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Dune morphology response to water level change, Pinery Provincial Park, Ontario, Canada

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DUNE MORPHOLOGY RESPONSE TO WATER LEVEL CHANGE, PINERY PROVINCIAL PARK, ONTARIO, CANADA

by

Michael C. A. Bitton
Bachelor of Science, Wilfrid Laurier University, 1999

THESIS
Submitted to the Department of Geography and Environmental Studies
in partial fulfilment of the requirements for the
Master of Environmental Studies degree
Wilfrid Laurier University
2002

ABSTRACT

This thesis describes the geomorphological changes to a trough blowout in Pinery Provincial Park's sand dunes. The Park is located on Lake Huron's southeastern shore where, due to rapid changes in Lake Huron water levels, a study could be completed examining the changes to blowout morphology based on the change in beach sediment supply. The study took place during relative low Lake Huron levels (1999-2000) and was compared to data collected during a period of relative high Lake Huron levels (1994-1995).

Field research included; erosion pin measurement to monitor and verify morphological change through the throat of the blowout, aeolian sediment trap volume measurements and grain size analysis, and three-dimensional mapping to calculate areas of erosion and deposition by volumetric analysis.

Erosion occurred through the blowout throat during both study periods but less so during the low lake level study period. The increased beach sediment supply provided a catalyst for increased deposition landward and lakeward of the foredune ridge during the low lake level period. More beach sediment migrated through the blowout and onto the landward side of the blowout crest during the low lake level period.

ACKNOWLEDGEMENTS

A project of this size can not be done without help from several supportive individuals. First and foremost, I would like to thank my advisor Dr. Mary-Louise Byrne. Her assistance in the field, in the laboratory, and in writing this paper were, at all times, more than greatly appreciated. I am also deeply indebted to her for her support and guidance throughout the Masters program, while still giving me the latitude to pursue other activities throughout this course of study.

I would like to thank Dr. Houston Saunderson as well as other members of the Wilfrid Laurier University Department of Geography and Environmental Studies faculty who offered assistance on numerous occasions. I would also like to thank Alex Maclean for assistance in the field and extracting mapping data, Pam Schaus for assistance in the map library, Grant Simpson for solving abominable computer problems, and Jo-Anne Horton for being my guiding light through the whole degree process.

I would like to thank Terry Crabe, Pinery Provincial Park Naturalist and Superintendent, and Ontario Parks for allowing me to pursue this research at Pinery.

I would like to thank my Waterloo family who were my slightly demented roommates; Captain, Beav, The Wipf, Christoph, Do, and Titia who offered endless

encouragement; and the three-year masters crew, Tobi, Turks, Sheldon, R.B. Le-myux and Roadkill. Our discussion group sessions, in which we reminisced about our thesis goals and accomplishments, was of great comfort whenever we needed a break from relaxing.

Lastly, and most importantly I would like to thank my family for support through all of my academic goals, but most importantly through the writing of this paper. I am thoroughly indebted to them for their support to continue academic studies, as well as for the use of their vehicle to get me to and from the study site, and points in between. Through their repeated questioning: "Have you finished yet?", they helped me to realize the value of completing the degree, as well as the gratifying feeling of saying: "Yes I am done."

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1.0 INTRODUCTION

1.1 Background

Coastal dunes are found above high water marks of sandy beaches and can occur on ocean, estuary and lake shorelines (Carter *et al.*, 1990a). Dune formation is a function of sediment grain characteristics and supply, the beach profile, and the wind regime. Several areas of dunes can be found along Great Lakes shorelines. Davidson (1990) identified 20 different areas of sand dunes along Ontario's shorelines, all of which demonstrate different shapes and sizes. All of these dune areas are exhibiting some degree of erosion primarily due to human activity.

The study site is located on Lake Huron's eastern shore within Pinery Provincial Park near Grand Bend, Ontario (Figure 1.1). Lake Huron water levels fluctuate over different temporal scales. Water levels have been declining since 1996 due to a combination of lower precipitation, higher air temperatures, and increased evaporation in the Great Lakes basin (GLERL, 2000). The decreased lake level has allowed an opportunity to make a comparative analysis between data collected in 1995 (Byrne, 1997), when Lake Huron was at a relative high level, and during 1999 and 2000 when Lake Huron was at a relative low. Due to the lower water levels, the more recent study involved a much larger beach surface area, and ultimately a much larger sediment supply available to enter the dune system.

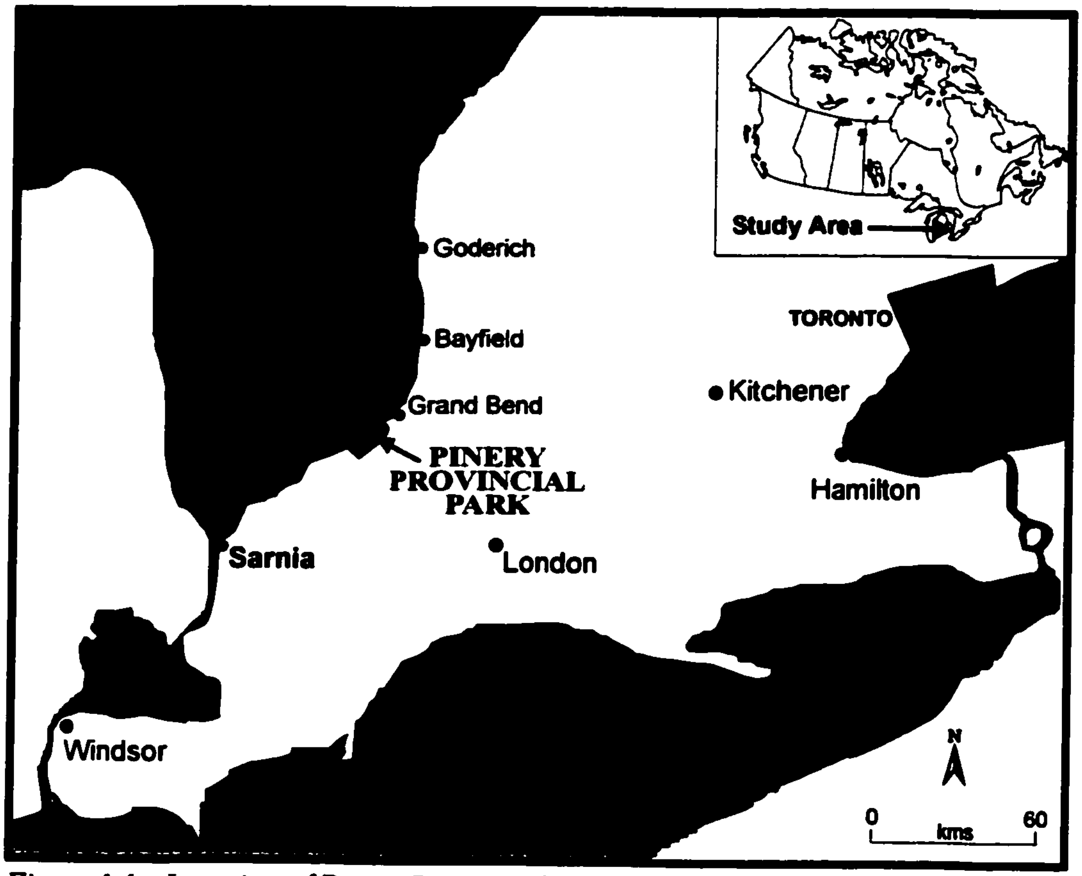


Figure 1.1 - Location of Pinery Provincial Park.

Byrne (1997) studied the seasonal variations of sediment transport through a blowout in a secondary dune ridge. Blowouts are saucer-, cup-, or trough-shaped depressions or hollows formed by wind erosion on a pre-existing sand deposit (Hesp and Hyde, 1996). By reproducing Byrne's study, a better understanding of morphodynamic change can be incurred during a period in which an increased amount of sediment is available to enter a dune system.

1.2 Research Need

Coastal sand dunes have experienced the greatest degree of human pressure of all coastal ecosystems, resulting in large- and small- scale dune morphology changes (Byrne, 1997; Carter, 1988). Carter *et al.* (1990b: 2) suggested that although the interest in coastal dune geomorphology has increased significantly over the past twenty years: "coastal dune research is still at a rather primitive age." Changes to the dune ecosystem result from various natural, industrial, and recreational activities. To date, there have been no geomorphological studies of sand dunes with regard to changing water levels, and very few with regard to rapidly changing sediment supply. With the possibility of rapid sea-level rise, documentation of the changing sea and the ensuing change in sediment quantity to the dunes is very important for coastal dune managers. Nordstrom *et al.* (1990) noted the need for more research into the possibility of reactivation of dune fields as a result of sea-level rise. Changes in sediment supply could have drastic effects on the morphology of sand dunes on a global scale.

In the Great Lakes, water level annual averages fluctuate far more rapidly than within ocean basins. This provides an opportunity to document water level changes and the effect on sand dune sediment supply before potential sea-level changes affect marine coasts on a much larger scale. Byrne (1997) studied the sand dunes at Pinery Provincial Park for seasonal variations through a trough blowout during a period of high lake levels. The data from that study can be compared with data in the current study to document differences between low and high water periods. This study's contribution to Byrne's (Longboat 1996; Byrne, 1997; Byrne and Bitton, 2002) ongoing geomorphic studies of Pinery Provincial Park's sand dunes is also important for creating a larger baseline data set. Sherman (1995), and Bauer and Sherman (1999) noted the need to monitor previously researched areas to create long term data sets.

Pinery Provincial Park dunes are part of a nature reserve section of the park (OMNR, 1986). The dunes are subject to intense recreational traffic which cause many erosional features, usually initiated by human trampling (Bowles, 1980). The park management plan includes increasing the size of the protected wilderness zones, in which park users are banned from moving freely off park road and trail networks. Part of the Park's mandate is to use research to make informed management decisions to protect the dunes and the associated Oak-Savannah ecosystem. The research conducted on sediment transport, and transport during different time periods will help managers to plan dune stabilization strategies.

1.3 Goal and Objectives

The goal of this investigation is to observe and analyze changes in sediment transport and the resulting change in morphology of a trough blowout in Pinery Provincial Park, as well as to create a larger baseline data set. The objectives that will be pursued through this thesis are as follows;

- Sediment volume comparison between seasons and different sediment supply periods,
- Sediment grain size analysis in order to compare sediment transport during different seasons,
- Erosion pin measurement to monitor morphological change through the throat of the blowout,

- Volumetric Analysis based on three-dimensional mapping of the study site to note changes in dune morphology.

1.4 Pinery Provincial Park

Pinery Provincial Park is located on the southeastern shore of Lake Huron in Huron County, Ontario, Canada (Figure 1.1). The park is 5 km south of the tourism based community of Grand Bend, and approximately 250 km from the provincial capital, Toronto. Pinery Provincial Park was established in October 1957, and officially opened in 1959 (OMNR, 1986). The landscape of the park is dominated by a series of inactive dune ridges and interdunal depressions. An active process of dune building still occurs today in areas adjacent to Lake Huron (OMNR, 1986).

1.4.1 Regional Physiography

The study area is underlain by limestone of the Hamilton formation (Matthews *et al.*, 1957, Chapman and Putnam, 1966). Overlying the bedrock are a series of tills. The St. Joseph Till has been identified as the uppermost of the till deposits beneath the lake. The Lake Huron shoreline closely parallels the relic Lake Algonquin and Lake Nipissing shorelines. Both lake were formed by glacial carving of the surface creating a large basin. This basin was in filled by meltwaters as the ice sheets retreated. This area, which encompassed all of the Great Lakes, was the Champlain Sea. Agricultural soils throughout southern Ontario result from nutrient rich lacustrine deposits deposited before the lake levels retreated and the land ascended isostatically.

The beach deposits along the Lake Huron shoreline were laid down during the Nipissing stage and were built from materials carried by longshore currents from the Lake Algonquin shore cliffs to north of Grand Bend (Lewis, 1969, Mittler, 1975). Cooper (1979), noted that there is a large embayment between Thedford and Grand Bend (Figure 1.2). Within the embayment there are two baymouth bars. The westernmost sand bar was dated to Lake Nipissing time (5500 to 3700 years B.P.: Lewis, 1969). The easternmost bar is Algonquin age (Lewis, 1969). Within the western portion of the embayment, sediment has collected and become a large source of sediment for the sand dunes in Pinery Provincial Park. As well, the bar itself has contributed a large amount of sediment towards the creation of the sand dunes (Cooper, 1979).

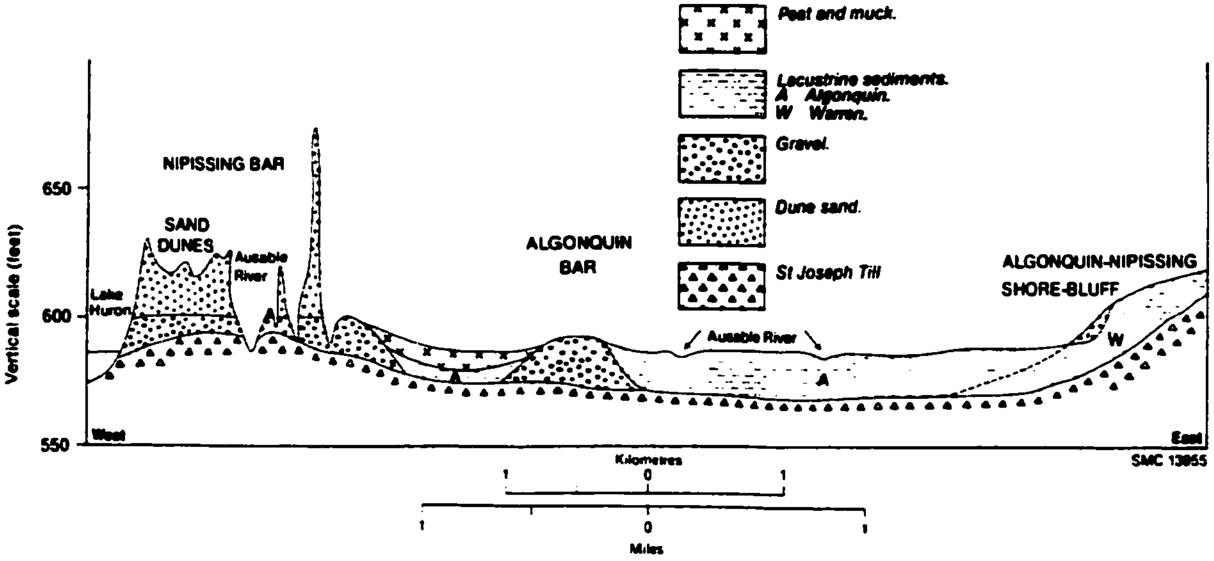


Figure 1.2 - Generalized geological cross-section through the Thedford Embayment near Grand Bend Cooper, 1979).

1.4.2 Study Site

The field studies were conducted on the sand dunes along Lake Huron behind the foredune ridge. The study site is a small trough blowout located in the wilderness area of Pinery Provincial Park (Byrne, 1997). The 250 m long 90 - 75 m wide dune is a complex, digitate dune (Pye and Tsoar, 1990). The axis of the blowout (northwest to southeast) is normal to the foredune ridge and the Lake Huron shoreline. The prevailing winds are

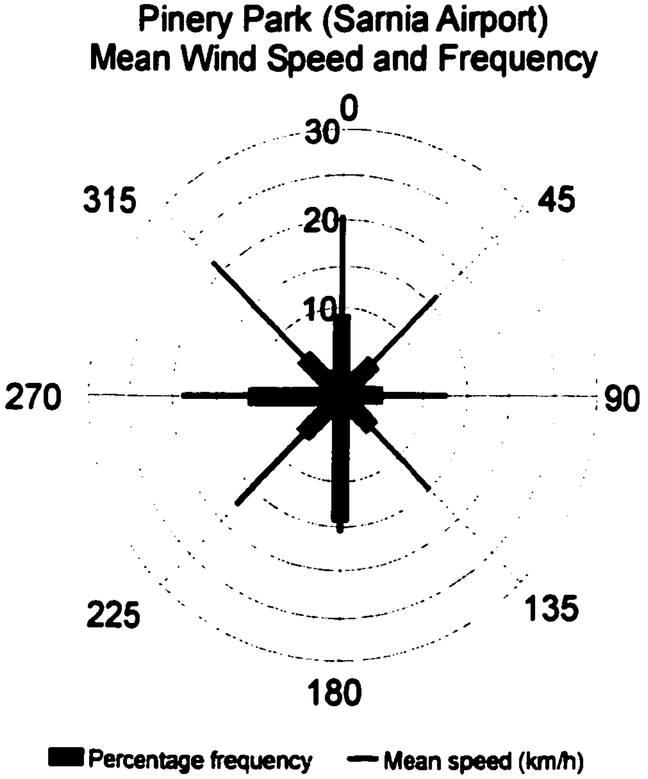


Figure 1.3 - Wind rose from Sarnia Airport, located 80 km southwest of Pinery Provincial Park (Byrne and Bitton, 2001).

from the south and west (Figure 1.3). Winds are strongest form the north and west, while easterly winds are relatively weak. Park climate is characterized by warm summers and cold winters, with rapid changes in conditions with the passing of mid-latitude depressions (Figure 1.4). Precipitation is spread evenly through the year with slight peaks in February and March (Byrne, 1997). Snowfall begins in late November and ends at the beginning of April. The mean frost-free period is 150-160 days, with a 205 day growing season (Fisher *et al.* 1987). The dominant vegetation in the foredune and along the crest of the trough blowout is *Ammophila breviligulata* (marram grass), with occasional clumps of *Calamovilfa longifolia* (sand reed). Both plants are perennial dune forming grasses, and are effective in trapping sand and possess pronounced abilities to elongate upwards in response to sand accumulation (Maun, 1984, 1985). Areas of discontinuous

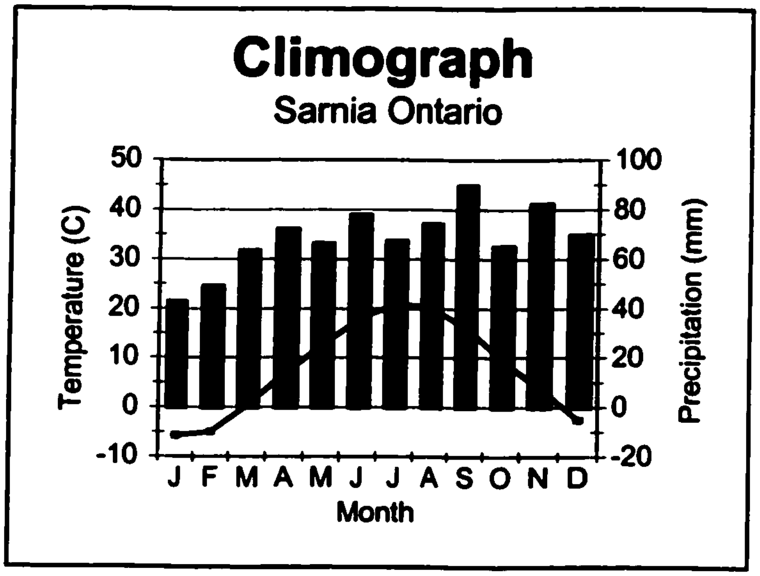


Figure 1.4 - Temperature-Precipitation climograph for Sarnia, Ontario.

vegetation include scattered clumps of trees and shrubs including; *Prunus pumila* (sand cherry), *Juniper communis* (common juniper), *Cakile edentula* (sea rocket), *Juniperus virginiana* (Eastern Redcedar), and *Populus deltoides ssp. deltoides* (eastern cottonwood), and *Thuja occidentalis* (Eastern White Cedar).

1.5 Structure of Thesis

This thesis is divided into six chapters. Chapter 2 introduces climate change and Great Lakes water level changes. The second chapter also discusses our current state of knowledge regarding aeolian research, narrowed to coastal dune blowout morphology. Chapter 3 discusses the field instrumentation and data collection techniques used. A description of data management and data analysis approaches are included in Chapter 3 for the field measurements taken. The results derived from the data analysis are described in Chapter 4. Chapter 5 discusses the results, and the implications of these results. Chapter 6 outlines the strengths and weaknesses of the study, and the recommendations for future research.

2.0 LITERATURE REVIEW

2.1 Introduction

Pinery Provincial Park contains a well developed dune system that has been investigated geologically, geomorphologically, and ecologically (Morrison, 1973; Bowles, 1980; Maun and Lapierre, 1984; Maun, 1985; Fisher *et al.*, 1987; Davidson, 1990; Byrne, 1997). This study will add to the growing body of research about this dune system, as well as provide further insight into trough blowout morphology that can be used in many locations.

This chapter provides background information to which later chapters will refer and will expand upon. The chapter is divided into two main sections; the first reviews sand dune research including an introduction to aeolian processes and coastal dune research, the second section is a brief review of Great Lakes water level change.

2.2 Sand Dune Research

A large portion of the early research on sand dune geomorphology was generated from desert sand dunes. The first significant contribution to aeolian transport processes was completed by Bagnold (1941). Since then, a series of desert and coastal sand dune research investigations have been completed around the world (Nickling, 1986; Davidson-Arnott and Law, 1990; Nordstrom *et al.*, 1990; Carter *et al.*, 1992; Lancaster, 1995; Livingstone and Warren, 1996; Goudie *et al.*, 1999; Wiggs, 2001). As well, wind tunnel research has added to the growing literature on sediment transport and air flow (Wiggs, 2001).

