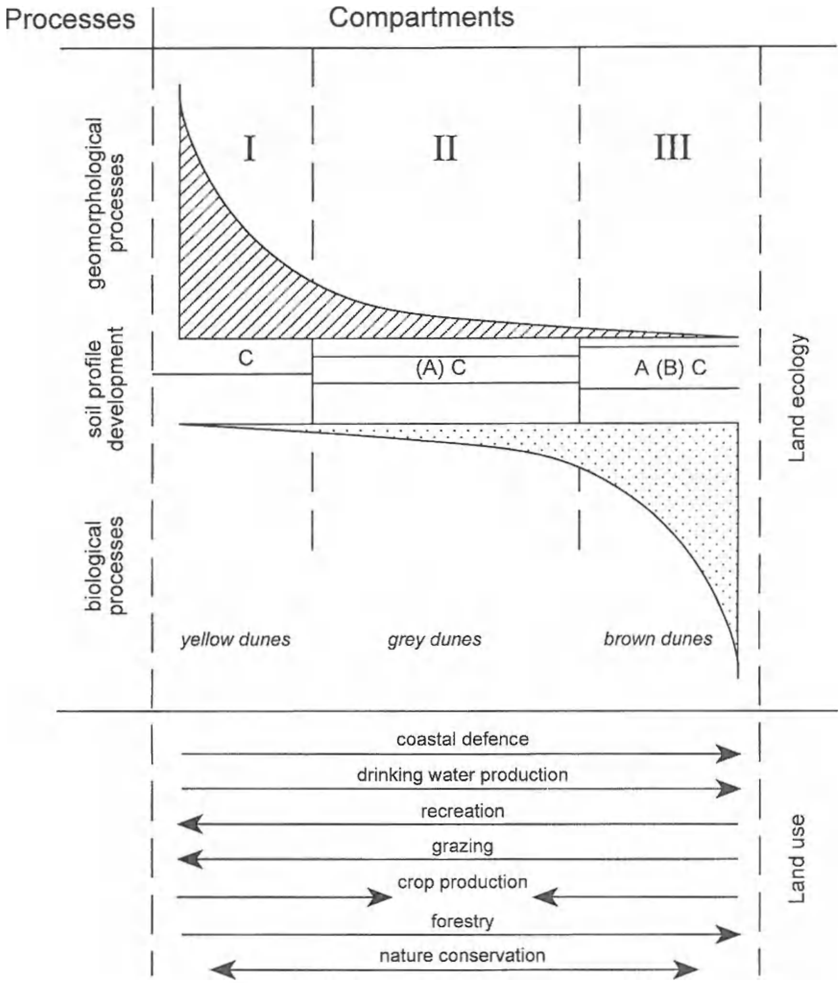

Figure 9.2. Schematic representation of the dune ecosystem and the effect of land use (after Jungerius and Van der Meulen 1988; with permission from Elsevier Science).

the establishment and development of vegetation. By biological processes we mean the production of biomass, the building up of vegetation structures, the change in species composition and increase in biodiversity. Underground biological processes include the formation of organic horizons leading to soil profile development. The role of animals is indirect. Rabbits and other grazers reduce the vegetation cover which apparently induces instability.

The first compartment of Figure 9.2 represents the beach and the foredunes where new landforms are created. Some plants such as marram grass

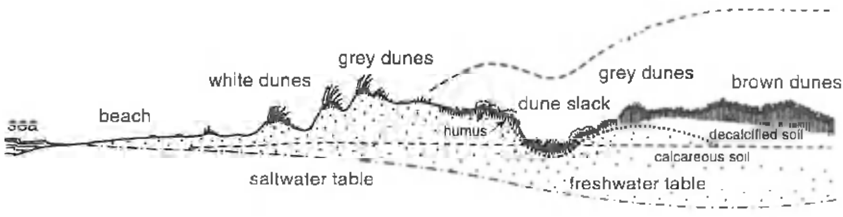

Figure 9.3. Cross-section of a coastal dune area along the North Sea (from Ellenberg 1978:493; with permission from Verlag Eugen Ulmer).

(*Ammophila arenaria*) are adapted to the geomorphological dynamics of this zone, but biological processes are generally of minor importance. No soil profile is found here. These are the white or yellow dunes, *Weissdünen* (Figure 9.3) or *dunes blanches*. The second compartment comprises the inner dune landscape where various combinations of geomorphological and biological processes prevail. This results in great landscape diversity. The soil is coloured grey by organic matter and develops an AC profile (grey dunes, *Graudünen* or *dunes grises*). The third compartment corresponds to inner dunes that are completely covered with vegetation (*Braundünen*).

Besides these, another group of processes which cannot be readily inferred from Figure 9.1 is of vital importance. These are hydrological processes (Bakker 1990). Once dunes have been formed, a geohydrological equilibrium causes the formation of a bell-shaped freshwater body within the dunes. The top is the phreatic level; the base is the brackish interface between fresh water and salt water in the deeper underground. The width of the terrestrial part of the coastal system and the average sea level are the main determinants for the shape of this fresh water body (see Carter 1991). The response of groundwater to long-term shoreline erosion and sea level rise is shown in Figure 9.4. In the terrestrial part of the dune, especially the resting zone subsystem, blow-outs can form dune slacks: when wind excavation of sand reaches the phreatic groundwater level, aeolian processes cease. From then on, the development of the slack is largely dominated by hydrological processes, for example the seasonal fluctuations of the groundwater level. Dune slacks have become the prime subject of conservation management because of their botanical values.

The steering processes give coastal environments a highly dynamic character that should be seen both in a temporal and a spatial context. Understanding this context is essential to management for conservation or for any other function. Restoring these processes means the (re)introduction of the natural dynamics into the coastal environment (see, for example, Van der Meulen and Jungerius 1989).

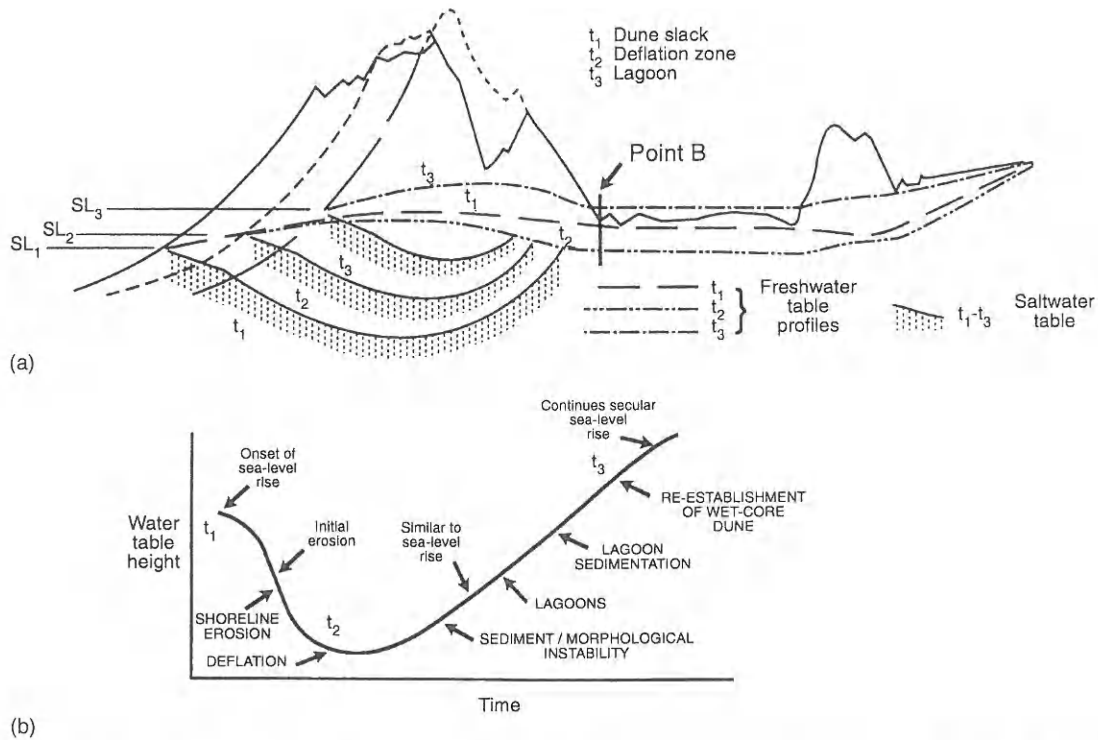

Figure 9.4. (a) Response of groundwater in a dune system to long-term shoreline erosion; (b) graphic representation of water table height over time through a phase of sea-level change (from Carter, 1991; with permission from Kluwer Academic).

THE SCOPE OF DUNE COAST CONSERVATION

HISTORICAL CHANGES IN THE CONSERVATION ISSUES

The need for conservation comes with the human use of coastal dunes. The conservation tradition is, therefore, longest in the **inner dunes**. From recent historical records it is clear that the resting zone has not always been so stable as it is today. People have used sand dunes for purposes of hunting and various forms of agriculture since prehistoric times (Higgins 1933) and along many European coasts there were mobile dunes, often threatening the local population. For at least a thousand years in most of Europe, this zone has received some form of protection. Various techniques of sand fixation were applied and legislation was developed, for example in Denmark, where the first royal decree was as early as 1539 (Skarregaard 1989). Westhoff (1989) believes that in The Netherlands 'the dune area was rather like a desert' in the past, but evidence to support his point is conflicting. Paintings from the end of the sixteenth century and photographs from the end of the nineteenth century show that the landscape of much of the inner dunes was, in fact, little different from that of today apart from the forests that have since been planted. The large fossilised blow-outs that have been observed from the Pyrenees to Jutland must have been spectacular spots of deflation in the past, but their very existence is also proof that the surface in between the blow-outs was stable.

