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Relative rates of sand transport through an incipient parabolic dune at Pinery Provincial Park, Ontario (Ammophila breviligulata, Calamovilfa longifolia, Cakile edentula, Juniperus virginiana, Populus deltoides)

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RELATIVE RATES OF SAND TRANSPORT THROUGH AN INCIPIENT PARABOLIC DUNE AT PINERY PROVINCIAL PARK, ONTARIO

By

Sheri A. Longboat

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ABSTRACT

Factors controlling the development, migration, and stability of an incipient parabolic dune in Pinery Provincial Park, Ontario were investigated in terms of grain size characteristics, rates of sediment transport, and local and regional winds. The parabolic dune, situated approximately 60 meters inland of Lake Huron, is dominated by sparsely scattered dune grass species of marram grass (*Ammophila breviligulata*), sand reed (*Calamovilfa longifolia*), and sea rocket (*Cakile edentula*). Small tree species of red cedar (*Juniperus virginiana*) and eastern cottonwood (*Populus deltoides*) emerge and increase in number beyond the parabolic dune. Mean grain sizes along a profile were coarsest on the beach and interdunal area, and finest through the foredune and the parabolic dune, which was to be expected. The primary depositional processes responsible for the evolution of the dune is grainfall through vegetation, with intermittent, short periods of tractional deposition. The annual resultant wind vector by frequency is from the east-southeast at 102°, when all winds were considered, and 117° with the effects of onshore winds only. There is no general agreement between the vector resultants calculated and the actual measured dune orientation, which is approximately 190°. Sand trap samples revealed that twice as much sand was transported through the interior of the dune (55.5 kg), than at the mouth (22.8 kg), over a one year period. Transport through

the mouth exhibited greater directional variability than the interior, where transport was dominated by a landward, northerly trend. Overall, the amount of sand transported did increase as mean wind speed increased, with the exception of April. Seasonally, transport through the interior reached a maximum during the spring/early summer, decreased through late summer and fall, until it reached a minimum during winter. Transport through the mouth reached its maximum during the late summer/fall season, declined during the winter, and maintained a relatively constant low from the winter though the spring/early summer season.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

A sand dune has been defined as "an accumulation of loose sand that acts as an obstacle to wind and is also subject to deformation by the wind" (Goldsmith, 1985, p.331). Early work conducted by Bagnold in 1941 (p.188), referred to an individual sand dune as "a mound or hill of sand which rises to a single summit". More recently, Pye and Tsoar (1990) have defined a sand dune as a hill or ridge of sand piled up by the wind.

Sand dunes have an important geomorphic role in the coastal environment acting as buffers to extreme wind and waves, thereby sheltering landward communities; and, on a marine coast they assist in the retention of freshwater tables against salt-water intrusion (Carter, 1988).

1.2 Previous Dune Studies

Current knowledge related to coastal sand dune research has often been derived from previous studies such as those conducted by Bagnold (1941), Bigarella, (1972), and McKee (1979), which have examined the result of natural movement of sand over dry land, or desert dunes. Bigarella (1972) noted that coastal sand dunes have several factors in common with desert dunes. Both require an adequate supply of well-sorted sand for deposition, and sufficient winds capable of moving sand for at least part of the year (Pye, 1983). However, in form, coastal dunes are quite different from desert dunes types, and in some respect coastal dunes are more complex (Bigarella, 1972). For example, desert dunes develop as a response to aeolian processes, whereas, coastal dunes rely on wave action to first supply the sediment source which is subsequently transported and deposited by aeolian activity.

Pethick (1984) suggested that the primary difference between desert and coastal dunes is the unique morphology of coastal dunes. This has been attributed to the presence of vegetation (Hesp, 1981, 1984), and coastal wave action. Developing vegetated coastal dunes normally have a relatively steep windward slope, and a much less steep leeward slope (Bigarella, 1972). The reverse can be said for desert dunes, which are characterized by a gentle windward slope, and a steep lee slope. The steepened windward slope of a coastal dune can be credited to the wave action undercutting and scouring the dune face, as vegetation on the lee side acts as a stabilizer for newly deposited sand. Since the erosive nature of wave activity is missing in a desert environment, desert dunes develop a more gently inclined windward slope. Waves are the mechanism which re-shape the beach, replenish sediment sources, and rework the existing foredunes. Vegetation is the agent which fixes, traps, and accumulates sediment. The combined effect of waves and vegetation distinguish coastal dunes from active dunes in arid regions (Carter et al., 1990).

An availability of adequate supplies of well-sorted beach sand, winds blowing at a velocity which exceeds the threshold necessary to move the sand (Sherman and Hotta, 1990), and a vegetation cover which promotes sand accumulation, are the primary controlling processes in coastal dune formation, and will be discussed in detail in Chapter 2.

Davies (1973) added humidity and sand grain characteristics as additional factors affecting sand dune development. The presence of sand moisture caused by increased humidity increases threshold velocities necessary for sand movement by presenting a smoother surface to the wind, thereby reducing the surface roughness. A reduction of surface roughness results in a decrease in shear velocity, thus reducing the force acting on the sand particles.

Grain characteristics can also affect the rate of sand transport, and therefore, dune development. Bagnold (1941) experimentally found that rates of transport by wind increased when the sediments were initially poorly sorted. However, Davies (1973) suggested that this may only pertain to higher wind speeds. Also, more spherical material has been found to move at a greater rate with high velocity winds (Davies, 1973).

Vegetation plays an important role in the formation of coastal dunes. Thomas and Tsoar (1990) conducted a study on desert dune vegetation and determined that dune formation could not be explained in terms of wind and sediment characteristics alone. This was previously noted by Hack (1941). He concluded, that along with wind and grain characteristics, vegetation is a third major variable which would influence dune development.

1.3 Vegetated Coastal Dune Studies

Studies which have investigated the role of vegetation have been minimal and until recently have received very little attention. Bagnold (1941) was one of the first to accept that vegetation creates a type of surface roughness which can in turn trap sand. In 1958, Olson examined the relationship between coastal dune development and vegetation type. He found that rates of deposition and erosion could be estimated by analysis of annual growth cycles which have been preserved in underground roots. A later study conducted by Goldsmith (1973) examined the origin and growth of vegetated coastal sand dunes by measuring cross-bed dip azimuths, angles, and elevations. Final analysis, showed that dune geometry is closely dependent on dune vegetation; for example, dunes inhabited by grasses yielded low angle cross-beds. Goldsmith attributed this to the fact that vegetation anchors and stabilizes the dunes which in turn, prevents migration, and therefore, promotes the formation of low angle cross-beds.

Hesp (1981) conducted field and laboratory experiments to determine the relationship between wind velocity, secondary air flow, vegetation, and the formation of shadow dunes. Shadow dunes were described as pyramidal-shaped bedforms that develop to the lee of a discrete roughness element, which in this case were two typical sand dune grasses (Hesp, 1981). Hesp documented a detailed account of both horizontal and vertical air flow patterns at various locations surrounding the vegetation. In general, it was found that shadow dunes formed in the wake region by the eddies which flow around the plant. The shadow dune height is dependent on the angle of repose of the sand, and the basal width of the vegetation. However, dune length is determined by the basal width, and wind velocity.

Some of the more recent studies have investigated vegetated coastal dune morphology from stratigraphic analysis (Byrne, 1986, 1991). Byrne (1986) examined the sedimentary structures of coastal dunes from a marine, and freshwater environment. Upon comparison, it was found that since the processes of dune development were the same in both environments, so too were the internal structures. However, a notable difference in dune morphology did occur between each environment. Differences were attributed to variations in sand supply, local wind regime, and relative water levels.

Byrne and McCann (1990, 1993) conducted studies which examined the internal structure, bedding, and lamination of vegetated sand dunes on a marine coast. A descriptive code for analysis of internal structures was developed, as well, a genetic summary of the modes of deposition was presented. Byrne and McCann found that based on the type of stratification, four phases of dune development existed in the dunes of Sable Island. The first phase consists of tractional and grainfall deposition through sparse vegetation. The second phase is primarily grainfall deposition through dense vegetation. The third phase is characterized by a paleosol; while the fourth phase consists of horizontal laminated beds of loosely packed finer sand resulting from grainfall through dense vegetation.

It has been suggested by Carter et al. (1990, p.2) that although the interest in coastal dune geomorphology has increased significantly over the last 20 years, "coastal dune research is still at a rather primitive stage." Dune studies are often fragmented, and very little is known of the coastal ecosystem. Many studies still uncritically accept the methods and results obtained by studies on arid desert dunes, and apply these to coastal dunes. However, coastal dunes are quite different in that they are subject to a greater variety of processes.

1.4 Purpose

The purpose of this thesis is to investigate the factors controlling the development, migration, and stability of a vegetated coastal sand dune in Pinery Provincial Park, Ontario, with particular attention given to grain characteristics, rates of sediment transport, and local and regional wind regimes.

1.5 Thesis Layout

The remainder of the thesis is made up of four chapters. Chapter 2 is the background information relating to aeolian transport, coastal dune development, and the selected study area. Chapter 3 will provide a description of the methods employed in the field, and the techniques of laboratory and data analysis. In Chapter 4, the results of the study will be presented, and will be further discussed in Chapter 5.

CHAPTER 2

BACKGROUND

2.1 Introduction

The purpose of this chapter is to provide the necessary background information to which the later chapters will refer and upon which they will expand. Explanations of sand dune classifications, coastal classifications, aeolian transport processes, and coastal dune formation will first be presented in a "chronological" literature review. Particular attention will be given to those investigations examining vegetated coastal sand dune.

The final section of this chapter will introduce the study area selected for this investigation. An examination of factors such as climate, wind, waves, sediment source, and vegetation type within Pinery Provincial Park, Ontario will be provided.

2.2 Sand Dune Classifications

Two principal attempts to classify different dune types transpired in the 1940's: "A Tentative Classification of Sand Dunes: Its Application to Dune History in the Southern High Plains" by Melton, 1940, and "Dunes of the Western Navajo Country" by Hack, 1941. These two pioneering schemes provided a framework from which the later more developed classifications would evolve.

Hack (1941) devised an empirical classification for desert dunes of the Navajo Country, Arizona. He considered that if wind and climate were relatively constant within a given area, then vegetation must be the primary factor which influences different dune forms. The presence of vegetation alone was not the controlling factor, but rather the ability of vegetation cover to resist the movement of sand, and this in turn, was dependent on the amount of sand available to the wind for subsequent transport (Hack, 1941). Therefore, he determined that the dunes of Navajo Country fell into one of three simple forms based on sand supply: transverse dunes, longitudinal dunes, and parabolic dunes (Fig. 2.1).

Hack (1941) found that transverse dunes, more recently defined by Whittow (1984) as asymmetrical sand dunes which stand at right angles to the direction of wind flow, occurred where the sand supply is large enough to destroy all, or almost all the vegetation. On the other extreme, longitudinal dunes, which are long ridges of sand whose axis lies parallel with the direction of the prevailing wind (Whittow, 1984), were found to occur where the sand supply is relatively meager. Parabolic dunes, or crescent shaped sand dunes with two trailing arms which point upwind (Pye and Tsoar, 1990), were considered by Hack (1941) as intermediate types between the two extremes. Parabolic forms could develop where great quantities of sand are moved, provided that the vegetation was aggressive enough to withstand the sand attack (Hack, 1941).

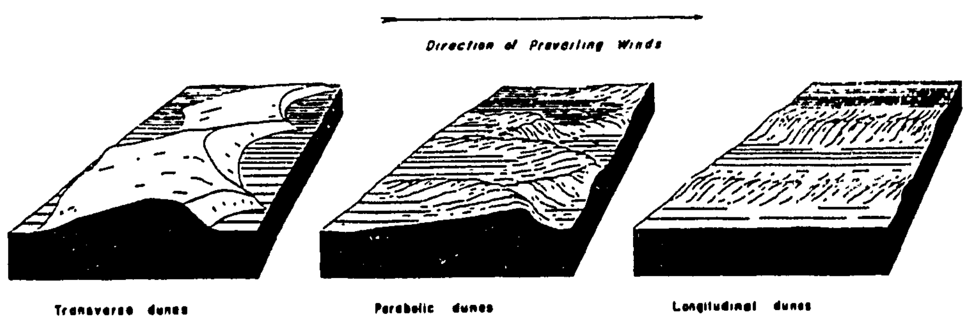


Fig. 2.1 Three common dune types. (Hack, 1941, Fig. 1)

The intermediate parabolic dunes were further sub-divided into two types (Hack, 1941). Parabolic dunes that occurred in exposed places where wind removed sand under a thin vegetation cover were called parabolic dunes of deflation. Parabolic dunes of accumulation were those that occurred in sand depositional areas, and were a more symmetrical parabolic shape compared to the scoop-shaped blowouts formed under deflation (Hack, 1941).

Although the classification appears to be quite subjective in determining the quantity of sediment supply, and the amount of vegetation destruction, Hack (1941) did identify the fact that there may be circumstances unlike the idealized, where other dune forms may result, such as climbing dunes which form as a result of sand piling up against a cliff. However, these forms were omitted from Hack's classification, because the topography and wind regime of the Navajo Country were not conducive for the development of these forms. Furthermore, Hack questioned the suitability of his method for use in other areas. "The classification here used is probably applicable to similar areas elsewhere but not to dune areas unlike in topography, wind regime, and vegetation cover" (Hack, 1941, p.241).

Another primary classification to develop during the 1940's was that produced by Melton (1940). He developed a genetic classification which grouped all existing desert dunes into two types: simple, and complex dunes. Simple dunes types were those that formed by sand moving winds which blow with unvarying direction. Whereas complex dune types formed as a result of two equally effective winds moving at right angles to each other at different times of the year. Both types were further sub-divided on the basis of surface roughness. Each type could form under bare surfaces or loose sand, or vegetated surfaces (Melton, 1940).

Melton's technique of classification provided a simple method for classifying, however, dune types are more dynamic than was indicated by his method. Hack (1941, p.40) went as far to say that the classification produced by Melton, although ambitious, "is based in part on erroneous assumptions". The assumptions referred to are those regarding the very distinct wind regimes that differentiated the two major dune types.

One of the first attempts to classify coastal sand dunes into different types was that produced by Smith (1954). As documented and summarized by King (1959), Smith's classification grouped coastal dunes into seven main types. Foredunes, characterized as mounds up to 10 feet high adjacent and parallel to the beach, and parabolic dunes, were said to be the most common types found on many coasts (King, 1959). Transverse, longitudinal, barchans, blow-outs, and attached dunes are the remaining types classified by Smith (1954). King (1959) characterized barchan dunes as crescentic dunes with a steep slip-face slope on the lee side facing away from the beach. Blow-outs were described as hollows or troughs which cut into dunes of the previous five types (King, 1959).

Attached dunes differ from the others in that their formation depends on some obstacle around which sand accumulates (King, 1959). Bagnold (1941) used the term sand shadow to describe the accumulation of sand in the lee of an obstacle. More recently, this dune type has been termed shadow dune (Hesp, 1981).

Currently, the most commonly used term to represent this dune form is, lee dune (Pye and Tsoar, 1990), shown in Fig. 2.2. However, as not to confuse a lee dune with a lee slope, the term shadow dune will be used to represent dunes which form around an obstacle.

From analysis of the literature it appears that coastal sand dune research has recently gained more attention, and hence, several more classifications have emerged. The classifications produced by Davies, 1973; Goldsmith, 1977a; Rosen, 1979; and Hesp, 1983, 1984, 1988; are the primary schemes used by coastal researchers when classifying coastal dunes.

Davies (1973) recognized the need for a classification which would provide uniform terminology for analysis of geographical variation in coastal dune form. Davies believed that the overall schemes produced for desert dune systems, such as Melton's (1940), although sufficient for arid regions, were not clearly defined. Therefore, a new system was needed. Davies considered the seven dune type scheme produced by Smith (1954) to be the most thorough, and used it as the basis for a new classification. Using a format similar to Melton and the terminology presented by Smith, Davies grouped coastal sand dunes into two main categories: primary, and secondary dunes.

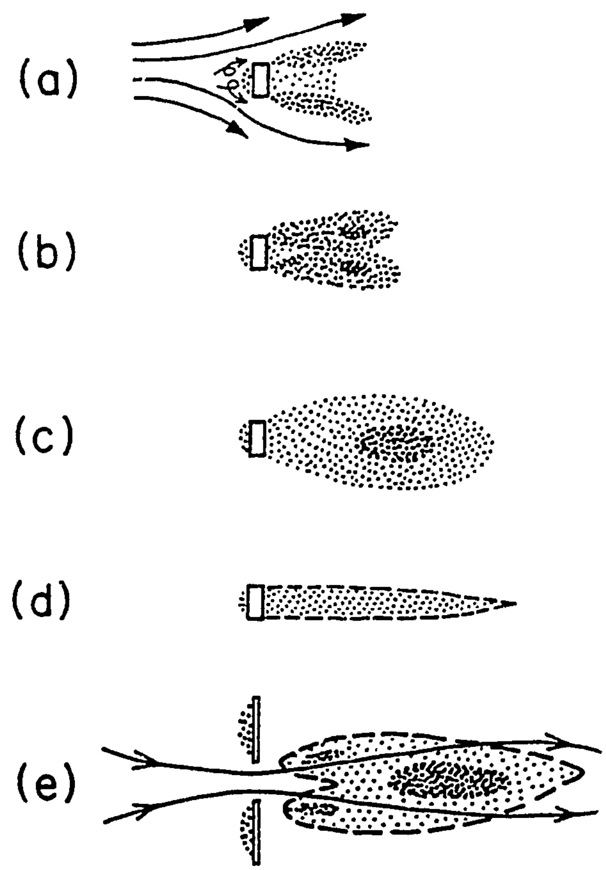


Fig. 2.2 Development of lee or shadow dunes. (Source: Pye and Tsoar, 1990, Fig. 6.9)

Primary dunes are those dune forms which develop as a response to sediment accumulation derived directly from the beach. This type can be further sub-divided based on importance of vegetation. Free dunes are those forms whose development is not directly related to the presence of vegetation. This includes barchans, transverse ridges, and oblique ridges. These dunes are wind orientated and lie perpendicular to the prevailing wind direction. Impeded dunes, such as foredunes, require vegetation for their development. They commonly lie parallel to the beach, and are orientated around the nucleus from which they first formed (Davies, 1973).