2.2.1 Aeolian Transport

2.2.1.1 Wind Velocity Profile

The energy to lift and carry sediment comes from wind as it shears the Earth's surface (Bagnold, 1941; Livingstone and Warren, 1996). When air blows across a stationary surface, friction occurs along the surface. The friction caused by the bed's resistance to flow is transmitted upwards through air. The force, known as shear stress, is the tangential force per unit area, and is given as:

$$\tau_o = \mu \frac{du}{dz}$$

where τ_o = shear stress at the bed (2.1)

μ = air viscosity

$\frac{du}{dz}$ = the velocity gradient

The wind speed increases logarithmically with height above the surface because of this resulting friction (Figure 2.1). The zone of maximum frictional forces is confined to a thin layer or effective surface roughness, denoted by z_o (Olson, 1958). Within this zone, the wind speed is zero. The depth of this viscous sub-layer is related to the roughness of the bed, and is approximately 1/30 the height of protruding irregularities (Livingstone and

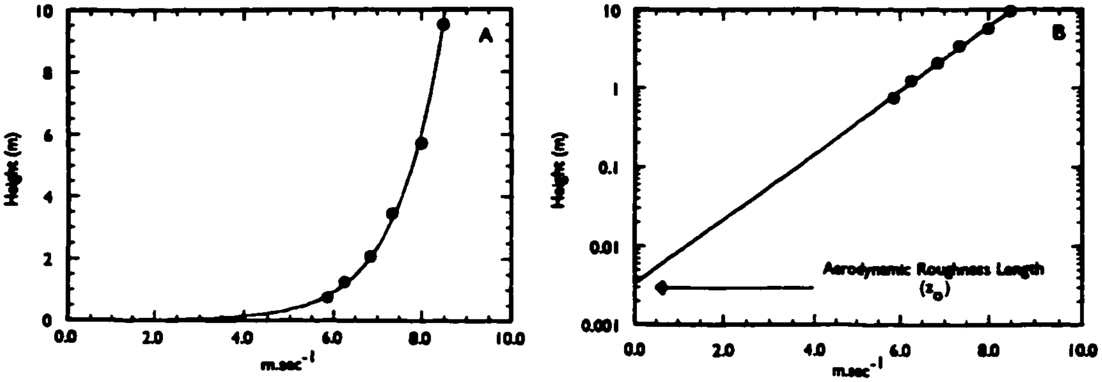


Figure 2.1 - Example wind profile using the same data. The left graph uses a linear scale. The right graph uses a logarithmic scale on the y-axis. The y-intercept is an estimate of the aerodynamic roughness length (Lancaster, 1995).

Warren, 1996). This value varies with slope and average distance between individual grains of sediment or other roughness elements (Nickling and Davison-Arnott, 1990). The velocity profile above the viscous sublayer for aerodynamically rough surfaces is characterized by the Prandtl-von-Karman equation (Lancaster, 1995):

$$\frac{u}{u_*} = \frac{1}{k}\ln\frac{z}{z_o}$$

where u = velocity at height z
z_o = roughness length
z = height above the bed (2.2)
u_* = shear velocity
k = von Karman's constant (~ 0.4)

The shear velocity (u_*) is proportional to the slope of the wind velocity profile when plotted with a logarithmic height scale and is related to the shear stress at the bed and the air density by:

$$u_* = \sqrt{\frac{\tau_o}{\rho_a}}$$

where u_* = shear velocity (2.3)
τ_o = shear stress
ρ_a = air density

The wind gradient equation *2.2* was given for a bare surface. In coastal dune studies, the sand surface is barely free of obstacles. Where the surface is covered by tall vegetation or other roughness elements, the wind velocity profile is altered. The boundary layer increases in height. The profile becomes displaced upwards from the surface to a new reference plane. This is a function of height, density, porosity, and flexibility of the roughness elements (Carter, 1988) and is illustrated in Figure 2.2. Dominant factors affecting coastal sand dune velocity profiles include sand grain size and vegetation. These interrupted flow conditions create a new zero plane displacement height. Under these conditions, equation 2.2 becomes (Bagnold, 1941):

$$\frac{u}{u_*} = \frac{1}{k}\ln\frac{z-d}{z_o}$$

where u = velocity at height z
z = height above the bed
z_o = roughness length (2.4)
u_* = shear velocity
k = von Karman's constant (~ 0.4)
d = zero plane displacement height

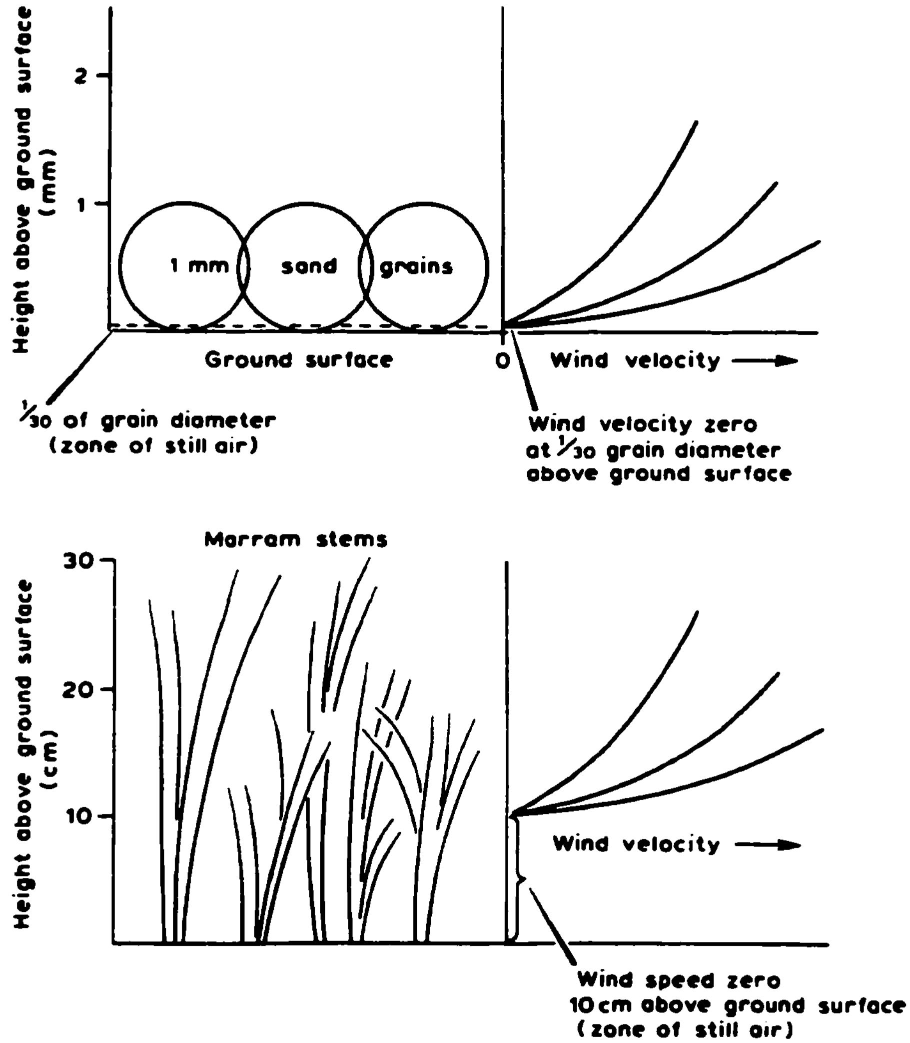


Figure 2.2 - Velocity profiles over a sandy surface and under marram vegetation. The zone of zero wind velocity on a bare sand surface (upper diagram) extends to approximately 1/30th of the grain diameter above the bed. Under marram vegetation cover (lower diagram), the zero velocity may be 10cm or more (Pethick, 1984)

2.2.1.2 Threshold of Motion

In theory, loose particles on a surface over which wind is blowing experience a vertical lift force which can overcome resistant forces (Livingstone and Warren, 1996).

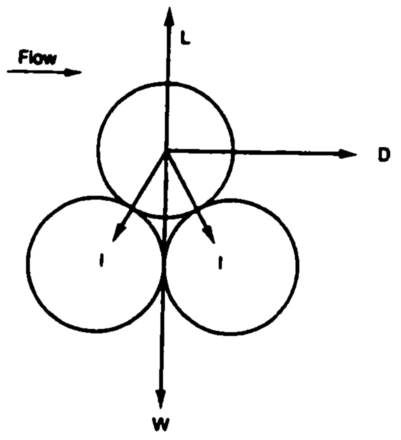


Figure 2.3 - The forces acting on a stationary particle resting in fluid flow. The fluid exerts lift (L) and drag (D) and these are resisted by the particles weight (W) and interparticle cohesive forces (I) (Livingstone and Warren, 1996).

The resistant forces are particle weight (gravity) and interparticle forces (cohesion and adhesion).

The shear force, or drag, acts horizontally in the direction of wind flow (Figure 2.3). It is composed of overall skin friction drag caused by the roughness of the grain on the bed, and drag which is related to the geometry of the bed. A positive pressure on the upwind side and a negative pressure on the downside of the grain occurs. The air stress, which acts tangentially to the surface, is the skin friction drag (Pye and Tsoar, 1990). The lift force, which acts vertically upwards, or normal to the bed, is the result of the pressure difference between the upper and lower sides of the sand grain. On the upper side of the grain, the pressure is reduced below the static pressure because of the curvature of the streamlines within the wind, and the increased wind velocity above the grain (Streeter, 1961).

Grain weight is the most effective resistive force, acting directly opposite to the lift force (Pye and Tsoar, 1990). Cohesive forces between grains and adhesive forces between grains and other surfaces are considered significant resisting forces. These forces are of greatest importance for very fine sediment (Pye and Tsoar, 1990).

Beach and dune sand will begin to move when the forces of lift and shear caused by wind will overcome resistance to motion. The threshold of entrainment has been measured in terms of critical shear velocity (Bagnold, 1941). Bagnold determined that the critical shear velocity is dependent on grain size and density:

$$u_{*_t} = A\sqrt{\frac{(\rho_p - \rho_a)}{\rho_a} gd}$$

where u_{*_t} = fluid threshold shear velocity (2.5)
A = an empirical coefficient dependent on grain characteristics
ρ_p = grain density
ρ_a = air density
g = acceleration due to gravity
d = mean grain diameter

Once particle threshold has been reached, stationary particles begin to roll or slide (surface creep) because of direct pressure from the wind (Bagnold, 1941). Once particles begin to move, they accelerate and start to bounce off the surface into the air stream and initiate saltation. Bagnold (1941) identified that, as a result of the impact of saltating grains, particles are ejected into the air stream at shear velocities lower than those required to move stationary grains (Figure 2.4). Bagnold termed this new lower threshold to be the dynamic or impact threshold. He found that the dynamic impact threshold followed the same equation (2.4) for stationary particles, but with a value for A of ~ 0.08 instead of ~ 0.1. Critical threshold is also affected by moisture content, binding agents,

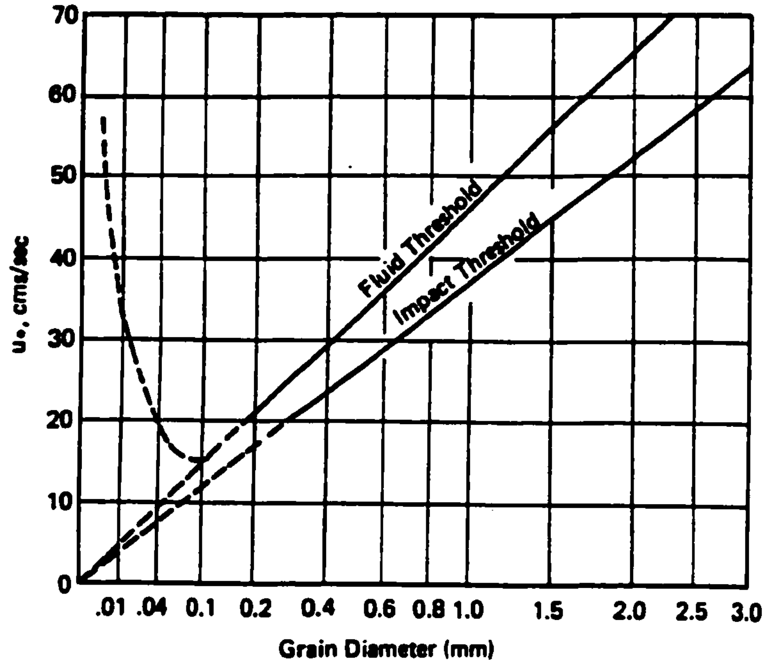


Figure 2.4 - Relationship between fluid and impact threshold shear velocity and particle size (after Bagnold, 1941).

surface roughness, surface crusts, and sediment distributions (Pye, 1983, Nickling and Davidson-Arnott, 1990).

2.2.1.3 Sediment Transport

Sand transported by wind travels by three distinct modes; suspension, saltation, and creep (Pye, 1987). The movement of fine grained sand by wind usually occurs at wind speeds of 3-4 m/sec (at 10 m). The transport mode depends primarily on the grain size of the available sediment (Figure 2.5). Very small particles (<60 to 70 μm ≈ 4 to 3.75 φ) are transported in suspension. These particles are kept in the air flow by turbulent eddies. Larger particles (60 to 500 μm ≈ 4 to 1 φ) move downwind by saltation.

Saltation is the movement of grains by impact between moving and stationary grains which flicks the moving grain into the air. In the higher velocity wind, the grains shoot further downwind, and may be in short term suspension. Large grains (> 500 μm ≈ 1 φ) move by surface creep. Surface creep is set in motion by descending saltating grains. These large grains react to the impact by rolling or pushing slightly downwind across the surface. Bagnold (1941) found that ~ 75% of mass flux was by saltation. Sediment creep made up another ~ 25%. Chepil (1945) and others (Williams, 1964, Nickling, 1978) found that the proportion of sediment transported in creep can vary significantly, and is dependent on textural characteristics of the eroding sediment and the surface roughness characteristics (Nickling and Davidson-Arnott, 1990). Nickling and Davidson-Arnott (1990) suggested that the grain size distribution directly affects the percentage of sediment transport in each mode, and that the percentage of suspension appears to increase with increased shear velocity.

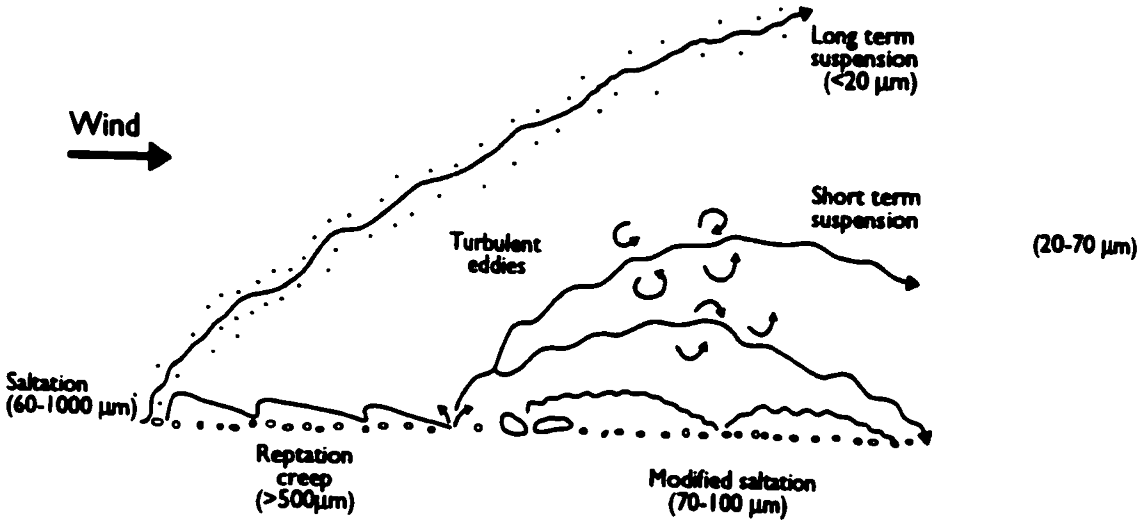


Figure 2.5 - Modes of sediment transport. Values listed beside mode of transportation are grain sizes (Pye, 1987).

The most important influencing factor on sand transport is wind velocity, although other factors such as sand size and grain shape are important in total sediment transport (Willetts *et al.* 1982). As saltating grains are projected above the zero boundary layer they move forward or downwind. As the grains rise higher into the faster wind speeds, their trajectory is further downwind and the grains will impact the base layer with more force, thus moving more grains above the zero boundary layer. Pethick (1984) summarized that the amount of sand transported per unit beach width per unit time has been shown to be related to the cube of the shear velocity (Bagnold 1941; Cooke and Warren, 1973; Hsu, 1973):

$$q = (C\sqrt{D})(u'_*)^3$$

where q = weight of sand moved per unit width per unit time (2.6)
C = a constant
D = grain diameter
u'_* = shear velocity during saltation

The formula for this relationship has been studied by many authors with no agreed upon succinct equation. Greely and Iverson (1985) as well as Sarre (1987) reviewed these equations and noted that it is difficult to derive and confirm the formula. All the formulae are in agreement with the relationship between transport rate and shear velocity and can be best expressed in the following form (Livingstone and Warren, 1996):

$$Q \propto u_*^a (u_* - u_{*_t})^b \qquad (2.7)$$

where Q = transport rate (weight / beach width / time)

u_* = shear velocity

u_{*_t} = fluid threshold shear velocity

$a + b = 3$

2.2.2 Sand Dune Geomorphology

Coastal sand dunes may develop where there is an adequate sand supply, sufficient wind to move the sediment, and vegetation, or some other obstacle that can initiate stabilization (Pye, 1983; Carter, 1988). Coastal dune sands are typically medium to fine grained, and well-sorted (Pye, 1983; Carter *et al.*, 1990a). The process is often initiated by the movement of marine (or lacustrine) sands moved onto the nearshore by wave action. The grains may then dry, and can be moved further inland by onshore winds. The wind strength necessary to move different sized grains has been discussed in previous sections.

When moving sand encounters a discrete roughness element projecting above the bed, sand deposition occurs. Deposition and accumulation of sand result from disturbances in the wind flow, and thus the first stages of sand dune development. This small dune is often referred to as an embryo dune. Bagnold (1941) identified many embryo dune forms, naming one common type of embryo dune a shadow dune which formed on the leeward side of obstacles, such as pioneering vegetation. Hesp (1981) intensively studied the characteristics of air flow, sand transport and deposition and the ultimate accumulation of sand as a result of vegetation stands acting as a roughness elements. Pye (1983) noted that although vegetation is not essential for coastal dune formation, it had an important controlling effect on the dune morphology. As embryo dunes grow in height, they grow laterally as well. As the embryo dunes begin to coalesce, they will form a dune ridge parallel to the shoreline. This foredune ridge will often reach as high as two meters (Pethick, 1984). With the increasing height, a change in vegetation will occur. This is often due to a change in moisture conditions. In most locations around the world, the vegetation will switch from an intermittent pioneer species to complete cover by marram grass as the dune builds upwards (Ranwell, 1972). The dominant marram vegetation species at Pinery Provincial Park is *Ammophilia arenaria* (Maun, 1985). As the vegetation cover becomes more dense, the surface friction (z_0) increases. Olson (1958) found z_0 to be 1 cm under *Ammophila breviligulata* (marram grass). The vegetation intercepts descending saltating grains and acts as a soft surface which absorbs a large portion of their energy (Pethick, 1984). Although the saltation process does not stop, the fore-dune vegetation does lower the transport rate significantly. Marram grass, and many other dune species will continue to grow upwards as more sand deposition continues, and therefore an upward building of the dune ridge occurs. Landward winds will continue to shift the foredune ridge further inland and new embryo dunes will begin to form on the seaward side of the foredune ridge.

Olson (1958), Bressolier and Thomas (1977), Hesp (1981), and Maun (1984, 1985) have studied the complex vegetation structures and their effects on sand entrapment. The landward migration of dune ridges is highly controlled by vegetation. Erosional landforms, such as trough blowouts, are often initiated by the trampling of vegetation by human and faunal activity, which may lead to an increased migration rate of dune ridges. It has been documented that dunes can move in discrete episodes as a response to a common cause as well as out-of-phase local causes (Pye, 1983). "Attempts to establish the degree of synchroneity and possible causes of transgressive dune phases at the regional and global scale are hampered by a lack of radiometric age data." (Pye, 1983, 549). This problem may be solved by the increasing use of thermoluminescence as a method of dating quartzose sediments (Pye, 1982a; Ollerhead *et al.*, 1994; Wolfe *et al.*, 2002).

2.2.3 Beach Dune Interactions

Coastal dune sands come from their adjacent beaches. Traditionally, wave current dominated beaches and wind-dominated dunes have been examined as distinct and separate systems (Sherman and Bauer, 1993; Sherman, 1995). However, the beach-dune interaction is very important in the morphology of coastal dunes (Illenberger and Rust, 1988). Sherman and Bauer (1993) modified Valentin's (1952) model to develop a conceptual framework of beach-dune interaction. In this framework, coastal change can be a result of relative displacement of the water-land interface through either horizontal or vertical movement of the water level and/or the land mass, over a spectrum of spatiotemporal scales (Sherman and Bauer, 1993). Two results of this framework are unconditionally advancing coasts and unconditionally retreating coasts, which are divided by the dotted line (Figure 2.6). The dotted line represents a coast line in equilibrium, and only the center of the diagram represents conditions that are completely static. The

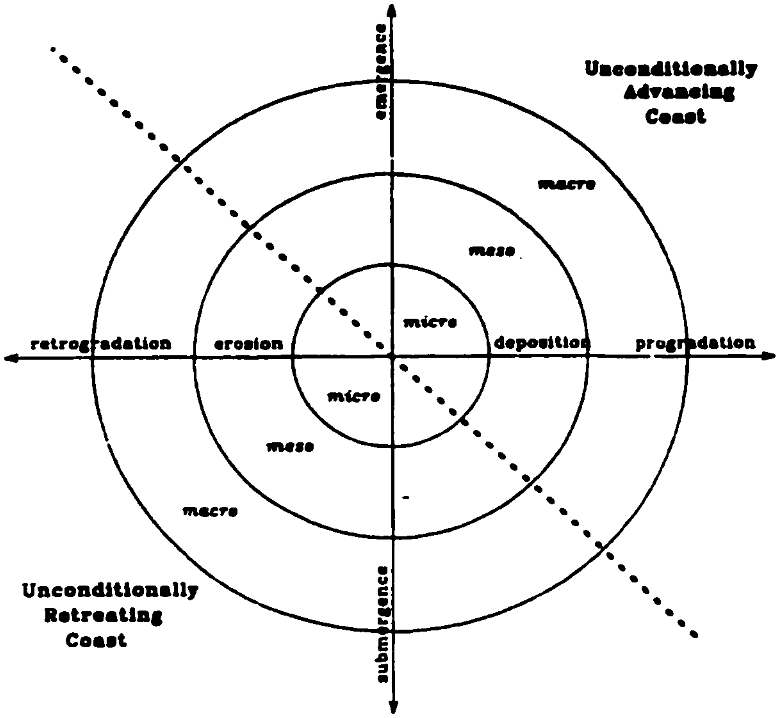


Figure 2.6 - A scheme for the classification of beach and dune systems (after Valentin, 1952). Relative sea or lake-level changes and erosional and depositional processes are indicated as co-ordinate vectors, the interaction of which suggest a spectrum of possible resultants of shoreline migration. Micro, meso and macro scale domains indicate time and space scales appropriate to the degree of coastal change occurring (Sherman and Bauer, 1993)

scheme displays macro-, meso-, and micro-scale with which different process-response interactions are represented. Figure 2.7 shows Psuty's (1992) conceptual model of the morphological evolution of the foredune as a function of the beach sediment budget and the foredune sediment budget. "This matrix is a two-dimensional cross-profile model of foredune development using the concept of net sediment budget produced by the variety of processes operating on the entire beach-dune profile." (Psuty, 1992, 6). The matrix contains a temporal component to the sequential development of the foredune, indicated

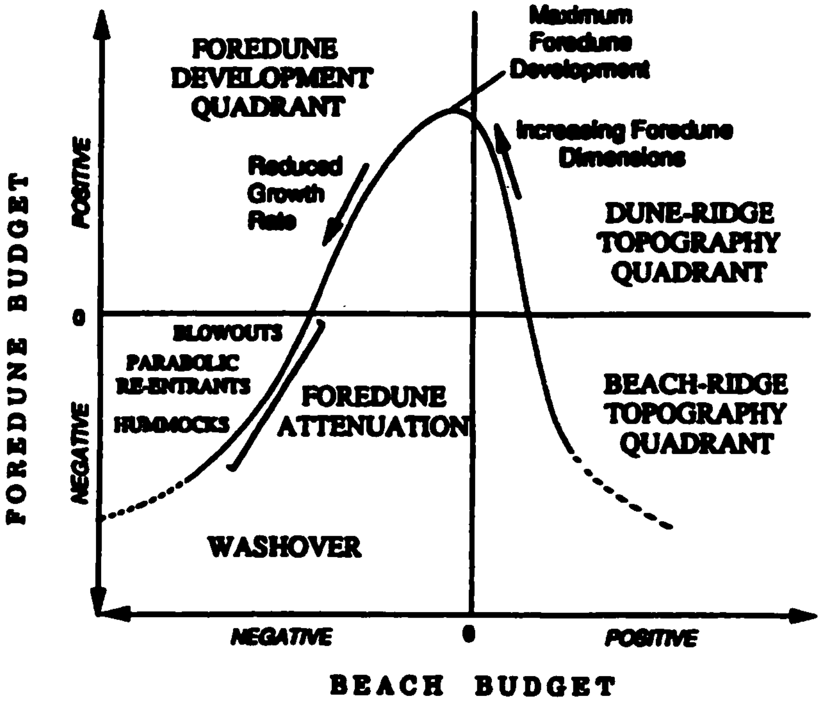


Figure 2.7 - Morphologic evolution of the foredune as a function of the beach sediment budget and the foredune sediment budget (Psuty, 1992).