Agriculture was never very successful and gradually the use of the dune landscape became more diversified. Each type of land use left its imprint on the landscape and determined future management. An interesting case is presented by De Raeve (1989). From Cap Blanc Nez to the Wadden islands, the Flemish coastal plains and the Dutch lowlands are part of a common geological setting and are both entirely bordered by coastal dunes. These dunes belong to the same system as far as climatic and floristic conditions are concerned. This holds true also for the properties of the sand (Depuydt 1972). Contrasting with the natural similarities are the strong differences in human interference which have developed over the last 100 years. The Flemish plain almost everywhere rises 2–4 m above sea level, so the dunes were not needed to protect the hinterland. Moreover, the hydrogeological conditions of inner Belgium render the dunes redundant for drinking-water supply. Flemish coastal dunes therefore kept their former status as waste land. Their only use were for sand exploitation, afforestation, and house and hotel building for the growing tourist industry. The chaotic developments linked with the '*laissez-faire*' mentality in the Belgian landscape caused the loss of 70% of the Flemish dune area but, on the other hand, left practically intact the major natural processes in the few unexploited areas, including active parabolic systems and large masses of moving sand (De Raeve 1989).

In contrast, in The Netherlands where coastal defence and the extraction of water were essential functions of the dune landscape, dune management was equivalent to dune conservation. The large-scale measures to stabilise blow-outs (which reached lengths of 50 m and more) came into effect from the middle of the nineteenth century and are in places still applied today. The effect of the stabilisation measures has been that the young phases of the vegetation succession have disappeared, the areas covered by mature stages have increased and there is consequently a loss of natural variation. This development results in a landscape with low ecological value.

This approach in which 'the total mastery of aeolian dynamics' is the main aim of dune management persists in some countries (Barrère 1992). But dunes under natural conditions are the product of accumulation, not erosion, and they disappear only on a receding coastline. In this case the sea is to blame, not the wind.

In The Netherlands, the character of coastal dune conservation has changed considerably under the influence of a growing appreciation of natural processes. Legal obstacles against tolerating wind activity are being removed (Anon. 1994). The policy of non-intervention was first introduced in the inner dunes after it was shown by many years of monitoring that blow-outs are stabilised by a number of natural processes (Van der Meulen and Jungerius 1989). The change in conservation attitude has been drastic. The very acts which were condemned in the past — rabbit burrowing, heavy grazing pressure by cattle and horses and recreational use — are now stimulated to destabilise the vegetated surface of the dune. However, it takes many years before the dunes are restored to their natural state. Experiments with artificial reactivation of blow-outs have been carried out to accelerate the process (see below).

The historical development of the management of the **foredunes** followed a different path. Protecting the coastline against a landward shift, including the conservation of the foredunes, traditionally posed different management problems from conserving the landscape of the inner dunes. The processes that create problems are mainly marine, and the conservation measures to control unwanted developments are usually carried out by engineers. They include the construction of groynes, beach nourishment and sand trapping to increase the volume of the foredunes. Traditionally, the approach adopted by engineers does little to enhance the ecological quality of the coast, but subsequent to the change in attitude towards a more natural approach to the conservation of the inner dunes there has recently been a marked switch in the appreciation of ecological values by coastal management organisations. A policy analysis study for coastal defence management in The Netherlands carried out by Rijkswaterstaat (1990) resulted in a more nature-oriented policy for coastal defence management. Part of this was the decision by the government to maintain the 1990 coastline by 'dynamic preservation' (Hillen and Roelse

1995). This was achieved with regular beach nourishment which is the most natural conservation method (Carter 1988).

The effect of the shift in attitude on the stabilisation of sand was comparable with the development in the inner dunes: suspension of the erection of fences or planting marram grass, allowing blow-outs to develop in the foredunes, and recently even excavating trenches through the foredune ridge to stimulate the formation of parabolic dunes and 'slufters' which are low-lying area through which the sea has access to the area behind the foredunes (see below).

The **offshore** zone is the realm of marine processes such as longshore currents, waves and tides. All these processes result in the movement of sand masses. In their interaction they produce a specific foreshore profile perpendicular to the coast and a specific configuration of the coastline. The control of these processes needs insight into the hydrodynamics involved, and engineering methods to remedy any unwanted developments. There have as yet been few efforts to manipulate the processes of the foreshore along dune coasts in order to conserve the coastline, apart from sand nourishment, not on the beach, but on the foreshore (De Ruig 1997). However, it is considered feasible to make use of geological and geomorphological principles to expand the Dutch coastline (see below). This is an important break from the traditional method of making new land by dumping sand and rubble on the sea bottom.

STEERING THE PROCESSES

The landscape is the result of the interaction of a number of processes. The dune manager has to possess a certain knowledge of the way these processes operate, because his decisions usually affect the characteristics of the dune landscape which means he interferes with the processes involved. He can steer the geomorphological and biological processes in many ways. Basically, it comes down to increasing or decreasing the effectiveness of these processes. But there are many ways to achieve this goal. The interference with processes will result in a shift along the stabilisation–destabilisation axis. The direction of development for a number of land use types is indicated in Figure 9.2. For example, coastal defence benefits from a stable system: geomorphological processes are suppressed, whereas recreation tends to destabilise the system because of physical destruction of plants. Even measures taken for nature conservation interfere with natural development.

A number of well-known measures are:

- Groynes, breakwaters, dykes, dune-toe protection and banquets to counteract wave erosion
- Beach and dune nourishments to affect sediment transfer
- Planting, fences, creating open spaces to affect aeolian processes
- Grazing, sod removal, burning to influence biological processes.

Measures have to be taken with caution, because there are often side effects. For example, stabilisation of the surface results not only in a decrease of geomorphological activity but also in a change in species through vegetation succession. Beach nourishment reduces the erosional characteristics of an area. Placement of fences or planting of marram grass in the foredunes reduces the potential inland transport of sand, which affects dune morphology and vegetation. Hard structures make a system static and consequently enforce repeated interference and often increase coastal erosion elsewhere along the coast.

THE NEED FOR SPACE

Conservation strategies are strongly dependent on the size of the management unit. Figure 9.5 is a translation of Figure 9.1 in terms of management. Figure

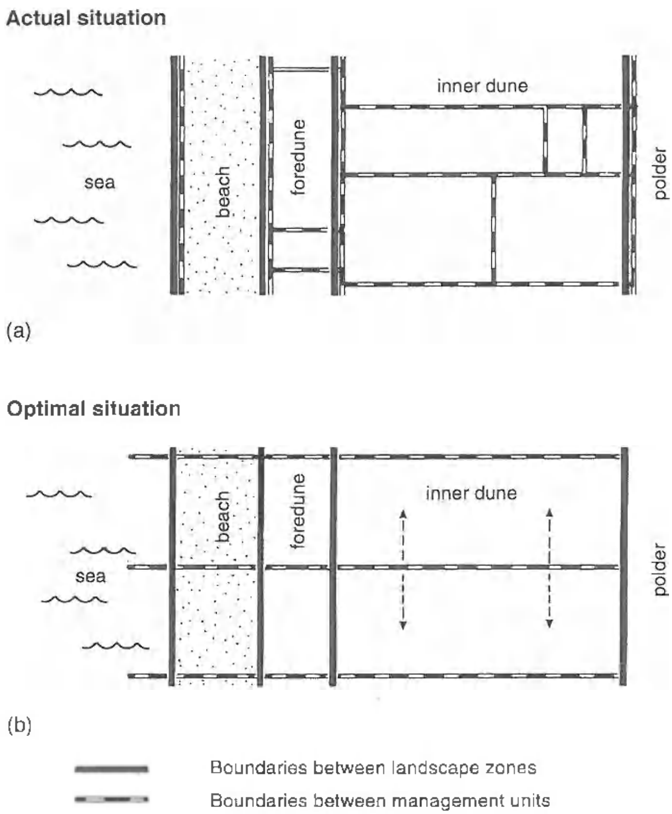

Figure 9.5. (a) Actual and (b) optimal boundaries of management units (from Van der Meulen and Van der Maarel 1989).

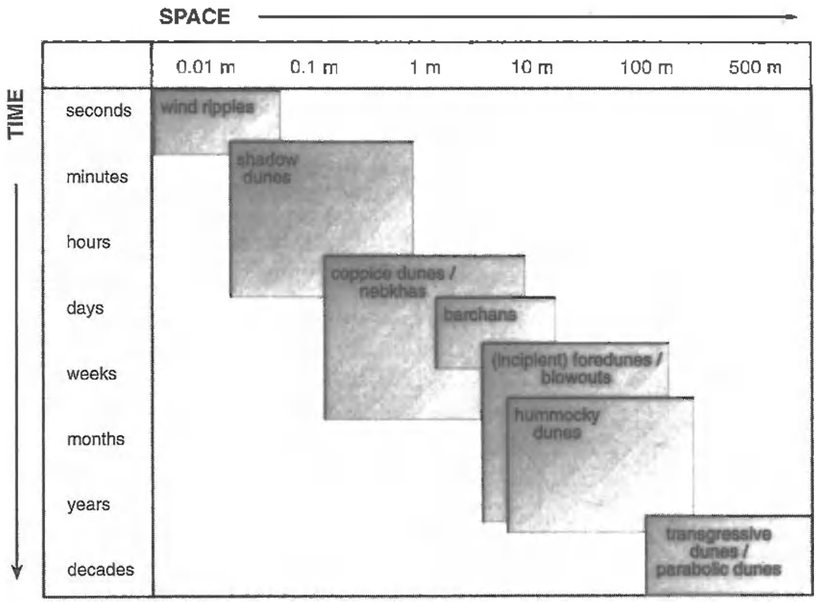

Figure 9.6. Requirements in space and time for the formation of aeolian features.