Secondary dunes are formed as a result of erosion of primary impeded dunes, and can be sub-divided into transgressive, or remnant dunes. Transgressive dunes are wind orientated and usually lie parallel to the direction of the prevailing wind. The resultant dune forms include blow-outs, parabolic dunes, and longitudinal dunes. Remnant dunes are the eroded remains of well established vegetated primary dunes (Davies, 1973).

Davies (1973) realized that the categories of the classification scheme were not mutually exclusive. It was explained that the classes may not always be fully separate as the scheme may have suggested. However, the classification did meet the needs for a uniform terminology, and according to Giles (1992) in his study of coastal dunes on the Magdalen Islands, Davies classification is the most applicable to coastal dunes.

Goldsmith et al., (1977a) produced a genetic classification which divides all coastal dunes into four basic types: vegetated, artificially inseminated, medanos, and parabolic. A fifth unnamed category, includes other dune forms such as lunettes and eolianites, but these forms are relatively rare in occurrence compared to the other four dune types (Goldsmith et al., 1977b). This system has been termed the "VAMP" classification based on the first letter of each dune type (Goldsmith, 1985).

Vegetated dunes are the most common type, and are usually in the form of foredune ridges (Goldsmith, 1985). Artificially inseminated dunes have an anthropomorphic origin, but the transport and accumulation processes are natural. They can be accidentally inseminated, in which the seed or nucleus of formation is an obstacle not intended to stimulate dune growth such as an abandoned beach house, or insemination can be planned by techniques such as bulldozing, snow fencing, or beach grass planting (Goldsmith, 1977b). The third type, medanos, are large isolated unvegetated sand hills ranging in elevation from 10 to 100 meters. They are asymmetrical in profile and migrate downwind. Parabolic dunes are similar to medanos in form, but are different in internal geometry. The internal geometry of a parabolic dune is more characteristic of a vegetated dune, which will be further explained in a later section.

Several methods for classifying foredunes have been documented. Rosen (1979) studied the morphology of a barrier island along the New Brunswick coast and observed two very distinctive forms: accretional, and erosional dunes. Accretional dunes have a gradual seaward slope, grow vertically, propagate seaward (Rosen, 1979), and have a positive sediment budget (Giles, 1992). Erosional foredunes exhibited a significant vertical wave-cut scarp, they undergo landward retreat (Rosen, 1979), and have a negative sediment budget (Giles, 1992). The wave-cut scarp prevents landward sediment transport. Vertical growth will not occur unless the scarp is filled in.

A series of studies by Hesp (1983, 1984, and 1988) focused on foredune development and classification. In an attempt to link dune morphology with ecologic, aerodynamic, and transport processes, Hesp (1983) defined two types of foredunes which occur on the backshore zone of sandy beaches. "The initial foredune formed by the trapping of sand within a pioneer vegetation species" (Hesp, 1983, p. 325) was termed an incipient foredune. Established foredunes differ in vegetation types, and are colonized by shrubs and trees (Hesp, 1984).

Further investigation (Hesp, 1984) determined four modes of incipient foredune formation based on vegetation type, and accretion around vegetation rhizomes or seedlings. Examples of each type in Southeast Australia were thoroughly documented (1984). Several years later Hesp (1988) introduced another foredune classification for the same study area, but this time based on percentage of vegetation cover. This classification went well beyond the incipient versus established classification previously introduced. Hesp (1988, p.20) identified five morphologic stages of development and found that "the morphological organization switches from being dominated by vegetation (fixed, shore-parallel ridges) to one characterized by wind forms (free, barchan or sand wave dunes)", shown in Fig.2.3.

All of the classifications systems are quite helpful since they give researchers a set of terminologies to use when referring to dunes, and they also provide additional information associated with each dune type. For example, each system groups similar dune forms into distinctive categories or types based on factors such as vegetation cover, dune form, and dune formation in terms of wind regime, source of sediment, and the sediment budget. Therefore, background knowledge of the classifications and the criterion used for classifying, can provide researchers with background information characteristics to each dune type.

The early classifications produced by Melton (1940) and Hack (1941) were successful attempts to classify all dune forms. Although, each of the two systems are generally not used in their entirety, they did set the framework for the classifications to follow.

The classification system developed by Davies (1973) is the most useful method of classifying coastal sand dunes. It is simple, informative, and incorporates all seven coastal dune types previously classified by Smith (1954). Davies method provides information regarding the stage of coastal dune development, in that primary dunes are the first dune forms, and secondary dunes are erosional features. The further sub-division of primary dunes also provides valuable information regarding the presence of vegetation.

The foredune classification systems produced by Hesp (1983, 1984, and 1988) are quite extensive and based on a variety of criterion. These classifications are more difficult to use but encompass a greater number of criteria.

2.3 Beach-dune Nomenclature

Discussion concerning the beach system should include a brief explanation of those terms to be used throughout the duration of this paper. Several techniques to delineate each of the beach system zones have been presented in the literature (King, 1959; Davies, 1973, Pethick, 1984; Sherman and Bauer, 1993). King (1959) provided an early useful approach, however, for the purpose of this paper a more up-dated method of depicting beach zones will be presented.

Figure 2.4 illustrates the beach-dune system with the associated sub-environments presented by Sherman and Bauer (1993). The beach zone consists of the backbeach and the foreshore. The backbeach or backshore, extends from the beginning of the dune system out to the upper limit of swash motion. Sherman and Bauer (1993, p.415) defined the foreshore as "the upper limit of swash motion out to the upper limit of the nearshore ". The surfzone is the region from the "top of the foreshore out to and including the zone of breaking waves" (Sherman and Bauer, 1993, p.415), known as the nearshore zone. The offshore zone is the area which extends seaward from the outer limit of the nearshore zone.

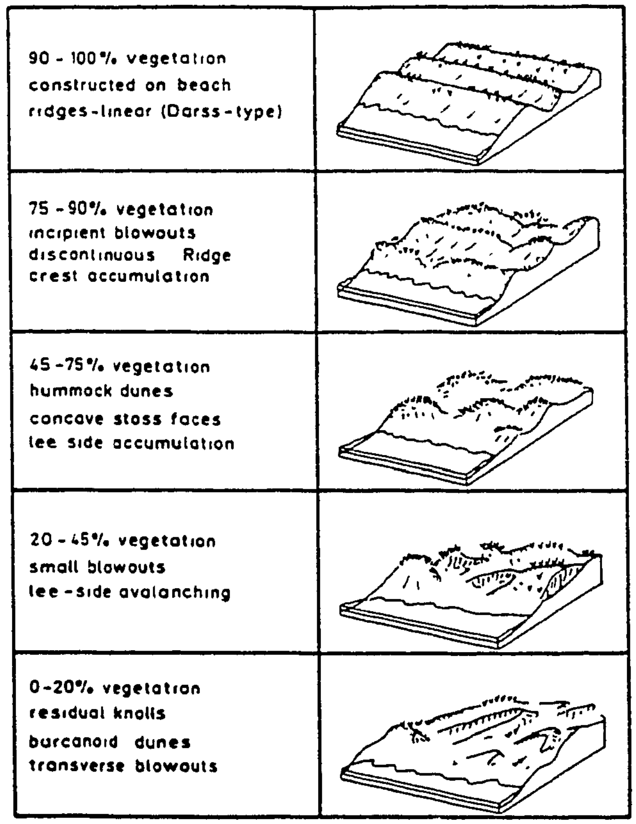


Fig. 2.3 Classification of coastal dune types based on the proportion of vegetation cover. (Source: Carter, 1988, Fig. 160)

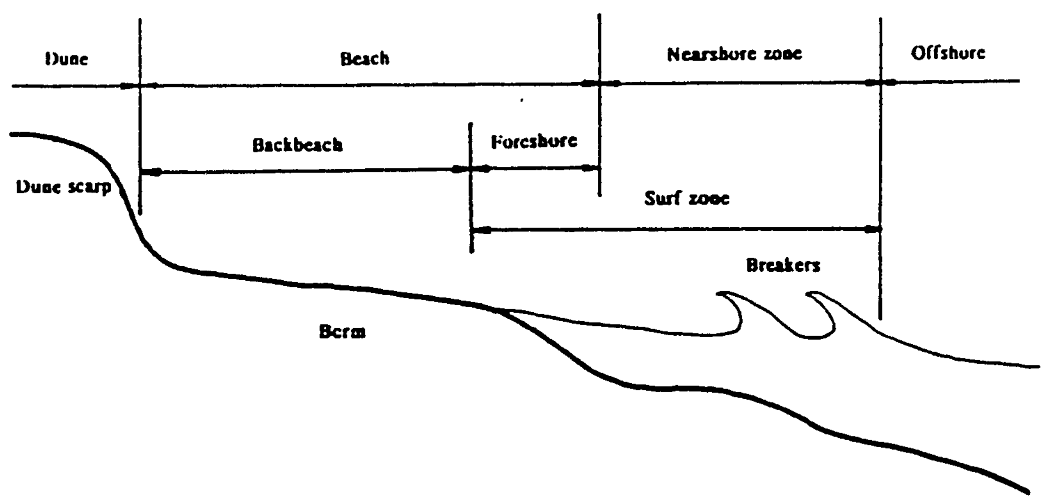


Fig. 2.4 Sketch showing the beach-dune systems with subenvironments. (Source: Sherman and Bauer, 1993, Fig. 2)

2.4 Beach System Classifications

King (1959) provided a classification system which was based primarily on the character of the beach material. Beaches could be first categorized into shingle or sand beaches. Shingle beaches were steep with little variation in profiles overtime. Compared to sand the sediment source of a shingle beach was well rounded and very well sorted. Sand beaches were less steep, sand dominated, and exhibited more variety in profiles. King further sub-divided sand beaches into those affected by tides and those that were tideless. Tidal sand beaches displayed smooth profiles, or ridged profiles and could therefore be divided even further. Tideless beaches were either smooth in profile, or demonstrated crescentic or straight bars in profiles.

King (1959) acknowledged that there are numerous beaches which are predominantly sand, however contain small amounts of shingle material. These beaches can still be classified as sand, provided that the greater part of their width at low water level is sandy.

Wright et al., (1979) conducted studies in Southeastern Australia, and recognized that the dynamics of water motion on the beach changed depending on whether the incident wave was reflected, or broke and propagated onshore. It was therefore determined that two general types of beach systems occurred. The terms reflective and dissipative, which Wright et al., (1979) adapted from Guza and Inman's (1975) study of edgewave and beach cusp formation, were used to describe the beach types.

A reflective beach system occurs when the incoming energy of the incident wave is reflected from the beach face. The resultant beach form is "characterized by steep, linear beach faces, well developed berms, beach cusps, and surging breakers as defined by Galvin (1972)", (Wright et al., 1979, p.110).

Galvin explained the terms for three main breaker types which have been in use since about the late 1940's. They are spilling, plunging, and surging breakers. A fourth type, the collapsing breaker, was described by Galvin as a relatively newer term. See Fig. 2.5.

Dissipative beach systems exhibit wide surfzones and high turbulent energy dispersion of incoming waves. Much of the energy is dissipated before reaching the beach as waves break up to several hundred meters seaward of the beach (Wright et al., 1979). Furthermore, Wright et al. (1979) determined that six morphologic types of dissipative beaches exist; the first type having the greatest total dissipation. Energy dissipation decreases through the remaining five types, with type six representing a fully accreted beach state.

Short (1981) added the term rhythmic, which was adapted from Hom-ma and Sonu (1962) in their study of the relationship between longshore bar pattern and sediment characteristics, to represent an intermediate stage between the high energy dissipative beach, and the lower energy reflective beach. According to Short, rhythmic beaches are distinguished by rip circulation, transverse and crescentic bars, and megacusps. All of which produce the characteristic rhythmic longshore variation in beach morphologies.

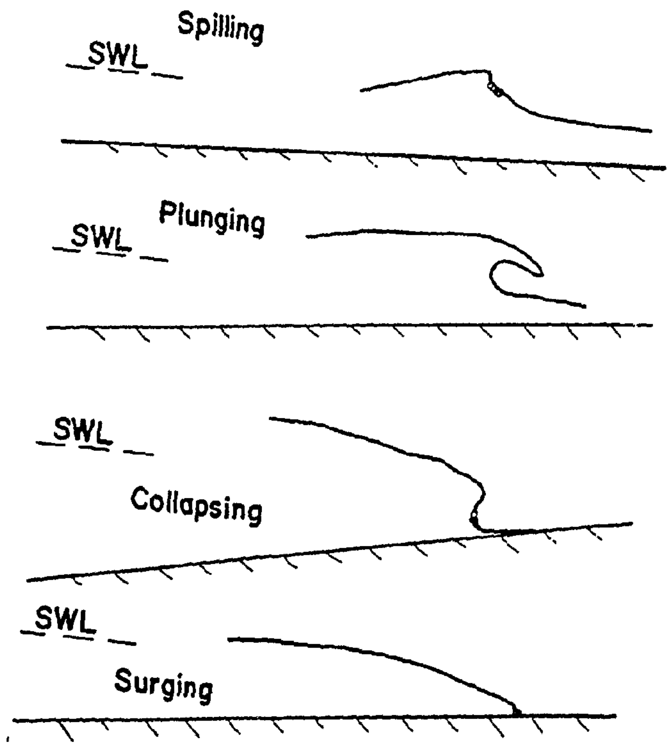


Fig. 2.5 Cross sections of four breaker types. (Source: Galvin, 1972, Fig.4)

Short (1981) explained that field and laboratory experiments on eroding and accreting wave conditions have been numerous and well documented. High storm wave conditions cause beach cuts and seaward transport of beach material into the surfzone resulting in a lowering of the beach profile. Low waves or long waves allow for onshore sediment movement and beach fill which produces a steeper profile than that produced by high waves. Short (1981) was interested in looking at the morphological beach responses to actual changes in breaker heights. By analyzing the variability in temporal changes, which are associated with variations in breaker height and the resulting sediment transport and beach profile changes, and spatial changes, which are associated with alongshore variation in beach profile, Short was able to quantify beach mobility and stability. Using terms previously established, Short categorized beach response into three types based on wave energy or breaker height. Low wave energy reflective beaches occur where breakers are less than 1 meter in height. Moderate energy rhythmic beaches require breakers between 1 to 2.5 meters. High energy dissipative beaches occur where the breaker height exceeds 2.5 meters.

Short and Hesp (1982) expanded on these findings by analyzing not only the wave-beach environment, but they also included the response of the dune system. Dissipative beaches, where potential on-shore sand transport is at a maximum, are usually characterized by large transgressive dune fields. Reflective beaches exhibit the smallest aeolian forms, because on-shore sand transport is at a minimum. Some minor amount of beach erosion can also occur. These beaches develop foredunes which are often scarped, and from which occasional small scale blowouts may develop. Furthermore, the once termed "rhythmic" beach was more appropriately named intermediate beach. This beach type occupies states between fully dissipative, and fully reflective, and therefore, exhibits a wide range of morphologies. Short and Hesp (1982) found it necessary to sub-divide the intermediate beach into high, moderate, and low energy, on the basis of modal wave height, beach form, and zones of sediment storage. In general, intermediate beaches are characterized by large scale parabolic dune systems during high wave energy, and small scale blowouts when wave energy is low.

2.5 Aeolian Transport Processes

The processes of sediment entrainment and transport by wind on beaches results from the complex interaction between air forces, ground variables, and sediment characteristics (Nickling and Davidson-Arnott, 1990). The combination of these interactions can act to promote or resist entrainment. However, because the interaction between these variables is so complex, their relationships are often not well defined (Nickling and Davidson-Arnott, 1990). An understanding of air, ground, and sediment may begin with analysis of shear stress and the associated wind profile.

2.5.1 Shear Stress

During aeolian sediment transport, the fluid, or air, provides the force acting on the sediment grains lying on the bed. The relative amount of force provided by the air depends on the air velocity and viscosity (Pethick, 1984). This will now be explained.

When air blows across a stationary bed of solid particles, friction arises between the two matters. The zone of frictional forces is confined to a thin layer adjacent to the bed which has been previously termed the "boundary layer" by Ludwig Prandtl in 1904 (Allen, 1994). At the bed, there is no flow as the air is unable to slip over the immobile bed. Air above the thin layer of zero flow does move, however, very slowly (Pethick 1984). The friction caused by the bed's resistance to flow is transmitted upwards through the layers, or streamlines, within the air. As each layer slides or shears over the one below, the velocity of the shearing layer increases upwards because the resulting friction is reduced (Pethick, 1984). The result is an equal and opposite force applied by the wind flow to the bed known as the shear stress, and may be determined by a plot of the velocity curve (Pethick, 1984). The shear stress is the tangential force per unit area (Allen, 1994), and is given as:

$$\tau_o = \mu \frac{du}{dz} \qquad (2.1)$$

where τ_0 = shear stress at the bed
μ = air viscosity
du/dz = the velocity gradient

and is therefore, related to both the air viscosity, and the velocity profile (Pethick, 1984). However, this relationship only holds true for a laminar flow in which the layers of air flow parallel to one another over the bed (Nickling and Davidson-Arnott, 1990). In a laminar flow the layers are never intertwined, and are highly ordered in appearance (Allen 1994).

For flow conditions of faster velocities, and lower viscosity, the flow within the boundary layer becomes retarded and the air particles begin to move in random eddies (Pethick, 1984). The flow shifts from stable laminar to unstable turbulent flow.

The presence of turbulent eddies which change in size, shape, and velocity structure from one instant to another, causes the streamlines within the flow to become intertwined with no general pattern except that which may be averaged over a sufficiently long time (Allen, 1994). As a result of turbulent mixing, the flow of energy throughout the boundary layer is quite different than laminar flow, causing the velocity profile to exhibit a more abrupt increase with height. Furthermore, the viscosity of the air is also altered due to resistance to shear stress caused by the existence of turbulent eddies (Pethick, 1984).

The shear stress for a turbulent boundary layer is now modified to:

$$\tau_o = (\mu + \eta)\frac{du}{dz} \tag{2.2}$$

where τ_o = shear stress at the bed (turbulent)
μ = air viscosity
η = eddy viscosity caused by turbulence
du/dz = the velocity gradient

Since, "most natural currents are turbulent" (Allen, 1994, p.33), the remaining discussion will be concerned with these airflow conditions.