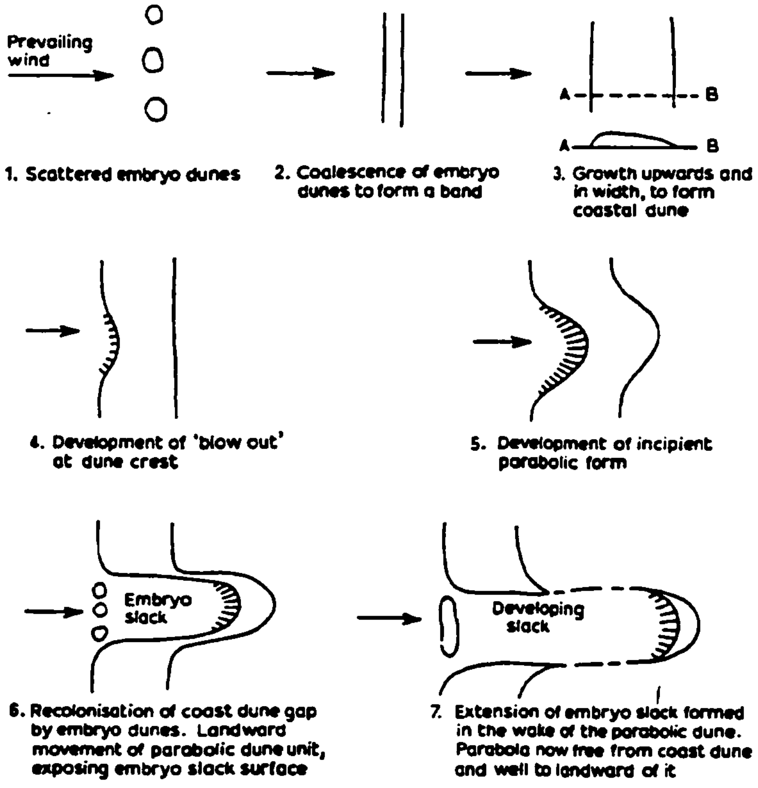
by the arrows on the diagram. Although this model only applies to the foredune, very often sediment movement and wind patterns in the landward dunes are controlled and/or modified by the beach profile and foredune alignment (Short and Hesp, 1982; Nickling and Davidson-Arnott, 1990; Pye, 1983). As well, this model applies to the backdunes due to the sediment movement from the foredune inland during the foredune attenuation phase in the matrix.

Sediment can move inland from the beach over foredunes, as well as through breaches, or foredune blowouts through the first dune ridge (Carter *et al.*, 1990b; Carter and Wilson, 1990; Psuty, 1992). This is a major pathway for beach sediment to move into a dune system, such as the trough blowout in this study. These breaches are often caused by wave attack (Short and Hesp, 1982; Psuty, 1992; Sherman and Bauer, 1993). Breaches may be caused by human activity by trampling of vegetation as well as faunal trampling and feeding. Bate and Ferguson (1996) recognized cases where bare areas in the foredune ridge have been created by topographic steering of offshore winds across and through the foredune ridge.

In cold climate regions, the study of seasonal sediment transport is becoming more important. Byrne and Dionne (2002) reviewed coastal sand dunes in cold climate regions. Researchers initially believed that during winter months, dunes would freeze, and snow cover and freezing temperatures would curtail aeolian processes (Law, 1990). Marsh and Marsh (1987) identified cold climate dunes in Ontario, and described winter deposits and niveo-aeolian deposits on Lake Superior dunes. Law (1990) identified that the shape of coastal dunes may vary significantly with the seasons where ice develops during the winter months. Law noted that in winter that the dune system responds differently to external stimuli due to ground ice and snow fall. Byrne (1997) documented the seasonal sand transport through a trough blowout at Pinery Provincial Park where there was a definite winter freeze/snow period. Byrne's results indicated that there was an increase in sediment moving through the blowout during winter months, and also an increase in erosion during the winter.

2.2.4 Blowout Geomorphology

A blowout is defined as an erosional hollow, depression trough, or swale within a dune complex (Carter *et al.*, 1990b). The term blowout first appeared in Melton's (1940) paper on semi-arid dunes and in Bagnold's *The Physics of Blown Sand and Desert Dunes* (1941). Cooper (1958), Olson (1958), and Ranwell (1972) referred to Bagnold's definition of a blowout, and henceforth was continued in the literature. Blowouts may form as areas of non-deposition between mobile dune ridges or as gaps in incipient foredunes that remain as the dune forms around them (Carter, *et al.* 1990b). Two major types of blowouts have been identified by Cooper (1958), saucer blowouts, and trough



1. Scattered embryo dunes
2. Coalescence of embryo dunes to form a band
3. Growth upwards and in width, to form coastal dune
4. Development of 'blow out' at dune crest
5. Development of incipient parabolic form
6. Recolonisation of coast dune gap by embryo dunes. Landward movement of parabolic dune unit, exposing embryo slack surface
7. Extension of embryo slack formed in the wake of the parabolic dune. Parabola now free from coast dune and well to landward of it

Figure 2.8 - The formation and development of a parabolic dune unit from embryo dune, to ridge, to blowout, to parabolic (Ranwell, 1972).

blowouts. "Saucer blowouts are shallow, ovoid, dish-shaped hollows with a steep marginal rim and commonly a flat-to-convex downwind depositional lobe. Trough blowouts are relatively deep, narrow, steep-sided topographies with more pronounced downwind depositional lobes, and marked deflation basins" (Carter *et al.*, 1990b: 231). Trough blowouts are especially well developed through high dunes, and commonly evolve into parabolic dunes. Parabolic dunes are similar to blowouts in shape, but their form is controlled in part by stabilisation from mature vegetation along the arms or side walls which are no longer connected to the dune ridge (Pye, 1982b). Parabolic dunes will continue to bulge in the leeward direction, as the dominant winds continue to deposit sand on the leeward side of the dune (Figure 2.8). By this process, the parabolic dune will migrate in the direction of the original blow-out form but will maintain its connection to the original dune form with the vegetated sides still intact.

The orientation of parabolic or u-dunes was studied by Jennings (1957). This basic review of blowout morphology and orientation of increased erosion/deposition was complemented by Pluis's (1992) study of the relationship between deflation and wind velocity in a blowout. Hesp (1996), and Hesp and Hyde, (1996) reviewed major papers studying dune blowout morphology. Hesp's (1996) research found that in conditions where the wind approaches a trough blowout directly or parallel to the throat orientation, the flow within the blowout is highly turbulent. There is a flow separation over the leeward side of the dune, and flow separation and corkscrew vortices occur over the crests of the erosional walls. Similar large corkscrew vortices have been observed by Robertson-Rintoul (1990) over parabolic dune edges as well.

Blowouts enlarge as the side walls recede and the deflation continues downwind (Carter *et al.*, 1990b). Blowouts may grow large enough to breach their host dune, revegetate if winds become insufficient to transport sediment, or be halted by available relief (Carter, *et al.*, 1990b, Nordstrom, 2000).

2.3 Great Lakes Water Level Change

Water level change in the Great Lakes are highly dependent on precipitation levels and evaporation rates during previous years (Lawrence, 1995, Mortsch, 1998). The change in water levels will have an effect on shoreline morphology, especially non-cohesive shorelines, such as Lake Huron bluffs, and the beach at Pinery Provincial Park. Generally, increased erosion occurs during higher lake level periods and increased deposition occurs at lower lake levels.

2.3.1 Global Climate Change

The Intergovernmental Panel on Climate Change (IPCC, 2001) has confirmed an increasing trend in global average temperatures. The IPCC (2001) estimates a range of 1.5 - 6.0 with an average of 2.3 degrees Celsius increase in the global temperature average over the next century. Associated with the temperature change will be changes in weather patterns, especially related to storm events, which will contribute to changes in precipitation, infiltration, evaporation and run-off patterns in the Great Lakes Basin. It is predicted that, based on temperature, precipitation and climate change parameters, that Lake Huron minimum levels would drop to new lows (Donnelly, 2002). Lake Huron minimum levels could drop over two meters lower than current lake levels over the next century (Donnelly, 2002).

2.3.2 Great Lakes Basin

The Great Lakes basin covers an area of ~ 1.05 million km^2 in Canada and the United States. The lakes comprise ~247000 km^2, roughly 25 % of the total surface area of the basin (Sousounis and Albercook, 2000). The Great Lakes contain 23000 km^3 of water, approximately twenty percent of the world's fresh water supply (GLIN, 2001). The Great Lakes system extends from the western shore of Lake Superior to the end of the St. Lawrence River (Hartman, 1990). Over this distance, water surface drops from 183 meters above sea level to sea level at the Atlantic Ocean (Hartmann, 1990). Lake Superior is the largest and deepest (147 m) of the Great Lakes. Michigan, Huron and Ontario are also deep (85, 59, 86 m respectively), while Erie and St. Clair, (although not considered a Great Lake, Lake St. Clair is recognized as a connecting channel,) are quite shallow (19 and 3 m deep respectively) (GLIN, 2001).

Lake Superior to Lake Ontario water levels are regulated under the direction of the International Joint Commission (Schwartz, 2001). However, the actual lake level control is minimal. The objective of the Lake Superior regulation plan (Plan 1977A) is to bring the levels of Superior, Michigan and Huron to a similar level with respect to their historical range (IJC, 1993, Schwartz, 2001). The outflow from Lake Ontario is similar, following Plan 1958-D. This plan was designed to accommodate extended periods of above average water supplies, but allows for 'discretionary authority' during extreme conditions (Hartmann, 1990). During the high lake levels in 1985 and 1986, discretionary authority was credited with reducing Lake Ontario 0.76 m, thus preventing record high levels (Hartmann, 1990).

Lawrence (1995) and Mortsch (1998) both identified precipitation, temperature and evaporation as the predominant variables controlling water levels in the Great Lakes. The volume of water available in the Great Lakes is a function of the total amount of lake evaporation from the combined total of runoff and over-lake precipitation. Lake levels are determined by the hydrologic cycle in the Great Lakes basin, and ultimately the changes in climate within the basin (Hartmann, 1990, Mortsch, 1998). Hartmann (1990) noted that low water levels occurred in the 1930s and 1960s. Water level fluctuations occur naturally in the Great Lakes basin (Figure 2.9). Short-term fluctuations are due to wind set-up and storm surges, as well, there are regular seasonal fluctuations, and long-term, inter-annual and decadal fluctuations of all Great Lake levels (Mortsch, 1998.)

The Great Lakes basin includes 3 major (greater than 10 km^2) and 19 minor (greater than 0.1 km^2 and less than 10 km^2) contemporary sand dune systems (Davidson, 1990). The formation of these dunes has been controlled by pre-existing topography, a supply of reworked glacial sediments, and prevailing westerly winds (Davidson, 1990, Chapman and Putnam, 1966). Pinery Provincial Park dunes are big bay dunes by Davidson's (1990) classification.

2.3.3 Lake Huron

Lake Huron is the fifth largest freshwater lake in the world containing 3540 km^3 (GLIN, 2001). Lake Huron's surface area is 59600 km^2, and it has a drainage basin of 134100 km^2 (GLIN, 2001). The Lake Huron shoreline is characterized by gradually sloping and shallow sandy beaches although the Georgian Bay area is characterized by

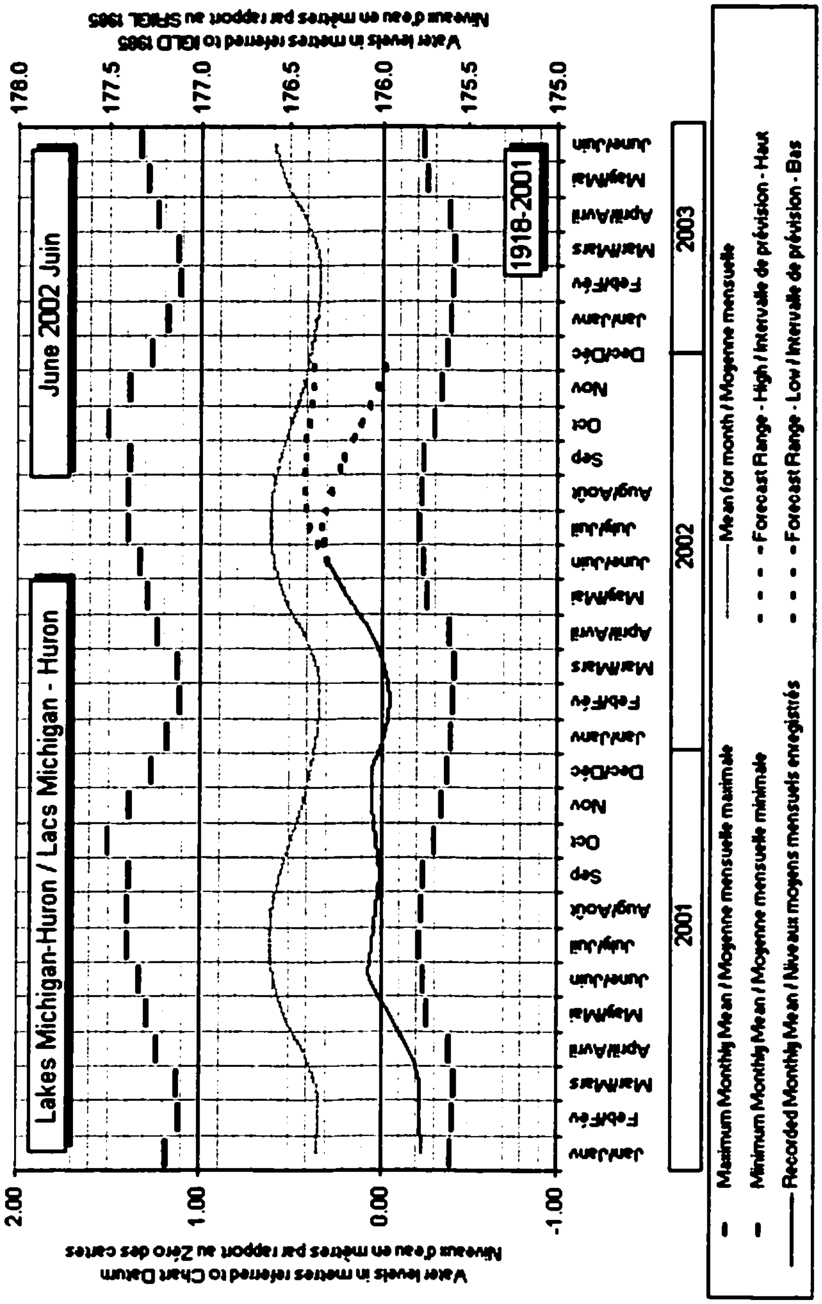


Figure 2.9 - Short term lake level fluctuations. The graph represents the seasonal changes in lake level fluctuations based on the International Great Lakes Datum (1985) for Lakes Michigan-Huron. The forecasted lake level range is a result of the potential variability of climatic factors, such as temperature and precipitation. (CHS, 2002).

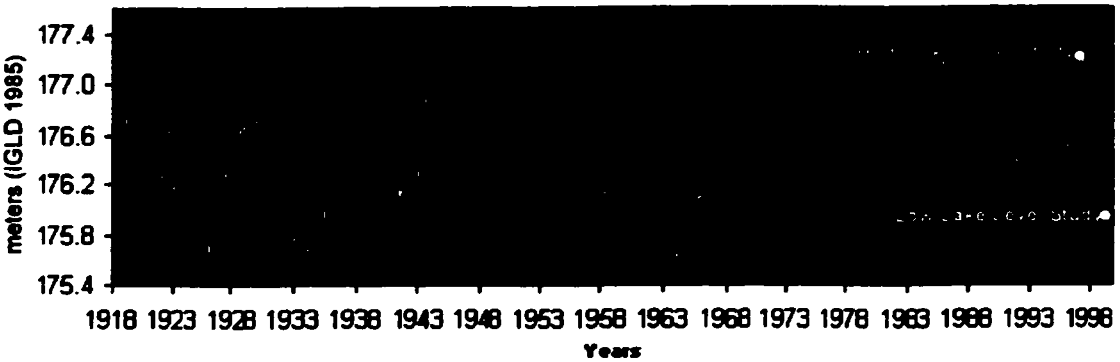


Figure 2.10 - Lake Michigan-Huron levels. The graph represents the average water level based on the 1985 International Great Lake Datum. Indicated on the graph are the high lake level study period and the low lake level study period. (USACE, 2002).

rock formations. The largest dune formations along the Huron shoreline occur in the Ipperwash-Pinery area which are approximately 36 km^2 in area (Davidson, 1990).

Lake Huron is linked to Lake Michigan through the Straits of Mackinac where there are unregulated flows (Hartman, 1990, Changnon, 1993). Lake Michigan-Huron water levels are measured against the 1985 International Great Lakes Datum (GLIN, 2001). The datum is periodically revised to account for gradual changes in benchmark elevations due to isostatic rebound. Water levels are derived for each lake by measurements taken in reference to this datum. The current chart datum for the Lake Huron and Michigan is 176.0 m (GLIN, 2001). Figure 2.10 represents Michigan-Huron water levels. Highlighted on the graph are years of the two study periods.

2.3.4 Shoreline Morphology Changes

Most of the natural features found on the world's coastlines formed during the period of relatively stable sea level (the Holocene stillstand) that followed the world-wide Late Quaternary marine transgression (Bird, 1993). Bird (1993) noted, in cases where water level decreased, or land rose, an increase in sediment deposition on the coastline, and an impedance of erosion occurred. Conversely, where water levels have risen, deposition has been impeded and erosion on the coastline has increased. Such patterns of erosion and deposition will continue to alter the shoreline.

In the Great Lakes Basin, shoreline landforms change according to the relative rise and fall of water levels. Lake levels rise and fall frequently, as noted above in Figure 2.10, due to climatic factors. The land mass is still experiencing a slow isostatic rise, which has a very minor influence on the relative lake levels in the basin. [The current isostatic rise is 1.4 mm/a (Shum *et al.*, 2002).]

On sandy coastlines, a positive beach sediment budget will lead to increases in sediment movement moving inland by aeolian processes (Psuty, 1988, Nickling and Davidson-Arnott, 1990). Conversely, a negative sediment budget will lead to decreased aeolian transport due to a smaller surface area sediment source, greater wave run-up that increases the moisture content thus reducing aeolian transport availability, and further erosion of beach material and sand dune scarping (Short and Hesp, 1982, Psuty, 1988, Nickling and Davidson-Arnott, 1990). This study compares a relative positive sediment budget (low lake level period) to a negative sediment budget (high lake level period).

2.4 Chapter Summary

This chapter has provided a background of literature pertaining to aeolian transport, coastal sand dune morphology, and Great Lakes water level change. The remainder of this thesis will build on sand dune research by documenting the morphological changes to a coastal dune blowout subject to rapid lake level change.

3.0 METHODOLOGY

3.1 Introduction

The purpose of this chapter is describe investigation techniques employed throughout this study. The primary methods of investigation follow Byrne's (1997) work conducted during a high lake level period. Byrne's methods were replicated in order to have a comparable data sets.

3.2 Site Selection

The study site was the same area used by Byrne (1997). This would allow for comparative results between high and low lake level periods. Byrne (*personal communication*) chose this site to fulfill the needs of the original study. This blowout was chosen after examining air photos along the Pinery shoreline and the adjacent dunes. This blowout was representative of the blowouts within the park and had the advantage of being situated away from any day-use areas or campgrounds. However, the blowout was located relatively close to the road, where a car may be parked. This would alleviate the problem of transporting equipment through the wilderness zone, therefore making the site logistically easier to get to, especially during winter months. By entering the study site through the woods it would draw less attention to the site, and thus hopefully minimize human impact.

3.3 Field Instrumentation

The field instrumentation used during this study included: Rosen-style sand traps, erosion pins, Leica Total Survey Station, and a Leica GPS Base Station. Details of the field equipment are presented below.