9.5(a) describes the situation which has often developed historically and which still prevails in many dune terrains: a pattern of small management units each with its own, short-term aims and package of measures. The situation of Figure 9.5(b) is preferable from the viewpoint of management: it has large multi-functional landscape units for which an integrated conservation plan can be devised. The larger the area, the more room there is for undisturbed natural processes (Wanders 1989). Figure 9.6 shows the space required for the formation or restoration of specific aeolian features. Large units also allow spatial planning such as the installation of zones with different functions.

Management of large units can be achieved even if the unit is divided among several owners. Houston (1989) gives an example for the Sefton Coast, a 25 km stretch of dunes in north-west England. The approach is based on the Coast Management Scheme established in 1978. The fundamental principle of the Sefton Coast Management Scheme is that the dune system must be managed as a single unit, rather than the fragmentation in the early twentieth century which had led to an overall loss of land quality. The Scheme has been able to restore a cooperative approach to the management of dune areas with such different functions as nature conservation, forestry and recreation. The appointment of a project manager to promote inter-functional cooperation is central to the concept of coordinated land management (Houston 1989).

PRACTICAL ASPECTS OF DUNE MANAGEMENT

Van der Meulen and Van der Maarel (1989) published an impact matrix for more than ten land-use types in coastal areas, arranged according to the ecosystem component they are affecting. The aim of the management is to sustain all the selected functions, be they nature conservation, coast protection, forestry, water extraction, recreation or any other activity. Therefore, the aims of management first must be made clear. Maps and other inventories of relevant terrain features are prepared in the field, from aerial photographs and satellite images. Research must be carried out to identify the requirements for the various sectors of dune users. Conflicting functions have to be brought in harmony. The desired steps and activities are finally listed in a management plan, again with mapped documentation. Various GIS techniques are available to assist in this kind of spatial planning. Many of these aspects of dune management are elaborated in Van der Meulen, Jungerius and Visser (1989) and Carter, Hesp and Nordstrom (1990).

Planning is followed by the execution of conservation activities, such as organisation of the work, planting marram grass, placing fences, shooting animals, guiding visitors, carrying out research, preparing reports and other documentation, to name a few identified by Wanders (1989). Practical handbooks are available in some countries. The conservation handbook written by Brooks and Agate (1986) is a good example. An environment checklist such as proposed by Davies, Williams and Curr (1995) can also be useful.

PREREQUISITES FOR DUNE CONSERVATION

Wanders (1989) lists a number of prerequisites for modern dune landscape conservation. The management organisation needs expertise that covers the entire range of functions. The financial means should be sufficient not only for the actual work in the dune area itself but also for research facilities and management planning. Biological research cannot stand alone. Research has to be extended to the physical environment, because insight into the physical processes is necessary to appreciate the dune systems' essential characteristics. Therefore, hydrology, geomorphology, soil science and related sciences of the physical environment should be integrated in management research. Politicians and all those who are responsible for utility functions must realise that dune management not only takes care of animals and plant species but is involved in all aspects of a dune landscape. Ecologists and geomorphologists see dunes as a dynamic system, while policy makers, planners and the general public see dunes as stable or static features. This creates the dilemma between maintaining processes and maintaining forms (Carter 1988).

Other requisites can be added, such as the availability of historical documentation about the area, and the provision of facilities for (public) education and information.

THE SUBSYSTEMS

The processes, types of land-use and management issues are different in the three subsystems. We will begin with the transitional and resting zones because they are traditionally the main concern of dune conservation. However, the technical possibilities of offshore management are rapidly increasing and should therefore be included in a chapter on dune management.

THE SUBSYSTEM OF BEACH AND FOREDUNES

Characterisation

General Characterisation

The transitional zone is characterised by a dynamic, geomorphologically active environment. Geomorphological processes operate at a short timescale, causing continuous change. The landscape comprises two linked geomorphological units, the beach and the active dune. In most systems, the active dune consists of distinctive dune ridges, called foredunes, backed up by less active dune forms. In this text, the foredune is defined as the first dune ridge, irrespective of the presence of specific plant species. The sharing of sediment, the active link in the sediment budget is an essential element of this zone. Its character is determined by the transgressive or regressive characteristics of the coastal zone and the magnitude of the processes in the beach and nearshore zone (Psuty 1989). In the development of foredunes, vegetation plays an important role.

Their constantly changing appearance makes foredunes different from inner dunes. Foredunes reflect present-day geomorphological processes, whereas the inner dunes (including fossilised foredunes) usually reflect geomorphological processes of the past. Geomorphological processes create a range of different depositional and erosional forms. The dunes themselves are depositional: smaller-scale embryonic and barchanoid dunes and sand sheets. Erosional forms are scarps, blow-outs, wind gullies and deflation surfaces (Carter, Hesp and Nordstrom 1990).

The impact of human action on foredunes is considerable along many coasts in temperate regions. Often, foredunes are stabilised, adapted in form or even artificially created (Nordstrom, McCluskey and Rosen 1986). This causes an important distinction between natural systems (undeveloped) and developed systems. Because of interference, foredunes are often considered as unnatural landscapes, resulting in limited scientific interest (Nordstrom, Psuty and Carter 1990).

Features

The predominant temperate coastal dune types are foredunes, blow-outs, parabolic dunes and transgressive dune sheets (including transverse, barchan and oblique dunes) (Hesp 1988). In most sandy coastal systems, some kind of foredune is present, but its extent depends on the specific local physical characteristics. Primarily, the action of the sea at the border of a large sand body is responsible for the creation of a linear feature. Second, foredune development depends on sand supply, degree and type of plant cover, rate of aeolian sand accretion or erosion, initial dune morphology, and magnitude and frequency of wave and wind forces (Hesp 1988). In general, extensive foredunes develop when there is a balance between the trapping ability of plants, the availability of sand and wind energy. Sand supply must not exceed the trapping capacity of the vegetation. Marram grass can outgrow deposition of up to $1\,m\,yr^{-1}$. If the vegetation cannot stabilise the sand, a precipitation ridge will develop. All sand is then trapped in a slipface which will move inland. The higher the dune, the slower the movement. There is no landward transport of individual grains, except in very high winds and through gaps.

In extreme cases, transgressive dunes may develop and the main form of dune development is inland and not by seaward extension (Hesp and Thom 1990). Other exceptions are 'climbing' dunes where sand may be blown some distance upslope behind a sandy beach, forming a veneer of sand on rock (Doody 1989). In the 'machair' of Scotland and Ireland, sand is trapped by short grasses (Angus and Elliott 1992).

The Processes

A thorough understanding of the landscape forms the basis for good management here as elsewhere. This is not always easy, because sediment exchanges in the beach–dune environment are governed by complex feedback mechanisms that may have important repercussions for the evolution of integrated beach-dune systems (Chapman 1989 in Sherman and Bauer 1993). For example, Arens and Wiersma (1994) in their classification of the Dutch foredunes make a major distinction between progressive, stable and regressive foredunes, which appear to have completely different characteristics with respect to management, features of aeolian activity and therefore conservation value.

The processes can be grouped under the headings shoreline dynamics, wind (energy) and vegetation.

Shoreline Dynamics

A number of marine processes contribute to the formation of beaches and foredunes (Figure 9.7). Longshore drift brings the products of coastal erosion

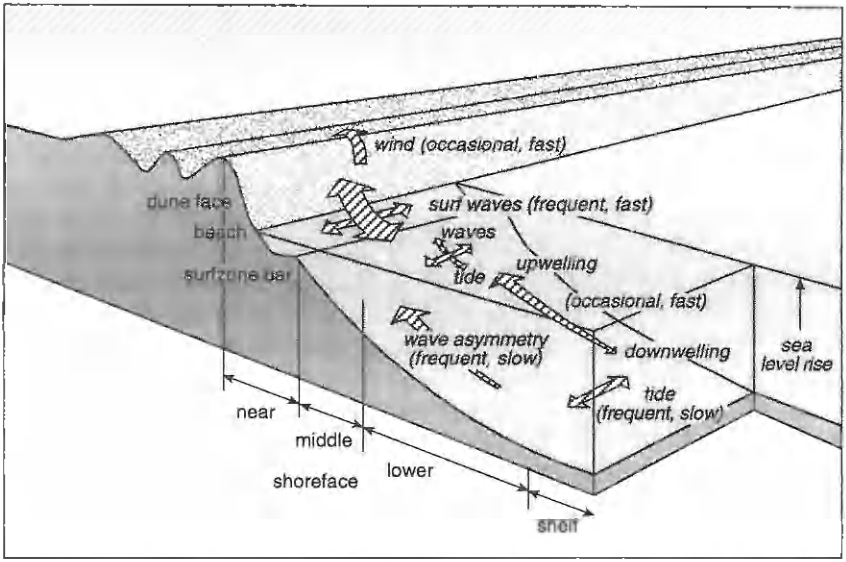

Figure 9.7. Hydrodynamic processes in the shoreface (from Stive and De Vriend 1995; with permission from Elsevier Science).

and material supplied by rivers to the offshore zone. From here the sediment is transported towards the beach by tidal currents and waves. On the beach it is taken up by the wind and deposited in a vegetated environment. Short and Hesp (1982) give a classification of dune coasts according to tidal regime, with transgressive dunes on high-energy coasts and foredunes, intermediate blowouts and parabolic dunes on low energy coasts. Constant, temporally asymmetric sediment exchange between beach and dune is an important natural process for maintaining both morphological stability and ecological diversity (Carter 1988).

Winds

Sand-transporting winds are necessary for dune formation, but onshore winds do not need to be dominant: the prevailing winds on the east coast of England are offshore, but there are dunes in many places. The direction of the most effective winds is often visible in the dune landscape. The more wind, the more sand can be transported, but the trapping capacity of plants may be a limit to dune building. The relationship between wind force and height of the foredunes is less clear: according to Depuydt (1972) higher foredunes are found where the beach and offshore profile are steep, whereas it is also known that high foredunes are associated with regressive coasts because of the large amounts of sand that are made available by the erosion processes.