2.5.2 Wind Profile

Within the turbulent atmospheric boundary layer, which was determined to be approximately 50 meters high by Ayra in 1982, wind velocity increases logarithmically with height (Giles, 1992). The velocity profile can be described by the Prandtl-von Karman Equation (Nickling and Davidson-Arnott, 1990). The wind gradient equation is expressed as:

$$\frac{U}{U_*} = \frac{1}{k}\ln\left(\frac{z}{z_o}\right) \tag{2.3}$$

where U = wind velocity at height z (m/sec)
U_* = friction or shear velocity (m/sec)
z = height above the bed (m)
z_o = roughness length (m)
k = von Karman's constant (= 0.4)

This equation includes the height above the bed at which wind velocity is reduced to zero by resistance to flow and is given as z_o. This height has been termed the "effective surface roughness length" by Olson (1958), and is a parameter used to measure the aerodynamic roughness of the surface. For bare sand surfaces, z_o has been found by numerous investigators to be approximately equal to 1/30 the mean grain diameter, but varies with the slope and average distance between individual grains or other roughness elements (Nickling and Davidson-Arnott, 1990). See Fig. 2.6.

The wind gradient equation also incorporates shear velocity given as U_*. Shear velocity is proportional to the slope of the wind profile when plotted with a log-height scale, and is related to the shear stress (τ_o) and the air density (ρ_o). Shear velocity is determined by:

$$U_* = \sqrt{\frac{\tau_o}{\rho_a}} \qquad (2.4)$$

where ρ_a = air density (kg/m^3)

The previous wind gradient equation was given for a bare surface, but in coastal sand dune studies the sand surface is rarely bare or free of obstacles. Where the

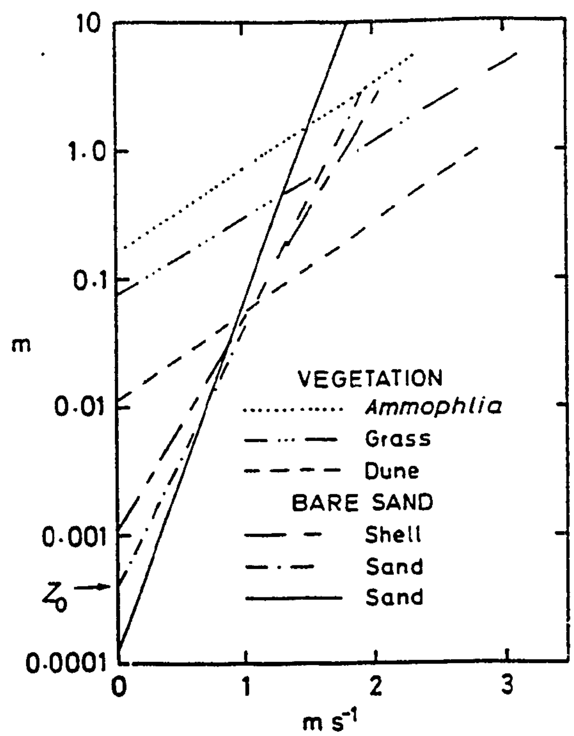


Fig. 2.6 Logarithmic wind velocity profile across different dune surfaces. Note the change in roughness and the height of Z_o. (Source: Carter, 1988, Fig. 156)

surface is covered by tall vegetation or similar roughness elements, the wind velocity profile is altered. The profile becomes "displaced upwards from the surface to a new reference plane which is a function of height, density, porosity, and flexibility of the roughness elements" (Nickling and Davidson-Arnott, 1990, p.5). The displacement is termed the "zero plane displacement height" given as, d. Under these conditions the wind profile equation becomes:

$$\frac{U}{U_*} = \frac{1}{k}\frac{(z-d)}{z_o} \qquad (2.5)$$

where d = zero plane displacement height (m)

2.5.3 Sand Grain Entrainment

Sand grains at rest will begin to move off a stationary horizontal bed when the forces of shear and lift, caused by the wind flow, exceed the opposing forces of grain weight, cohesion, and adhesion (Pethick, 1984).

The shear force or drag acts horizontally in the direction of wind flow. It is composed of overall skin friction drag caused by the roughness of the grain on the bed, and form drag which is related to the geometry of the bed itself. Form drag results from positive pressure on the upwind side of the sand grain and negative pressure on the downwind side. The air stress, which acts tangentially to the grain surface, is the skin friction drag (Pye and Tsoar, 1990).

The lift force, which acts vertically upwards or perpendicular to the bed, is the resultant pressure difference between the upper and the lower sides of the sand grain. On the upper side, the pressure is reduced below the static pressure because of the curvature of the streamlines within the wind, and the increased velocity above the grain relative to the lower side (Streeter, 1961).

Compared to shear stress, the lift force has been difficult to define, however, lift can be identified using the Bernoulli equation (Allen, 1994). This equation states that pressure head, plus elevation head, plus velocity head equals a constant. If any one variable changes, another must in order to maintain the balanced equation. A sand grain lying on a stationary bed under the influence of a steady uniform wind flow can be considered to be at a constant elevation. Therefore, lift will occur as a result of the differences in pressure surrounding the grain due to velocity differences (Einstein and El-Samni, 1949).

As the grain leaves the bed, because of lift, there will be a tendency for the wind flow pattern around the grain to become equalized. This causes a subsequent decrease in the lift and a tendency for the particle to fall back towards the bed (Einstein and El-Samni, 1949).

Of the resisting forces, grain weight which acts directly opposite to the lift force is the most important (Pye and Tsoar, 1990). Cohesive forces between grains, and adhesive forces between grains and other surfaces, are considered significant resisting forces, and are of greatest importance for fine grains (Pye and Tsoar, 1990). For example, interparticle cohesion and adhesion is significant in warm sunny climates where at low tide the sand grains are exposed. They can develop a sticky surface film of algae or bacterial mucilage. Grains can also develop a coating precipitate which remains after the evaporation of overnight dew. As a result of an "unclean" grain surface, greater wind forces are needed for particle entrainment than if the sand surface was "clean" (Allen, 1994). Adhesive and cohesive opposing forces are minor in relative importance and can normally be ignored, which leaves the grain's immersed weight as the primary resisting force (Allen, 1994).

2.5.4 Determination of Particle Threshold

Beach sand will begin to move when the forces of lift and shear caused by the wind overcome resistance to motion. Wind shear is the primary force involved in initiating grain movement (Pye, 1983). However, what magnitude of shear stress is necessary to entrain grains of a given size? A problem arises in that it is difficult to gain universal agreement as to what constitutes entrainment. In general, it has been accepted that entrainment has occurred "once the flow conditions permit a sustained and general grain motion" (Allen, 1994, p.53).

The threshold of entrainment, or the point at which grains begin to move, has been measured in terms of critical shear velocity (Bagnold, 1941).

Bagnold developed an expression to define critical shear velocity and determined that it is dependent on grain size and density (Pye, 1983):

$$U_{*}^{c} = A\frac{\sqrt{\sigma-\rho}}{\rho}gd \tag{2.6}$$

where U_{*}^{c} = critical shear velocity (cm/sec)
ρ = air density (1.22×10^{-3} g/cm^3)
σ = grain density (2.65 g/cm^3 for quartz)
g = acceleration due to gravity (980 cm/sec^2)
d = mean grain diameter (cm)
A = a coefficient whose value is = 0.1 in air and for grains > 0.2mm in diameter

When there are sand grains already in motion, lower wind velocities will sustain sand movement. The sand grains in transport will dislodge those grains lying at rest on the surface. Under these conditions the value of A in Eg. 2.6 will decrease to 0.08, "as a result of increased momentum transfer by impacting grains" (Sherman and Hotta, 1990, p.20).

Subsequent investigations have shown that the critical threshold velocity (shear velocity) is also affected by moisture content, binding agents, surface roughness, and sediment sorting (Pye, 1983). As documented by Pye (1983), Johnson (1965) and Belly (1962) experimentally determined that moisture contents greater than 1 % sufficiently increase the critical threshold velocity.

Johnson modified Bagnold's (1941) equation to incorporate the effect of moisture content as follows:

$$U_*^c = A\frac{\sqrt{\sigma-\rho}}{\rho}gd(1.8+0.6\log_{10}W) \quad (2.7)$$

where W = percent moisture content

Once the critical shear velocity has been reached, with or without the consideration of moisture content, the stationary grains begin to move. As a result of the direct pressure of the wind flow, the grains will begin to roll, slide, or hop downwind (Nickling and Davidson-Arnott, 1990).

2.5.5 Modes of Sand Transport

Once the critical threshold has been exceeded, sand grains will begin to move in one of three modes depending primarily on grain size: saltation, suspension, and surface creep (Pye and Tsoar, 1990), see Fig. 2.7.

Sand transport by saltation occurs for relatively large grains ranging from 70 to 500 µm in diameter (Nickling, 1994). Once the grain has been lifted off the bed it enters into increasingly faster wind velocities. After reaching a maximum height, the grain is carried by the wind, where it is accelerated until it reaches the same velocity as the surrounding wind. The grain will follow a smooth trajectory, the

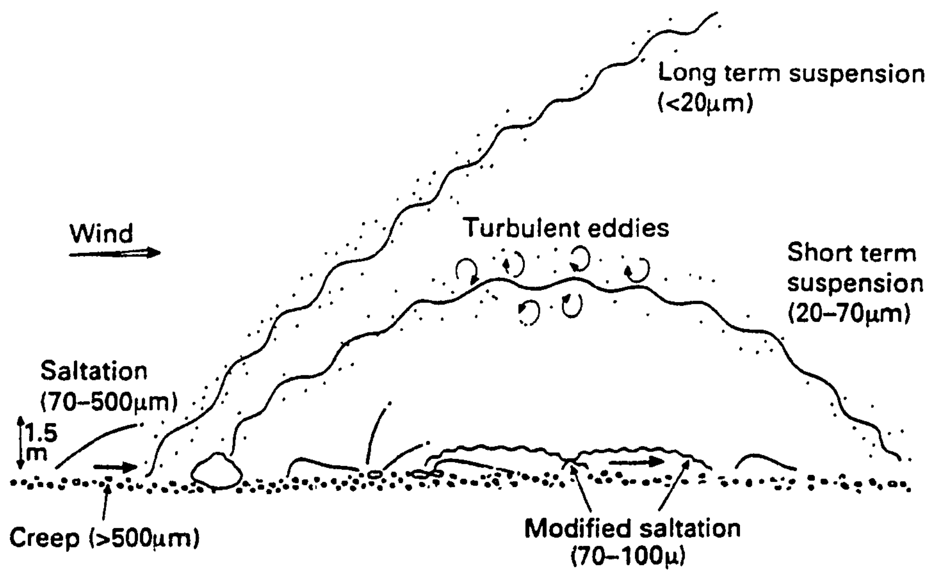


Fig. 2.7 Modes of sediment transport by wind. (Source: Nickling, 1994, Fig. 9.20)

saltation trajectory, while it begins to fall back to the surface. On the beach, saltating sand grains may rise up to 1.5 meters before they begin to fall back to the surface (Nickling, 1994). Once at the surface the grain may become imbedded into the surface, or impact and "explode" other sand grains into the wind stream, and these grains may continue the saltation process (Pethick, 1984).

Transport by suspension occurs for very small sand grains ranging from < 60 to 70 μm in diameter. They are kept in suspension for long distances by the upward turbulent eddies in the wind flow (Nickling, 1994). The fine grains rise, become suspended, and may be eventually blown away from the beach and dune system (Pethick, 1984).

As noted by Nickling (1994), Tsoar and Pye (1987) distinguished between long-term suspension for those grains which remained aloft for long periods of time, and short-term suspension for sometimes larger particles which settle back to the surface relatively quickly.

Modified saltation is a transitional process between true suspension and pure saltation. It is characterized by random grain trajectories, and is therefore, a function of grain size. True suspension occurs when the settling velocity, "velocity a particle of given diameter will fall in a still fluid", is relatively small compared to the shear velocity of the wind (Nickling, 1994, p.309). When the turbulent vertical component of velocity has no notable effect on the saltation trajectories, pure saltation has occurred (Nickling, 1994).

Surface creep is a transport process resulting from the impact of descending saltating grains. When a saltating grain falls back to the surface it may hit larger grains, > 500 μm, which are too heavy to begin saltating themselves, therefore they are pushed or rolled along the sand surface (Nickling, 1994).

Of the three modes of transport, saltation is the primary process responsible for sand dune formation. Bagnold (1941) determined that saltation was typically responsible for 75 % of the total volume transported. Approximately 25 % of the total volume is transported as surface creep, and only a trace amount is carried in suspension (Pethick, 1984).

The combined effect of saltation and creep results in the sorting of sand based on size. The finer grains in saltation move much further and quicker than the larger grains involved in surface creep which tend to move slower and over shorter distances (Pethick, 1984).

2.5.6 Wind Profile During Saltation

Sand transport by saltation distorts the wind profile near the sand surface by causing an increase in surface roughness. As discussed by Sherman and Hotta (1990), Bagnold (1941) found that the velocity profiles with their associated shear velocities, converged at a focal point. "No matter how great the velocity gradient, the wind velocity at a height of about 3 mm remains almost the same" (Bagnold, 1941, p.59). During saltation, the focus height is displaced upwards to a new height, z_{ot} which is greater than the previous roughness height given as z_o.

Therefore, the basic velocity gradient equation, Eq. 2.3, may be rewritten to incorporate the effect of saltating grains. The equation now becomes:

$$U(z)=\frac{U_*}{k}\ln\left(\frac{z}{z_{ot}}\right)+U_t \qquad (2.8)$$

where z_{ot} = focus height of wind speed during saltation (m)
U_t = threshold wind speed at z_{ot} (m/sec)

2.5.7 Sand Transport Equations

Numerous equations for estimating the rate of sand transport have been introduced and are reviewed by Pye and Tsoar (1990). Some of the methods are based on theoretical principals while others are based on experimental modelling. In most equations presented, the sand transport rate is represented by q, with the units of mass per width per unit time (Pye and Tsoar, 1990).

Hsu (1971, 1973) introduced a method for determining the rate of aeolian transport for commonly occurring sand sizes. From the linear relationship between shear velocities and wind velocities a "special Froude number", Fr, was established. It expresses the relationship among wind stress, acceleration due to gravity, and mean grain size.

The Froude number multiplied by a sand transport coefficient results in determination of the rate of sand transport and is expressed as:

$$q = K \cdot Fr^3 = K\left(\frac{U_*}{(gD)^{1/2}}\right)^3 \tag{2.9}$$

where q = rate of sand transport by wind (g/cm/sec)
K = aeolian sand transport coefficient (g/cm/sec)
U_* = shear velocity (cm/sec)
g = acceleration due to gravity (cm/sec^2)
D = mean grain diameter (cm)

Hsu (1971, 1973) incorporated a value, K, and defined it as the dimensional aeolian sand transport coefficient, and has the same dimensions as q. The coefficient K, is a function of mean grain size of sand, D, as shown in Fig. 2.8.

2.6 Coastal Sand Dune Formation

Coastal sand dune formation becomes a function of aeolian transport processes once a sediment source becomes available for transport. This will now be explained.

2.6.1 Waves and Nearshore Currents

Wave processes are primarily responsible for sediment erosion, transport and deposition in the beach and nearshore zone, and are therefore indirectly related to the sediment supply for sand dune growth (Fisher et al., 1987).

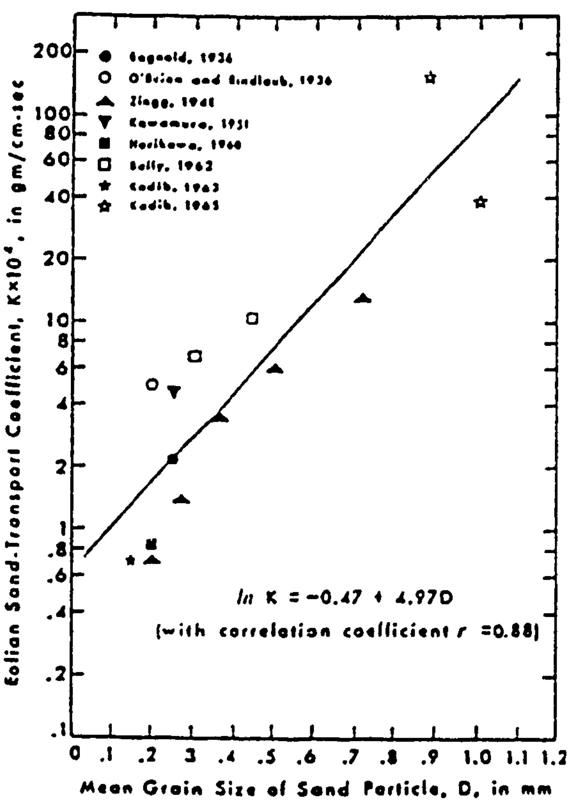


Fig. 2.8 Determination of aeolian sand transport coefficient, K, from known mean grain size. (Source: Hsu, 1971, Fig. 3)

Waves develop from the transfer of wind energy to the water surface. Within the waves, water particles near the surface move in circular orbits with diameters equal to the wave height. Below the surface the circular orbit continues, however, their diameters will decrease with depth until they disappear, at a depth of 0.5 of the wavelength. In deep water the orbital movement does not affect the sea bed, and the individual waves move at speed which equals 1.56 times the wave period (Fisher et al., 1987).

Waves become geomorphically significant once they enter shallower water, where their orbital motion intercepts the bed causing frictional resistance. The orbital motion of the waves is the primary force leading to sediment transport in the beach and nearshore zone, and is affected by nearshore zone currents which move sediment on and offshore (Fisher et al., 1987). A full detailed analysis of wave processes has been documented by Pethick (1984) and therefore will not be discussed here.