3.3.1 Sand Traps

To quantify a relative amount of sediment movement through the trough blowout, measurements of sand flux were obtained using vertical cylindrical traps developed by Leatherman (1978) and enlarged by Rosen (1978). The traps were installed in the same locations and orientations as in Byrne's (1997) study. These sand traps are constructed of polyvinylchloride (PVC) piping with two vertical openings which, when the traps are partially buried, sit flat with the sand surface (Figures 3.1 and 3.2). The smaller opening is covered with 60 micron mesh to collect transporting sand. The larger opening is left open for the sand to enter the trap. The sediment entering the trap is stopped by the micron mesh, while wind passes through the mesh to minimize air flow deformations. The captured sand falls into the inner PVC pipe which has a sealed bottom. The captured sand can be removed from the trap by pulling out the inner pipe, and depositing the collected sediment into resealable bags for transport. Unfortunately, some visits to the study site revealed wind scour around the base of the trap, and therefore some loss of sediment may have occurred. When this occurred, a new hole was dug for the trap to be reburied with the opening level to the surface. As well, if a sand wave migrated over the location of the trap, the trap was buried above the opening. In this case, the trap was reestablished level to the present sand level, at the same location. Rosen-style traps were

Figure 3.1 - PVC sand traps. The pipe on the left is the exterior portion of the trap, which is buried up to the trap opening. The opening is on the opposite side of the silkscreen mesh. The pipe on the right sits inside the exterior pipe and collects sediment. The interior pipe can be removed to empty trap contents into a bag for transport to the laboratory.

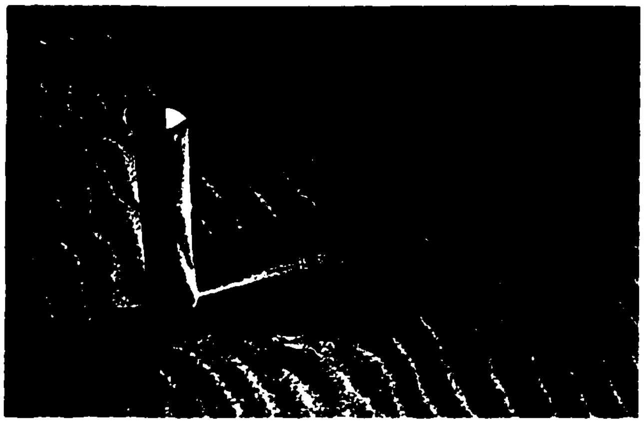


Figure 3.2 - Sand trap in the field. The trap was buried to the opening of the trap. Although the micron mesh allows the passage of wind, the trap still alters sand transport patterns as seen in the sand wave patterns. The flow disturbance is most prominent in the lee of the trap. The windward side displays minimal flow disturbance. Unfortunately there is some surface scour in front of the trap opening.

chosen because they are a cheap effective method of measuring sand transport. Minor damages to the trap can be repaired in situ. As well, damaged traps can easily be replaced during visits to the park to collect captured sediment.

The traps were placed in two arrays of four traps; traps one through four were lined up in the lower opening of the blowout and traps five through eight were lined up in the throat at the crest of the blowout. The open direction of the traps, which were lined up in four cardinal directions relative to the blowout's orientation, are as follows; traps one and five to the southwest, traps two and six to the northwest, traps three and seven to the northeast, and traps four and eight to the southeast (Figures 3.3 and 3.4).

Sand traps were emptied approximately every ten days, or two to three times per month. High lake level data was collected between August 1994 through August 1995. Low lake level data was collected June 1999 through August 2000.

3.3.2 Erosion Pin Data

Erosion pin data were collected to identify areas of erosion and deposition within the trough blowout. The erosion pins were 6 mm round steel rods approximately 2 m in length. The pins were half buried, standing normal to a level plane. A large washer was placed over the pin and set flush to the sand surface. During each site visit, every pin was measured from the top of the pin to the sand surface (Byrne, 1997; Jungerius and van der Meulen, 1989). If the washer was not visible at the surface, sand was excavated locally to the washer. The washer depth below surface was recorded. This was used to compare relative erosion and deposition from the previous visit to the site. The high lake level

Figure 3.3 - A view of the study site looking south east. The arrows indicate the orientation of the sand trap opening. The upper row of traps match the orientation of the lower traps.

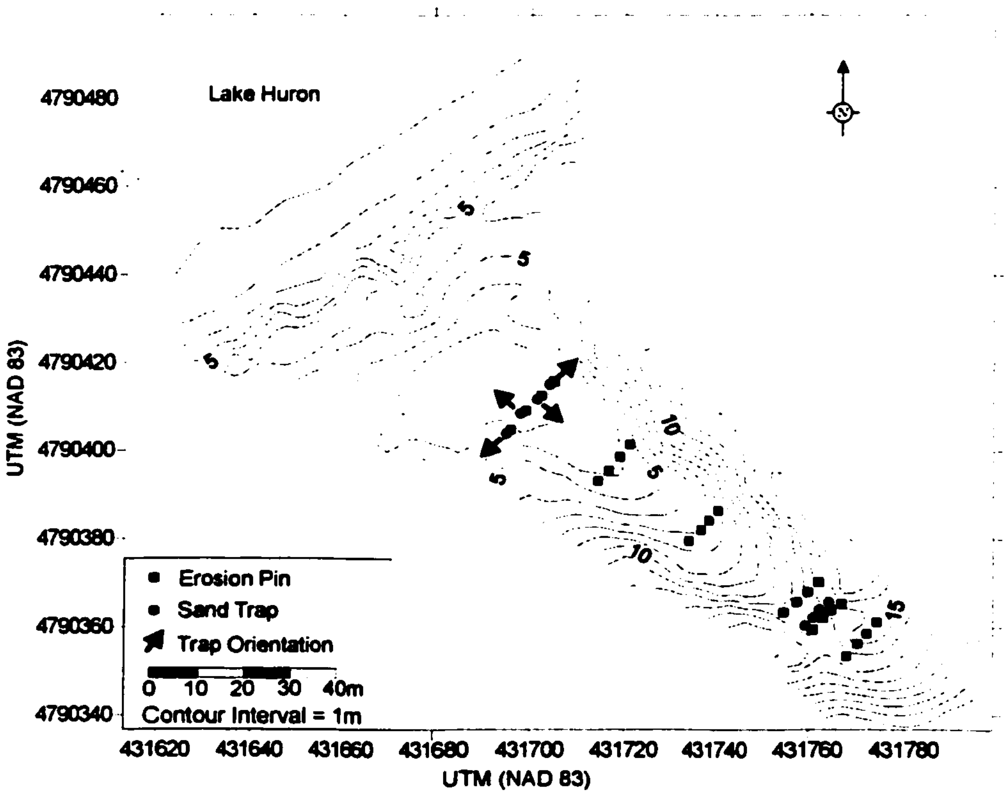


Figure 3.4 - Study site contour map. This topographic map shows the sand traps and the erosion pins. Arrows indicate the orientation of the sand trap openings for the lower set of traps (1-4). The upper traps have matching orientations.

period initially had four pin arrays of four pins each. Unfortunately, the uppermost array was removed by vandals (Byrne, 1997). The low lake level period study used the initial three arrays, but added three more arrays early in the study towards the upper portion and leeward side of the crest of the blowout (Figure 3.4). The first, or lowermost, array of pins were located approximately15cm away from sand traps one through four. The second through fourth array of pins were located approximately 25 meters up the blowout. Pins were spaced evenly across the width of the blowout within each array. The fifth pin array was in line with sand traps five through eight. The sixth array of pins was located just past the crest of the blowout.

3.3.3 Mapping Equipment

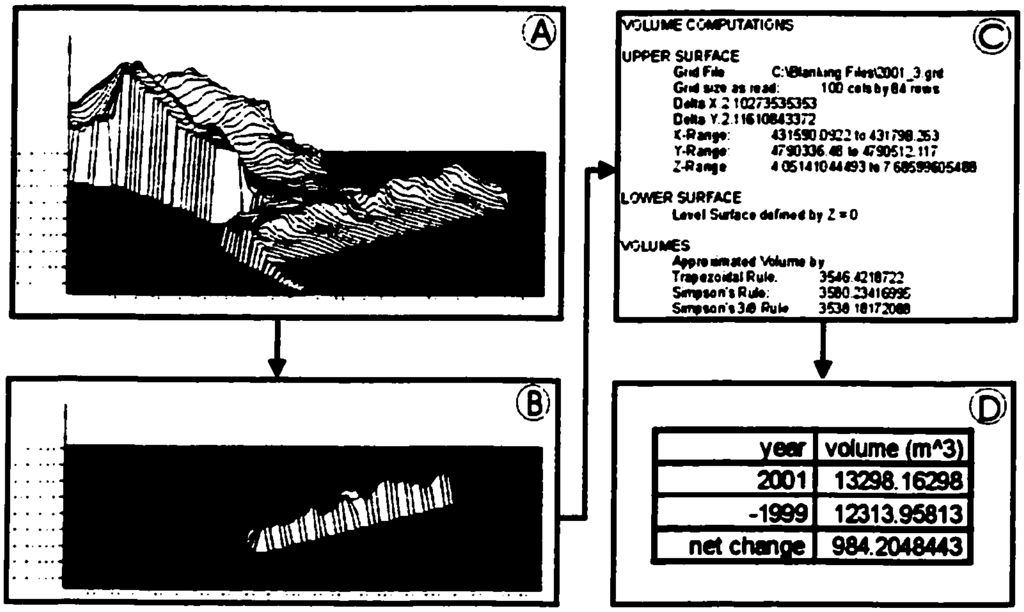
Three detailed maps were created during the high lake level period. The maps were created using a Leica T1600 Total Survey Station in summer 1999 and a Leica Model SR530 Dual Frequency Geodetic Real-time receiver GPS Station during summer 2000 to create a three-dimensional data set. The total station used an established location on a raised vegetated area northeast of the upper sand traps for stability and to have a line of sight to the maximum number of locations within the blowout. The backsight reference point was located in a clearing south of the crest in the vegetated back dunes. Elevation measurements were recorded along the crest, mid-slope, break-in-slope, on both sides of the blowout, as well as a profile along the axis of the blowout. Measurements were taken in the slack between the foredune and the blowout, the break-in -slope, mid-slope, and crest points on the foredune ridge. Measurements were taken of the beach to the waterline as well. The data sets were formatted to UTM coordinates and verified for accuracy between data sets by comparing two control points and a back sight. The x,y,z, coordinates were entered into Surfer mapping software.

This mapping software was used because of its simplicity. *Surfer 7* is a raster based interpolation package comparable to many GIS programs. A true GIS program was not used because there was no need to overlay maps, the most important tool of GIS software. Surfer is capable of performing the volumetric tasks needed for this project. Surfer interpolated (using Kriging gridding) all points between the collected coordinates to create a smooth surface for creating contour and wireframe maps. The end result of the interpolation process created a grid file. This grid file designated every data point to have an x, y, and z (or latitude, longitude, and elevation) coordinate. Using grid files, the three-dimensional maps were created.

To ensure that similar boundaries are used on both the 1999 and 2000 maps, blanking files were created. Blanking files are user chosen areas within a grid file. The user creates a polygon shape based on chosen grid points, and then the user can choose to include everything within, or outside, of that grid box. All other values become zero.

Blanking files were also used to compare areas within the map for deposition and erosion. For this study, blanking files were designated based on personal observations of areas of erosion and deposition, and were delineated at breaks of slope in the sand dunes.

From the beach moving landward, the study site was broken into 11 sections, or blanked files. For volumetric analysis, areas outside of the blanked region were assigned a zero value. Volumes were calculated for each of the 11 sections for both the 1999 map



```
VOLUME COMPUTATIONS

UPPER SURFACE
        Grid File            C:\Blanking Files\2001_3.grd
        Grid size as read:        100 cols by 84 rows
        Delta X 2.10273535353
        Delta Y 2.11610843372
        X-Range:             431590.0922 to 431798.353
        Y-Range:             4790336.48 to 4790512.117
        Z-Range              4.05141044493 to 7.68599605488

LOWER SURFACE
        Level Surface defined by Z = 0

VOLUMES
        Approximated Volume by
        Trapezoidal Rule.         3546.4218722
        Simpson's Rule:           3580.23416895
        Simpson's 3/8 Rule        3538.18172088
```

year	volume (m^3)
2001	13298.16298
-1999	12313.95813
net change	984.2048443

Figure 3.5 - Example of calculating volume change between data sets. The first step is to create a three-dimensional grid based on surveyed points (diagram A). A volume is calculated for identically defined areas on both maps (diagram B). All areas outside the region are assigned a value of 0. Diagram C displays a portion of the output file created by Surfer that includes volume calculations for the designated area. The final step is to subtract 1999 map volume from the corresponding 2001 map volume (diagram D). Positive values indicate net deposition, negative values indicate net erosion.

and the 2000 map. The volume from the 1999 section was then subtracted from the volume of the exact same section of the 2000 mapping data. Positive values from subtracting the two maps indicates an overall increase in sediment in the section, or an area of deposition. Negative values indicate overall erosion in the area.

Volumes for each of the 11 subsections were calculated by averaging the volumes from the surfer output file. The Surfer output file contained volume calculations based on 3 surface fitting interpolation methods; Trapezoidal Rule, Simpson's Rule, and Simpson's 3/8 Rule. All three rules approximate definite integrals to create an upper dimension for calculating volumes. Trapezoidal rule calculates using a straight line within each subinterval, while Simpson's and Simpson's 3/8 rules calculates to a quadratic and a fifth power respectively. These averaged volumes were next used to subtract the 1999 volume calculation from the 2000 calculation. These results give an absolute value of volume change (Figure 3.5).

During the 1999 surveying, large hummocks were not mapped. Lack of time using the equipment prevented fine detailed mapping using the totla survey. During the 2001 survey it was felt that these hummocks were important to monitor, and therefore were included in the survey data. The change in surveying protocol included the mapping of large amounts of sediment that were eliminated from the 1999 survey of this section.

3.4 Lake Level and Climate Data

Internet sources (GLIN, 2001, GLERL, 2000) provide the most frequently and accurately updated lake levels for the Great Lakes Basin. Lake level data were taken directly from these sources.

No in situ wind data were used in this study. The study site is easily accessible to park users. Although the site is in the wilderness protection zone, park users move through the area. Because of previous vandal activity at the study site, a decision was made between park managers, Dr. Byrne, and M. Bitton, not to set up a temporary meteorological station within the study site. The nearest Environment Canada weather station was located in Sarnia, Ontario, located 80 kilometers southwest of the park on Lake Huron. Wind speed and direction, and precipitation data were acquired from Environment Canada for the study period.

3.5 Data Management and Analysis

All data collected were entered into a spreadsheets. Initially, data were inputted for the full study period, then broken down into four three month seasons. Further discussion of data analysis follows.

3.5.1 Sand Trap

The sediment collected in the sand traps was used to identify relative volumes of sand moving through different directions at different points of the blowout, and identify different grain sizes to potentially identify different sources of sediment grains.

The sediment volumes were grouped by season. The seasons include, Summer (June, July, August) 1999, Fall (September, October, November) 1999, Winter (December, January, February) 1999-2001, Spring (March, April, May) 2000, and Summer (June, July, August) 2000. Comparison statistics were performed between each trap, lower versus upper traps, and traps by orientation.

The grain size characteristics were analyzed following the methods described by Folk (1974). All of the grain size data were grouped into the five seasons (as described above) of the study period. Five grain size summary charts were created for each trap. The summary charts used all of the sediment collected during the respective season. Cumulative Frequency charts were drawn for each trap's five seasonal summaries. Graphic Mean, Inclusive Graphic Standard Deviation, and Graphic Skewness measurements were calculated from values read from the cumulative frequency charts as described by Folk (1974). Kurtosis was not calculated because; "...the geological significance of kurtosis is unknown, and it appears to have little value in interpretive grain size studies." (Boggs, 1995; 90).

3.5.2 Erosion Pins

Erosion Pin data were examined to identify areas of deposition and erosion. Values for pins 1-12 were compared between both high and low lake level study periods. As well, seasonal summaries of erosion and deposition were compared. Pins 13 - 24 were studied for comparisons with other seasonal summaries during the low lake level period. All data were graphed as linear data plot over time as well as a histogram to compare changes in topography through the blowout.

3.5.3 Mapping Data

Survey data were used to create a profile through the axis of the blowout. Visual comparisons of the profiles were done to identify areas of erosion and deposition through the axis during the high lake level study period.

Three-dimensional data sets were inputted into *Microsoft Excel*. These files were read by Surfer. The method of interpolation used was universal Kriging with a linear semivariogram. Kriging assumes that the spatial variation of any variable can be expressed as the sum of three major components: a structural component, associated with a common mean value or a constant trend; a random, spatially correlate component; and a random noise term (Burrough, 1986). The end result of the interpolation process created a grid file. This grid file designated every data point to have an x, y, and z (or UTM and elevation) coordinate. After grid files have been created, the three-dimensional maps can be created.

Blanking files were created to have adjacent borders for calculating volumes for each of the 11 subsections. These files were stored as Excel files then incorporated into the Surfer data files. Each of the volume output files were saved. Volume data for each of the 11 subsections were recorded into a separate spreadsheet.

3.5.4 Climate Data

The weather data was purchased from Environment Canada for the Sarnia weather station. Wind resultant vectors were calculated for the study season using the methods described by Landsberg (1956) and Jennings (1957).

3.6 Chapter Summary

This chapter described the protocols used throughout the study for collecting data. The primary goal of the methods was to mimic Dr. Byrne's (1997) high lake level study, and broaden her research methods for analyzing morphologic changes to the blowout and adjacent area. The expanded research methods will create a larger baseline data set for future research. Chapters 4 and 5 will discuss the results of this field research, from which conclusions can be drawn with regards to morphological changes at the study site.

4.0 RESULTS

4.1 Introduction

The purpose of this chapter is to introduce the results of field work and laboratory analysis including; sand trap data, erosion pin data, volumetric data from three-dimensional analysis, and wind data. Discussion and further analysis will be provided in Chapter 5.

4.2 Sand Trap Data

4.2.1 Volumes

Listed below in Table 4.1 is a summary of total sediment captured for the eight sediment traps. The data are divided into four three month seasons. A comprehensive list of sediment captured can be found in Appendix 1. Noted in Table 4.1 and seen in Figures 4.1 a-f, the largest amount of sediment (~151 kg) was captured by the lakeward facing sediment trap, in all seasons. Traps one through four, the lower array of sediment traps, show significantly less sediment captured than the upper array (traps five - eight). Trap two (lakeward facing) captured the most sediment (~15 kg) of the lower traps during all seasons. Traps one and four showed the next largest amount of sediment capture at ~ 2.9 kg and 4.1 kg respectively for total sediment captured through all seasons. Trap three,

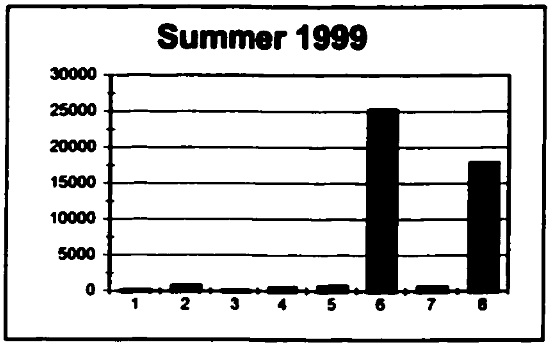


Figure 4.1a

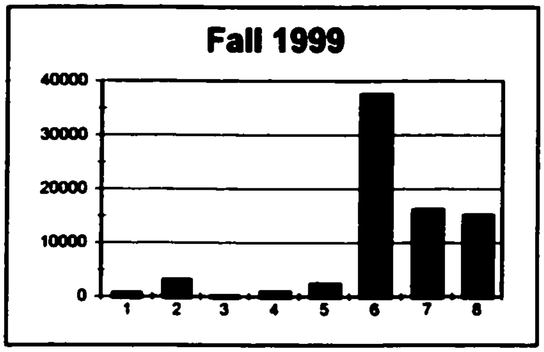


Figure 4.1b

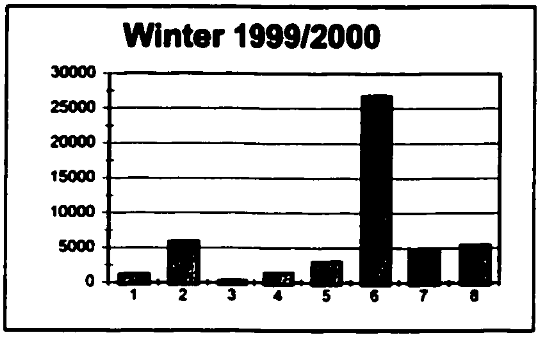


Figure 4.1c

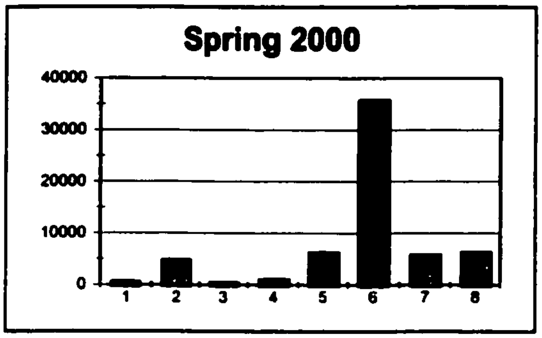


Figure 4.1d

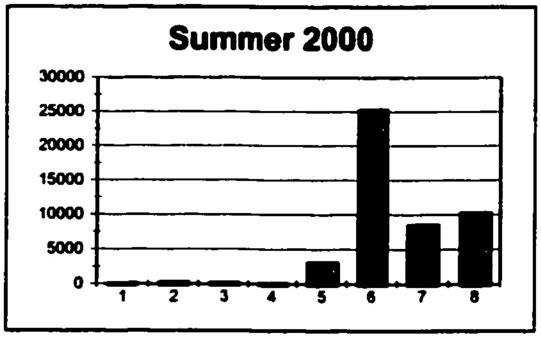


Figure 4.1e

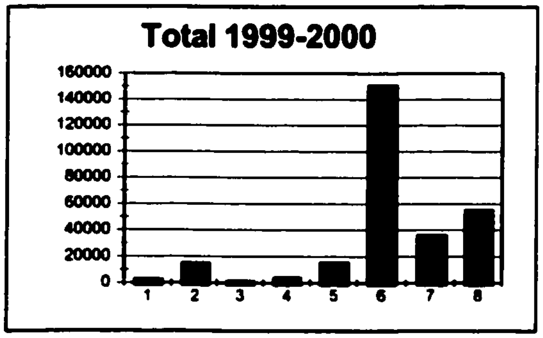


Figure 4.2f

Figure 4.1. Total sediment captured by Rosen-style traps. The x-axis indicates trap number and the y-axis indicates total weight of dry sediment captured (grams).

trap	summer 99	fall 99	winter 99/00	spring 00	summer 00	totals
1	177.9	740.2	1257.2	624.9	88.2	2888.4
2	828.4	3238.6	5991.1	4851.8	274.8	15184.7
3	131.1	235.3	369.2	427.0	178.4	1341.0
4	547.9	1007.6	1448.0	1090.8	83.4	4177.7
5	742.4	2477.1	3050.3	6308.9	3130.6	15709.3
6	25260.6	37652.1	26861.8	35804.2	25371.8	150950.5
7	719.5	16260.1	4731.3	5896.4	8561.2	36168.5
8	17916.5	15219.8	5461.6	6317.2	10318.0	55233.1

Table 4.1 - Sand trap sediment capture weight (grams).

which faces landward, or up the blowout throat, displayed the least amount of sediment transfer with ~1.3 kg. The order from most sediment captured to the least, (trap two, four, one, three) remained constant through all seasons except the 2000 summer season, in which trap three had the second largest amount of sediment captured. This result is partially a result of human activity noted around the trap area when the trap was emptied on June 16 and June 23, 2000. These two collection dates had noticeably higher than expected sediment volume capture compared to previous collections and comparison with the other lower array traps. Over half of the sediment collected for summer 2000 was collected on the two aforementioned dates.