Vegetation

Dune growth in temperate regions is caused by sand trapping in vegetation (so-called organogene Dünenbildung, Van Dieren 1934). If there is no vegetation, there will be no foredunes, but transgressive dune sheets as in South Africa (Short 1987). The species of trapping plants differs for different climatological conditions. A few large graminoid geophytes are the most effective (Westhoff 1989). A geophyte has (dormant) buds, corms or rhizomes buried well below the soil surface. In Europe, these species are: first the pioneer halophyte *Elymus farctus* or sand couch-grass, which is able to germinate in accumulations of organic tidal litter. The very first pioneers are some specialised halonitrophilous annuals, mainly sea rocket (*Cakile maritima*), but the dunes they form rarely survive winter storms. *Elymus farctus* is not an optimal sand binder; it is succeeded by the major sand accumulators *Ammophila arenaria* or marram grass and *Leymus arenarius* or lyme grass. The sterile hybrid between marram grass and wood small reed, named *Calammophila baltica* or *Ammocalamagrostis baltica* which can only propagate vegetatively but is often planted for dune stabilisation, is even more effective. Towards southern Europe *Elymus farctus* is replaced by *Leymus arenarius* (Westhoff 1989). In boreal climates *Elymus farctus* is replaced by *Euphorbia paralias*, sea spurge.

Continuous supply of fresh sand is needed for marram grass to evade the nematodes and fungi which affect its root system (Van der Putten 1989; Van der Putten, Van Dijk and Peters 1993). Inland, where salt spray diminishes, it is succeeded by other species including shrubs and trees (the latter mainly in calcareous dunes).

Human Interference

Three types of human interference can be distinguished. The first is intervention with hydrodynamic processes. This is an indirect influence on the dune system, since only the boundary conditions for dune development are affected. Examples of such activities include the construction of groynes and breakwaters, and shoreface nourishment. The second type is the direct intervention with dune-forming processes, thereby in some way stimulating dune development. Examples are the construction of sand fences to force and enhance sand deposition within a defined zone, or the planting of vegetation for the same reason. The third type of intervention is the adaptation of the dune form itself, for example the building of dunes to meet safety requirements. Examples are dune nourishment, or the creation of dunes by bulldozing beach sand. Other examples are the reshaping of foredunes by bulldozers to eliminate blow-outs, in order to prevent loss of sand by wind erosion.

Functions

Foredunes (the transition zone) are important for three completely different functions. Depending on the specific setting, there is an order in the importance of these functions.

Sea Defence

The main function of foredunes in many lowland coastal areas is sea defence. Dunes in general act as a buffer to extreme waves and wind because they are able to absorb wave attack (Carter 1988). In parts of Europe dunes form the only barrier to the sea. Foredunes here provide protection against flooding. In addition, foredunes may also safeguard specific coastal features against the dynamics of the transition zone, mainly against burial by sand. Examples are the protection of planted pine forests in Les Landes (Barrère, 1992; Favennec 1995), wet dune slacks in The Netherlands and tourist infrastructure, villages and settlements in many places.

Nature

Because of their characteristics, the landscape of foredunes form an ecological niche in which the plants are adapted to extreme conditions. These conditions involve (heavy) salt spray, intense activity of the wind and blown sand, an almost complete lack of nutrients and drought. Only a few plants are adapted to this environment. The gradients in the system and the intensity of the geomorphological processes make foredunes very important for nature. Tall pioneer stands with grasses having large rhyzomes (like marram grass, *Ammophila arenaria*) are common in exposed sites. In a natural system, the pioneer species disappear when sand accumulation decreases. More sheltered sites have low stands with more species, including mosses like *Tortula ruralis* and small herbs. In southern Europe, *Euphorbia panalis* and *Erynchyum maritimum* are characteristic. In the north, the geophytes of strictly coastal distribution are replaced by a group of tiny winter therophytes. The risk of severe drought in summer is a determining ecological factor, and further succession hardly goes beyond low shrubs of buckthorn (*Hippophae rhamnoides*). Conservation of this system is most effective when there is room enough or when the dunes are not developed for other purposes.

Recreation

The third important function is recreation. This function is mainly related to the beach, but the supporting infrastructure is mostly concentrated in the foredunes for safety. The foredunes are also much favoured for buildings, boulevards, hotels and houses because of the view they provide over the beach and the sea.

Implications for Management

In a completely natural landscape, species diversity and physical conditions are in balance. Physical processes do not threaten the natural function, they are part of it. This is often not understood by managers. Foredunes, especially along a prograding coast, require little or no management. In a natural system we can expect that sand taken from one area of the dune will be deposited in another, even in the case of increased erosion due to sea-level rise. The loss of dune areas in one place is compensated by a gain in another. However, since man likes to keep what he has got, he often upsets the balance between erosion and accretion of dune areas.

With respect to **sea defence**, the major threat is a loss of sedimentary volume due to dune erosion. Sand at the dune toe is removed by wave erosion. As a result the dune front collapses, a process known as scarping. Often a very steep, bare slope remains, vulnerable to wind erosion. A loss of volume in this way may result in the disappearance of the foredune and therefore in the degradation of the sea defence. Managers respond by trying to stabilise the foredune, to keep its volume intact. If the coastal sediment budget is slightly negative, stabilisation of foredunes may result in a loss of volume in the beach zone. This causes a gradual steepening of the coastal profile which may end up in a catastrophic loss of foredunes. It has also been shown that stabilisation by planting marram grass favours soil development which in turn stimulates soil pathogens. These, which include nematodes and fungi, affect the root system and may eventually destroy a naturally vital stand of marram grass (Van der Putten 1989).

The main threats for **nature** today are the loss of a very specific geo-ecological environment by erosion. This applies especially in the many situations where the landward boundary of the dune system is fixed. Other threats include pollution from beach littering and refuse from ships, deposited in the dunes during storm tides. The problem of littering by plastics is described in a number of publications (see Williams and Simmons 1996). Beach nourishment may have important effects on the landscape. For example, sand blown from a nourished beach often differs from the local sand in size, nutrient content or colour. Little is known about the effects on vegetation of this process.

Most of the physical processes impose a threat to the **recreational** function of foredunes. Facilities can be lost either by burial or by erosion. Blowing sand is a nuisance to visitors. Stabilisation of the foredune is not always the answer; it may result in a decreased beach width, which means a loss of recreational area.

The main conservation issue is how to reconcile the conflicting interests of the three functions. Excessive recreational use of beaches and foredunes may disturb natural processes, as may fixation of the beach and dune system for maximum security. Sea defence and recreation require stability, but these conflict with the interests of nature conservation (Van der Meulen and Van der Maarel 1989). Natural processes involve instability which conflicts with sea defence and recreation functions, but new insights are being developed (see next section).

Often, there is no conflict: sustainable development, natural beaches and foredunes are as attractive for recreation as for nature conservation. Nature education and guided tourism in nature areas nurture care for vulnerable areas. Beach nourishment as a new means for sea defence offers possibilities for nature by suspending the need for excessive stabilisation measures and for recreation (by providing wider beaches).

Case Studies: Dynamic Preservation of the Coastline

Scientific Research for Management

One of the fears of dune managers is a landward loss of sand by the wind. Research has found that a closed foredune acts as a very effective sand trap. Arens (1996) showed that the decrease in landward transport from beach to foredune is dramatic. Transport on the foredune, during a moderate storm event (average wind speed on the beach $15\,ms^{-1}$ at 5 m height), is less than 0.1% of the transport on the beach. During lower wind speeds, transport into the foredunes declines to zero. Figure 9.8 shows two examples for some Dutch foredunes, one near Groote Keeten, in the northern part of North Holland, the second on the Wadden island of Schiermonnikoog. The figure shows the decrease in landward transport during onshore winds. Measurements indicated that due to the presence of vegetation, transport capacity decreased to zero at a small distance from the vegetation border. Both vegetation and lee-side effects prevent the sand from leaving the foredune system. The research indicated that the fixation of sand at the seaward side of foredunes is not necessary to prevent substantial landward losses.

Figure 9.9 shows the mechanisms of sand transport over vegetated and bare foredunes. In the case of a vegetated seaward slope, landward transport is negligible, because all sand is trapped in the vegetation. If the seaward slope is bare, some landward transport may occur. Depending on the steepness of the slope, sand will be transported in either saltation or suspension. In the last case, the sand will be transported further landward, but still, most of the sand will be arrested within about 100 m from the foredune.