Three types of currents in the nearshore zone control the on-offshore sand transport: the net drift velocity under waves, rip cell circulation, and undertow. Net drift velocity is a net displacement in the direction of wave advance caused by the orbital motion of waves. This results in the movement of sediment onshore towards the beach, and is opposed, somewhat, by gravitational forces which move sand grains downslope or offshore. Undertow and rip-cell circulation result as a response to short term water level fluctuations caused by wave set-up. Wave set-up results from the excess of energy and water brought into the breaker and surf zones by breaking waves. Water becomes "piled up" against the beach, increasing the water level. The increase in water level forces water offshore in the form of undertow or rip currents. Undertow currents are weak currents which occur uniformly along the beach in the lower portion of the water column. Rip-cell circulation develops with feeder currents which flow alongshore and turn offshore in narrow high velocity rip currents which extend from the bed to the water surface (Fisher et al., 1987). Rip and undertow currents act to balance out the rate of input of water to the surfzone with the output. Both currents move sediment offshore and balance the sediment transported onshore by the net drift velocity (Fisher et al., 1987).

2.6.2 Controls of Dune Development

Coastal sand dunes may develop where there is an adequate sand supply, sufficient winds to move it, and vegetation capable of initial stabilization (Carter, 1988). Since the beach environment can be a very dry harsh environment, vegetation must also be tolerant to rapid sand accumulation, water table fluctuations, wind and water erosion, wide temperature fluctuations, and low nutrient levels (Fisher et al., 1987).

Coastal dune sands range in mean sediment size from 0.2 to 2.0 millimetres (Carter et al., 1990), and are typically medium to fine grained, and well-sorted to very well-sorted (Pye, 1983).

The processes involved in dune formation begin when marine sand is transported to the beach from the nearshore by wave action. On the beach the sand becomes exposed to the air, may be dried, and can be entrained by onshore winds, provided that they exceed the entrainment threshold for the sediment size. Tidal range becomes of importance in that a high range exposes a large intertidal zone which dries out between tides, providing a major source of wind blown sand. Where tidal range is low, the aeolian sand source becomes limited to sediment which is transported and deposited by waves around storm limits (Carter, 1988).

2.6.3 Development of a Foredune

The first dune which forms is called a shadow dune, or embryo dune, and has been thoroughly investigated by Hesp (1981). Shadow dunes are triangular shaped bedforms which develop when winds transporting beach sand onshore come in contact with vegetation, which is typically clumps of pioneering dune grass. Saltating sand becomes trapped within the grass as momentum is transferred from the wind to the vegetation (Fisher et al., 1987).

Fig. 2.9 illustrates the three-dimensional wind flow around a vegetation clump. On the sides of the grass the wind speed increases, as shown by the streamlines, while on the lee side the velocities decrease to zero and then rise slowly downwind. As a response to the wind flow pattern around the grass, sand is eroded from the sides and deposited to the lee of the grass where velocity is at a minimum (Pethick, 1984). Depending upon the shape of the grass and its porosity, a convex, semicircular bedform within the vegetation is formed. Deposition around the

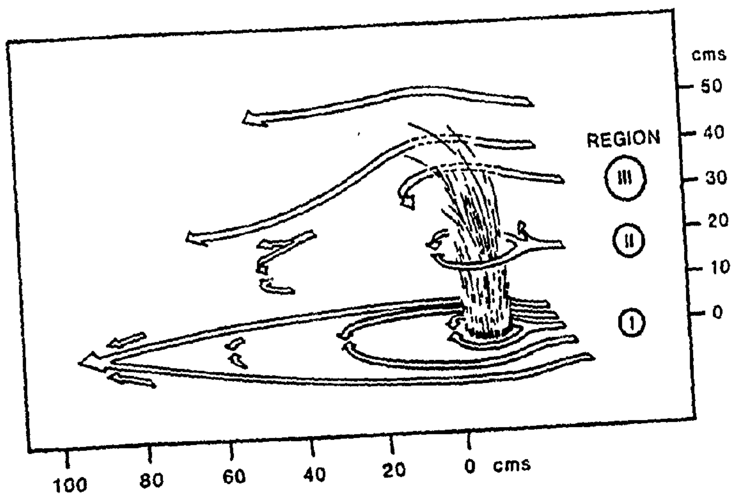


Fig. 2.9 Three-dimensional diagram showing the flow path past a dune grass plant. (Source: Hesp, 1981, Fig. 2)

bedform will continue until it reaches a critical height where porosity is reduced, thereby transforming the grass clump into a barrier to wind flow (Fisher et al., 1987). The zone of maximum deposition occurs at the mid-plant centerline behind the grass. Here, reverse flow within the horizontally separated wake region cause opposing vortices to collide, resulting in maximum deposition (Hesp, 1981).

Vegetation or some semi-circular, semi-permeable obstacle is a necessary requirement for shadow dune formation, and also controls the size and dimensions of the developing dune. Shadow dune height is dependent on the repose angle of the sand, which is typically 27- 34 degrees (Hunter, 1977), and the basal width of the vegetation. Shadow dune length is dependent on the basal width of the vegetation, and the wind velocity (Hesp, 1981).

The first stage in foredune development is the formation of multiple shadow dunes to the lee of pioneer dune grass. Over time the shadow dunes will grow laterally and eventually coalesce to form an incipient foredune which is approximately 2 meters high and parallel to the shoreline. Related to foredune development is a change in vegetation type. It shifts from an intermittent pioneering grass species typical of shadow dune formation to a major dune species such as marram grass which is capable of reaching the water table through greater depths as dune height increases (Pethick, 1984). The newly formed foredune will continue to grow in size as vegetation increases in height and density (Fisher et al., 1987).

It is important to note that coastal dune formation is a spatial sequence of dune succession. As developed shadow dunes begin to coalesce into a foredune ridge, new shadow dunes are forming parallel to the ridge (Pethick, 1984).

The foredune ridge will migrate landward as a result of erosion and deposition caused by the wind flow pattern over the dune form. The dune form on the windward side causes an acceleration of wind over the dune until it reaches a maximum on the dune crest. Sand from the stoss side and crest is entrained and deposited downwind on the lee side where the dune form causes a divergence and flow separation of the wind. The processes of erosion and downwind deposition cause the foredune to migrate landward from the shoreline.

2.6.4 Formation of a Parabolic Dune

Parabolic dunes form by blowout formation in the foredune ridge or by disruption of vegetation on older sand deposits (Pye, 1983).

Parabolic dunes may begin to form on areas of the foredune where vegetation from the crest has been removed by trampling, overwashing, flooding, a drop in the water table, or some combination of these factors (Fisher et al., 1987). Once the dune surface is bare, wind may scour away the sand creating a large depression in the dune crest, called a blowout (See Figure 2.10). Wind can be channelled through the lowered crest causing an increase in wind velocity which further erodes the sand surface. As erosion continues the size of the gap in the dune crest is increased and the once straight dune form begins to bulge out (Pethick, 1984). Sand eroded from the depression migrates downwind and accumulates in a concave U-shaped form with vegetated sides still intact to the foredune. This

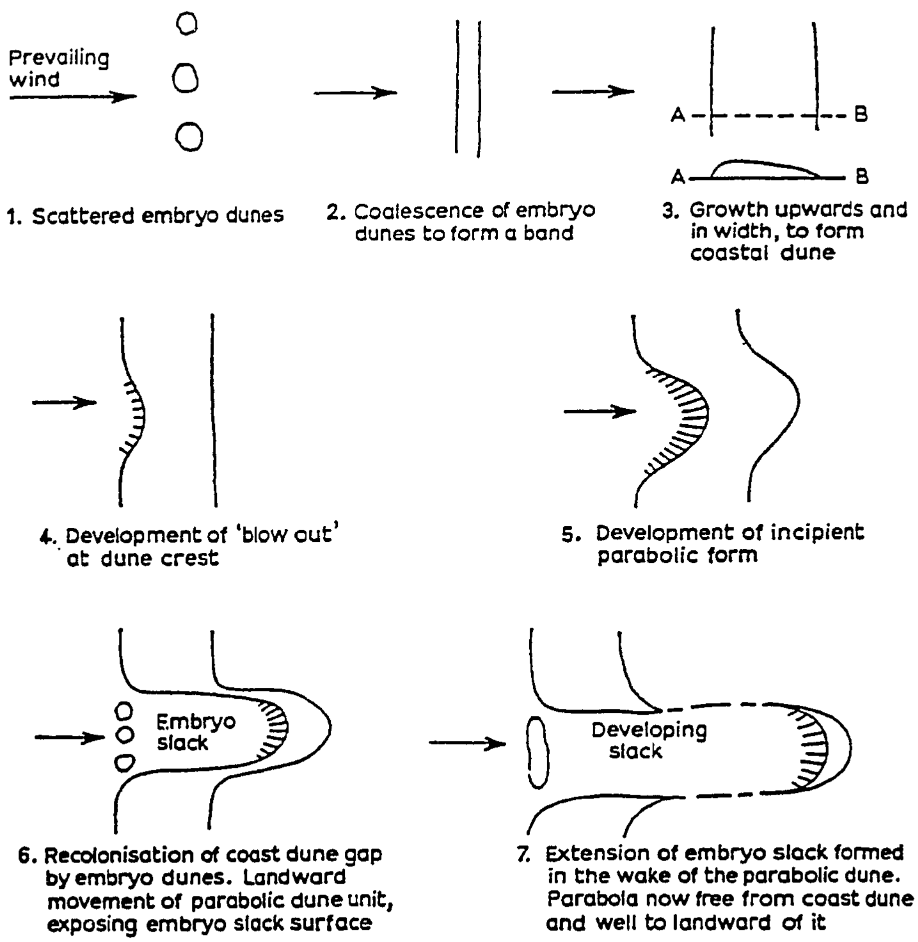


Fig. 2.10 The formation and development of a parabolic dune. (Source: Ranwell, 1972, Fig. 50)

process continues until the landward tip breaks off, leaving the sides parallel to the wind direction. The parabolic dune develops its characteristic form as the center of the U shape migrates downwind, while the sides remain anchored by the vegetation cover (Pethick, 1984).

2.7 Study Area

The study area selected for this investigation is located on the south-eastern shore of Lake Huron in Pinery Provincial Park at 43°15'N, 81°50'W (Morrison and Yarranton, 1973). The Park is situated approximately 6 km south-west of Grand Bend, Ontario in Bosanquet Township, Lambton County, and spans nearly 2600 hectares. See Fig. 2.11.

2.7.1 Climate

Pinery Park is located within the Lake Huron-Georgian Bay climatic region which is characterized by cold winters and relatively warm summers (Fisher et al., 1987). Mean annual temperature for the area, as recorded by the nearest meterological station at the Sarnia Airport, is 8.0 °C, and the total annual precipitation is 825 mm (Atmospheric Environment Service, 1990). During the warmer months the Park temperatures may be modified by the "lakebreeze" effect which generally results in cooler air flowing onshore during the daytime, and relatively warm air flowing offshore at night as the beach cools (Pye and Tsoar, 1990). This results in the Park

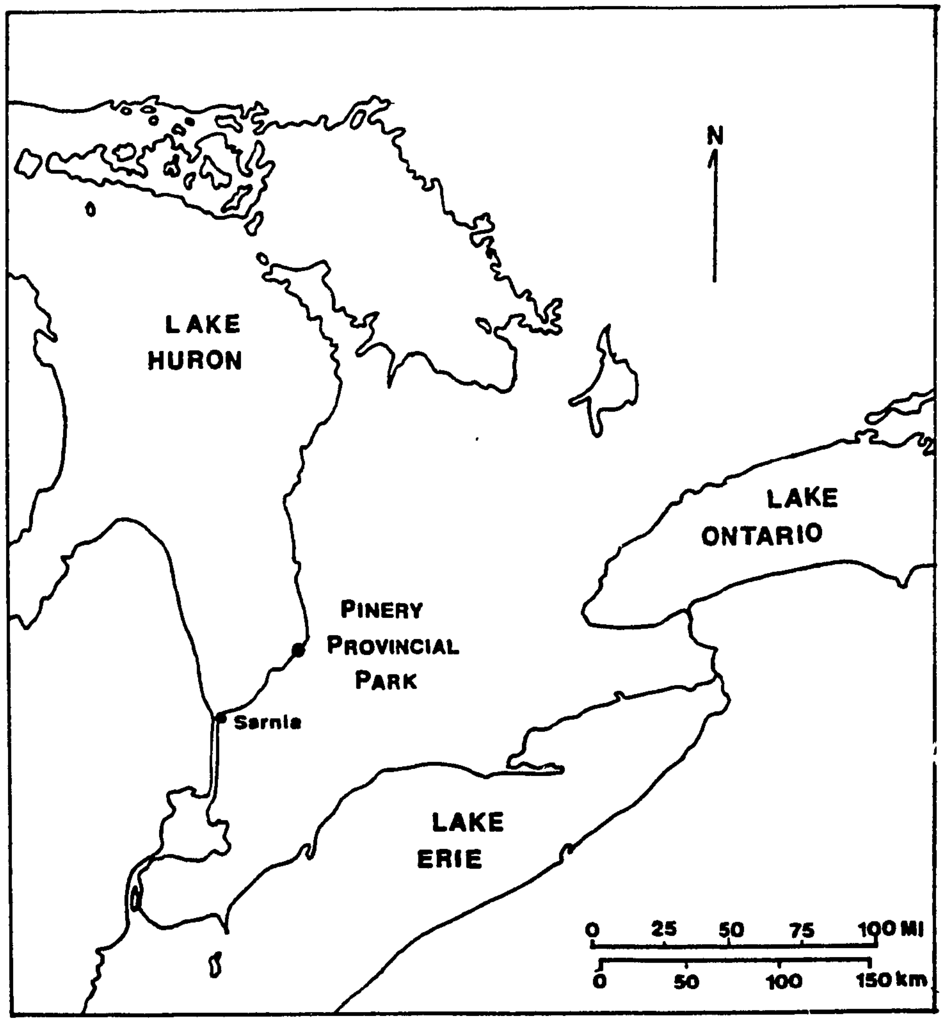


Fig. 2.11 Location of Pinery Provincial Park, Ontario, Canada.

experiencing somewhat cooler daytime temperatures during the summer, and warmer temperatures in the fall and early winter (Fisher et al., 1987).

Precipitation at the Park is generally spread evenly during the year with slightly higher amounts recorded in February and March. During the colder months, from late November to early April, precipitation is mainly in the form of snow, and much of the summer rainfall is from a few intense thunderstorms (Fisher et al., 1987).

Mean water temperatures adjacent to the Park closely follow the mean air temperatures and peak at around 20 °C in late July and early August when the air temperatures are at their warmest (Fisher et al, 1987).

During the winter months when water temperatures decrease below the freezing point for a sufficient period of time, lake ice forms. The presence of ice varies from year to year in the length of the season, and the extent of coverage. Generally, ice starts to develop in late November or early December, begins to break up in March, and disappears by April. In severe winters almost all the lake is covered with ice, however typically ice coverage is around 65 to 70 % and is at a maximum in February. During mild winters ice coverage may be as low as 29 % (Fisher et al., 1987).

2.7.2 Wind and Wave Climate

Waves reaching the Park are generated by winds blowing in a roughly easterly direction over Lake Huron. The fetch lengths, or distances over which the winds generating the waves blow, are N 240 km, NW 300 km, W 120 km, and SW 50 km.

The largest waves occur during severe storms which are most frequent in spring and fall. They are generated by winds from the NW region and can exceed 3 to 4 m, with periods of 6 to 9 seconds. Waves generated by winds blowing from the SW region are smaller due to the shorter fetch lengths. In the summer these waves rarely exceed 1 m in height and 5 seconds in period (Fisher et al., 1987). Further analysis of the wind regime within the Park will be provided in Chapter 4.

Wave generation in the winter months is prevented by the presence of lake ice which can almost completely cover the lake. Wave action on the beach may also be restricted for a longer period because of shorefast ice. Shorefast ice develops earlier and breaks up later than lake ice. Overall, lake and shorefast ice protect the Park's beach from wave activity for about 4 months of the year (Fisher et al., 1987).

2.7.3 Tides and Water Level Fluctuations

Tides are insignificant in Lake Huron, however water level fluctuations are important on different time scales. Long term fluctuations over years or tens of years reflect variations in precipitation, and to some degree temperature and evaporation. Periods of low water levels tend to follow several years of below average precipitation, while high levels reflect previous years of above average precipitation (Fisher et al., 1987).

Superimposed on the long term fluctuations are annual changes which reflect seasonal variations in run-off to the lake, and evaporation from the water surface. Overall the average annual variation in water levels in Lake Huron is approximately

30 - 45 cm (Fisher et al., 1987). Water levels are at their lowest in the winter and begin to rise in the spring as snowmelt increases runoff. When spring snowmelt occurs early, maximum water levels may peak as early as the beginning of May. Typically, water levels reach a maximum in early to mid-summer. Following mid-summer water levels begin to decline as runoff from streams and the groundwater table is decreased, and evaporation caused by warmer temperatures increases (Fisher et al., 1987).

Short term water level fluctuations, which are caused by storm surges, are the most dramatic at the Park. A storm surge is a local increase in the mean water level close to the beach as a result of wave and wind set-up. Storm surges reflect changes in wind and wave climate, and barometric pressure. It is impossible to separate the contribution due to wave breaking from that due to wind-set up. However, the combined result is an increase in water level during the storm surge, and a relative decrease as the storm system passes. During severe storms, surges of 0.5 - 1.0 meters can be expected at the Park. As a result the zones of wave action may be moved onshore, thereby reducing the beach width, and possibly causing erosion of the backshore and even the foredune (Fisher et al., 1987).

2.7.4 Beach and Nearshore Zone

The nearshore zone opposite the Park consists primarily of sand averaging about 0.16 mm in diameter. It contains two or three nearshore bars with their crests aligned parallel to the shoreline, and a deeper trough landward of them. The outer bar is relatively stable and oscillates about a mean position offshore. The inner, landward bar, is highly mobile and is subject to a greater range of conditions such as undertow and rip-cell circulation. Therefore, the inner bar changes rapidly in position, height, and shape through the year (Fisher et al., 1987).

The beach zone of the Park is simple in form with little variation alongshore, however, the beach profile is dynamic as it changes in response to fluctuating wave conditions. During storms and high water levels, wave action increases the effect of the backwash, which carries sediment offshore. This results in erosion of the beach foreshore and backshore, and sediment is carried offshore and deposited in the inner bar trough system. The beach, under these conditions, develops a stable, low-angle gradient. During non-storm conditions offshore movement is at a minimum and sediment moves landward due to net drift. Sediment is deposited on the swash slope forming a wide, gently sloping berm with a relatively steeper swash slope (Fisher et al., 1987).