Trap six captured the most sediment of the upper traps, and more sediment than all lower traps as mentioned earlier. Trap eight captured the second most, followed by trap seven. Trap five captured the least amount of sediment of the upper traps over the course of the low water study.

Unfortunately, due to trap eight's location, the sediment captured totals are unreliable. On eight different trips to the study site, trap eight was buried above the opening, due to a 'sand lobe' migrating through this area of the blowout. This frequent migration of sand lobes through the area forced the trap to be raised and lowered according to the new ground level. The trap would have to be raised when the lobe was present so that the trap opening would be at ground level. After the lobe had passed, the trap would have to be lowered. During the time the trap opening was above ground level, bedload transporting sediment would not be captured, as the grains would not lift off the surface high enough to enter the trap.

Figure 4.2 displays summary graphs for the eight traps. The lower trap array (one - four) show a distinctive pattern of increasing sediment captured from summer to winter, then decreasing sediment captured from winter to summer (Figure 4.2a-d). This can be best explained by vegetation growth at is peak in the summer months. The vegetation, primarily *Ammophilia breviligulata* and *Calamovilfa longifolia*, are both very effective at capturing sediment. Both species thrive in conditions of continual burial, and will continue to grow upwards. During fall, the vegetation begins to go dormant and therefore ceases upwards growth. Less sediment can now be captured by the vegetation. Snow cover over the vegetation creates a relatively smooth surface when frozen, and sediment can freely pass over, and therefore the sand more readily transports across the surface and into the sand traps.

The upper sediment traps did not show the same seasonal patterns of sediment capture. The capture rate in trap five was lower (~ 3.1kg/season) than the averaged sand captured per season in the other three traps indicating a minimal amount of sediment transport across the blowout throat (Table 4.2). The greatest sediment capture in trap five occurred during spring (Figure 4.2e). This resulted from a major bank slope failure. The trap was close to the blowout wall, and the slope failure allowed a sediment flow to enter

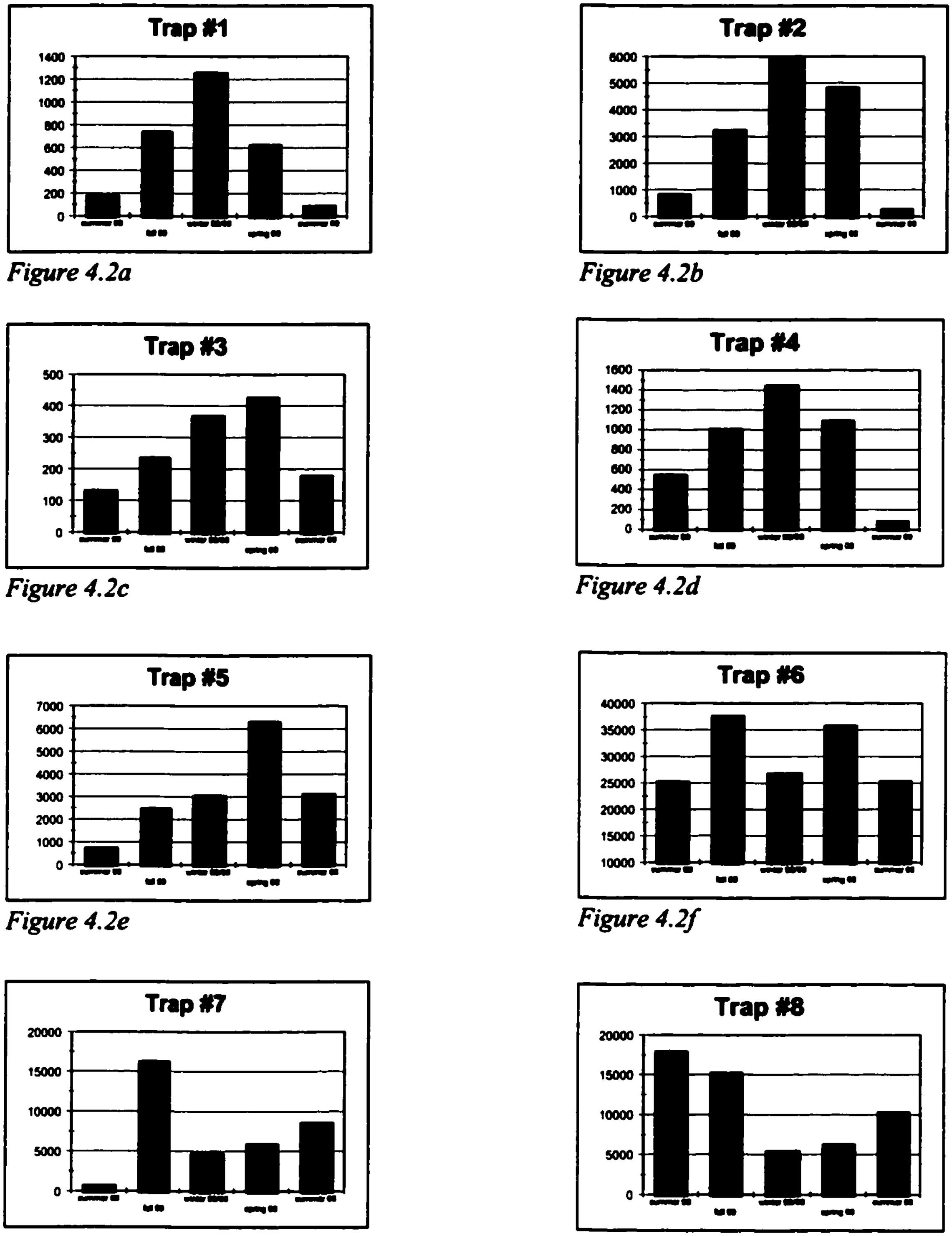


Figure 4.2a

Figure 4.2b

Figure 4.2c

Figure 4.2d

Figure 4.2e

Figure 4.2f

Figure 4.2g

Figure 4.2h

Figure 4.2 - Sediment captured during low lake level study period. The x-axis lists the seasonal divisions, the y-axis is sediment captured in grams.

trap	sediment captured (kg/season)
1	0.58
2	3.04
3	0.27
4	0.84
5	3.14
6	30.19
7	7.23
8	11.05

Table 4.2 - Sediment Capture for all eight sediment traps measured in kilograms per season.

the trap, the trap was oriented such that the flow entered the trap directly. This was noted on March 6 and March 18, 2002, after the bank was subject to thawing as well as heavy rains which may have caused the slope failure.

Trap six displayed relatively lower sediment transport in summer and winter months. The low sediment transport in the summer is caused by lower wind speeds which will be discussed later in the chapter. The winter sediment capture volumes were lower in all winter traps because the traps would fill with a sand-snow mix (Figure 4.2h-f). The values still represented relative sand capture rates between the traps because the snow level in all traps was equal. Unfortunately, the total sediment transport for the winter months may not be comparable to other seasons. Trap seven (figure 4.2g) had an extremely low amount of sediment (~ 0.7 kg) moving into the trap during the summer of 1999, followed by a marked increase (~ 16.3 kg) during fall. This is due to sand lobes moving through the blowout in the location of traps seven and eight as described earlier. This local change in morphology partially explains the changes in sediment transport through the dune in this area. An increase in sediment transport coming from the landward area of the blowout results in the increased sediment capture found in spring

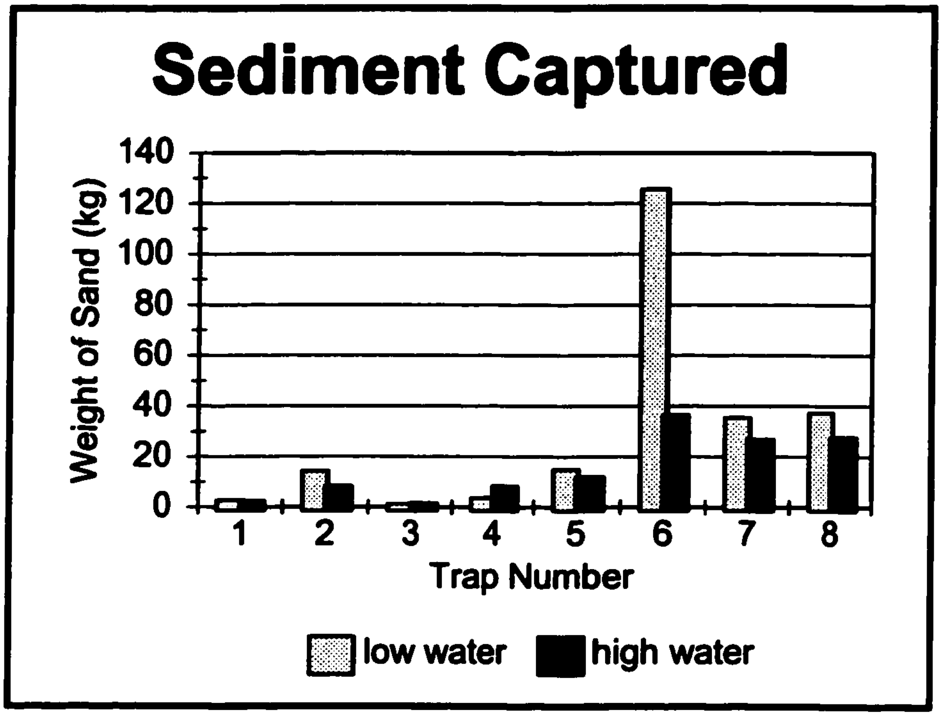


Figure 4.3 - Total Sediment Captured during low water level study and high water level study. The values graphed are in kilograms of dry sediment. Only September 1999 to August 2000 values are included in the totals so that both the high level and low water level studies are of the same duration.

and summer 2000.

Figure 4.3 and Table 4.3 clearly indicate that more sediment is moving through the blowout in a landward direction. This is revealed by the comparison between the volumes being transported through sand trap two and six, the two traps that are facing lakeward. Trap six captured 125.6 kg during the low lake level period where the same trap only captured 36.6 kg during the high lake level period. Similarly, but not as pronounced, trap two collected 14.4 kg during the low lake level period and only 8.5 kg during the high lake level period. Traps one, five, seven, and eight collected more sediment during the low lake level study period as well. Trap four received the greatest amount of sediment during the low level study, intercepting sand eroded from the eastern wall of the blowout (Byrne, 1997) and from the leeward side of the blowout to the north. Byrne (1997) predicted that a large portion of this sediment was carried by strong northwest winter winds, combined with local topographic steering, into the trap (Byrne, 1997).

trap	low water (kg)	high water (kg)
1	2.71	2.41
2	14.36	8.47
3	1.21	1.67
4	3.64	8.47
5	14.97	12.15
6	125.69	36.59
7	35.50	27.02
8	37.32	27.70

Table 4.3 - Total sediment captured during low water level study and high water level study. The values are in kilograms of dry sediment. Only September 1999 to August 2000 values are included in the totals so that both the high level and low water level studies are of the same duration.

4.2.2 Grain Size

Mean grain size, graphic standard deviation, and inclusive graphic skewness tables are listed below (Tables 4.4 - 4.6).

	TRAP 1	TRAP 2	TRAP 3	TRAP 4	TRAP 5	TRAP 6	TRAP 7	TRAP 8	mean
SUMMER '99	1.98	2.08	2.00	2.22	2.20	2.05	1.95	2.20	2.09
FALL '99	2.03	1.98	2.20	2.08	2.15	1.97	1.82	2.17	2.05
WINTER '99/'00	2.08	2.12	2.48	2.08	1.90	2.02	2.02	2.07	2.10
SPRING '00	2.08	2.22	2.33	2.18	2.03	2.00	2.10	2.27	2.15
SUMMER '00	1.75	1.88	1.58	1.93	2.17	2.12	1.90	2.17	1.94
mean	1.99	2.06	2.12	2.10	2.09	2.03	1.96	2.17	

Table 4.4 - Sediment graphic mean. All values listed in phi (φ) units.

	TRAP 1	TRAP 2	TRAP 3	TRAP 4	TRAP 5	TRAP 6	TRAP 7	TRAP 8	mean
SUMMER '99	0.49	0.48	0.70	0.38	0.38	0.43	0.56	0.44	0.48
FALL '99	0.49	0.54	0.52	0.53	0.41	0.39	0.58	0.37	0.48
WINTER '99/'00	0.46	0.50	0.53	0.52	0.50	0.44	0.44	0.50	0.48
SPRING '00	0.53	0.41	0.48	0.43	0.50	0.44	0.37	0.40	0.44
SUMMER '00	0.87	0.82	1.06	0.81	0.44	0.35	0.59	0.38	0.66
mean	0.57	0.55	0.66	0.53	0.45	0.41	0.51	0.42	

Table 4.5 - Inclusive Graphic Standard Deviation. All values listed in phi (φ) units.

	TRAP 1	TRAP 2	TRAP 3	TRAP 4	TRAP 5	TRAP 6	TRAP 7	TRAP 8	mean
SUMMER '99	-0.24	-0.23	-0.32	-0.20	-0.22	-0.22	-0.27	-0.02	-0.21
FALL '99	-0.16	-0.16	-0.25	-0.22	-0.07	-0.12	-0.13	-0.11	-0.15
WINTER '99/'00	-0.09	-0.22	-0.21	-0.26	-0.24	-0.13	-0.13	-0.25	-0.19
SPRING '00	-0.37	-0.33	-0.39	-0.29	-0.13	-0.04	0.10	-0.19	-0.20
SUMMER '00	-0.45	-0.45	-0.52	-0.37	-0.04	-0.14	-0.12	-0.01	-0.26
mean	-0.26	-0.28	-0.34	-0.27	-0.14	-0.13	-0.11	-0.11	

Table 4.6 - Inclusive Graphic Skewness. All values listed in phi (φ) units.

The graphic mean grain sizes (Table 4.4) indicate an average grain size for the study period ranging from 1.6 to 2.5 φ (.33 to .18 mm), based on seasonal averages for each trap. The mean for the whole study period was 2.06 φ (.24 mm). The largest grain sizes (smallest φ) occurred during the summer 2000 season in traps one through four. The largest grain sizes, found especially in trap three and one, are a result of the area facing the trap opening being deflated, or rather, the finer sand grains have been previously blown away or in other directions. The surface has became deflated because the winds had been strong enough to move all of the fine grained sediment out of the lag area. The larger grains need much faster wind speeds to be moved into the traps, especially if there are no fine grained particles extending above the boundary layer to initiate movement through particle collisions.

The Standard Deviations indicate the sand samples were well sorted (.35 - .50φ) to moderately well sorted (.50 - .71φ) as described by Folk (1974). Traps one through four were moderately sorted (.71 - 1.0 φ) during the summer 2000 months, as well as trap three during summer 1999 (Folk 1974). The variance is a result of the larger grains entering the lower traps, especially during the summer 2000 months. This is a result of the mouth of the blowout, or the lag area, being deflated of smaller grains. Fewer smaller grains are left to enter the traps by creep, saltation, and suspension. Therefore, proportionally, more larger grains have entered the traps by surface creep. This occurred during periods of local high winds.

The graphic skewness values are negative for all seasons in all traps. The negative values indicate the following verbal limits: 0 to -10, near-symmetrical; -10 to -.30, coarse skewed; and -.30 to 1.00, strongly coarse skewed (Folk, 1974). Most seasons for each trap are coarsely skewed. Traps one through four in spring and summer 2000 were strongly coarse skewed. This again, is a result of the deflation of the finer grained sediments from the lag area at the base of the mouth of the blowout and only larger grains remained to enter the traps by surface creep.

Comparison between the two study periods indicate a difference in grain size characteristics (Table 4.7 and Table 4.8). The average grain size during the summer season was 1.14 φ for the high lake level study (1995) and 2.09 and 1.94 φ during the low lake level study (1999 and 2000 respectively). The winter had larger grains moving through the high lake level study period as well, 1.66 φ during the high water study and 2.10 φ during the low water study. This is indicative of a change in sediment supply. As noted previously, the deflated area around traps one through four account for the larger grain sizes being captured in both winter and summer months for both the high

	1	2	3	4	5	6	7	8	avg.
SUMMER '95	0.50	0.85	0.25	1.20	1.52	1.80	1.28	1.70	1.14
SUMMER '99	1.98	2.08	2.00	2.22	2.20	2.05	1.95	2.20	2.09
SUMMER '00	1.75	1.88	1.58	1.93	2.17	2.12	1.90	2.17	1.94
WINTER '95	1.63	1.75	1.72	1.80	1.08	1.90	1.47	1.90	1.66
WINTER '99/'00	2.08	2.12	2.48	2.08	1.90	2.02	2.02	2.07	2.10

Table 4.7 - Mean grain size comparison between high (1995) and low (1999/2000) lake level periods. Grain sizes are given in phi (φ) values.

	1	2	3	4	5	6	7	8	avg.
SUMMER '95	1.10	1.05	1.25	0.79	0.60	0.43	0.79	0.48	0.81
SUMMER '99	0.49	0.48	0.70	0.38	0.38	0.43	0.56	0.44	0.48
SUMMER '00	0.87	0.82	1.06	0.81	0.44	0.35	0.59	0.38	0.66
WINTER '95	0.62	0.46	0.57	0.55	0.65	0.63	0.52	0.42	0.55
WINTER '99/'00	0.46	0.50	0.53	0.52	0.50	0.44	0.44	0.50	0.48

Table 4.8 - Inclusive graphic standard deviation comparison between high (1995) and low (1999/2000) lake level periods. Grain sizes are given in phi (φ) values.

and low lake level study periods. The grains are one full φ size larger (finer grain size) when comparing the summer 1995 and summer 1999 study season. The upper traps showed similar results showing 0.68, 0.25, 0.67, 0.50 φ larger (finer grain) in traps five, six, seven and eight respectively. The winter months showed larger phi sizes as well ranging from .82 φ (trap five) to .12 φ (trap six) larger.

4.3 Erosion Pin Data

Figure 4.4 is a reference map that displays the erosion pin numbers used in this study and their relative location to eachother. This sketch map is not drawn to scale. Figures 4.5 through 4.13 display the elevation changes at each erosion pin. The graphs depict the elevation change over time; with the x-axis scale representing the number of days during the study period, the y-axis representing the change in elevation. The data

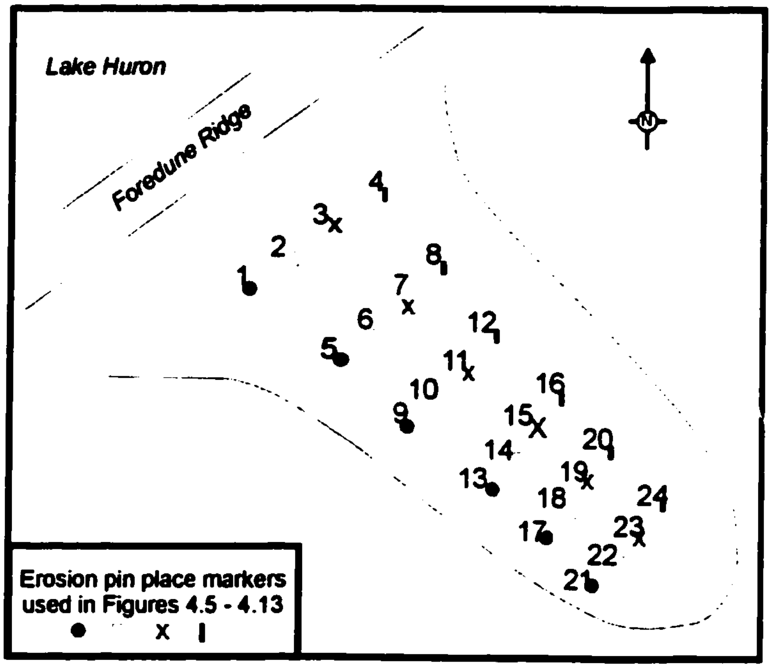


Figure 4.4 - Erosion pin reference map. This map does not show actual pin locations, but rather displays the pins' relative locations in the blowout. The symbols used are the same symbols used on the charts in figures 4.5 - 4.13.

displayed on the low lake level graphs includes the whole study period, June 1, 1999 to August 31, 2000. The data displayed on the high lake level graphs includes the period form September 8, 1994 to August 4, 1995. Figure 4.5 displays the elevation change for pins one through four over the low lake levels study period. The peak in the centre of the graph is a result of measuring the erosion pin at snow height. The measurements included snow depth to include the sand in the snow-sediment mix. There are three other peaks in the graph. They are a result of small sand waves moving past the pins. Aside from these peaks, the elevation stayed relatively stable throughout the low lake level study. During the high lake level the elevation of pins one through four remained very stable as well, although pins one, two and three show approximately 5 cm of erosion

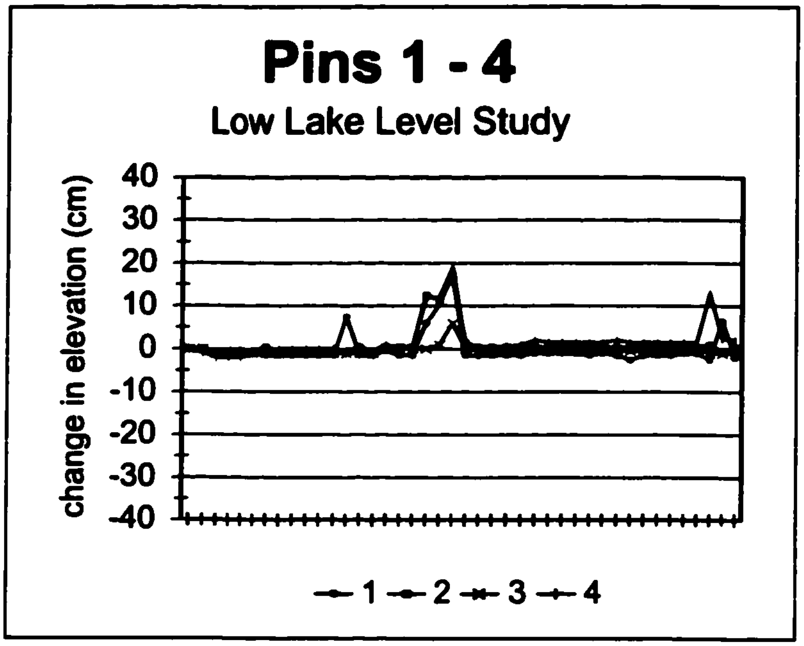


Figure 4.5 - Elevation change at pins 1 - 4 during the low lake level study period.