Decreasing Management Efforts for Nature Development/restoration

A large part of the Dutch mainland coast consists of rigorously managed foredunes, resembling static sand dykes rather than dynamic geomorphological

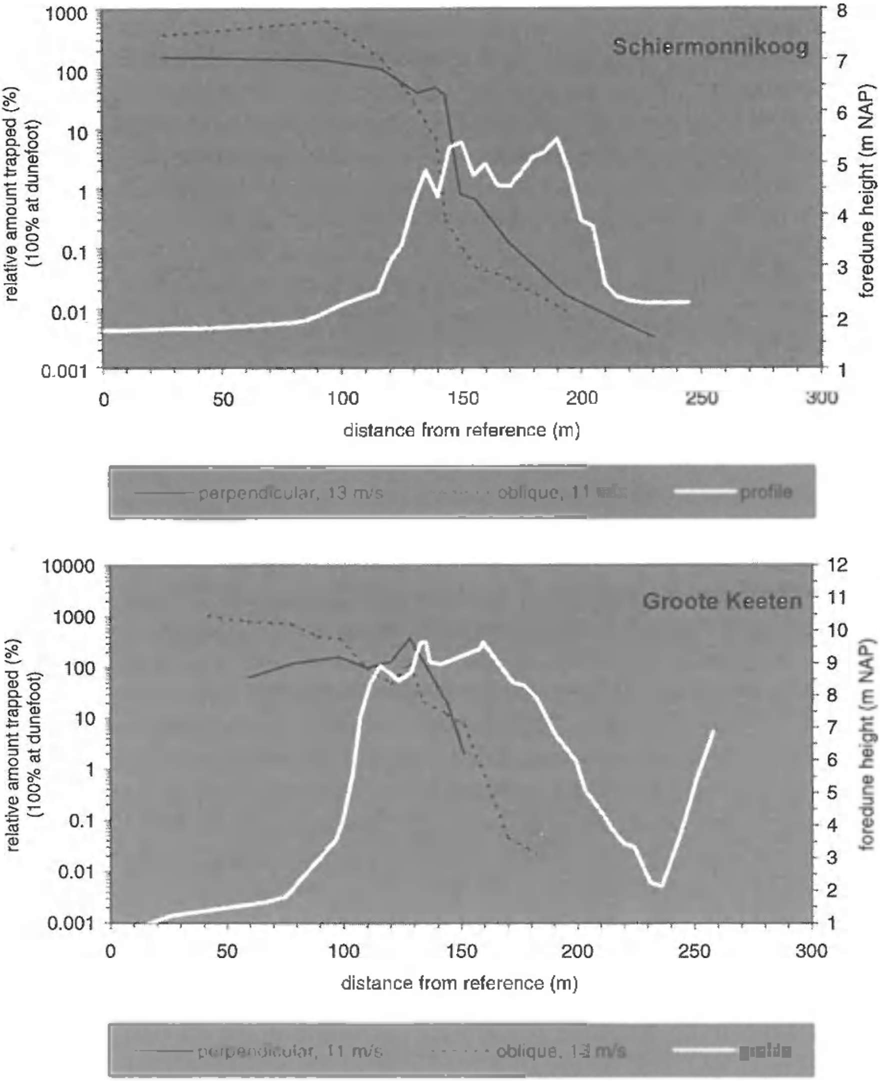

Figure 9.8. Sand transport over foredunes (after Arens 1996).

systems. Traditional management has involved immediate recovery of storm damage by the smoothing of cliffs and the planting of bare spots with marram grass, thereby reducing potential wind erosion. In 1990, the authority in charge of coastal safety decided to suspend the current management along a 1 km wide section of the shoreline, in line with a strategy of 'Dynamic Preservation'

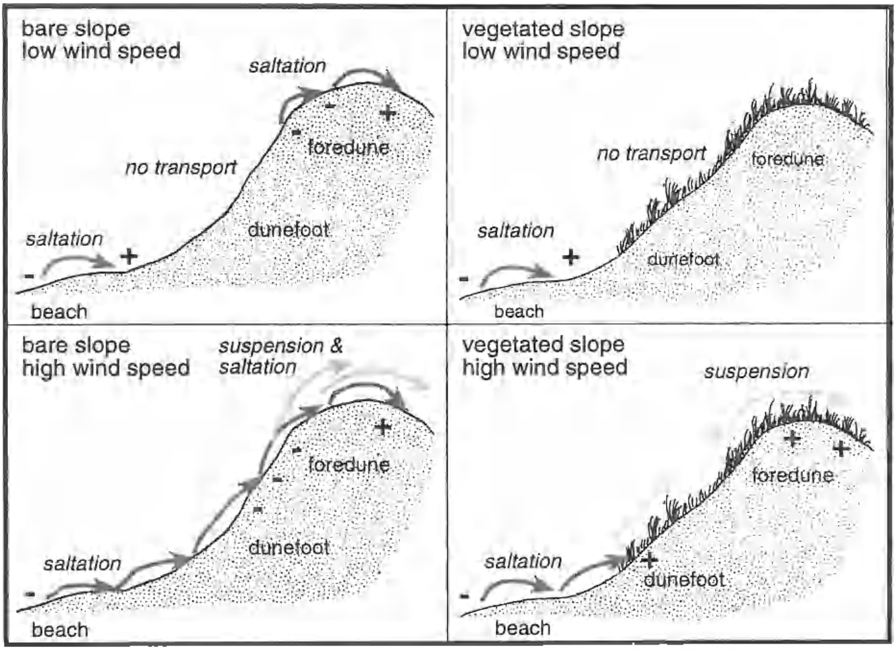

Figure 9.9. Conceptual scheme of landward transport over foredunes (from Arens 1996; with permission from Elsevier Science).

adopted by the Dutch government. The loss of sediment from the beach-foredune system by either wind or wave erosion was prevented by periodic beach nourishment. In 1999, the foredune exhibited a steep cliff-like slope which was mostly being eroded by the wind. Small blow-outs had been formed. The foredune slope was slowly adapting to the new situation, but it was not clear yet what the final form would be. The presence of a steep and bare cliff induces suspension transport (see Figure 9.9), causing some of the sand to be blown over the foredune, to be deposited at a few tens of metres in the lee. This gave some problems for the maintenance of a road behind the foredune, because of sand deposition on the road accompanied by an increase in verge height due to the increased growth of grass. The shape of the foredune contrasted with the static sand dyke feature it used to be, which is illustrated by Figure 9.10.

Active Interference for Nature Development including Habitat Restoration

Near Schoorl, in The Netherlands, the foredunes are backed by a dune area several kilometres wide. In the past, these foredunes were maintained as that part of the dune zone which ensured safety and on which safety regulations

Figure 9.10. The foredunes near Parnassia (mainland coast, The Netherlands).

were applied. The foredunes were managed by the Hoogheemraadschap Uitwaterende Sluizen, whereas the inner dune area is managed by the State Forestry Department. Because of grass encroachment and centuries of stabilising activities (Kooijman and Van der Meulen 1996; Veer 1998) dynamic geomorphological processes in the dune area have declined. Currently, only some small spots are active, mainly due to the digging activities of rabbits: most geomorphological activity is limited to the foredune zone. In the past, occasional major storms created gaps in the foredunes, which were closed immediately by the foredune managers. In 1995, a project proposal was presented to restore the natural dynamics (Stichting Duinbehoud 1995). The project involved cooperation between all the authorities in the region with responsibilities in coastal management. The main idea was artificially to create a gap in the foredunes, through which the sea would occasionally inundate the swale behind (Figure 9.11). To accomplish this, the idea of the foredune as a primary sea defence had to be abandoned. Because of the width of the dune zone behind, a new sea-defence zone could be defined, landward of the swale. In the swale, vegetation and soil were removed, to initiate aeolian activity. These activities should restore several gradients, such as fresh–salt, dry–wet, carbonate-rich–carbonate poor.

In 1997 the plan was executed. The sea has now entered and inundated the dune swale several times. Small parts at the border of the swale have been buried

Figure 9.11. Artificially created gap in the foredunes between Bergen and Schoorl.

by aeolian deposits. The project has drawn much attention in the media, and this has attracted large quantities of visitors, who further interfere with the intended 'natural' development. The initiators of the project have already expressed doubts that the gap will not be sealed by the sea and the wind within a few years.

One of the curious aspects of this kind of project is the eagerness for immediate results. One could ask whether, in a case like this, it would not have been preferable to let nature do the work in its own good time, and learn from the results. The answer to this question is not clear. After some years of non-management, natural blow-outs might have developed in the foredunes, which might gradually have evolved into natural gaps. However, the outcome of the strategy is very uncertain: there is no guarantee of success, and the desired result might take years to develop. Besides, it is very unlikely that aeolian activity in the completely vegetated dune swale could ever be created without human intervention.

THE SUBSYSTEM OF THE INNER DUNES

Characterisation

In the model presented in Figure 9.1, the subsystem of the inner dunes is shown as 'the resting zone'. Inner dunes are found in many countries between the active foredunes and the hinterland. They have also been called 'secondary dunes' (Klijn 1990). Ecologically, this zone covers the *Graudünen* (grey dunes) and the *Braundünen* (brown dunes) in Figure 9.3. There is a variety in dune forms including parabolic dunes, comb dunes, precipitation ridges, blow-outs and secondary dune slacks. Most of these dunes are remnants of the past (Klijn 1990). Secondary dune formation is triggered by the destruction of plant cover and subsequent wind erosion. Here, active processes create forms superimposed on a fossil aeolian landscape.

The Processes

A number of processes are relevant in the conservation of the inner dunes such as erosion by wind and water, soil formation, biomass production, salt spray and the fluctuations of the groundwater level. These are grouped as geomorphological and biological processes in Figure 9.2. In this figure, the inner dunes are represented by compartments II and III. The geomorphological and pedological processes are touched upon below.

Wind

The wind as a geomorphologic agent is much less important in the inner dunes than in the foredunes: it has been calculated that the wind on the beach can, at force 7, move more sand in two minutes than that produced by a sizeable blow-out in the inner dunes in one whole year, in terms of flux across a line of equal width (Jungerius 1989). The aeolian processes in the inner dunes are described by Carter, Hesp and Nordstrom (1990) and Hesp and Thom (1990). The effect of wind erosion depends on the relationship between the erosivity of the wind and the erodibility of the site. The erosivity of the wind is largest in exposed areas such as dune ridges and summits. The erodibility of the site is determined by vegetation and soil properties. Higher plants break the force of the wind, but a continuous cover of vegetation as low as moss and algae is also sufficient to protect the soil against erosion. Whether a surface without vegetation cover is affected by wind depends on the characteristics of the sand. The presence of loam, coarse material and even a thin coating of organic matter on sand grains will effectively reduce erodibility. Prevalent among the aeolian forms in the inner dunes is the blow-out (Carter, Hesp and Nordstrom 1990), a shallow depression of mostly elliptic outline which is free of vegetation.