In July and August the beach width is at a maximum since storms are less frequent and lower in intensity. During this time water levels decrease because of seasonal fluctuations, which further increases beach width. The combined result a wide, dry backshore zone which is capable of providing large quantities of sand for aeolian transport.

2.7.5 Sediment Sources

Sand which has been deposited to form the beaches and dunes at Pinery is supplied from erosion of the bluffs and nearshore zone to the north of Grand Bend, or about 80 km north of the Park (Fisher et al., 1987). There, the bluffs are primarily composed of glacial till with small amounts of glacio-fluvial sands.

A secondary sediment source is the sediment discharge from the Ausable River which lies immediately south of the Park. Although data on the volume of sand transported by the river was not obtained, "it is likely to be considerably less than the amount supplied from bluff erosion" (Fisher et al., 1987, p.30).

2.7.6 Pinery Dunes and Vegetation

Sand dunes of Pinery Park began forming during the Lake Nipissing stage about 5000 years ago, and have continued to develop to the present (Maun, 1986). The dunes extend 3 km inland, and range in height between 6 and 10 m above the present lake level, but one reaches 30.5 m (Morrison and Yarranton, 1973).

The most dominant vegetation species on the beach up to the first foredune is sea rocket (*Cakile edentula*). Other species include bugseed (*Corispermum hyssopifolium*), seaside spurge (*Euphorbia polygonifolia*), wormwood (*Artemisia caudata*), and Russian thistle (*Salsola kali*). Since these plants exist on the beach, they are subject to frequent erosion and deposition, and must be tolerant to high wind velocities, and washover by waves (Maun, 1986). These plants have developed mechanisms which enable them to withstand this environment. For example sea rocket is a succulent, which means it is able to store water in its leaves for dry periods.

The vegetation of the foredune ridge in the Park is a marram grass (*Ammophila breviligulata*) - sand reed (*Calamovilfa longifolia*) community (Maun, 1986). Marram grass is the primary stabilizer of sand in the Park because it is able to withstand rapid deposition. Marram grass forms underground stems, called rhizomes, which are capable of reaching downward to the water table, and upward to the surface, where they can form new plants. The underground network of stems also acts to hold newly deposited sand in place, and is illustrated in Fig. 2.12. Sand reed is a relatively taller grass and is the dominant dune builder in areas of slower deposition or erosion rates.

The secondary established dune ridges of the Park are characterized by an increase in vegetational heterogeneity. These dunes, are approximately 800 years old and are dominated by a juniper (*Juniperus virginiana* and *J. communis*) - bearberry (*Arctostaphylos uva-ursi*) - bluestem (*Andropogon gerardii* and *A. scoparius*) community (Maun, 1986). The vegetation on these dunes out competes pre-existing dune grasses, and tend to favour a more "woody" plant community. For example, bearberry has a creeping habit which quickly expands laterally, thereby smothering grassy vegetation. As a result, the relative density of grasses such as sand-reed is greatly reduced compared to the first foredune ridge (Maun, 1986).

Beyond the secondary dune ridge, vegetational diversity switches from being Oak (*Quercus prinoides*, *Q. velutina*, *Q. rubrum*, *Q. alba*) - Pine (*Pinus resinosa* and *P. strobus*) dominated to a fully established Beech (*Fagus grandifolia*) - Sugar Maple (*Acer saccharum*) forest.

It is beyond this region that the dunes no longer act like coastal dunes as they are not directly affected by wave processes. The beach only supplies the sediment source for subsequent deposition, and therefore these dunes were not of concern to this study.

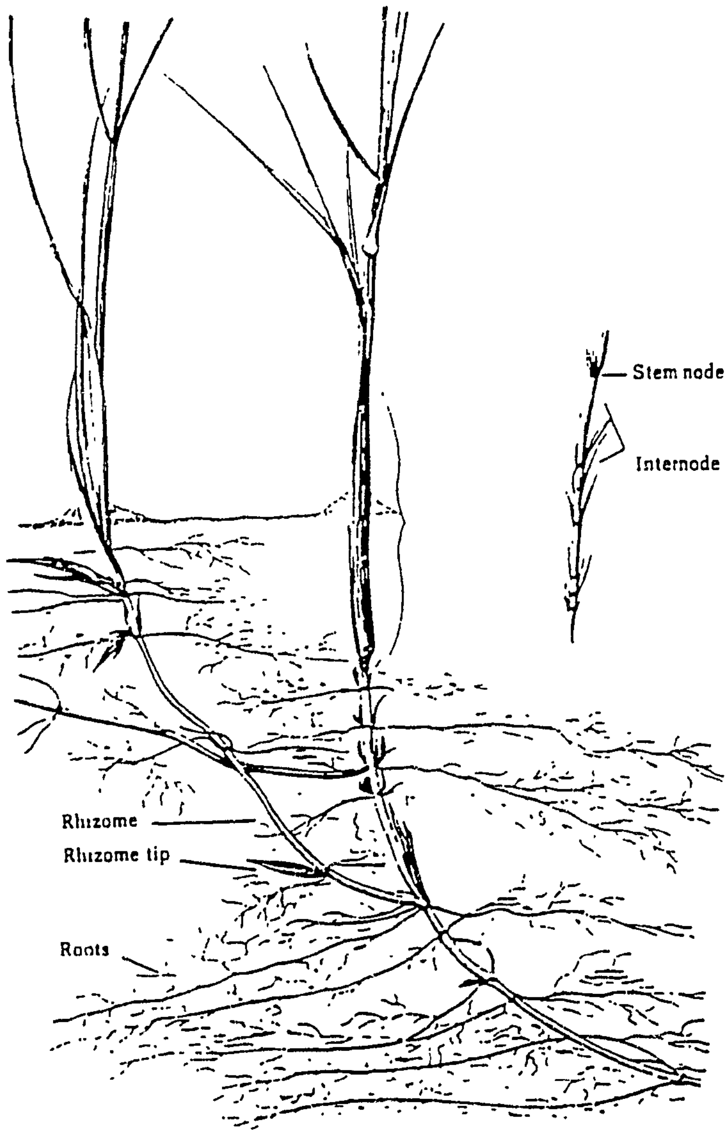


Fig. 2.12 Marram grass, showing underground root system. (Source: Ministry of Resources, 1992, Fig. 7)

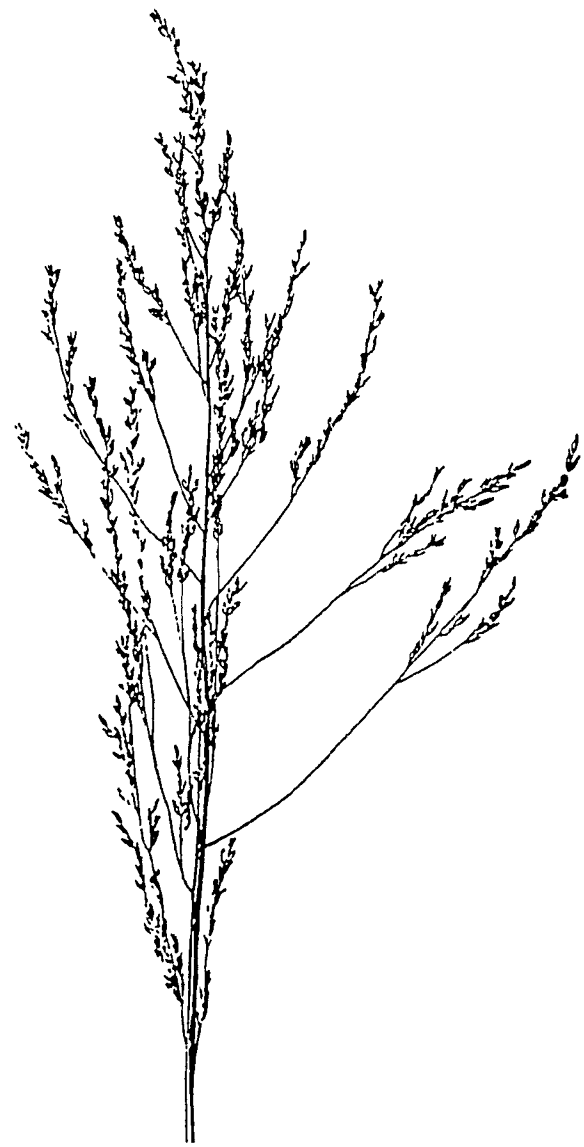


Fig. 2.13 Sand reed grass (Source: Ministry of Natural Resources, 1992, Fig. 8)

CHAPTER 3

METHODOLOGY

3.1 Introduction

The purpose of this chapter is to introduce the investigation techniques employed throughout the study. Discussion is in two parts: on site field methods, and laboratory procedures and data analysis. Additional information will be provided in Chapter 4 as it relates to discussion of the results.

3.2 Field Methods

The bulk of the field work was conducted in July and August, 1993. During this period a site was selected and surveyed. Sand samples were collected, trenches were dug for analysis of internal structures, and sand traps were aligned for subsequent monitoring throughout the year.

3.2.1 Site Selection

The selection of a specific dune for investigation was based primarily on dune type, accessibility throughout the study period, and the extent of possible human disturbance to both the site and field equipment.

An incipient parabolic dune, shown in Fig. 3.1, was selected for investigation. The dune was considered incipient since it has not yet fully separated itself from its blowout predecessor. Furthermore, the dune has not developed an avalanche slope on the lee side which is also indicative of a transitional stage.

Although the dune is considered incipient, throughout the remainder of the paper it will be referred to as a parabolic dune. It should be kept in mind however, that the dune has not yet fully developed the typical parabolic form. A parabolic dune was selected for examination since it represents a dune type which has not been as thoroughly investigated in the coastal environment as foredunes have. Furthermore, since the arms of parabolic dunes are generally orientated in the direction of the dominant sand carrying winds (Robertson-Rintoul, 1990), the expected prevailing wind direction for the site could be visually estimated at the onset of the study for later comparison to known wind data. A more detailed site description will be provided in the Results, in Chapter 4.

The parabolic dune is a secondary dune form and it is not visible from the beach since it is masked by the primary foredune ridge, shown in Fig. 3.2. It was hoped that this would reduce the chances of site disturbance or equipment damage by Park users.

This dune was also selected because it is situated approximately 1 km roughly south of the nearest parking lot and day use swimming area. This provides the easiest access to and from the site, while still providing a great enough distance to prevent site disturbance by curious Park visitors.

Fig. 3.1 Photograph showing study site.

Fig. 3.2 Photograph showing the beach, foredune, and interdunal area.

This dune was also selected because it was like a number of the secondary dunes located in the Park. From direct observation it was found that, although there was a range of dune orientations and sizes, the selected dune was fairly typical of the dunes present.

Upon selection of a study site, a portable meteorological station was installed which would provide on site data for temperature, relative humidity, and wind speed and direction. However, the equipment was damaged by human interference the first week it was erected, and was therefore unavailable to collect the necessary local data.

3.2.2 Field Surveying

In order to obtain information on the dune form and to quantify its dimensions, topographic surveying was conducted. Using a transit and stadia rod, 15 cross-sectional profiles, averaging 2.5 m apart, were obtained. The profiles extended from the water level, through the beach, foredune and interdunal area, up to the crest of the parabolic dune. Beyond the crest stadia measurements were difficult to obtain because of the increase in vegetation, and instability of the dune caused by the steep slopes.

Along one of the profiles, marked stakes were dug into the sand, and their location was surveyed and recorded. This was to provide constant known points for later sand sampling. However, most of the stakes were removed, possibly by Park visitors, since some of the stakes were recovered well away from the site.

3.2.3 Sand Samples

From the beach windward toward the parabolic dune, 13 sand samples were taken: 3 from the beach, 3 from the foredune, 3 from the interdunal area, and 4 from the parabolic dune. The purpose of this was to determine the range of sand sizes that existed, and to determine if any range of sizes were characteristic to a particular area.

3.2.4 Sedimentary Structures

The internal sedimentary structures of the dune were examined in order to gain knowledge on the depositional environment and processes. Approximately 20 trenches were dug from the basal area of the dune to the crest. Fig. 3.3 is a photograph showing a trench near the dune crest.

Once a trench was dug, the face was cleared of loose sand, and left to dry. Once dry, the face was measured, photographed, sketched, and examined. The thickness and number of beds, and their dip and orientation, were measured and recorded. The presence of vegetation in the form of root fragments, decomposing roots, or stains from decomposed matter, was recorded in terms of location, size, and relative abundance. Other factors such as changes in grain size, grain compaction, and colour were also noted.

3.2.5 Sand Traps

In order to quantify some measure of relative sand movement through the dune,

Fig. 3.3 Photograph showing study site with a trench near the dune crest.

vertical aeolian sand traps were installed. The traps consist of a section of polyvinylchloride (PVC) piping with two slits cut, in opposite directions, at one end of the pipe. One slit was covered with 60 micron mesh to collect transporting sand, while the other was left open to allow entry of sand. Once dug into the ground a second PVC was inserted into the first, flush to the dune surface, to gather the collected sand. For further information regarding sand trap construction see Rosen (1979).

The traps were placed in 2 arrays of 4 traps. In Fig. 3.4, from left to right (roughly southwest to northeast), both trap arrays are orientated as follows: east (#4,8), north (#2,6), south (#3,7), and west (#1,5). The upper trap array, shown in Fig. 3.5, was placed in the concave interior of the U-shaped dune, about 4.2 m apart. The lower array was situated at the mouth of the dune about 4.8 m apart.

The sand traps were installed on July 22, 1993, and were monitored daily until early September when the primary field season ended. From September until July 1994 monitoring continued every 2 to 3 weeks depending on weather conditions, and the availability of time and transportation to reach the Park, with the exception of January and February 1994. During these months, no sampling took place since the traps were frozen and snow covered, and access to the site was too difficult. Regular visits to the site began again in March 1994, however, the traps still remained frozen and therefore sampling could not take place until April 1994.

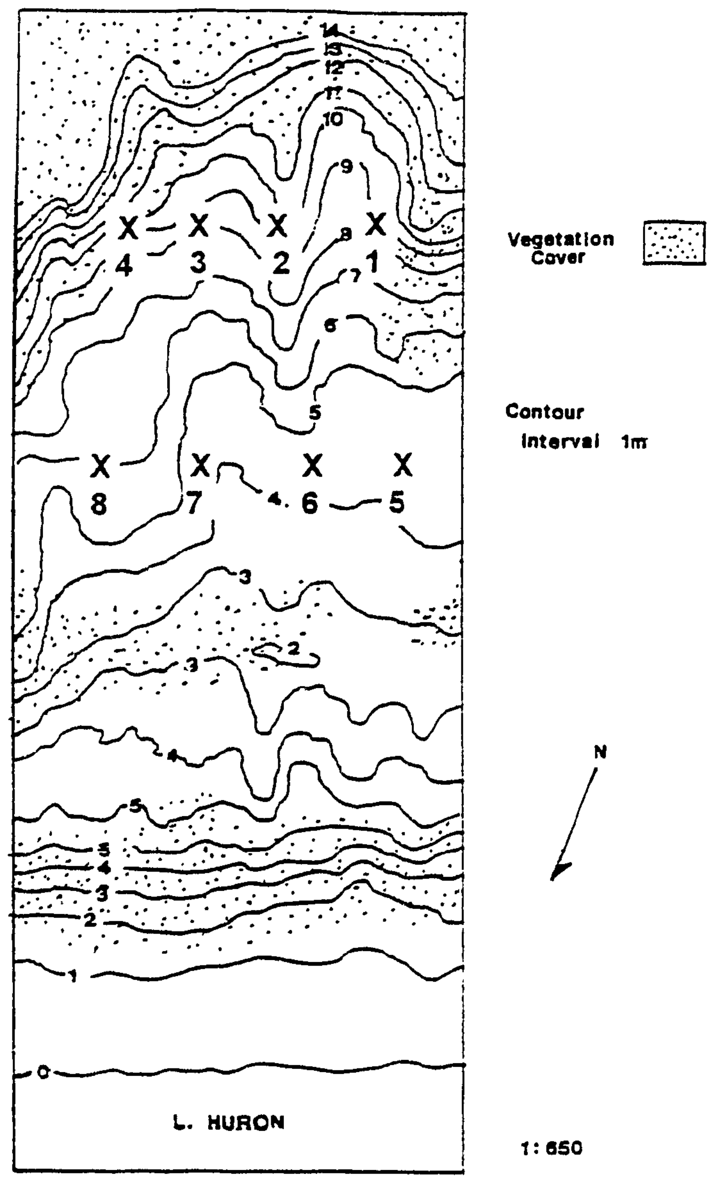


Fig. 3.4 Sketch of study site showing relative location of sand traps.

Fig. 3.5 Photograph of study site showing upper trap (#1-4) alignment.

3.3 Laboratory Procedures and Data Analysis

Laboratory procedures and data analysis were conducted throughout 1994. This included sieving of sand samples, analysis of the available wind data, and examination of air photos.

3.3.1 Sand Samples

Sand samples were air dried, weighed, and sieved at an interval of 0.5 Φ (phi) using standard sieving procedures. Weights retained by each sieve size were recorded and converted to percentages, and graphed on a cumulative curve for statistical analysis.

Statistical parameters of mean, standard deviation, skewness, and kurtosis were calculated for all samples using the moments method. The moments method is considered useful if all the grain sizes present lie within the defined grain size limits (Mcmanus, 1988). All the collected samples fell within the selected sieve size intervals. Using this method each grain in the population is taken into account in computing the parameters of the sediment, and was therefore considered to be most applicable.

3.3.2 Wind Data Analysis

Several methods of wind data analysis were employed to determine the expected dune orientation from available wind records. Wind records were obtained for the nearest Principal Meteorological Station at Sarnia Airport, located at 43°00' N, 82°18'W. Table 10 (Atmospheric Environment Service, 1984), was used as the data source since on site data for the study period could not be completely obtained.

A method introduced by Landsberg (1956), in a study which compared expected dune orientation to the measured orientation, was applied to the available wind data. The method is based on the assumption that of all the environmental factors, wind has the dominant effect on coastal dune orientation. Therefore, wind is the only factor incorporated into this technique.

The percentage frequency of wind speed by direction, for the year, was determined for each wind speed class. A threshold value of Beaufort number 3, or approximately 16 km/h, was subtracted from each wind class mid-point. The resulting value was then cubed and multiplied by the percentage frequency. After addition, a resultant vector was calculated. The resultant represents the expected direction of dune orientation with respect to wind regime only, and takes into account all wind directions recorded.