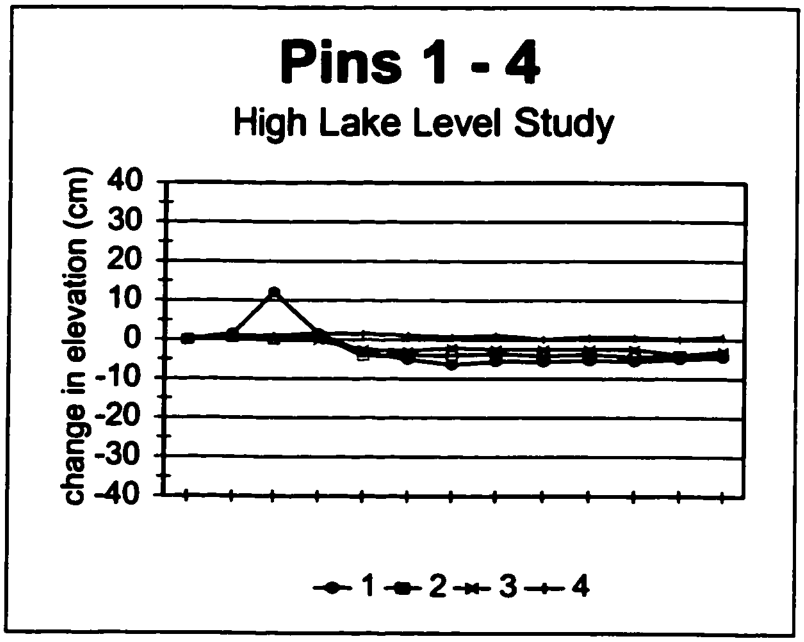


Figure 4.6 - Elevation change at pins 1 - 4 during the high lake level study period.

during the high lake level study (Figure 4.6). There was no winter peak because the

Pins five through eight display the same winter peak that pins one through four displayed (Figure 4.7). Pin five's elevation increased when the side of a hummock extended through the area of the pin. This occurred during the high level study period as well (Figure 4.8). Pins six through eight's elevation stayed relatively stable during both periods, although there was slight erosion through the throat. At the end of the low water period, a small sand wave (~20 cm) migrated through the south west side of the blowout near pins five and six, and hence the peak at the end of the graph in Figure 4.7.

During the low lake level study, erosion occurred through the center axis in the throat of the blowout as seen in Figure 4.9. Pins ten and eleven showed erosion, while pins nine and twelve remained relatively the same elevation through the study. A winter

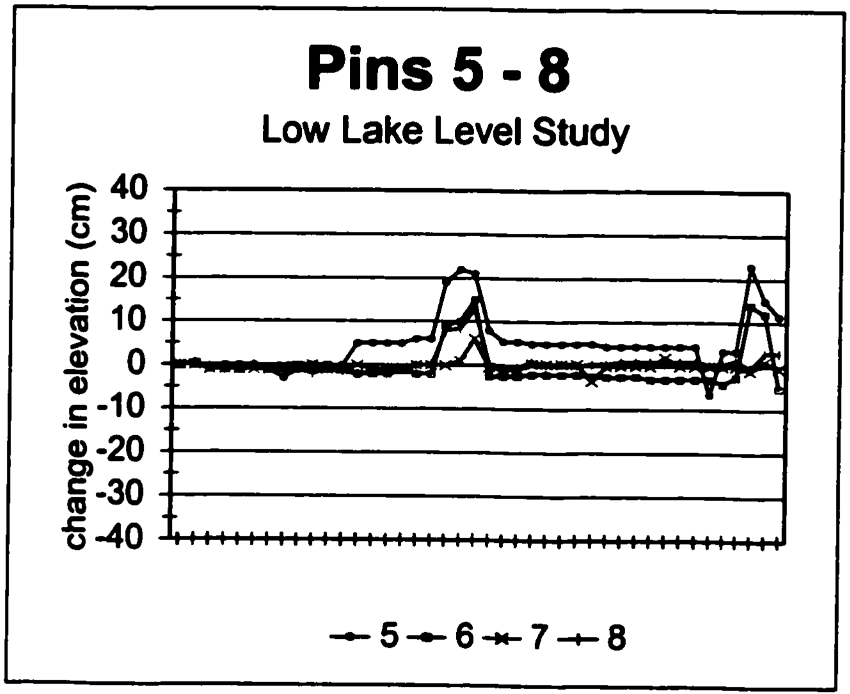


Figure 4.7 - Elevation change at pins 5 - 8 during the low lake level study period.

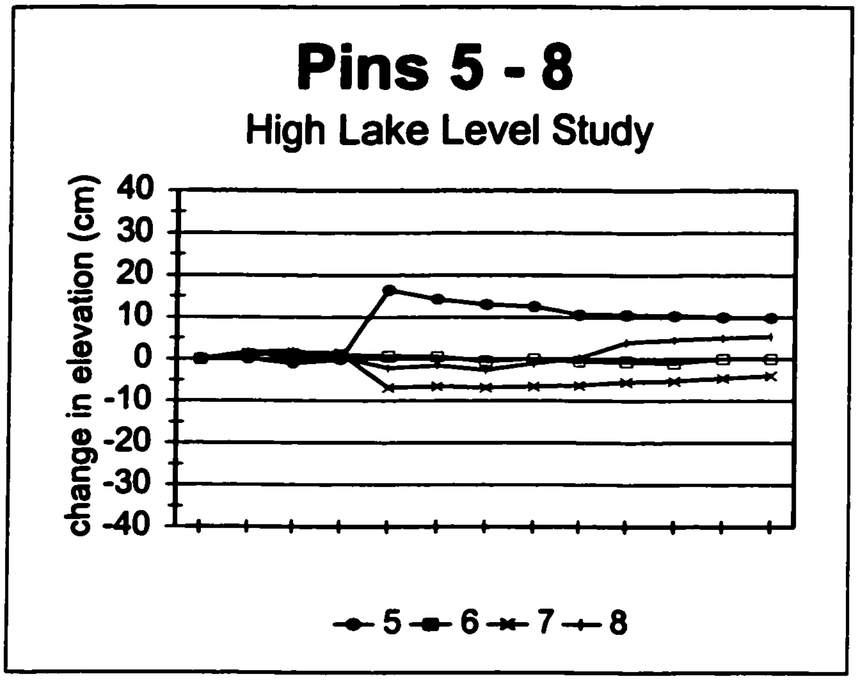


Figure 4.8 - Elevation change at pins 5 - 8 during the high lake level study period.

increase in elevation can be noticed for the two northeastern pins, eleven and twelve, where snow accumulated. There was no snow accumulation around pins nine and ten. The location of the snow accumulation in an area of the blowout is most likely due to topographic steering within the blowout, creating different transport pathways in which the snow is being blown. Snow distribution is also effected by the radiation distribution from the sun. During the high lake level study, the greatest decrease in elevation for this set of pins occurred at pin twelve (13.8 cm). The other pins remained at the same elevation from the start of the study (Figure 4.10).

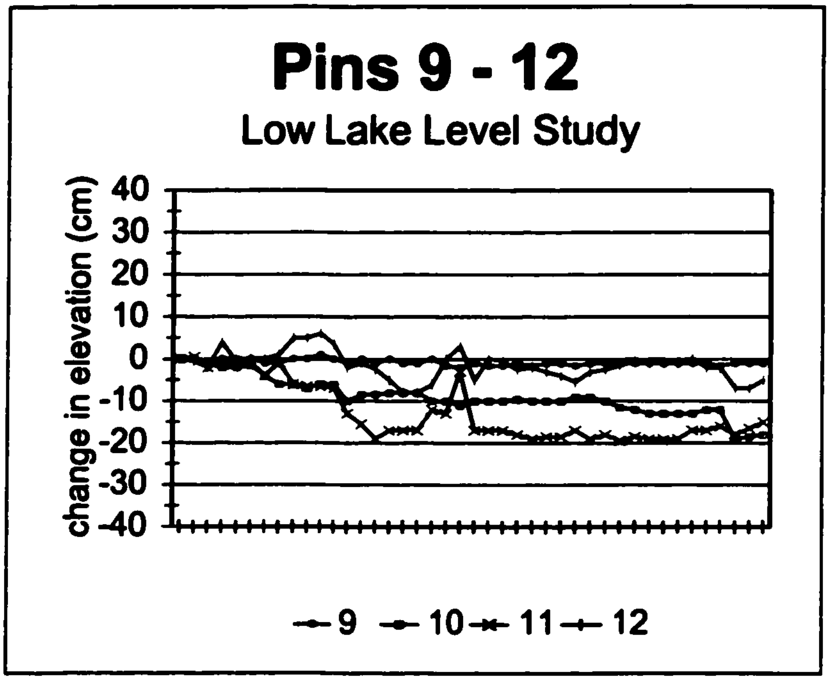


Figure 4.9 - Elevation change at pins 9 - 12 during the low lake level study period.

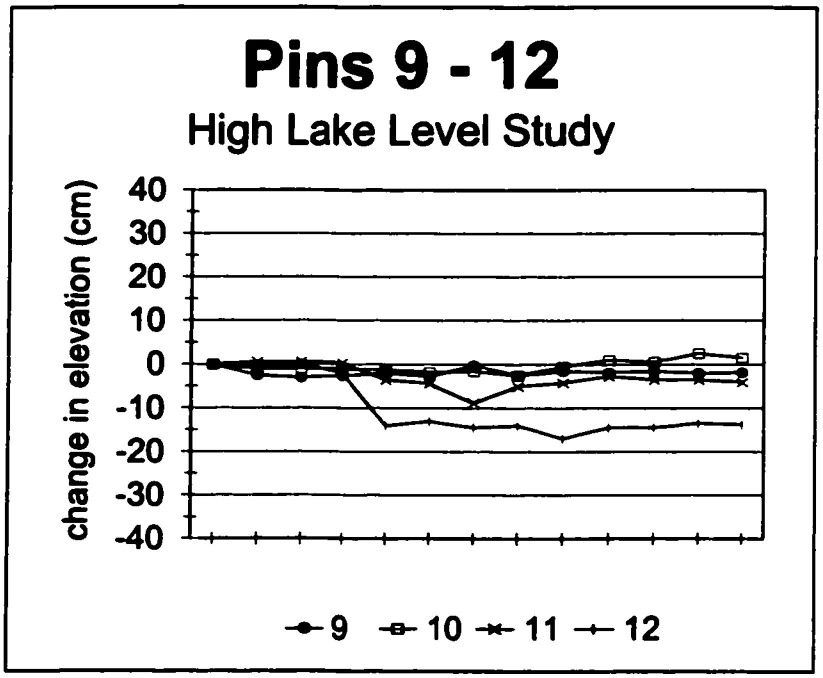


Figure 4.10 - Elevation change at pins 9 - 12 during the high lake level study period.

Figures 4.11, 4.12 and 4.13 reveal no data during the first part of the time period. The no data area represents the time period when data collection for pins one through twelve had already commenced, but pins thirteen through twenty-four were not on site. The upper pins were not installed until July 30, 1999, and therefore, no comparisons can be made between the two study periods.

Pins thirteen through sixteen all show erosion during the low lake level study period (Figure 4.11). Pin sixteen's sudden drop in elevation is a result of the bank experiencing a major slope failure immediately after the pin was put in place. After this initial drop in elevation, the surface elevation remained constant until the end of summer 2000, when further erosion occurred. The surface at pins thirteen, fourteen and fifteen experienced the same decrease in elevation at the end of the summer 2000 season as well.

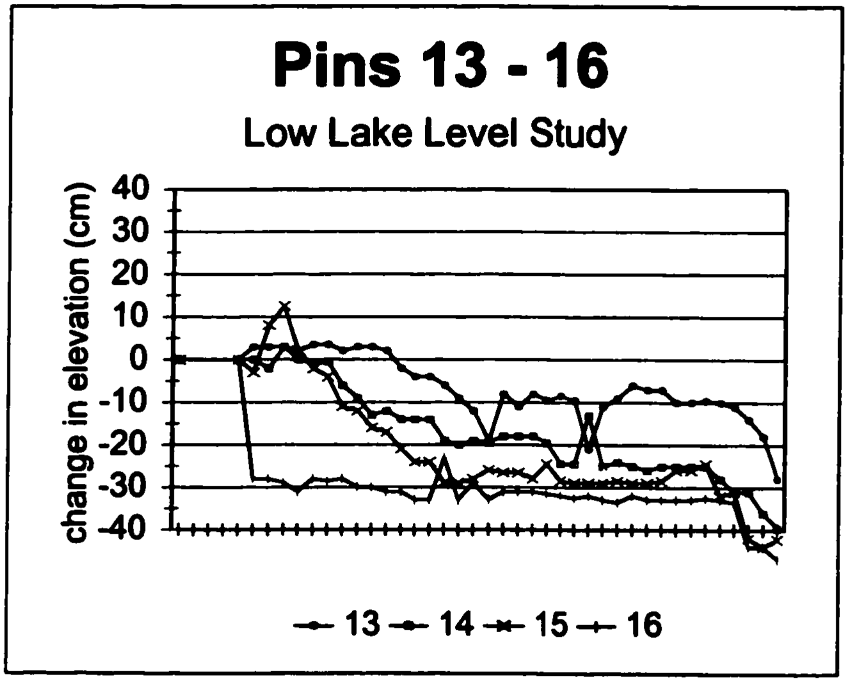


Figure 4.11- Elevation change at pins 13 - 16 during the low lake level study period.

Increasing erosion occurred at these three pins from October through February. This may be attributed to increased wind speeds moving through this area of the blowout throat in combination with; a) sediment being trapped by vegetation that has died and fallen, creating a denser sediment catchment area, and therefore limiting the amount of sediment available to move through the lower portion of the blowout during late fall; and b) available sediment being wet and/or frozen on the beach, foredune and lower portion of the blowout, and therefore not as readily transported up the blowout throat. Pins seventeen and eighteen displayed the same fall and winter erosion that occurred at pins thirteen through fifteen (Figure 4.12). Steady erosion occurred at pin seventeen through the remainder of the study, while periods of erosion and deposition alternated at pin eighteen. Rapid erosion and deposition occurred at pins nineteen and twenty throughout

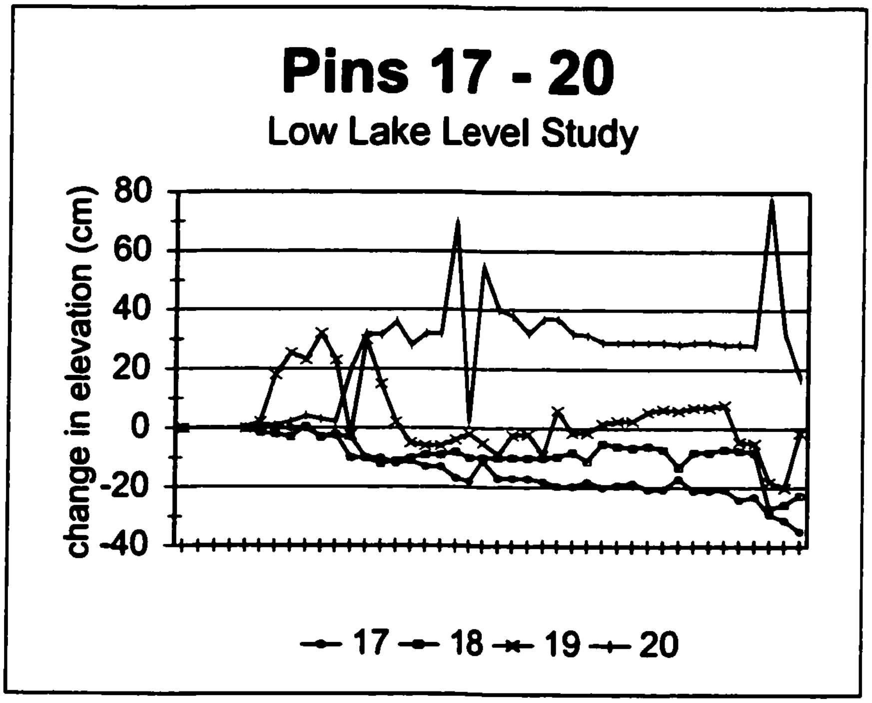


Figure 4.12 - Elevation change at pins 17 - 20. Note: The y-axis scale is -40 to 80cm., all other graphs the y-axis is -40 to 40cm.

the study. These ups and downs in elevation are a result of lobes building and being blown through the upper portion of the blowout, especially on the northeast side. Deposition up to 78 cm occurred at pin twenty, and in one month went from 70cm (January 25, 2000), to 2cm (February 5, 2000), to 55cm (February 20, 2000) at this location. The range of elevation change at these pins, especially pin twenty, indicates that this is the most volatile area of the blowout.

Pins twenty-one, twenty-two and twenty-four all experienced deposition. This is indicative of the upward building of the backdune. The greatest deposition, noticeable by both pin measurements and visual observations, occurred to the east and northeast landward of the blowout throat. Although overall erosion occurred at pin twenty-two, this area may have experienced an upward building as well. One reason for erosion at

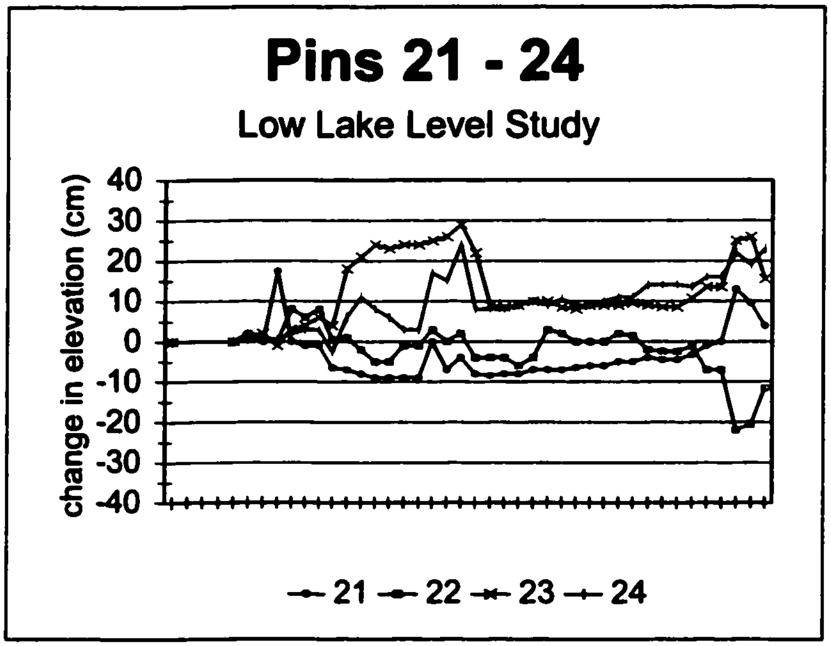


Figure 4.13 - Elevation change at pins 21 - 24.

this site was that it was very close to the route taken to access the blowout from the backside. Walking up the backside of the dune often caused large amounts of sediment to slump due to the many steps needed to climb the steep slope. A winter peak occurred at these pins as well because snow was able to accumulate at the crest and backside of the dune because of flow separation from the crest. The flow separation allows snow and sediment to be deposited in this area of the blowout.

4.4 Mapping Data

Three-dimensional data were collected during 1999 and 200 to create files that could be interpreted by the mapping software. The final volume calculations for the 11 blanked regions are listed in Table 4.9.

blanked region	volume change (m3)	relative volume change (m3)
1	964.5	7.3
2	84.6	2.4
3	1210.0	15.2
4	-168.8	-4.7
*5	1768.9	16.8
6	-254.9	-4.1
7	29.0	0.6
8	-108.2	-13.1
9	-196	-19.9
10	-19.1	-1.5
11	119.3	1.8

*Table 4.9 - Volume change for the subdivided regions. Each region has an actual volume change calculation (m^3) and a relative volume change calculation. The relative volume change is calculated by dividing the volume change by the total average volume produced in the Surfer output file, and multiplied by 100. (*Region five data is inconclusive due to a change in mapping protocol.)*

The first section is lakeward of the foredune ridge. This area increased in volume by 964 m^3 during the study period. This can be attributed to the large sediment budget available on the bach. This available sediment is blown into the foredune, and because there is a longer beach surface, no wave attack at the foot of the foredune. This is a direct result of the lake level dropping, and exposing more beach sediment. The new sediment promoted the growth of *Ammophilia breviligulata*, which in turn captured more sediment.