Water

The traces of water erosion in the inner dunes are much less conspicuous than those of the wind and have generally not been subject to conservation measures. Yet much material is shifted downslope during rain, especially in summer when the sand of the A horizon is very dry and water-repellent (Rutin 1983). The main types of erosion by water are splash and surface wash. Their effect is the gradual flattening of relief. Colluvium is deposited at the base of the slope, with the seeds entrained from the surface soil in the upper slope positions. Water erosion often paves the way for wind erosion, by removing the humic surface soil on upper slopes.

Soil Formation

The development of soils on sand dunes has been described by Wilson (1990, 1992) and Jungerius (1989, 1990). Although soils are not generally studied in a dune terrain, their colour is often used to classify the dunes (Ellenberg 1978). Soil formation as part of the landscape is shown in Figure 9.2. In compartment I, where geomorphological processes prevail, there is no soil formation. These are the 'raw sands' of Wilson (1992) and consist of little altered mineral material.

Compartment II is characterised by great variability in the balance between geomorphological and biological processes. As a result there is also great variability in the development of the soil profile. On stable sites the formation of a B horizon is no exception, but shallow and truncated soils prevail where erosion is active, especially on the upper parts of steep slopes. Profiles lower downslope reflect the balance between colluvation and soil formation. Where soil formation can keep pace with the deposition of colluvium, abnormally thick A horizons are formed. Sites with a sequence of buried A horizons are an indication to the manager that periods of stability and plant growth have alternated with periods of instability and deposition of colluvium or aeolian sand. Wilson (1992) classifies the A–C profiles in this compartment as sand-pararendzinas and the A–B–C profiles which occur where acidification and decalcification can proceed for some time, as brown calcareous sands. In compartment III where soil development continues unhindered under a closed vegetation cover, podzols are eventually formed (Wilson, 1992). In The Netherlands this stage has nowhere been reached although there are podzolic trends in the northern districts where the calcium carbonate content of the dunes sand is low.

Functions

Nature Conservation

The outstanding natural and ecological value of the dune landscape has been praised in so many publications that there is no need to elaborate on this theme here. The European Union of Coastal Conservation was expressly founded in the 1980s for the purpose of safeguarding the 'golden fringe of Europe'. The proceedings of the congresses they organise contain contributions from all European countries where nature conservation of the inner dunes is an issue. Holistic nature conservation embraces all components of the landscape: climate, geology, landforms, soils, water, vegetation and fauna.

Recreation

The inner dunes combine outstanding scenic variation with a wealth of animal and plant life and an equally valuable abundance of geomorphologically interesting landforms. This makes them very attractive for human activities which at the same time constitute the main threat for conservation. Well-known sources of damage to vegetation and wildlife are trampling, the construction of roads and car parks, vandalism, camping, and the increased risk of fire (Brooks and Agate 1986). Trampling causes shifts in species composition and decreases in vegetation cover (see Williams and Randerson 1989).

Many dune managers are confronted with increasing use of the dunes for recreation. If the proper measures are taken, there does not need to be a problem. Management aspects are discussed by Carter (1988: Chapter 13).

Water Extraction

The groundwater stored in the dunes is an attractive source of drinking water and its extraction has become an important use of dunes in several countries. In The Netherlands, groundwater is the main reason that the dune landscape is protected from urban development and mass tourism. On the other hand, water extraction can cause ecological impoverishment and the construction of associated infrastructure can damage valuable dune forms. Lowering of the groundwater table is often followed by the disappearance of valuable dune slack ecotopes. In recent times these dune areas have been fed artificially with surface water from elsewhere.

Forestry

At present, forests cover extensive parts of the coasts of several European countries such as Denmark, Poland, the United Kingdom and southern France. Many of these forests are plantations, often of exotic pine species. The pines lower the groundwater table by transpiration. Moreover, the decaying needles have an acidifying effect on the soil. In countries where forestry is no longer a profitable enterprise, these plantations have been removed or converted into natural forests.

Implications for Management

The management issues depend on land use. Nature conservation management includes restoration, the maintenance of intrinsic landscape diversity, preserving the undisturbed relationship between biotic and abiotic processes, the regulation of groundwater level, etc. Obviously, for recreation the issues are quite different: the maintenance of carrying capacity, the development of an aesthetically pleasing landscape, and the creation of an adequate infrastructure with sufficient recreational amenities. For the extraction of drinking water it is also necessary to create a specific infrastructure and to control the hydrological properties of the terrain. Only the implications of management for nature conservation are elaborated in this section.

Management in this context is concerned with intervention in the landscape-forming processes. If these interventions cause unwanted disturbances for other functions, mitigating measures must be taken. Zoning the use of the dunes is one of the possibilities. But there is not always a need for conflict. As Westhoff (1989) puts it: 'Human impact on nature is both beneficial and deleterious. The main concern of environmental management is to promote the former and counteract the latter aspect'. There are a number of techniques to reach this goal.

Stabilisation–destabilisation

Stabilisation of moving sand is no longer seen as essential to the conservation of nature, unless the sand may bury rare plant species or valuable dune slacks. Where this applies, or infrastructure has to be protected, common stabilisation techniques can be applied (Brooks and Agate, 1986). For blow-outs, the common type of wind erosion in the inner dunes, this is generally not necessary. Often, a leeward dune develops which catches all the sand leaving the blow-out. Moreover, monitoring experiments have shown that there are a number of natural stabilisation processes and that most blow-outs have a limited lifespan if left alone (Van der Meulen and Jungerius 1989). Natural stabilisation mechanisms include the growth of algae which colonise deflational areas within the blow-outs, and the accumulation of sand within the blow-out when its ratios of length, width and depth are no longer aerodynamically appropriate, or the fact that the blow-out may become too deep for the sand to leave. If stabilisation measures have to be taken, it is recommended that they join forces with natural mechanisms. For example, to stabilise blow-outs it is best not to counteract the erosion of the inner parts, but to stimulate the growth of the leeward dune which will eventually prevent the sand from leaving the deflation area.

As we stated before, stabilisation is increasingly seen as a danger to nature because of its stifling effect on the landscape. People are not always to blame for the stabilisation. The decrease in the rabbit population in the 1950s also contributed to the increasing stabilisation of many European dunes. Human intervention may be needed to restore natural values. There are a number of measures to choose from: removal of vegetation, removal of sod or the introduction of grazers.

Grazing

Grass encroachment is one of the consequences of increased atmospheric deposition of acidifying and eutrophying components, although it can also be caused by the suppression of natural processes by continuous artificial stabilisation. Grass encroachment can be counteracted by grazing. The effect of grazing by rabbits was realised many years ago (Pickworth Farrow 1917). Where the number of rabbits was reduced, large grazers such as sheep, goats, cattle and horses were successfully introduced. Numerous studies have dealt with the effects of grazing on the vegetation of grassland communities (see Belsky 1992; Gibson and Brown 1992). Grazing results in a reduction of the standing crop and a more open vegetation structure, a change in humus form, and a shift in species composition in favour of smaller species, associated with conditions of more light near the soil surface. The specific effects of grazing are dependent on many factors including soil development, hydrology, management history, grazing density and type of grazer (Kooijman and Van der Meulen 1996). Until the beginning of the twentieth century, extensive grazing by domestic animals was common practice in dunes, so the acceptance of grazing as a management tool to restore biodiversity levels is in fact a reintroduction of this old practice (Kooijman and De Haan 1995).

Mowing (Anderson and Romeril 1992) and sod removal have also been applied to restore botanical diversity, but these methods may have deleterious effects on other components of the ecosystem: for example, both methods drastically reduced the number and depth of occurrence of soil fauna in the Dutch dunes (Jungerius *et al.* 1995).

Groundwater Control

Extraction of drinking water causes the lowering of the groundwater table and concomitant desiccation of the soil. Infiltration of water from outside usually remedies this problem but creates new ecological problems when this water is polluted or eutrophic. Van Dijk (1989) made a thorough analysis of the impact of drinking-water production on the dune landscape. Elaborate and costly measures are necessary to purify the water before it is suitable for infiltration. In The Netherlands, surface infiltration has gradually been substituted for artificial infiltration into deep aquifers.

Maintenance of wet dune slacks needs special care. For dune slacks to support a valuable vegetation it is necessary to keep the water table at a constant level. Restoration of dune slacks also depends on the quality and the flux of the groundwater in the surrounding area (Van der Meulen and Jungerius 1989).

Case Study: the Reactivation of Blow-outs as a Measure to Restore the Natural Dune Landscape

Active blow-outs are, at present, rare in the Dutch coastal dunes. Even in areas where stabilisation measures have been suspended and wind action is allowed, there has been a gradual decrease in the number of blow-outs. Reduced grazing pressure by rabbits due to repeated outbreaks of myxomatosis in the last few decades is part of the cause, but there are other factors such as the increased input of nutrients by atmospheric deposition. Eutrophication stimulates vegetation growth and is therefore thought to be responsible for the encroachment of certain algae (Pluis and Van Boxel 1993), grasses and shrubs. This may lead to the stabilisation of active blow-outs and prevent the formation of new ones.

Artificial reactivation of blow-outs can help to restore the natural dynamics of coastal dunes (Van Boxel *et al.* 1997). Around active blow-outs there is a range of deposition rates, depending on the size of the blow-out, from up to 50 cm yr^{-1} near the edge to a few mm yr^{-1} at a distance of about 100 m from the blow-out. Calcareous and nutrient-poor sand deposited here can counteract the effects of acidification and eutrophication. Vegetation type and cover will react to the changes.

Within the framework of a programme sponsored by the Dutch government to test various measures for counteracting the deteriorating influence of air pollution (Van der Meulen *et al.* 1996), experiments were carried out to reactivate blow-outs. Two study areas were selected. The one discussed here is located in the inner dunes near Haarlem, at a distance of 1.5 km from the coast (Van Boxel *et al.* 1997). The relief of the study area is flat to undulating. The sand contains 7–9% calcium carbonate. The vegetation is open dune grassland, with increasing invasion of exotic moss (*Campylopus introflexus*) and sea buckthorn (*Hippophae rhamnoides*).