A study conducted by Jennings, "On the Orientation of Parabolic or U-Dunes" (1957), used the method employed by Landsberg (1956), but considered the effect of onshore winds only. Jennings presumed that "onshore winds must play a more vital role in coastal dune evolution than offshore winds" (p. 478).

The method proposed by Jennings was applied to the Sarnia wind data. The onshore wind directions used were from the north, northwest, west, and southwest. These directions were used because they represent the dominant fetch directions relevant to Pinery Park (Fisher et al., 1987).

Another method of wind data analysis introduced by Fryberger and Dean (1979) was used in order to determine the theoretical sand moving capacity of the available wind data. Weighting factors, "which represent the relative rates at which winds of differing average velocities can move sand" (Fryberger and Dean, 1979, p.146) were derived for each wind speed class, and then multiplied by a time factor. The results, when added represent the total amount of sand drift in vector units, and is a measure of the annual amount of wind energy. This method was utilized twice; with the effect of all winds, and with the effect of onshore winds.

3.3.3 Air Photo Examination

In order to measure the actual orientation of the studied dune to correlate with known wind data, air photo examination was conducted. Air photos taken on July 23, 1985, at a scale of 1:5000 were obtained. After careful examination of the photos it was decided that they would not be used. There were several reasons for this. First, it was difficult to detect the study dune in the air photos. The dune could be located but the actual orientation was not clear. Secondly, even if the orientation could be measured its accuracy could be questionable, and there is no way of determining a margin of error. Finally, the air photos were taken in 1985 and they may or may not reflect the current orientation of the dune.

CHAPTER 4

RESULTS

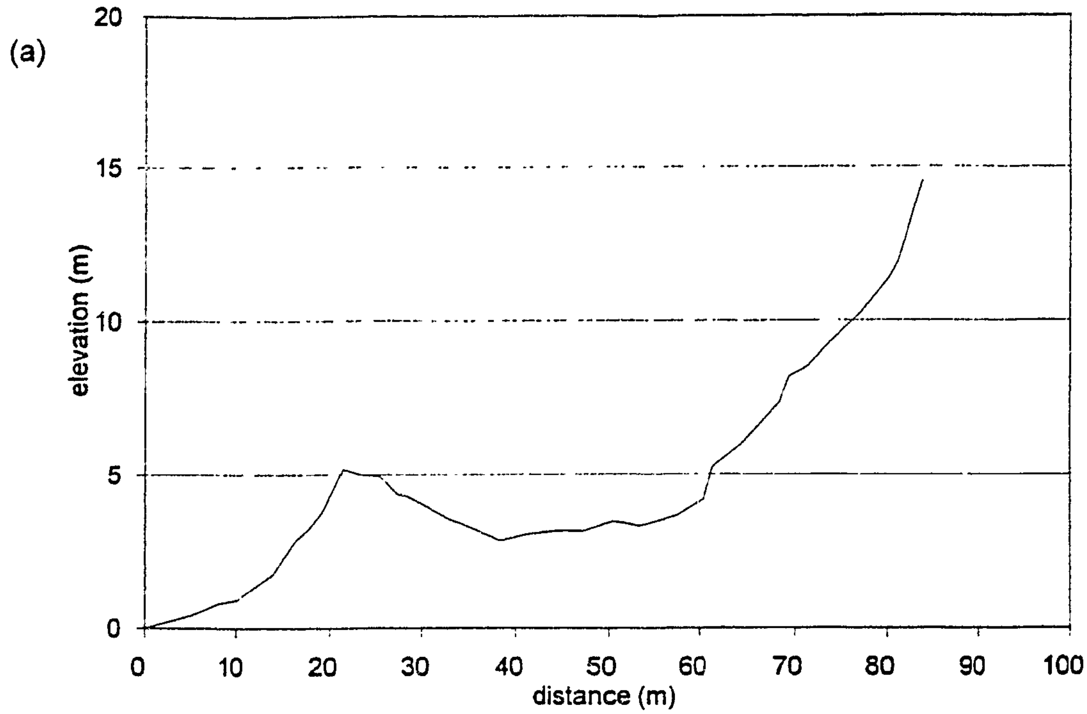
4.1 Introduction

The purpose of this chapter is to introduce the results of both field work, and laboratory procedures and data analysis. Discussion and further analysis will be provided in Chapter 5.

4.2 Physical Description of Study Site

The entire study site, extending from the water's edge through to the parabolic dune crest, or roughly northwest to southeast, is about 100 meters in length (Figure 4.1). The width, which lies approximately northeast to southwest, is 36 meters, and also represents the width of the parabolic dune.

Figures 4.1 and 4.2 illustrate four profiles: (a) the most northeasterly extending through the parabolic arm, (b) and (c) mid-dune profiles bisecting through the interior of the parabolic dune, and (d) the most southwesterly extending through the second parabolic arm.



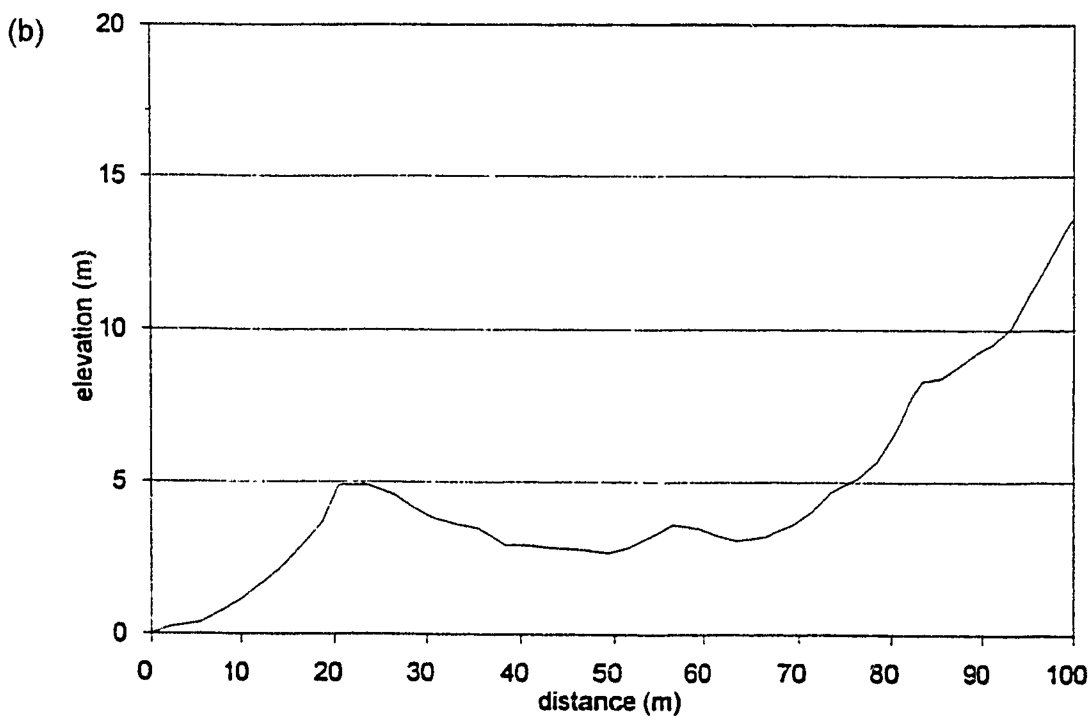
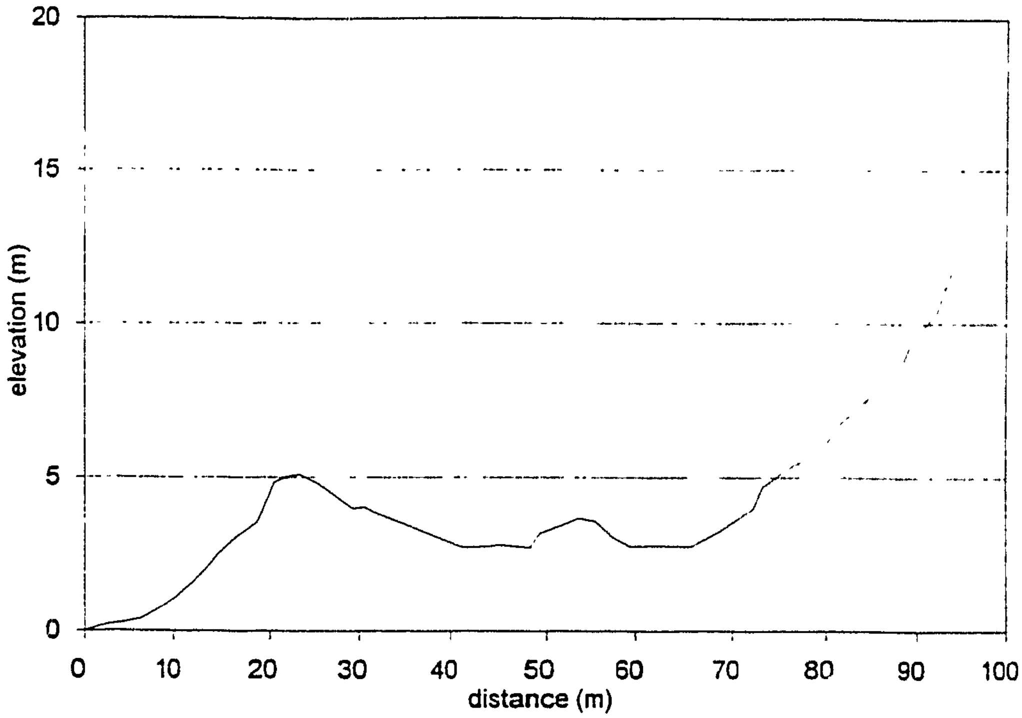


Fig. 4.1 Profiles of study site. (Vertical exaggeration 3.24 times)

(c)



(d)

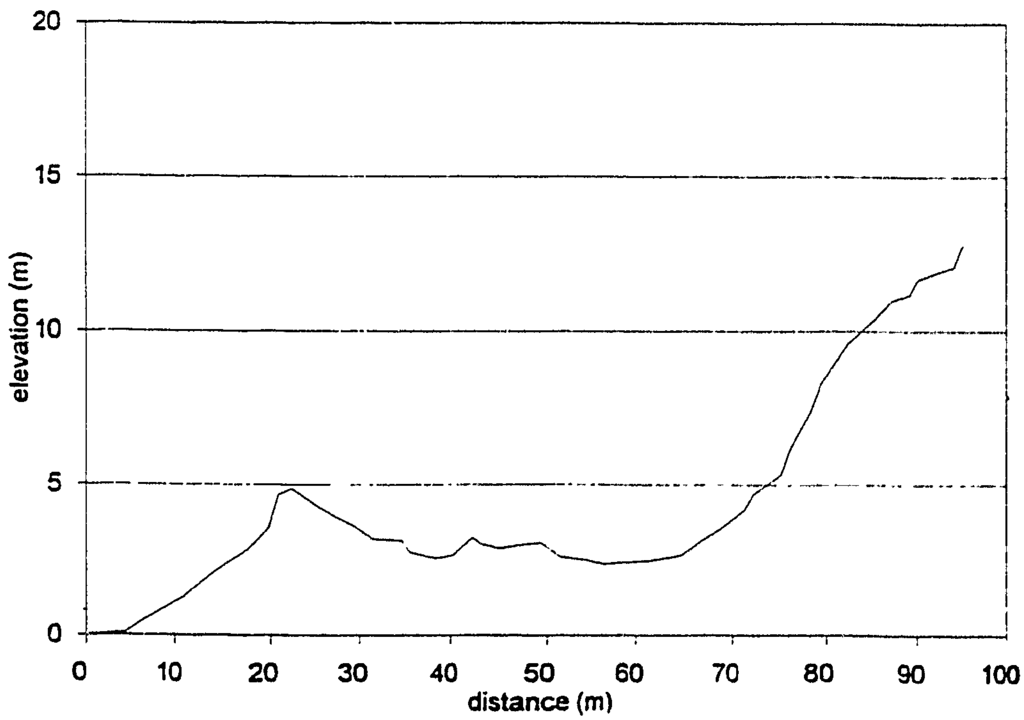


Figure 4.2 Profiles of study site. (Vertical exaggeration 3.24 times)

The surveyed study site consists of a 5 meter high foredune ridge which lies parallel to Lake Huron. It is located about 8 to 10 meters off the lake. The windward slope of the ridge is relatively steep and shaped concave up in all of the profiles, while the lee side is more gently sloped and greater in overall elevation.

The foredune ridge contains grass species of marram grass (*Ammophila breviligulata*), sand reed (*Calamovilfa longifolia*) and sea rocket (*Cakile edentula*), which during late spring and summer almost completely blanket the entire ridge, except for random areas where vegetation has been destroyed by footpaths.

An interdunal area, extending approximately 20 to 25 meters inland separates the foredune ridge from the parabolic dune. This area is quite variable in local topography, and may be a result of the presence of shadow dunes which develop to the lee of vegetation clumps. The form of the shadow dunes are illustrated in the profiles at a distance of 40 to 60 meters inland, and in several areas, they can be quite significant in elevation (Fig. 4.2c).

Vegetation of the interdunal area is not continuous and blanketing as on the foredune, but rather discontinuous and scattered in random clumps of shrubs such as sand cherry (*Prunus pumila*) and common juniper (*Juniperus communis*). Dune grass, marram and sand reed, are also present in this area, however in very small clumps with no general pattern.

The parabolic study dune lies approximately 60 meters inland. In Fig. 4.1 a, and 4.2 d, the stoss slope of dune begins at a closer distance to the Lake since it represents the windward extend of the parabolic arms. The arms reached an average height of 15 meters, and are orientated on a 190° axis. The width of the arms could not be measured since they were not fully separated from the adjacent dunes. Fig. 4.1 b and 4.2 c, represent the interior concave portion of the dune and therefore, the stoss slope is at a greater distance from the Lake. The dune extended to a maximum height of about 17 meters.

Vegetation on the parabolic dune is more diverse than the foredune and interdunal area. Still present are dune grasses, particularily on the dune arms and crest, but they are not as abundant. Grasses are separated by an increasing number of shrubs. Several small trees of red cedar (*Juniperus virginiana*) and eastern cottonwood (*Populus deltoides*) begin to emerge on the dune arms and crest, and increase in size and number to the lee side.

Vegetation through the interior of the parabolic dune, or that area enclosed by the arms, is sparse and consists of a few randomly scattered dune grasses.

Beyond the parabolic dune vegetation, species shift from being dominated by grasses and shrubs, to being dominated by coniferous and deciduous tress.

4.3 Grain Size Distribution

Analysis of sand samples collected along a profile extending from the beach, through the interdunal area, and into the parabolic dune indicates a range of grain sizes associated with each area.

Fig. 4.3 illustrates a plot of mean grain size by location along the profile. It should be noted that the y-axis is measured in phi units and the larger the value,

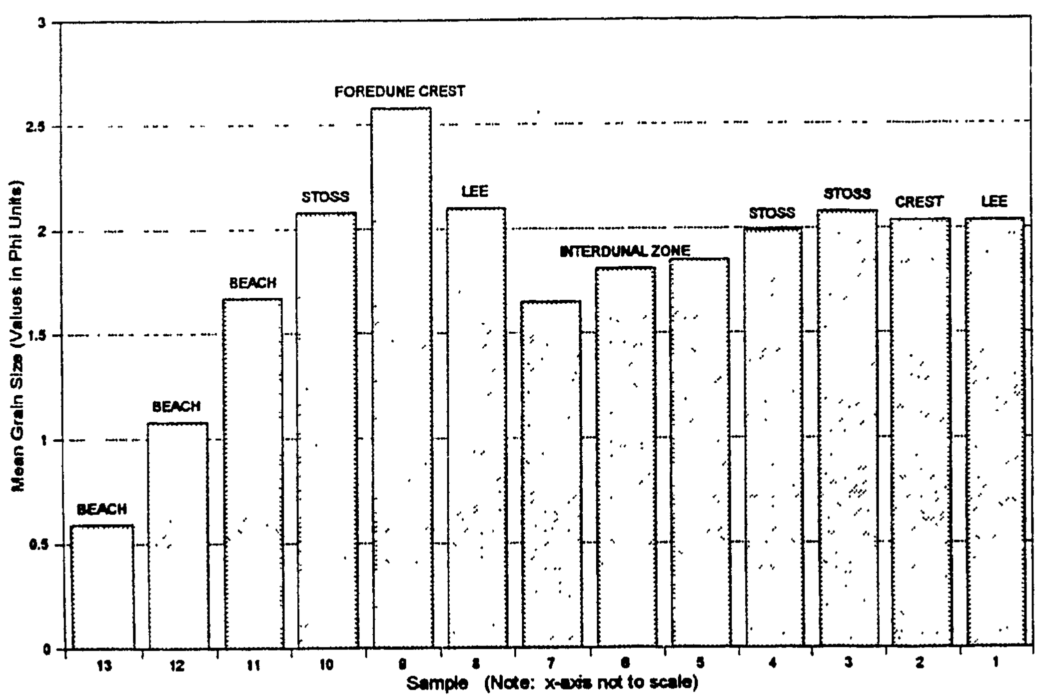


Fig. 4.3 Plot of mean grain size along a profile.

the smaller the grain size. Samples 1 to 4 represent sand collected from the parabolic dune, 5 to 7 are sand from the interdunal zone, 8 to 10 are from the foredune ridge, and 11 to 13 is sand that was collected on the beach.

As might be expected, the beach contained the coarsest sand. The mean grain size began decreasing, in size, inland from 0.59 Φ at the waters edge, to 2.58 Φ on the crest of the foredune. The lee slope of the foredune ridge contained coarser material than the crest, but was comparable to the mean grain size found on the stoss slope. The sand of the interdunal area was coarser than the foredune and had a mean value of 1.77 Φ.

The mean grain size of sand present within the parabolic dune showed little variation along the sample points, and ranged from 2.08 Φ to 1.99 Φ on the stoss side, while on the dune crest and lee the mean grain size was a constant 2.04 Φ.

4.4 Sedimentary Structure Analysis

An analysis of the internal sedimentary structures of the parabolic dune from the basal area to the dune crest was conducted using the interpretation techniques described by Hunter (1977) for unvegetated coastal dunes, and Byrne and McCann (1990, 1993) for vegetated coastal dunes.