The second region, was the top of the foredune ridge. This area experienced some building as well, but more likely the increase in volume of this area can be attributed to

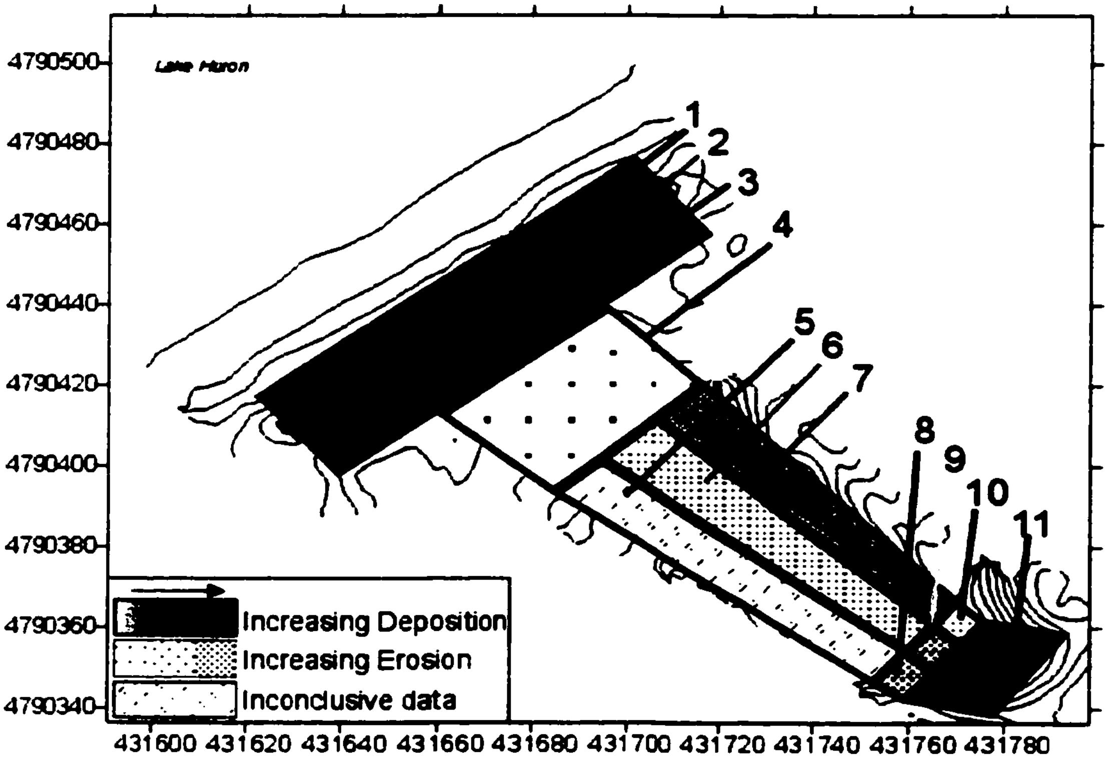


Figure 4.14 - Regions of erosion and deposition. The regions show darkening gray scale for increasing deposition and increased pixel concentration for increasing erosion. The values were based on the relative concentrations (Bitton and Byrne, submitted).

small depression landward and lakeward of the crest being filled in by new sediment, as opposed to a vertical building.

Region three, landward of the foredune crest, received the highest (aside from region five,) amount of new sediment. This area experienced rapid deposition from the assumed increase in sediment moving over the foredune and being deposited as a result of flow separation from onshore winds. The sand accumulation was accentuated by the increase of *Ammophilia breviligulata* as well.

Region eleven, the area landward of the crest of the experienced a large amount of deposition. The increased deposition on the landward side of the blowout indicates a migration of the blowout further inland. Region seven had a small amount of deposition as well. This was due to the presence of some vegetation at the base and working up this northeastern bank of the blowout. As well, sand ripples were often present. The orientation of these sand ripples indicated a movement of sediment up the throat of the blowout as well as up the northeastern bank. The ripple pattens indicate winds going up the side wall of the dune similar to climbing dunes found in desert dunes (Lancaster, 1995). Region five's data is inconclusive because of the different mapping protocols used. Region five's data suggest that there was a large amount of deposition in this area. This is due to large hummocks being included in the 2000 data point collection, while during the 1999 study, points around and on top of the hummock were not included in the data. The large hummocks create the large positive sediment volume change.

Regions four, six, eight, nine and ten experienced erosion during the low lake level study. The crest of blowout experienced the highest amount of erosion during the study period. This is where the strongest wind flows are found because there is an acceleration of flow up the blowout throat and at the crest (Hesp, 1996). Erosion occurred up the throat of the blowout as well as in the lag area at the base of the blowout.

4.5 Climate Data

A detailed analysis was not completed of this meteorological study because the wind speed and direction at Sarnia may not reflect the winds at Pinery Provincial Park. More importantly, the onshore winds give very little indication of what is happening within a dune complex due to topographic steering. The summary review of winds in this section is merely to show that the wind regime on Lake Huron was very similar during the two study periods.

The data purchased from Environment Canada for the Sarnia meteorological station were reformatted and entered into the program *Rose* provided by James Gardner. The output from the Rose program gave the resultant wind vectors and average wind speeds for the four seasons during both study periods (Table 4.10, Table 4.11).

High Lake Level	Resultant Wind Vector	Resultant Wind Vector	Low Lake Level
Fall 1994	217 (SW)	233 (SW)	Fall 1999
Winter 1994/1995	247 (SW)	232 (SW)	Winter 1999/2000
Spring 1995	331 (NW)	272 (W)	Spring 2000
Summer 1995	213 (SW)	239 (SW)	Summer 1999

Table 4.10 - Resultant wind vectors for each season during low and high lake level studies.

High Lake Level	Avg. Wind Speed (km/h)	Average Wind Speed (km/h)	Low Lake Level
Fall 1994	17.4	16.3	Fall 1999
Winter 1994/1995	19.6	20.3	Winter 1999/2000
Spring 1995	17.7	19.1	Spring 2000
Summer 1995	12.6	11.2	Summer 1999

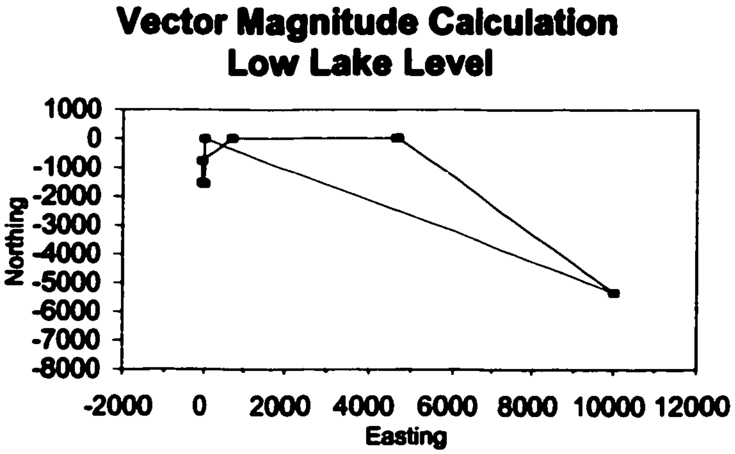


Figure 4.15 - Resultant Vector Calculation for the low lake level period. The direction the wind was heading is indicated by the resultant vector. The resultant vector for the low lake level period was 118.0 ° with a magnitude of 11348.

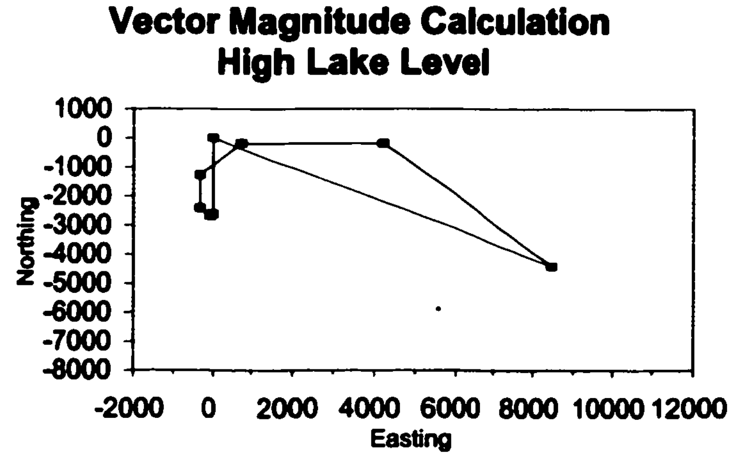


Figure 4.16 - Resultant Vector Calculation for the high lake level period. The direction the wind was heading is indicated by the resultant vector. The resultant vector for the low lake level period was 117.6 ° with a magnitude of 9549.

The resultant vectors were recalculated for winds stronger than 16 km/h. The resultant vectors are shown on the previous page (Figure 4.15, Figure 4.16). These calculations were created using the methods described by Landsberg (1956) and Jennings (1957). The resultant vectors displays, (from the 0,0 coordinate,) the direction the resultant wind was heading. The resultant wind directions were 118.0 and 117.6 for the low and high lake level period respectively. The resultant magnitudes were 11348 and 9549 for the low and high lake level respectively.

4.6 Chapter Summary

This chapter outlined the results from the sediment traps, erosion pins and the volumetric analysis different primary research for this study. The wind data provided a very limited insight into the similarities and differences in wind conditions. Although the wind conditions appear to be very similar, the results are not conclusive to what was happening at the study site. Chapter 5 further discusses the results presented and their relationships with each other, and the implications of these results.

5.0 SUMMARY DISCUSSION

5.1 Introduction

This chapter will further discuss the results presented in Chapter 4. A summary of the morphology changes will explain how the results from the previous section come together to generate final conclusions for this study.

5.2 Dune Morphology Changes

Sand trap data indicate that more sediment moves landward through the axis of the blowout during the low lake level period. This is clearly indicated by the total sediment captured in traps two and six, the lakeward facing traps. Trap two had a 70 % increase in sediment moving landward, by far, the greatest increase in the lower traps. Trap six had a 343 % increase in sediment moving landward. Again, none of the other upper traps demonstrated a comparable increase in sediment transport by sediment capture in the traps.

During the low lake level study period, the sediment captured in the traps were of much larger phi size (finer grains). The finer grained sediment source is the beach, which has an average mean grain size of 2.38 φ. During the high lake level study period, the beach was completely covered by wave run-up during storm (high wind periods), and had

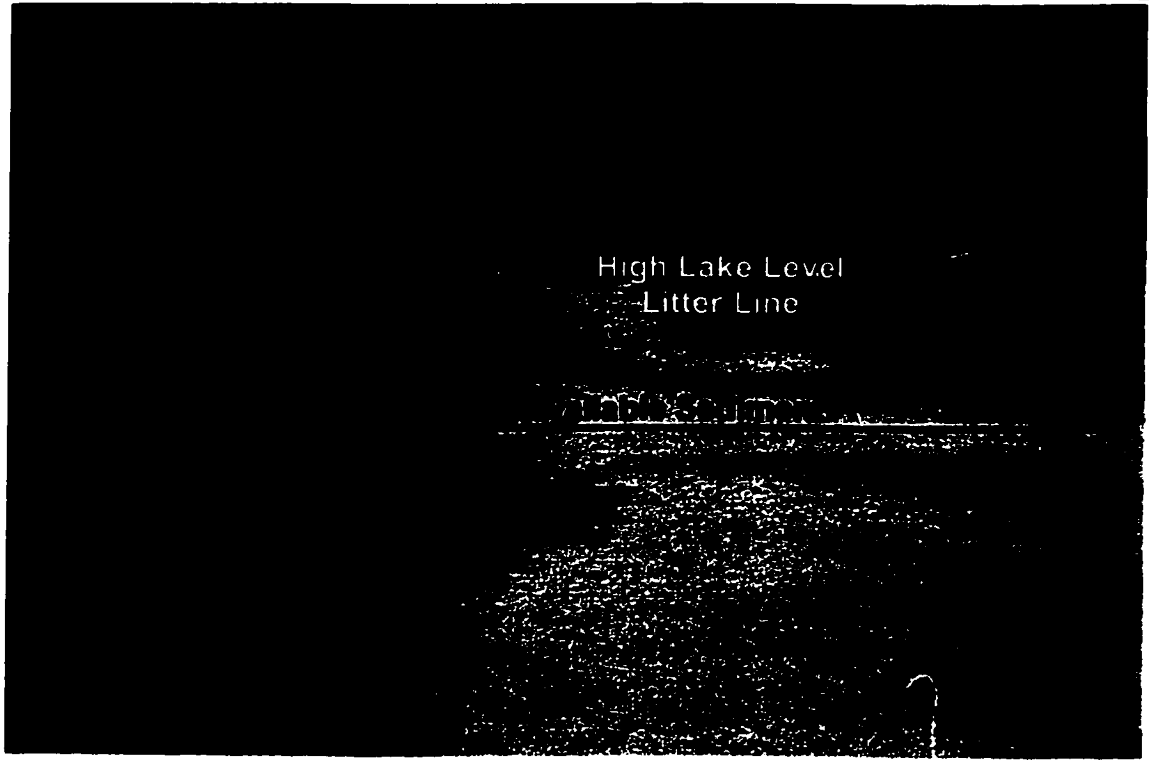


Figure 5.1 - Study Site beach view looking northeast. This photo was taken at the beginning of the low lake level study period. During the study period, the lake levels dropped, and an even larger sediment supply area evolved. The high lake level period litter line is still present as indicated in the photo. The total beach area was did not extend much further lakeward, or left on this photo. New deposition on the lakeward side of the foredune ridge and new marram growth is beginning.

a large amount of beach litter. The saturated sand, as well as the litter cover, left the sediment very hard to transport. Therefore, very little sediment could be transported into the system landward of the foredune during the high lake level period During the low lake level period, the large beach had readily transportable sediment available to move into the dune system into the foredune and further landward. The fine grained sediment from the beach was deposited lakeward of the foredune ridge, building a ramp over the foredune. The sediment created a more gradual slope for beach sediment to climb over the foredune ridge. The new beach sediment was transported and deposited on the lakeward side of the foredune ridge. The building of the foredune ridge was described in the volumetric analysis, indicating a great amount of deposition landward and lakeward of the foredune ridge. This beach sediment was then available to enter the trough blowout system.

Although the finer grained sediment moving through the system was much higher during the low lake level period, there was a slight increase in grain sizes being captured during the low level study. The second summer season revealed a decrease in sediment moving into the lower traps. As well, there was overall net erosion in this lag area around the lower traps found both by the erosion pin data and the volumetric analysis of this area. These points all can be explained by the increase in vegetation growth on the foredune ridge, especially the landward portion of the foredune ridge. Personal observation indicates that the new *Ammophilia breviligulata* on the lakeward and the landward side of the foredune is entrapping a large amount of sediment that would otherwise move right through the system. Although the sediment being captured was not as fine during the 2000 summer compared to the 1999 summer, the sediment was much finer than the sediment moving through the high lake level period (Table 5.1).

Trap	High Level Summer 1995	Low Level	
		Summer 1999	Summer 2000
1	0.50	1.98	1.75
2	0.85	2.08	2.00
3	0.25	2.00	1.58
4	1.20	2.22	1.93

Table 5.1 - Comparison of grain sizes for lower traps. (Values expressed in phi sizes.)

The change in sediment supply, as indicated by the grain size comparisons, is supported by the sand trap volume data indicating that there was more sediment moving through the system during the 2000 summer period compared to the high lake level period. The finer grain sized sediment suggests that the sediment was still coming from the beach source.

As well, the finer grains from the beach are more readily transported compared to the larger grains left on a deflated surface. The new beach sediment supply includes both larger and smaller grained sediment. At the time of the study though, the average beach grain size was still very fine because the fine grains had not yet been winnowed out of the total sand supply. The finer grains transported more easily over the foredune and were continuously transported through the blowout. During the high lake level study, the finer grains were not as abundant as a result of the winnowing of the finer grains. There was no supply to replenish the fine grains entering the blowout. Therefore, much stronger winds would have been necessary to move the sediment through the blowout. This explains the much smaller total sediment capture during the high lake level period.

Erosion pin measurements and the volumetric analysis revealed that there was definite erosion through the throat of the blowout during the low lake level study (Figure 5.2). A similar erosion pattern is revealed in the pin measurements during the high lake level study (Figure 5.3). The average change for the 12 lower pins is -4.54 cm and –2.55 cm for the high and low levels periods respectively. During both periods, the highest erosion occurred in the upper slope (pins nine - twelve) decreasing approximately 10 cm in elevation.

High erosion rates continue up the slope at the upper traps. This was noted during the low lake level period in the erosion pin results, as well as in the volumetric analysis. The highest erosion rates were found at this location by both research methods. The sand trap data indicate that there were very high transport rates through this area, suggesting

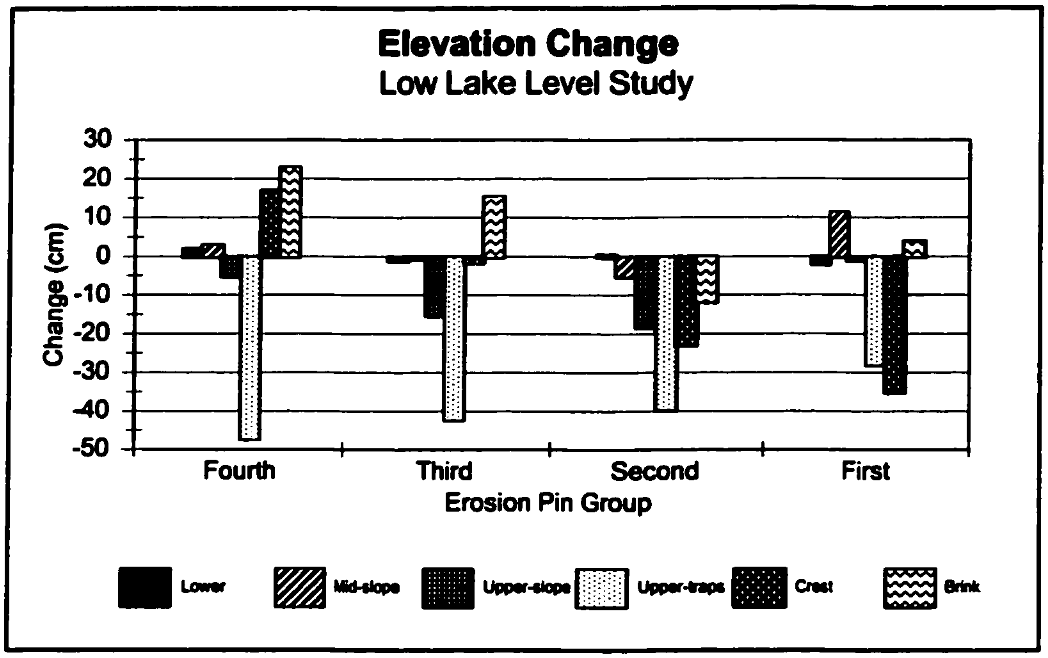


Figure 5.2 - Erosion pin measurement of elevation change during the low lake level study period. (Pin number representation: Lower, 1-4; Mid-slope, 5-8; Upper-slope, 9-12; Upper-traps, 13-16; Crest, 17-20; Brink, 21-24.)

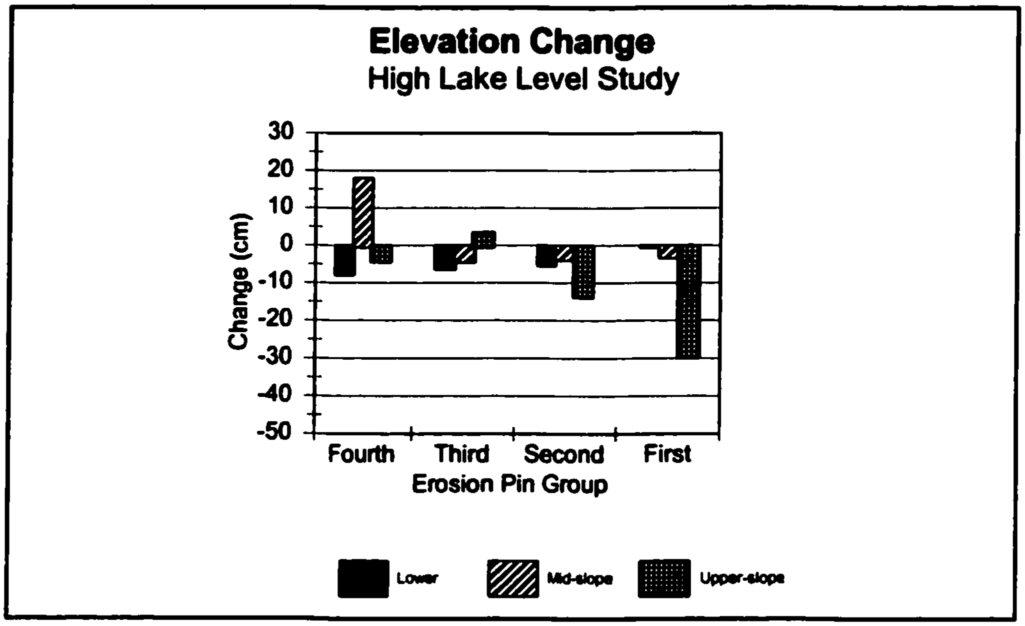


Figure 5.3 - Erosion Pin measurement of elevation change during the high lake level study period. (Pin number representation: Lower, 1-4; Mid-slope, 5-8; Upper-slope, 9-12.)

that large amounts of sediment could be eroding from the upper-slope to the traps. The crest pins, still within the same area defined for the volumetric analysis, experienced high erosion rates as well.

The last row of erosion pins, just beyond the blowout crest or on the brink, indicate that deposition is occurring on the landward side of the blowout. The volumetric analysis assists in confirming the idea: There was a large amount of deposition landward of the crest of the blowout. This landward area of the blowout accumulated over 100 m^3 of new sediment during the low lake level study period, compared to there being almost no building of the backdune during the high lake level period. This was indicated by the lack of deposition located adjacent to a row of pins that trace the base of the landward side of the blowout (Byrne, personal communication).