The blow-outs in this terrain were stabilised with branches in the 1970s. In order to reactivate them, the branches were removed, along with all the vegetation. However, the removal of vegetation was not sufficient to restore wind action. Organic matter in the sand acts as binder, so the whole of the A horizon had also to be removed. This meant an excavation to a depth of 20–30 cm even if the soil was still young, and more if the soil was old or if there were many roots of marram grass or other sand-binding plants in the soil. A mechanical shovel was used for this purpose, and special measures had to be taken to mitigate undue damage to the terrain. For the same reason, the sand could not be removed by trucks and had to be dumped close to the blow-out. Apart from the blow-outs, small bare patches were reactivated with spade and barrow. The effects of these measures were monitored with precision measuring techniques at yearly intervals, from 1991 to 1994.

The results (Van Boxel *et al.* 1997) showed that the small patches that were reactivated, stabilised spontaneously. This is not surprising, since most naturally formed blow-outs also stabilise in the first year after their formation and only a small percentage reach maturity (Jungerius and Van der Meulen 1989). The reactivation of the blow-outs was more successful. Their area and depth increased slowly. The deposition area is about four to six times the deflation area. Most of the sand was deposited within 30 m of the blow-out. This was as expected: it is rare to find sand more than 100 m away from even the largest blow-out in the inner dunes. *Campylopus introflexus* disappeared from the accumulation sites, but not the sea buckthorn. For this shrub to die off, the soil must be fully leached. This took at least 50–80 years on Texel, one of the Wadden islands, where the dune sand already has a low calcium carbonate content to begin with (Doing 1989).

Everyone would like deflation to continue until the groundwater level is reached, in which case a valuable dune slack vegetation might develop. However, experience has shown that the deflation stops when the capillary zone above the groundwater table is reached. This triggers plant growth in the blow-out. This not only stops further deflation but even promotes sand trapping. Where a dune slack is expected, a new dune develops! Even if a dune slack is created, geomorphic processes will effectively prevent plant growth if the banks are steeper than about three degrees.

THE OFFSHORE SUBSYSTEM

Characterisation

For our purpose, the subsystem of the offshore is defined as the shoreface. This is the realm of hydrodynamic processes. The shoreface (Figure 9.7) is that part of the sea-bottom lying between the dry–wet beach and the shelf. It has a slope of 1:100 to 1:1000. On the Dutch coast this more or less coincides with a narrow zone up to 20 m below average sea level.

The processes

The main processes of the shoreface are shown in Figure 9.7. The coast has been schematised and there are no inlets. This could well be the Dutch mainland coast. In cells of several kilometres in length, the offshore profile responds to a variety of hydrodynamic and sediment-transport processes. These differ in different compartments (near, middle and lower shoreface). As indicated by the thickness of the arrows, the main activity of the steering processes is working in a direction perpendicular to the coast. The surf zone is different from the rest in that processes are strongly depth-controlled; they are driven by an associated loss of momentum and dissipation of energy. Morphodynamic adaptation of the profile is assumed to be relatively fast in the upper part and slow in the lower. Observations suggest timescales of hours around the waterline to millennia near the inner shelf (Stive and De Vriend 1995). The external driving factors in this whole system are sea-level rise and lateral sediment supply.

Long-term analyses have revealed important processes in the large-scale sand balance along the Dutch coast (De Ruig 1997; Van Rijn 1995). They show that serious erosion occurs on the deeper (> 6–8 m below sea level) parts of the shoreface. Sand from the deeper zone is transported to the shallow zone and alongshore northward to the Wadden Sea. The natural supply from the bottom of the North Sea to the deeper part of the shoreface is limited. This means that the offshore slope is steepening.

Functions

The present functions of this subsystem are mainly fishery and recreation. Because the pressure on the coastal zone in Holland is increasing, there are now plans for land reclamation (cf. De Ruig and Hillen 1997; Waterman, Misdorp and Mol 1998; De Ruig 1998). The need for housing and recreation facilities in the dunes is also growing. The densely populated low-lying polder land of the western part of the country, immediately behind the dunes, has increasingly less space. For decades, building in the dunes was restricted because it was thought to endanger the coastal defence function of the dunes, at risk of flooding the polders. Since the 'dynamic preservation' policy has been adopted (see above), this is no longer a valid reason, especially not in the wider dune areas.

It is particularly in the Rijnmond region, the mouth of the Rhine River, that plans for development are being made. The province of South Holland is developing projects for reclamation along the coast between The Hague and Hook of Holland (roughly 4000 ha). These will accommodate urban, recreational and natural areas. The city of Rotterdam is studying the reclamation of land off the coast of Voorne. Here an extension of the Maasvlakte-1 is planned, to give the harbour of Rotterdam more port facilities. Recently, studies were published of plans to build an island in the sea in front of the Dutch mainland coast, which could be used for a new airport (Delft Hydraulics 1997a).

It is interesting to note that in all the plans there is also place for nature development. Studies are being carried out to define the making, management and evaluation of coastal ecosystems which could be located on the new land (LWI 1997). On the other hand, it may be more worth while to consider the development of nature not on new reclamation plans themselves but at other localities which offer better opportunities. In any case, compensation for losses of nature should be made and not in the form of small bits and pieces of land but in areas of substantial size for nature to develop.

Threats

While engineers and policy-planners often think positively about these plans, many other groups, among which are environmental groups and nature conservationists, have more doubts (for example, Janssen 1996).

Threats to valuable ecosystems include the isolation of the existing dune area from the sea resulting, for example, in the reduction of saltspray and the consequent maturing of the plant succession. This may lead to the disappearance of pioneer stages and open dunes, and the increase of shrubs and woodland (compare the development in Voorne since 1950s, well documented by Van Dorp, Boot and Van der Maarel 1985). The foredunes may not receive any more inputs of fresh sand, a precondition for their ecology. Another major influence will be the one on the ecosystem of the North Sea itself. First of all, all marine life will disappear when new land is formed. Second, the digging of sand will affect large areas of North Sea bottom. It is calculated that for 4000 hectares of reclaimed land, approximately 400 million m^3 of sand will be dredged from the sea. Over an area of 200 km^2, 2 m of sand will be taken off (Janssen 1996). New land in the sea will increase the need for infrastructure on land, increasing the pressure on coastal land and its nature. The valuable dune area will be 'squeezed' between the old and the new land.

How can the damage to nature be compensated for by creating new nature on new land, if at all? It is argued that alternatives, like rebuilding and renovating parts of the old suburbs, are a better answer to the need for housing, and that these alternatives should get more attention.

Implications for Management

Recently, some studies were carried out in the Netherlands about land reclamation in the North Sea. They are of interest to the topic of this chapter. They reveal the way of thinking in such large projects, where civil engineers and ecologists work together. How can new land be made? Which form and shape should it ideally have? What will the influence be on the existing coast? Which coastal ecosystems should be created? Is it possible to enhance the ecological quality of the coast as well as its resilience, and at the same time favour the coastal defence quality of the coast? Resilience is the (self-organising) property of the coast to maintain actual and potential functions under changing hydraulic and morphological conditions. This property is based on the morphological and ecological processes operating at the coast (Delft Hydraulics 1997b).

Questions like these illustrate how thinking is developing: (1) plans for reclamation should be seen in the context of all plans for the coast and in an integrated way, i.e. long-term effects on the total coastal system should be considered along with a discussion on the actual needs of specific developments; (2) land could be returned to the sea in order to increase the resilience of the coastal system, thereby decreasing the risk of flooding (De Ruig 1997, 1998).

Case Studies: the Making of New Land

An Island?

Delft Hydraulics has made a study of the feasibility of building an artificial island off the Dutch coast (Delft Hydraulics 1997a). It is meant as a technical contribution concerning the possible location, and lay-out, consequences for morphology and ecology and best options for mitigating negative effects (Figure 9.12). The effect of the island on tides and currents, sand and silt transport, water quality and marine ecosystems were examined.

The conclusion was that a large-scale project such as the construction of an offshore island requires careful consideration not only of its direct effects but also of the implications for the further evolution of the Dutch coast. It was concluded on the basis of the results of the investigation that the construction of an offshore island is technically possible and—if optimally shaped and carefully placed—would have only limited effects on the sea and coastal environment. However, if the island were built, the already limited resilience of the Dutch coast would diminish even further, because more coastal maintenance would be necessary. But if the island were to be combined with other measures, like seaward-protruding sand hooks, the resilience of the coast might improve. Table 9.1 gives an overview of the consequences of construction and presence of an offshore island.