Trenches dug into the basal portion of the parabolic arms exhibited low angled beds, dipping between 3 to 15 °, of fine sand. Alternating between these beds were thinner unlaminated beds, 1 to 3 cm, of loosely packed coarser grains. Evidence of vegetation was minimal with only a few very small decorticated root fragments of dune grass visible.

The trenches dug throughout the middle portion of the dune arms also exhibited alternating beds of fine sand separated by thin layers of coarser sand, however the average dip angles increased in range from 10 to 19 °. Capping some of the beds were distinct bedding boundaries which were roughly horizontal.

Evidence of vegetation and organic material increased with height of the dune. The trenches through the middle portion contained a lot of tiny decorticated roots, too numerous to quantify, and some large decaying root pieces from once present trees. Surrounding the decaying roots were dark brownish/black organic stains. As vegetation increased, the beds became more difficult to delineate, and very little, if any, laminae were visible.

Trenches dug into the upper portion, near the dune crest, were dominated by thick beds, up to 0.4 meters, of loosely packed, fine grained, unlaminated sand through very dense vegetation fragments. Small roots fragments were scattered throughout all of the upper trenches. Between the thick beds were thin, unlaminated beds of coarser sand. However, because of the density of vegetation present in these pits, individual beds were too difficult and often impossible to measure.

From the examination of the trenches in comparison with the interpretation techniques provided in the literature, it could be concluded that the depositional processes responsible for the evolution of the parabolic dune is primarily grainfall with intermittent, relatively shorter periods of tractional deposition.

Thick beds of unlaminated, loosely packed, non-graded sand, indicate periods of grainfall which commonly occurs in zones of flow separation. The thinner beds, separating grainfall beds, indicate tractional deposition during periods of high wind velocities. The presence of coarser sands, and lack of fine grains, further signifies high wind velocities during deposition. Coarser materials remain in the sedimentary deposit, while the finer material is blown away.

4.5 Wind Regime Analysis and Dune Orientation

A yearly wind summary, based on Principal Station Data (Atmospheric Environment Service, 1984), is illustrated in a wind rose diagram, in Fig. 4.4. The arm lengths are proportional to the percentage frequency of wind observations, for each direction, for the year. The prevailing annual wind direction is from the south, occurring 23.5 % of the year.

The mean annual wind speed, considering all directions, is 15.9 km/h. Mean monthly wind speed is highest in January (19.2 km/h) and April (19.1 km/h), and lowest in July (11.7 km/h) and August (11.1 km/h).

Using the method described by Landsberg (1956) the expected dune orientation with respect to wind regime was determined by calculation of the resultant wind vector. The calculated annual wind vector by frequency is from the east-southeast at 102°, when all winds were taken into consideration (Fig. 4.5).

As shown in Table 4.1, there appears to be a trend of winds from the east, east-southeast, and southeast dominating throughout the year. With the exception of

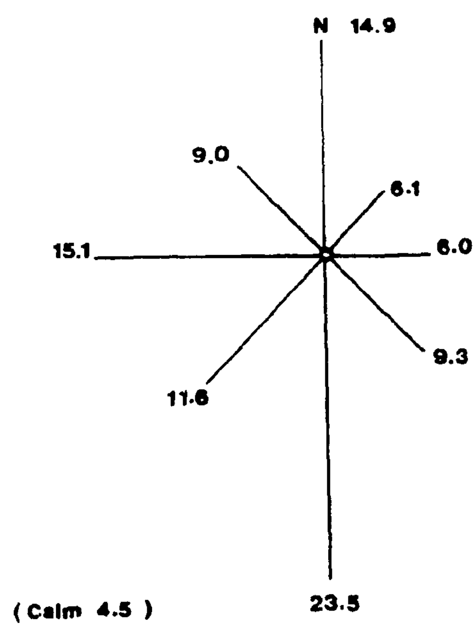


Fig. 4.4 Annual wind rose for Sarnia Airport. Values represent annual percentage frequency by direction.

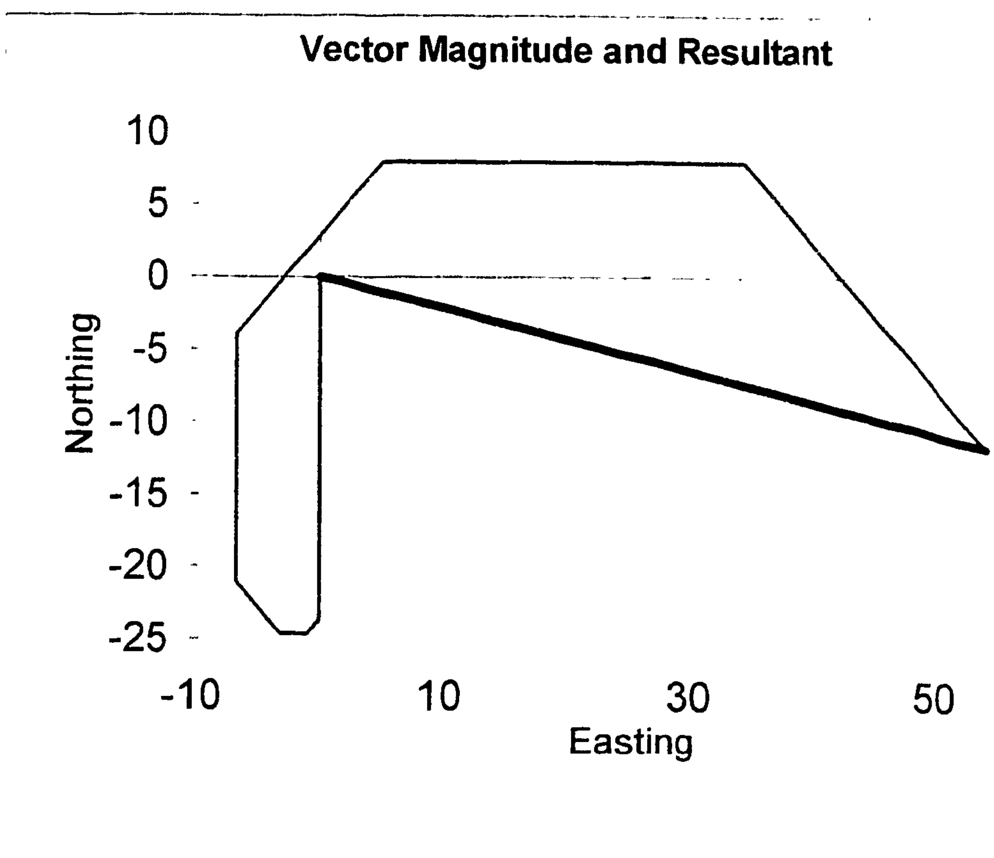
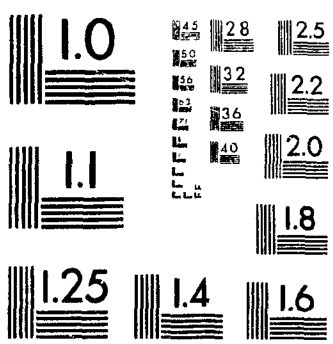


Fig. 4.5 Annual wind vector resultant for Sarnia Airport.

2 of/de 2

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT



PRECISION℠ RESOLUTION TARGETS

MONTH	WIND RESULTANT (degrees)	WIND RESULTANT DIRECTION	MEAN WIND SPEED (km/h)
JANUARY	5	N	19.2
FEBRUARY	99	E	18.3
MARCH	100	ESE	18.8
APRIL	115	ESE	19.1
MAY	145	SE	15.1
JUNE	3	N	14.2
JULY	20	NNE	11.7
AUGUST	111	ESE	11.1
SEPTEMBER	127	SE	13.2
OCTOBER	91	E	15.4
NOVEMBER	99	E	16.9
DECEMBER	111	ESE	18.1
YEAR	102	E to ESE	15.9

Note: Wind resultants were vectorially determined using Principal Station Data from Sarnia Airport. This data provides a summary of weather observations from 1967-1982.

Table 4.1 Summary of resultant wind data. (See Appendix 1 for calculations)

July and August, when the mean wind speeds are relatively low, and January, all months exhibit this east to southeast trend.

The annual wind vector resultant by frequency, when only considering the effect of onshore winds (Jennings, 1957), is 117°.

There is no general agreement between the vector resultants calculated by either method and the actual measured dune orientation, which was found to be approximately 190°.

Several possible reasons exist for the lack of correlation between the calculated and measured orientations. First, the method used may not be applicable to this study site. Landsberg (1956) and Jennings (1957) found a good correlation between the resultants calculated and the measure orientation of selected European dunes, but this is not the case for the Pinery. Second, the wind data source, which was from a great distance away may not reflect the actual wind conditions at the Park. The use of complete and accurate on site wind records may have resulted in a closer agreement. The assumption that wind is the dominant factor controlling the orientation of parabolic dunes may be true, however, at the study site, local factors rather than wind may dominate, and are therefore, not reflected in the methods. Factors such topography changes and the resulting local wind variations, vegetation cover, and availability of sand, vary so greatly that determination of dune orientation using regional wind data may not yield accurate result. Lack of correlation may also be related to the scale or size of the dunes under investigation. The method described by Landsberg and Jennings was applied to large dunefields on a small scale using regional data. However, the dune investigated at the Pinery was much smaller, or relatively larger scaled. Therefore, applying regional data to just one dune at this scale, may have caused the discrepancies.

4.6 Resultant Wind Drift Potentials

Using the method described by Fryberger and Dean (1979), the annual resultant drift potential, RDP, and direction, RDD, were determined to be 168 vector units, and 101°, respectively, when all winds were considered. When only onshore winds were used the RDD is 117° and the RDP is 68 vector units.

The directions calculated are the theoretical sand carrying direction of the winds, and these directions should correlate with the actual dune orientation. However, this is not the case. This method, when applied to the available wind data, lacks correlation between calculated and actual orientation. The same possible reasons for lack of correlation exist as suggested for the Landsberg (1956) and Jennings (1957) methods.

The results based on the Fryberger and Dean (1979) method does correlate with those of Landsberg (1956), which may further suggest, the need for on site data, and the importance of local factors on dune orientation.

4.7 Sand Trap Data Analysis

The total amount of sand captured or trapped represents the amount of sand that was moved, or transported through the area in which the traps were installed. Over a one year period, sand samples were collected from the lower array 15 times. The upper array samples were collected 14 times. This array could not be removed on April 1, 1994, because the traps were frozen. The samples were removed on the next date. The total amount trapped by sample date, for both arrays, is given in Table 4.2.

The amount of sand trapped, by array, was averaged on a daily basis by dividing the total amount trapped by the number of days (data taken from Table 4.2). A total monthly weight was calculated by summing the amounts trapped each day within each month. The results are provided in a summary table, Table 4.3, along with the monthly averavge wind speed, and prevailing direction.

The total amount of sand moving through the lower traps, at the mouth of the dune, for the year was 22.8 kg. The greatest amount of transport occurred in November 1993 (5.80 kg), while the least amount of movement occurred during August 1993 (0.39 kg). The transport in November is responsible for about 25% of the total moved through the lower traps, as compared to August which is only 1.7 % of the annual total.

The amount of sand moving through the upper array, inside the parabola of the dune, was 55.5 kg. The month which showed the greatest amount of transport was in May 1994 (13.51 kg), which is about 24% of the annual total moved through the interior. September exhibited the least transport (3.29 kg), with August (3.48) quite low as well. Combined, these two months represented 12.1% of the annual total,

SAND TRAP SAMPLING DATES			# of DAYS	TOTAL WEIGHT (g) UPPER ARRAY	LOWER ARRAY
July 27/93	to	August 7	11	101.91	10.87
		August 22	15	3044.86	97.42
		August 29	7	155.95	9.03
		September 20	22	2353.38	3058.78
		October 3	13	1496.71	300.80
		October 24	21	6191.45	3813.43
		November 7	14	3428.59	1663.56
		December 2	25	3895.78	5397.72
		December 22	19	163.31	172.75
1994		April 1	101	n/a	1845.25
		April 19	18	5868.04	2179.37
		May 13	24	9957.89	1827.28
		June 2	20	9019.36	502.66
		June 15	13	3461.39	870.99
		July 27	42	6422.11	1030.50
			365		
TOTAL WEIGHT (kg)				55.56	22.78

** n/a traps were frozen and were removed next sample date

Note: Total weights represent the total amount of sand trapped during the number of days indicated.

Table 4.2 Total amount of sand trapped by sample date.

MONTH	AVERAGE WIND SPEED (km/h)	PREVAILING DIRECTION	UPPER ARRAY (kg)	LOWER ARRAY (kg)
AUGUST	11.8	S	3.48	0.39
SEPTEMBER	13.6	S	3.29	3.01
OCTOBER	7.9	W	8.25	4.71
NOVEMBER	18	S	5.3	5.8
WINTER	18.2	SW	6.34	4.63
APRIL	20.6	N	4.56	0.84
MAY	17.3	N	13.51	1.44
JUNE	14	N	6.66	1.29
JULY	12.4	SSW	4.13	0.66
TOTAL			55.5	22.8

Note: Average wind speed and prevailing direction was obtained from the Monthly Meteorological Summary from Sarnia Airport for the months of August 1993 through July 1994, and therefore differ from Table 4.1 as those values are vector resultants.

Table 4.3 Amount of sand trapped by month from August 1993 to July 1994.

which is quite substantial compared to the lower array. Over twice as much sand moved through the interior of the dune than at the mouth.

4.7.1 Sand Trap Analysis and Wind Regime

To see if any correlation existed between wind regime and the amount of sand transported, Monthly Meteorological Summary Tables for the study period, August 1993 to July 1994, were obtained. Average monthly wind speed and total sand trapped were plotted for each month of the study. The results are illustrated in Fig. 4.6.

In Fig. 4.6, as wind speed increases from August 1993 through the winter period, the amount of transport also increased, more progressively in the lower traps than the upper traps. However, in April when the average wind speed was at a maximum, transport through both trap arrays declined compared to the previous period. The decline in transport may be caused by the presence of snow cover which remained on the site until mid April. Transport through the interior of the dune increased to a maximum in May, because the mean wind speed was high, and all of the snow cover had melted, leaving the sand surface exposed.

Overall, through both trap arrays, the amount of sand transported did increase as mean wind speed increased, with the exception of April.

4.7.2 Sand Transport By Season

In order to compare the relative amount of sand transported through the

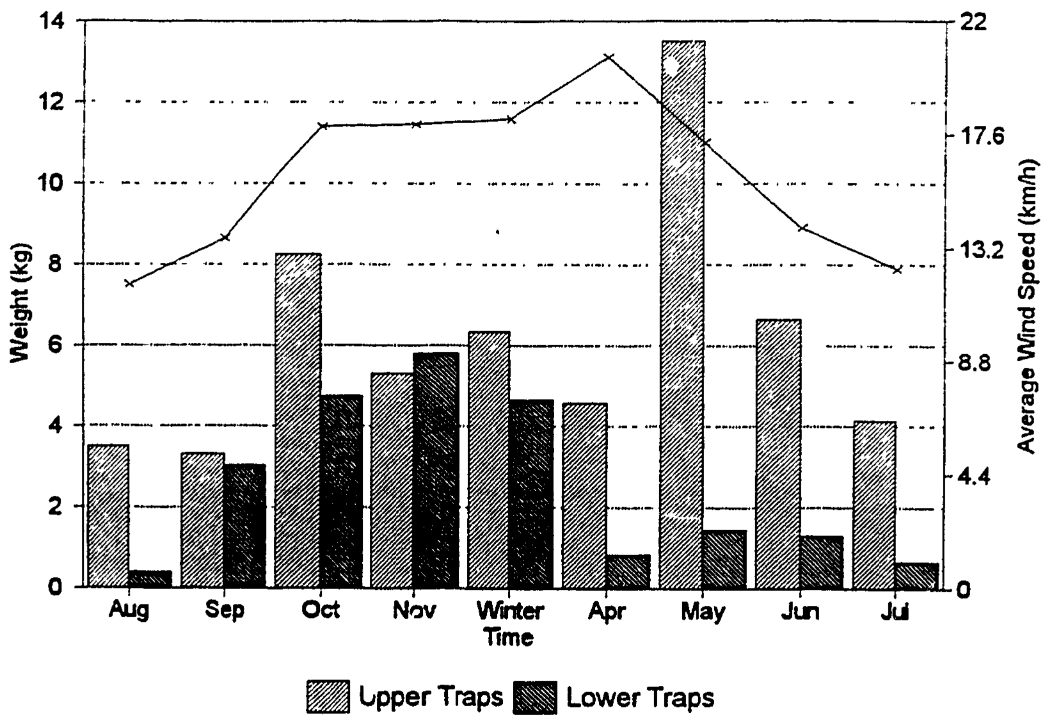


Fig. 4.6 Total amount of sand trapped and average wind speed from August 1993 to July 1994.

parabolic dune in terms of seasons, the sample period of one year was divided into three arbitrary seasons: late summer/fall, winter, and spring/early summer.

The late summer/fall season included the months of August through to December 22, 1993. The winter season began about December 23, when the traps became frozen, until April 1994 when they could be removed from the ground. The spring/early summer season extended from April 1, 1994 until July 27, 1994.

The amount of sand transported through the mouth (lower traps) and the interior (upper traps) of the dune was totalled for each season, and is shown in Fig. 4.7, and was also converted to a percentage of total annual amount trapped, shown in Fig 4.8.

Significant transport, through the dune interior, occurred during the late summer/fall season. Approximately 20 kg, or 37 % of the total, was moved. During this season, as shown in Table 4.4, 71 % , of the 20 kg, was transported from the north.

During the winter season, transport still occurred through the interior, however, only 6 kg moved. Fifty-six percent of this was transported from the north.

The greatest amount of sand transport occurred during the spring/early summer season through the interior of the dune. About 29 kg, or 52 % of the total amount transported, was moved during this season. Of the 29 kg, 47 % was transported from the north, 39% from the west, and the remaining 14% from the south and east.