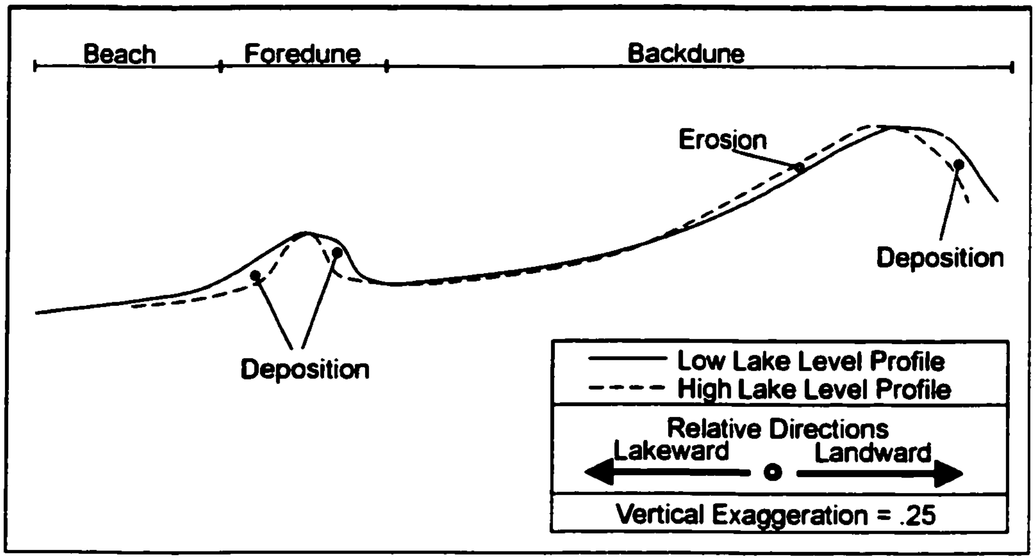


Figure 5.4 - Study site cross-section. Labels are given to areas discussed in the summary. The diagram points out major areas of erosion and deposition.
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5.3 Chapter Summary

Through comparing and combining the results of the different methods for measuring the morphology change, a clear picture of the blowout's morphology change has been presented. The data obtained from these methods reinforce the thesis conclusion. Although the high lake level study period did not have a volumetric analysis portion, nor did it have the upper pin data, the data still presents the variations in morphology changes that occur during the high and low lake level periods.

6.0 CONCLUSIONS

6.1 Introduction

This chapter will discuss the limitations of this research, and the possible implications that the limitations have for the final conclusions. The research conclusions will be listed, and what these conclusions mean for Pinery Provincial Park dunes and coastal dunes experiencing shoreline changes. The chapter will conclude with ideas for future research that can use this thesis for background information, and expand upon these ideas.

6.2 Limitations of Research

With all research there are limitations. The biggest limitation in this study was not having an on-site meteorological station. A comprehensive examination of wind speeds and directions at the study site during both the high and low lake level study periods would have greatly improved the study. An aeolian study was not done because there was no in situ wind data for the high lake level study, and therefore a comparison could not be made between the two study periods. Nevertheless, on site wind data would have added further insight into the sediment transport pathways from the beach, over the foredune, and through and over the blowout.

This study's original intention was to focus on changes to the trough blowout, and how the change in beach sediment supply may have affected the morphology changes. It became apparent during the study that the foredune, the intermediary between the blowout and the beach plays a crucial role in the sediment flux through the blowout. Erosion pins on the beach, lakeward of the foredune ridge, on the crest, and landward of the foredune ridge, would have greatly complemented the study. Unfortunately, these pins may easily be disrupted by vandals. These 'markers' would draw attention to the area which may lead to more human activity disrupting the natural processes on the foredune and through the blowout throat. Sand traps on the foredune ridge would have provided a good estimate of how much sediment was passing over the dune relative to the lag area and at the crest of the blowout as well. A series of upper pins during the low lake level study would have been very valuable to use as a comparison tool between the two study seasons. As well as upper pins being available during both studies, and erosion pins on the foredune, more pins on the landward side of the blowout crest would have contributed more information to the morphological changes of the whole sediment transport system. The volumetric analysis offset these shortcomings.

Due to the concentration of trees at the mid-slope of the backdune, a complete accurate map of the backdune has yet to be completed. Until this is done, estimating the total deposition of new sediment into the backdune area is very difficult to complete. Different mapping techniques would have to be employed to make a complete map of the area covered by vegetation.

The sand traps used in this study were used to replicate Byrne's (1997) study. It was important to use the exact same sand traps, erosion pins, and use this equipment in their same locations so that a comparable data set would be generated. Unfortunately, scouring and erosion around the sand traps, as well as the migration of sand lobes through the blowout, forced the traps to either capture excess sediment, or miss trapping some of the moving grains. The trap imperfections occurred during both studies.

Another limitation to this research was controlling faunal, especially human, activity in the blowout. Not being at the site every day makes it very difficult to determine how much human activity is occurring on site. Although there was no sighting of any park users or habitants in the study area, human and animal tracks were occasionally found in the blowout. No formal documentation was recorded of faunal activity, or possible effects caused by faunal activity in the blowout.

6.3 Research Conclusions

6.3.1 Data Summary

The following points summarize the data collected and the changes to the morphology of the study site;

- more sediment was transported landward through the blowout during the low lake level study period,
- the sediment moving through the blowout was much finer during the low lake level period indicating that more sediment moving through the system was coming from the beach as opposed to sources within the blowout,

- erosion occurred through the throat of the blowout during both study periods, but more so during the high lake level study period,
- the foredune ridge is expanding lakeward and landward while the lake levels remain low,
- rapid deposition is occurring landward of the crest of the blowout.

6.3.2 Contribution to Literature

Most beach supply studies focus entirely on the resulting morphological changes to the foredune. This study provides insight into a changing beach sediment supply, and the direct effect supply changes have on coastal dune blowouts. Some of the ideas of sediment supply change can be used to predict changes when lake levels rise as opposed to lower, thus creating a negative beach supply.

The potential for global climate change makes this research more beneficial: Regardless of the time scale, the research can be used to assist in predicting long-term sand dune changes where average water levels change at much slower rates, such as coastal sand dunes exposed to sea level rise. In the case of the Great Lakes, where climate change is predicted to lower average lake levels over the next 100 years, this research provides a glimpse into potential future changes to the Great Lake dunes.

This research adds new information to the relatively small amount of cold region dune literature. There has been very few geomorphology studies that compare seasonal sediment transport in sand dunes where there are periods of freeze-thaw, as well as snow and ice cover. This study provides further insight into the morphological changes sand dunes undergo in a cold climate location.

Calculating sand dune volume changes by comparing consecutively surveyed maps has not been presented in the literature. The methods employed in this study, (calculating areas of erosion and deposition by comparing maps at different temporal scales, supported by erosion pin and sand trap measurements,) offer a new way to study sand dune morphology.

This study expanded Byrne's (1997) data base on sand dune morphology change in a cold climate region at Pinery Provincial Park. The data collected during this study will help to build a long-term database that can be further analyzed in forthcoming studies on Pinery sand dunes. This information can help to make informed management decisions at Pinery as well as other cold climate locations.

6.3.3 Recommendations for Coastal Dune Management

Coastal dunes are constantly under pressure from urban expansion, tourism, mining, and recreational development. As more pressure is placed on dune systems, there is a need to make more informed management decisions. This research provides insight into erosion and deposition during different sediment supply periods. During time periods in which there is a positive sediment budget, managers can seize the opportunity to try to initiate new management strategies:

- promote the building and/or growth of foredune ridges,
- re-introduce native vegetation that thrives in sediment deposition environments to assist in stabilizing dunes,

- stabilize areas in backdunes which are experiencing high erosion.

Coastal managers should take advantage of a positive sediment budget to build dune ridges because it is the best form of natural coastal defence. Managers can introduce vegetation growth or other physical forms that decrease air flow and promote sediment deposition. Dune stabilization measures can be used in backdunes as well. This study proved that there is more sediment moving through the dune system, from beach to backdune, when there is a positive sediment supply. Erosion may be controlled beyond the foredune ridge by capturing sediment with vegetation that thrive in depositional environments. The system could be further stabilized by encouraging the growth of successive species that would continue to help contain the sediment , as well as reduce the air flow through the dune.

Pinery Provincial Park's shoreline will undoubtedly continue to experience fluctuating Lake Huron levels in the future. Park planners could exploit the positive sediment budget while the lake levels remain low to increase the protected area around the dunes. Educating park users to avoid trampling any new vegetation, especially the vegetation beginning to migrate further lakeward is essential. This will promote the growth of a larger foredune. If the lake levels rise, and a negative sediment budget on the beach ensues, the backdunes and their vegetation will be better protected by a larger foredune ridge.

If the Park would like to stabilize backdune erosional landforms, such as the blowout in this study, the best opportunity to do so would be during low lake levels. The best time to plant pioneering species like *Ammophilia breviligulata* and *Calamovilfa* *longifolia* which excel in sediment deposition conditions, would be during the low lake levels because of the higher rates of sediment transport and potential for deposition through the dunes.

6.4 Future Research

There are many potential avenues for investigation suggested by this thesis. The most valuable form of research will be to further develop a long term data base for the study site. The lake levels will continue to change. Documenting the sediment transport during different lake level periods will produce a more precise understanding of sediment transport through the backdunes as sediment supply changes.

A detailed aeolian study at this research site would be very valuable in predicting sediment transport patterns within the blowout. A study that would take place over various seasons and in many different wind conditions (speed and direction) is necessary to fully understand the air flow and sediment pathways through the blowout.

As ground survey methods have become easier and less time consuming, compiling data sets for volumetric analysis has become an increasingly effective method for detailed monitoring of larger sand dune systems. Creating large scale three-dimensional data sets for calculating areas of erosion and deposition is an enticing new method for analysing dune morphology changes. Continued mapping at this study site, encompassing a larger area, and collecting more data points would be very beneficial for detailed site volumetric analysis. Collecting three-dimensional data may be performed by using new remotely sensed data techniques such as LIDAR-Light Detection and Ranging

(Quinn *et al.*, 1995). Side-scaning aeroplane LIDAR techniques could facilitate the collection of very accurate, very high resolution, three-dimensional data sets over entire dune systems. Current LIDAR technology can calculate total biomass over areas as well. Biomass calculations would be very beneficial for estimating the vegetation density, and the effect the vegetation cover has on controlling beach sediment transporting into the backdunes. However, the technology is very expensive, and there are very few companies in North America that have the ability to conduct LIDAR data collection. Ultimately, physical geographers can continue field research by using current mapping techniques without the aid of the most expensive data collection techniques, and still broaden coastal dune geomorphology literature.

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8.0 APPENDICES

APPENDIX 8.1 - Sediment Captured

all volumes in grams of dried sediment

Trap	6/17/99	6/27/99	7/11/99	7/26/99	7/30/99	8/6/99	8/17/99
1	15.3	2	26.6	6.5	63.6	65.4	9.6
2	32	17.6	52.4	25	262.9	428.5	27.3
3	34.7	3.7	30.5	11.6	12.3	22.9	16.5
4	70.4	51.9	34.5	75	8.3	9.8	106.3
5	176.9	71.1	33.6	12.8	85.4	95.4	149.8
6	4295	191.2	4817.2	4664.8	3991.8	4053.4	4730.9
7	237.4	39	5958.6	60.4	34.4	39.9	154.5
8	2371.5	72.9	3543	5858.2	154.6	133.9	4160.7

Trap	8/31/99	10/1/99	10/11/99	10/21/99	11/6/99	11/18/99	12/2/99
1	15.3	61.6	133.2	6.4	61.9	11.5	33.8
2	35.1	87.7	198.3	29.4	181	83.4	76
3	29.4	40	39.3	27.5	20.3	5.8	42.5
4	226.2	47.8	181.7	344.8	59	344.8	67.1
5	35.8	225.5	284.9	263.1	208.3	81.8	95.9
6	3334.2	5158.4	5923	4875.6	3941.2	4469.8	4773.2
7	153.9	247.7	561.3	1897.7	316.7	2096.9	252.7
8	5167.7	4601.1	5848.1	385.2	415.9	84.1	327

Trap	12/12/99	12/23/99	1/3/00	1/14/00	1/25/00	2/5/00	2/20/0
1	89.1	269.9	156.8	66.8	609.3	24.5	7
2	667.7	1162.6	60.3	1918.1	2072.7	13.7	21
3	35.7	82.2	57.9	67.9	80.7	2.1	0.2
4	403	12.5	103.1	216.1	629.1	11.9	5.2
5	68.2	129	386.7	550.9	1349.9	471.3	0
6	4262.1	4817.1	4181.3	3945.3	4286.4	217.4	1259.6
7	24.9	94	446.6	3410	87.6	18	398.1
8	11.6	305.1	89.5	669.5	3968	55.5	35.4

Trap	3/06/00	3/18/00	4/1/00	4/24/00	5/12/00	5/24/00	6/2/00
1	223.8	20.8	22	14.8	21	83.7	3.5
2	1743.8	125.6	144	69.7	49.8	986.4	49.7
3	78.7	62.8	21.8	36.3	16.9	56.8	7
4	251.7	304.9	11.9	148.8	40.6	6.7	4.7
5	1878.1	1188.5	56.7	818.9	609.7	853	62.8
6	4812.9	5453.8	5329.4	5199	5382.4	5349.8	1070.1
7	162	237.1	143.8	118.2	372.1	4793.1	370.6
8	228.1	93.5	157.9	82.6	186.2	264	533.3

Trap	6/12/00	6/23/00	7/6/00	7/20/00	8/5/00	8/18/00	8/31/00
1	23.3	6.3	13.2	14.7	0	21.5	21.5
2	68.4	8.5	18	55.3	32.1	36.3	68.4
3	80.3	27.2	14.4	23.2	9	11.1	20.1
4	11.8	3.4	10.6	26.5	20.7	3.9	24.6
5	1691.6	32.2	64.6	430.1	191.4	457.2	648.6
6	4344	248.6	1418.8	4987.6	5110.5	5054	10164.5
7	817.8	21.3	319.9	4419.5	375.2	217.6	592.8
8	3029.3	179.8	357.7	411.5	79.2	774.1	853.3

APPENDIX 8.2 - Erosion Pin Measurements

Pin #	6/17/99	6/27/99	7/11/99	7/26/99	7/30/99	8/6/99	8/17/99
1	62.5	62.5	63.5	64	64	63.5	64
2	55.5	55.5	56.5	56	56	56	55
3	59	59	60	60	60	60	60
4	44	45	46	46	46	45	45
5	38	38	39	38	38	38	39
6	65	64.5	65.5	66	66	65.5	66
7	55	55	56	56	56	56	56
8	63	62.5	63.5	64	64	63	64
9	54	54	54.5	54	54	54	55
10	86	86	87	88	88	87.5	90
11	93	92.5	95	94	94	94	97
12	75	75.5	77	71	76	75	75
13					73	70	70
14					69	69	71
15					53	56	45
16					60	88	88
17					65	65	65
18					74	75.5	76
19					69	67	51
20					78	77	77
21					59	58	59
22					81	79	80
23					70	69	68
24					84	83.5	83

Pin #	8/31/99	10/1/99	10/11/99	10/21/99	11/6/99	11/18/99	12/2/99
1	64	64	64	64	64	55	64
2	56	56	56	56	56	56	55
3	60	60	60	60	60	60	60
4	44	44	44	44	44	45	44
5	41	39	39	39	38	33	33
6	65.5	65	65	65	66	67	67
7	55.5	55.5	55	56	56	55	56
8	64.5	64	65	64	64.5	65	64.5
9	55	54	54	53	54	55	54
10	92	92	93	92	92	96	94.5
11	94	99	99.5	99.5	100	106	108.5
12	74	70	70	69	71.5	77	76
13	70	71	69.5	69.5	71	70	70
14	66	69	70	69.5	75	78	82
15	40.5	51	55	57	64	65	69
16	89	91	88	88.5	88	90	90
17	65	65	68	67.5	68	75	75
18	77	73.5	77	76	84	84	86
19	43.5	46	37	46	71.5	39	54
20	76	74	75	76	58	46	46.5
21	41.5	59	60	60	65.5	66	67
22	81	73	75	73	80.5	80	83
23	71	67	66	64	66	52	49
24	83.5	82	81	81	86.5	78	73

Pin #	12/12/99	12/23/99	1/3/00	1/14/00	1/25/00	2/5/00	2/20/0
1	64	63	64	64	56.5	52	45
2	56	55	55	55	43	44	39
3	60	59	59	59	59	58	53
4	44.5	43	44	44	32	32	25
5	33	33	32	32	19	16	17
6	67	66	67	67	56	55	50
7	56	56	55	55	55	54	49
8	64	64	63	63	55	54.5	50
9	55	54	55	55	54	55.5	56
10	94.5	94	94	94	96	96	97
11	112	110	110	110	105	106	96
12	77.5	80	83	83	81	75	72
13	71	75	77	77	79	82	85
14	81	83	83	83	88	89	88
15	70	74	77	77	82	82	81
16	91	91	93	93	83	93	89
17	77	76	78	78	82	83	76
18	85	84	83	83	82	84	84
19	67	74	75	75	73	71	74
20	42	50	46	46	8	76	23
21	68	68	68	68	59	66	63
22	86	86	82	82	78	81	79
23	46	47	46	46	45	44	41
24	76	78	81	81	67	69	60

Pin #	3/06/00	3/18/00	4/1/00	4/24/00	5/12/00	5/24/00	6/2/00
1	64	64	64	64	64	63.5	63.5
2	54	55	55	55	55	55	55
3	59	59.5	59.5	59.5	59.5	59	59.5
4	43.5	44	44	43.5	43	42	42.5
5	30	32.5	32.5	33	33	33	33
6	67.5	67.5	67.5	67	67	67	67
7	55.5	56	56	54.5	54.5	54.5	54.5
8	62.5	63.5	63.5	62	63	62.5	63
9	55	55.5	55.5	55	55.5	55	55
10	96	96	96	95.5	96	96	96
11	110	110	110	111	112	111.5	111.5
12	80	75	75.5	77.5	77	78	79
13	92	81	84	81	82.5	81.5	82.5
14	88.5	87	87	87	88.5	93.5	93.5
15	79	79.5	79.5	81	77.5	81.5	82
16	93	91	91	91	91.5	92	92.5
17	82	82	82	83	84.5	84.5	83
18	84	84	84	84	83.5	82	85
19	78	71.5	71	78	63	70.5	70.5
20	38	40	46	41	41	46	46.5
21	67	67.5	67	67	66	66	66
22	85	85	85	87	85	78	79
23	48	61	61.5	61	60	60	61.5
24	76	76	76	75	74	75	73.5

Pin #	6/12/00	6/23/00	7/6/00	7/20/00	8/5/00	8/18/00	8/24/00	8/31/00
1	63.5	63.5	64	63.5	64	65	64	64
2	55	55	55	55	55	55	55	55
3	59.5	59.5	59.5	59	59.5	59.5	59.5	59.5
4	42.5	42.5	42.5	42.5	42	42.5	42.5	42.5
5	33	33.5	33.5	33.5	33.5	33.5	33.5	33.5
6	67.5	67.5	67.5	67.5	68	68	68	68
7	58.5	55	55	55	55	53	55	55
8	62.5	62.5	62	62	62	62	62	62
9	55.5	55	55	55	55	55	55	55
10	95	95	96	97.5	98	99	99	99
11	110	112	111	112.5	111.5	112	112	112
12	80.5	78	77.5	76.5	75.5	76	76	76
13	94	84	82	79	80	80	83	83
14	82	94	93	94	95	94	94	94
15	82	82	81.5	82	82	81.5	79	79
16	92	93	93.5	92	93	93	93	93
17	85	84	83.5	85.5	85.5	82	86	86
18	79	80	80.5	80	81	87	82	82
19	67.5	66.5	66.5	63.5	62.5	63	62	62
20	49	49	49	49	49	49.5	49	49
21	65.5	65	65	64	64	63	63.5	63.5
22	81	81	81	79	79.5	83	83.5	83.5
23	62	61	61	61	60.5	61	61.5	61.5
24	75	75	74	73	73	70	70	70

APPENDIX 8.3 - Sample Wind Resultant Calculation*

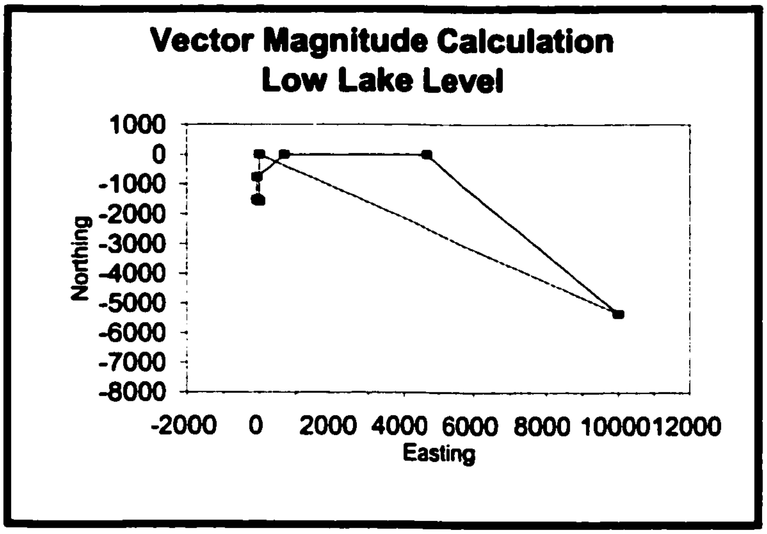
**as described by Landsberg (1956) and Jennings (1957)*

j Beaufort	Speed Class	Vj Class Mid-poin	Vt 16 km/h	(Vj-Vt)3	N	NE	E	SE	S	SW	W	NW
					n, number of occurances							
3	12-19	18	16	8	0.0058	0	0	0.0106	0.0356	0.0231	0.0135	0.0135
4	20-28	24.0	16	512	0.0635	0.0029	0	0.0365	0.1788	0.1067	0.1106	0.1702
5	29-38	33.5	16	5359.4	0.0279	0	0	0	0.0087	0.0212	0.0327	0.0971
6	39-49	44.0	16	21952	0.0048	0	0	0	0.001	0.0019	0.0048	0.0202
7	50-61	55.5	16	61630	0	0	0	0	0	0	0.0048	0.0038
8	62-74	68.0	16	140608	0	0	0	0	0	0	0	0
				b =	1.51	0.01	0.00	0.08	0.73	1.04	3.81	7.27

s = scaling factor of 10 to the -3

b = length of individual vectors

Dir Angle	cos of Angle	sin of Angle	Yi	Xi	x	y	mag	
					0	0		
0	1	0	1571	0	0	-1571		
45	0.7071	0.7071	4.3416	4.3416	-4.3416	-1575.3		
90	0	1	0	0.001	-4.3426	-1575.3		
135	-0.7071	0.7071	-58.11	58.11	-62.453	-1517.2		
180	-1	0	-754.58	0	-62.453	-762.63		
225	-0.7071	-0.7071	-764.32	-764.32	701.87	1.6872		
270	0	-1	0	-3962.6	4664.5	1.6872		
315	0.7071	-0.7071	5346.4	-5346.4	10011	-5344.7	-5344.7	
			5344.7	-10011	0		0	
					10,-10	-10,-10	-10,10	10,10
					-0.4904	-0.4904	-0.4904	-0.4904
					-28.097	-28.097	-28.097	-28.097
					118.1	118.1	208.1	-28.097



Vector Magnitude Calculation
Low Lake Level