Ecosystems on New Land

The extension of the Rotterdam harbour facilities into the North Sea will include 850 ha earmarked for nature. How can a new dune area be made out of the sea? Basically in three ways, wherein man's interference is decreasing but time is needed for realisation (Löffler and Veer 1999):

- Anthropogenic: sand is deposited in the area where dunes are planned: either 'dunes' are shaped with a shovel or other earth-moving equipment, or we

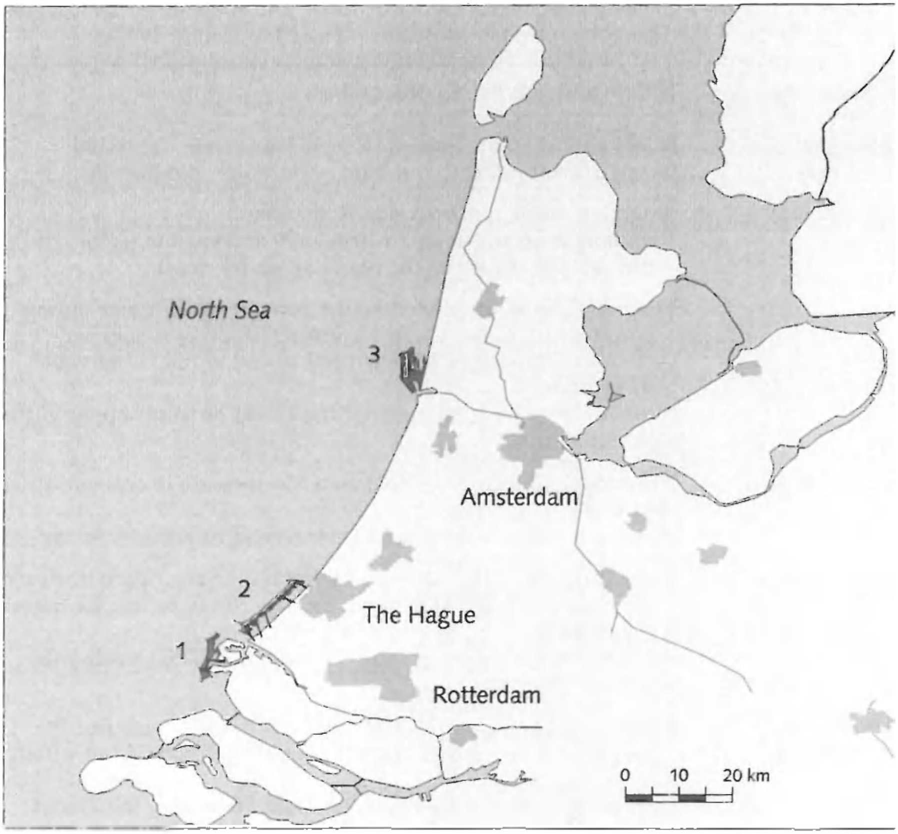

Figure 9.12. Map of the western part of the Netherlands showing locations for possible reclamation of new land. 1 = Maasvlakte II (extension of Maasvlakte I): harbour, industry, nature; 2 = New Holland: housing, recreation, nature; 3 = second international airport (also designed as island at various locations in front of the coast).

wait for dunes to be created by the wind. A dune area can be created within a few years, but the system lacks major natural characteristics.

- Geomorphic: sand is deposited to create a beach and provision is made (e.g. enough fetch) so that foredunes can form themselves by free wind activity. Within 10–50 years a natural dune landscape might be formed which basically possesses the same natural characteristics as a natural landscape.
- Geological: sand is deposited on the foreshore and left there; natural processes of tides, currents and winds are allowed to shape the landscape. A fully natural dune landscape might be formed after several decades, but there is no guarantee.

Table 9.1. Overview of the consequences of construction and presence of an offshore island in front of the Dutch mainland coast (source: Delft Hydraulics 1997a)

Consequences for	Nature and gravity of consequences
Tides and current	Could change in an area of 15 to 40 km around the island No significant influence on large-scale water movements
Morphology	Accretion at the northern side of the island Variation in accretion (*circa* 10 m yr^{-1}) and erosion (*circa* 6 m yr^{-1}) in the lee of the island along the coast
Mud budget	Temporal rise in suspended matter content of sea water during construction of the island (in winter 10–40%, in summer 30–60%; because of large natural variation only observable in summer) Probably no significant effect of the island on mud supply to the Waddensea
Water quality	Around the island up to maximum 5% increase in concentration of PAKs Hardly any effect on the large-scale spread of particles in the sea
Algae growth	Temporary, small (less than 10%) decrease of algae growth during the construction of the island, but few consequences for higher organisms Small increase of algae growth north-west of Texel (within the natural variation)
Marine ecosystems	Temporary loss of up to 2800 tonnes of biomass (ash-free dry weight) due to sand extraction (recovery of population within a few years) Permanent loss of 400 tonnes of biomass following the loss of submarine area Increase of biomass on the hard substrate of the sea defences of 500–800 tonnes and increase of bio-diversity
Birds	Small decrease in feeding area at sea due to the presence of the island New resting and feeding areas on the island New resting area for birds migrating over the North Sea
Coastal dunes	Hardly any effect on wind climate and salt spray Fragmentation of dune area and possible influence on geohydrology due to the construction of a connection with Schiphol Airport
User's functions marine and coastal zone	Hardly any effect on shipping Some hindrance for recreational shipping Damage to fishery due to a loss of fishing grounds and extra damage when fishery is restricted in an area around the island Effect on the openness of the seascape Some noise nuisance for inhabitants and visitors in the coastal zone

Which ecosystems should be developed on newly reclaimed land? The coastal ecosystems that score highly for nature are intertidal areas, dunes and so-called 'slufters'. Slufters are relatively small saltmarshes within areas of dry dune (see above). They drain a primary dune slack through the foredune ridge, or they are formed by a breakthrough of the sea or a parabolic dune through the first foredune ridge. When there is a low-lying area behind the foredune ridge, sea-water invades the dunes. The result is a valuable ecosystem with complex abiotic gradients. Slufters and parabolic dunes for a long time have not been the favourites of Dutch coastal engineers. But the new policy of dynamic preservation gives rise to new possibilities (cf. Hillen and Roelse 1995).

The ecosystems we have mentioned are believed to add to the resilience of the entire coastal system and to its ecological values. The making of such systems in front of the old land is of particular interest at those places where the dune ridge is narrow which means that the defence structure is also thin. In the philosophy of resilience, present agricultural land could even be returned to the sea in order to increase the resilience of the coastal system (see French and Reed, this volume).

DUNE CONSERVATION AND INTEGRATED COASTAL ZONE MANAGEMENT

The coast comprises more than the dune system: so does integrated coastal zone management (ICZM). The coastal zone is an interacting system of physical processes, chemical reactions, biological growth and economic activities. Examples of economic activities are fishery, shipping, recreation, defence, waste disposal, sand and gravel mining, land reclamation, and oil and gas exploration. Economic development in coastal areas depends on sustainable productivity and the viability of coastal resources. Coastal zone management should be based on an understanding of the complexity of the coastal system and its interaction with adjacent urban areas, river catchments in the hinterland, and seas and oceans (Hoozemans *et al.* 1995). Decisions have to take into account global change and international policy.

It is increasingly recognised that the sustainable development of the coast, and its multiple resources in accordance with their carrying capacity, is possible only by adopting a comprehensive strategy. According to Doody (1997) this will involve integrated action across the many functions of the coast (horizontal approach) and consensus building at the different levels of decision making and policy formulation (vertical approach).

Integrated coastal zone management can be practised at several scales. Van der Meulen and Udo de Haes (1996) sketched the role of nature conservation in ICZM on a global level. At the heart of the problem is the fact that 50–70%

of the Earth's population is concentrated in coastal areas. The competition between the various user categories operating along the coast is fierce, with recreation and tourism as the fastest growers. Combined use causes an ever-increasing tension between safeguarding natural resources, on the one hand, and economic development, on the other. Often short-term economic gains are chosen at the cost of irreversible ecological losses. There are many examples that show that this leads to environmental degradation which eventually backfires on economic development. Van der Meulen and Udo de Haes (1996) argue that sustainable development of the coastal zone is possible only if nature conservation has a strong position in integrated management.

ICZM is clearly a matter of the highest political level. Fortunately this is gradually being realised. In 1994 the Council of Environmental Ministers asked the European Commission to prepare 'a comprehensive strategy on integrated management and planning in the Community coastal zones, providing a framework for its conservation and sustainable use' (Doody 1997).

The tools and techniques developed for ICZM are based on system analysis. It is beyond the scope of this chapter to discuss this approach in any depth. The interested reader is referred to the course on coastal zone management written by Hoozemans *et al.* (1995).

CONCLUSIONS

SOURCES OF INFORMATION

The references to this chapter list the main handbooks for dune management and conservation. Those interested in more information on coastal management issues are referred to the *Journal of Coastal Conservation* (JCC), the *Journal of Coastal Research* (JCR), the *Journal of Coastal Management* (JCM) and *Ocean and Coastal Management* (OCM). The JCC is the official scientific organ of the European Union for Coastal Conservation (who also issue *Coastline*) and is published by Opulus Press AB, Uppsala, Sweden. The JCC focuses on applied research for integrated coastal management with a 'wise use' perspective. The journal has established a policy of cooperation with the JCR which is published in the USA and is more related to pure sciences. The JCM is also published in the USA. OCM is an Elsevier journal which is dedicated to the management also of ocean resources.

FINALLY

Coastal dynamics and management form an ongoing process. Along the Dutch coast we have seen the following phases in the past 10–15 years:

(1) The policy of dynamic preservation created possibilities for soft defence structures instead of hard ones; beach nourishment became an official policy.
(2) Wider coastal zones were thought to have greater resilience, offering more ecological values and greater safety, for example against rising sea level.
(3) This meant that on narrow (a few 100 m wide) coasts, external (i.e. offshore) activities can be beneficial, while on broad coasts (a few km wide) internal activities are opted for; in the latter case, one could think of the creation of slufters or of returning agricultural land to the sea.
(4) Reclamation plans should be seen in this context, taking into account the entire coast and its long-term development along with a discussion on the various present and future functions.

Finding an equilibrium between the interests of socio-economic development and the maintenance of a natural dynamic system is one of the great challenges of our time. The above points illustrate how necessary it is to propose a kind of management that uses natural processes rather than destroying them. The example of the Dutch coast shows what possibilities can be explored when dealing with a soft sedimentary type of coast.

But this is not valid only for the Dutch coast. Many of the world's lowland delta coasts have essentially similar characteristics: two parties competing for the same space; i.e. socio-economy and ecology in a dynamic natural setting. Once the space on land is almost gone, the eye turns towards the sea. These and other experiences can help to develop both on- and offshore space in a responsible way.

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