Sand transport through the mouth of the dune was considerably less throughout the entire year, with 61 % of the annual total 22 kg moving during the late

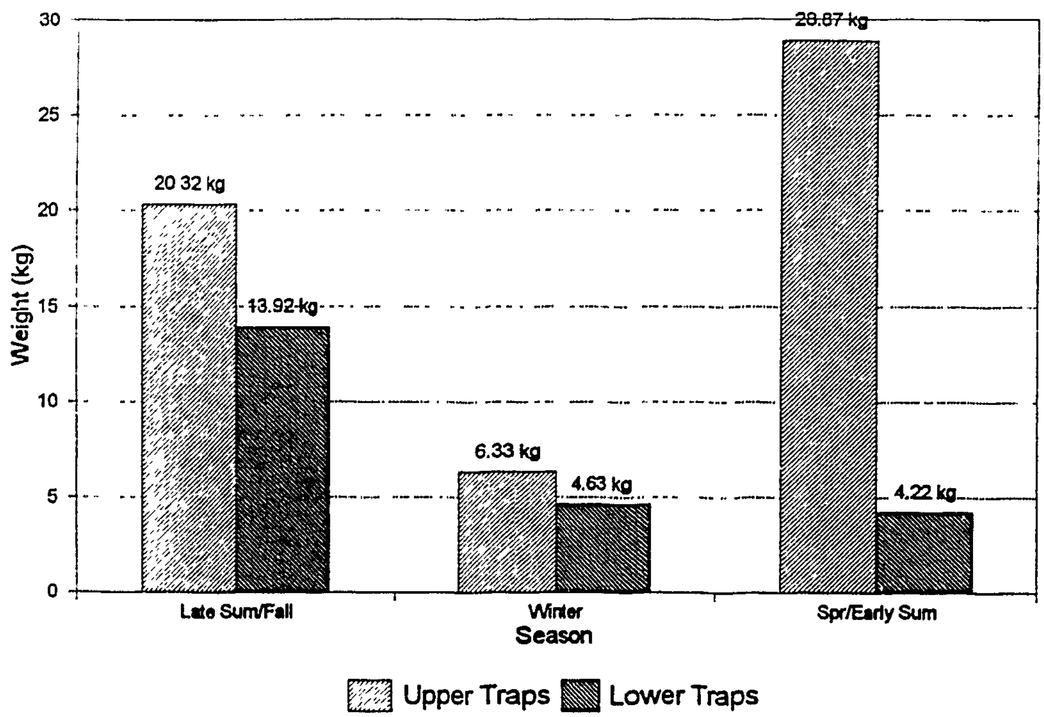


Fig 4.7 Total sand trapped by season for each trap array from August 1993 to July 1994.

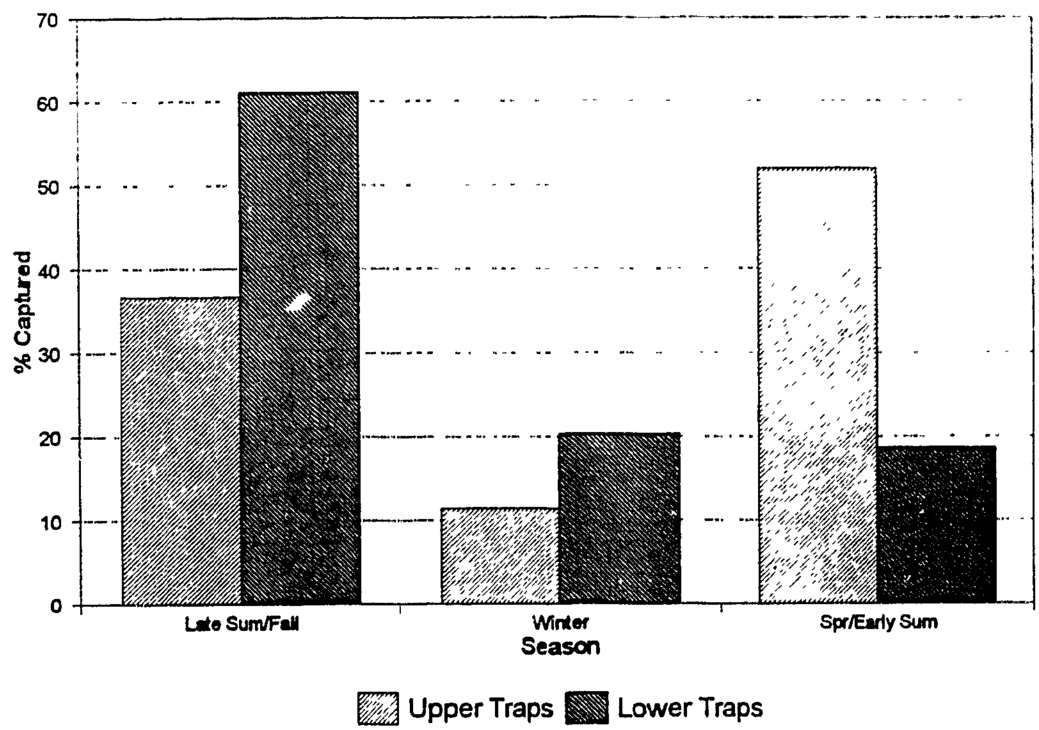


Fig. 4.8 Percent sand trapped by season for each trap array from August 1993 to July 1994.

	WEST	NORTH	SOUTH	EAST	TOTAL WT (kg)
UPPER TRAPS					
LATE SUMMER/FALL					
WINTER	5	71	14	10	20.32
SPRING/EARLY	10	56	32	2	6.34
SUMMER	39	47	3	11	28.86
					55.52
LOWER TRAPS					
LATE SUMMER/FALL	35	18	28	19	13.92
WINTER	32	8	37	23	4.63
SPRING/EARLY SUMMER	39	20	20	21	4.23
					22.78

Table 4.4 Percentage of sand captured by direction for each season.

summer/fall season. The amount transported through the mouth during the win and spring/early summer season, was relatively small, and each accounted for about 20 % of the annual total transported.

Overall, sand transport through the mouth of the dune was more variable in direction than through the interior of the dune, however, relatively less was moved. Transport in the dune was dominated by a landward, northerly trend.

Sand transport through the dune interior is at a maximum during the spring/early summer season, and decreases through late summer and fall, until it reaches a minimum during the winter.

Transport through the mouth reaches its maximum during the late summer/fall season, declines during the winter, and maintains a relatively constant rate from the winter through the spring/early summer season.

As shown in Fig. 4.7, a greater amount of sand was transported through the dune interior compared to the dune mouth. This would indicate that between the two trap arrays a zone of deflation developed. More sand was being supplied to the interior of the dune than was being transported from the mouth of the dune. A dramatic example of this occurred during the spring/early summer season when deflation between the trap arrays was at its greatest. Deflation continued through the late summer/fall season, and diminished throughout the winter. The result is a lowering of the dune surface between the two arrays and increased transport and possibly deposition within the interior.

CHAPTER 5

DISCUSSION AND SUMMARY

5.1 Introduction

There are considerable variations in total amount of sediment transported through the mouth of the dune as well as through the dune interior throughout the year. These variations reflect changes in local climate and wind regime, vegetation type and cover, sediment availability, and water levels.

5.2 Seasonal Variations in Sand Transport

The potential for sand transport from the beach to the foredune begins to increase from late summer to early fall. During this period, the beach width is at a maximum, because lake levels begin to drop, and storms become less frequent and lower in intensity. Overall, this results in an increase in sediment supply from the beach to the dune system. However, during this period, vegetation is at maximum height and density, as shown in Fig. 5.1. Sand that is supplied from the beach becomes trapped by the foredune vegetation, and very little is supplied to the parabolic dune.

The presence of vegetation influences the wind velocity gradient over the

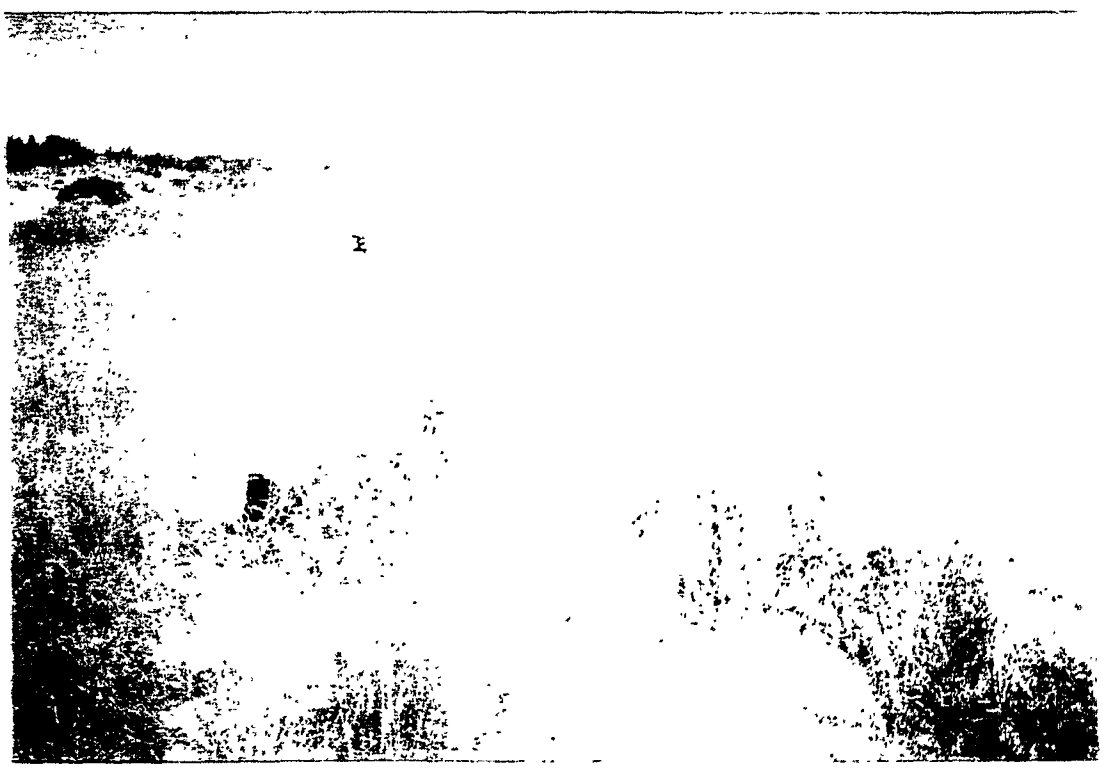


Fig. 5.1 Photograph showing beach and foredune during late summer.

effected surface by adding an increase in surface roughness, which displaces the velocity profile upwards from the bed. The effect of surface roughness has been incorporated into the basic wind gradient equation, given in Eq. 2.3, as z_0. As illustrated in Fig. 2.6, the height of z_0 increases with the presence of vegetation and results in a gentler sloping wind profile. Greater wind velocities occur closer to the surface as a result of surface roughness.

Sand transport through the mouth of the parabolic dune, during late summer and early fall, is limited as a result of a decline in sand supply from the beach and foredune. Transport through the mouth is dominated, not from a northerly onshore trend, but from a west and south trend. This corresponds to the prevailing wind directions during these months.

Transport through the interior of the parabolic dune is dominated by sand supplied from the mouth of the dune, or from the north. This would indicate that during the late summer and early fall when very little sand is supplied from the beach, the sand that is transported to the parabolic dune is supplied by erosion of the interdunal zone. This is also indicated by the profiles which show a relative drop in elevation through the interdunal zone.

The potential amount of sand, which can be transported to the parabolic dune, increases to a maximum during late fall. During this period, vegetation cover is reduced, thereby allowing the available sand to be transported from the beach over the foredune and through the interdunal zone. Wind speeds also increase, and generally exceed the threshold levels for sand transport throughout the season.

The availability of sand from the beach is limited during the winter because of lake ice, as shown in Fig. 5.2. Ice prevents wave action from depositing sand on to beach, thereby cutting off the sand supply. The sand transport through the mouth of the dune, during the winter, is minimal but highly variable in direction.

Sand transport through the parabolic dune during the winter is limited by snowcover and increase in moisture. Although transport is limited by snowcover, a sufficient amount of sand does move. Transport typically occurs in several isolated events when snowcover is removed by melting or redistribution by wind, and temperatures are warm enough to melt the surface sand, freeing it for possible transport. The effect of sand transport during the winter months has been often neglected by researchers, based on the premise that snowcover and freezing temperatures result in the immobilisation of the dune (Law, 1990). However, winter transport through the dune does occur. During the winter, wind speeds are high, and when available, sand is generally transported from the north.

Transport through the dune during the winter is also limited by the sand's moisture content which increases due to snowcover. The result is an increase in threshold velocities necessary for transport, as was presented in Eq. 2.7.

The greatest amount of sand transport through the parabolic dune occurs during the spring and early summer. Sand can be easily transported since the snow cover is removed, and vegetation is just beginning to re-establish itself. Average wind speeds, in the spring, still exceed threshold velocities, but begin to decline during the early summer. During the early spring, critical threshold velocities are lower

Fig. 5.2 Photograph showing beach and foredune during the winter.

than during the winter and summer seasons. The effect of snowcover has been removed, and vegetation has not developed a full cover. However, moisture content may still be high, depending on the amount of rainfall. An increase in precipitation results in an increase in threshold velocities.

5.3 Summary

Sand transport through the interior of the parabolic dune primarily moves from the north to the south. It is greatest during the spring and early summer, begins to decline in late summer and fall, and reaches a minimum during the winter. Transport at the mouth of the dune is more variable in direction, but less in total amount. Twice as much sand is transported through the interior than through the mouth. Sand moving through the mouth is at a maximum during the late summer and fall, and maintains a constant minimum through the winter, and into spring and early summer.

Sand transport through the parabolic dune, during late summer and fall, is generally limited by sediment supply, vegetation cover, and wind speeds. During the winter, sediment supply becomes the primary limiting factor. Sand supply to the beach is prevented by lake ice, and transport through the dune is prevented by snowcover. Transport through the winter generally occurs during a few isolated events when snowcover across the dune surface is reduced, either by redistribution, or by melting. Sand transport is limited by snowcover and moisture content in the early spring, and low wind velocities and increased vegetation density during the summer.

Sand transport between the dune mouth and interior shows that a greater amount of sand is transported within the dune interior. The amount of transport exceeded the amount that could be supplied from the dune mouth which suggests an area of deflation between the two trap arrays. With continuous inputs of sand entering the interior of the parabolic dune, combined with onshore winds which exceed the threshold levels necessary for transport, it could be hypothesized that over time the studied dune will further migrate onshore. It will continue to develop the parabola shape and eventually separate itself from the neighbouring dunes.

As was previously mentioned, the study dune was fairly typical, in terms of orientation and size, when compared to other parabolic dunes within the Park. Therefore, it may also be suggested that since the sediment supplying wave processes, and the aeolian transport processes responsible for dune development and migration are fairly constant within the Park, the dunefield as a whole is probably responding in a similar manner. The entire dunefield is migrating landward as individual dunes develop a more characteristic parabolic shape, and separate themselves from neighbouring dunes.

Coastal sand dunes have often been investigated during the spring, summer, and fall, while the winter has been omitted. This on-site investigation has shown that sand transport does occur during the winter. Subsequent studies should consider the effect of winter aeolian sand transport, especially in those areas affected by widely fluctuating temperatures, high average wind velocities, abudant sand source, and reduced vegetation. The relative amount of sand transported during the winter may be minimal compared to other seasons, however, neglecting winter transport without investigation, may lead to inaccurate estimates of annual rates of aeolian sand transport.

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APPENDIX 1 CALCULATING WIND RESULTANT

Calculation of annual wind vector resultant based on the methods described by Landsberg (1956) and Jennings (1957).

$$b\text{-}s\sum_{j=3}^{12} n_j(V_j\text{-}V_t)^3$$

Where:
b = vector magnitude
s = scaling factor (10^{-3})
j = Beaufort number (from 3 to 12)
Vj = mid point of wind speed class
Vt = velocity threshold (16 km/h)
n = number of occurrances or percentage frequency

Calculation of weighting factor , $(v_i - V_t)^3$

j Beaufort #	Wind Speed Class (km/h)	Vj Class Mid-point	Vt 16 km/h	Weighting Factor (Vj-Vt)3
3	12-19	16	16	0
4	20-28	24.0	16	512
5	29-38	33.5	16	5359.375
6	39-49	44.0	16	21952
7	50-61	55.5	16	61629.875
8	62-74	68.0	16	140608

Note: Beaufort numbers greater than 8, were not included since wind speeds never exceeded 74 km/h.

Calculation of vector magnitude by multiplying the weighting factor for each wind speed class by the number of occurrences, and finally summing to determine, b.

n, number of occurrances								Wind Speed
N	NE	E	SE	S	SW	W	NW	Class
4.8	1 9	1.7	2.7	7.1	3.6	4.7	2.3	12-19
3.3	0.8	0.9	1.6	4.8	2.7	4.3	2.4	20-28
1.3	0.2	0.3	0.4	1.5	0.9	1.8	1.5	29-38
0.4	0	0	0.1	0.3	0.2	0.5	0.5	39-49
0.1	0	0	0	0	0.1	0.1	0.1	50-61
0	0	0	0	0	0	0	0.01	62-74
23.60	1.48	2.07	5.16	17.08	16.76	28.99	27 81	= b

Determination of vector resultant magnitude by vector summation

vector dir	dir angle	vector mag	cos of angle	sin of angle	Yi	Xi
N	0	23.6	1.00	0	23.6	0
NE	45	1.48	0.71	0.71	1.05	1.05
E	90	2.07	0.00	1.00	0	2.07
SE	135	5.16	-0.71	0.71	-3.65	3.65
S	180	17.08	-1.00	0	-17.08	0.00
SW	225	16.76	-0.71	-0.71	-11.85	-11.85
W	270	28.99	0.00	-1.00	0	-28.99
NW	315	27.81	0.71	-0.71	19.66	-19.66
					11.73	-53.74
			Resultant Magnitude	=	55.01	

Calculation of the resultant vector direction was done by the use of a computer program provided by Shawn Munro. The following is an example of the results.

Vector Magnitude Calculation
Pinery Provincial Park, Ont.

Vector Dir	Vector Magnitude
N	23.60
NE	1.48
E	2.07
SE	5.16
S	17.08
SW	16.76
W	28.99
NW	27.81

Landsberg, 1956; and Jennings, 1957
** ALL WIND DIRECTIONS

Resultant Vector = 102.3143
Resultant Magnitude = 55.00612